ANGLIA RUSKIN UNIVERSITY

ACOUSTIC ANALYSIS AND TUNING OF CYLINDRICAL MEMBRANOPHONES

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ABSTRACT

FACULTY OF SCIENCE AND TECHNOLOGY
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ACOUSTIC ANALYSIS AND TUNING OF CYLINDRICAL MEMBRANOPHONES

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This research scientifically investigates the setup and tuning of cylindrical membranophones as musical instruments. To date there has been very little quantitative analysis of drum tuning with respect to performance sound, studio recording and music production.

Digital signal analysis has been used to quantify a number of acoustic factors related to drum setup and tuning. This is concerned with the evaluation of a drum's free vibration once excitation has occurred.

Novel analysis of membranophone response is performed with respect to tuning an 'equalised drumhead'. Such analysis has not previously been performed on cylindrical drums with two heads. The findings show that it is indeed possible to tune a drum to a chosen, uniform frequency response and to a quantified accuracy. With reference to previous, non-scientific literature, the fundamental frequency of each drum in the modern drum kit is shown for the first time to be objectively tunable to correspond to a musical pitch.

The research also investigates the role of the resonant head in tuning cylindrical drums. Unique analysis of the interaction between the two membranes shows for the first time that the ratios of the modal frequencies present in a drum sound are not fixed and can be manipulated to more desirable ratios. The fundamental frequency present is shown to be the same for both batter and resonant heads due to the strong coupling effect of the (01) modes. Furthermore the current research shows how this ability to manipulate the frequencies present in the drum can be extended to the drum kit as a whole and how the envelope profile of cylindrical drums with two heads can be manipulated via tuning and damping. This research therefore provides an original contribution to the knowledge of drum tuning for both scientific and musical purposes.

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Chapter 1

Introduction

1.1 The need for research into the tuning of cylindrical drums

Although much is known about the acoustics of many Western orchestral musical instruments, percussion instruments remain among the least researched. Of the literature published about the acoustics of percussion instruments only a small portion is on membranophones. Membranophones are musical instruments where sound is produced by the vibrations of a taut membrane. The term ‘drum’ can vary greatly in meaning. Any instrument with a drumhead stretched over a shell and struck can be termed a ‘drum’. This includes any membranophone with one head or two, with cylindrical shells, near-cylindrical shells, bowl-shaped shells, and anything in between. However, for the purposes of this research, unless otherwise specified the term ‘drum’ is used to refer to any membranophone with a tensioned drumhead both sides of a cylindrical shell, which forms an air-resonant chamber, an example of which can be seen in Figure 1.1. These cylindrical drums, namely the snare drum, tom drums and kick drum, are easily recognised as the main components of a modern drum kit and their construction is further discussed in Appendix A.

This thesis discusses the acoustics and tuning of the drum. It concentrates on the acoustic response of the drum, how tuning mechanisms affect the drum response and whether a scientific drum tuning method can be determined both for an individual drum and for the drum kit as a whole.

Until recently, scientific literature on the acoustic drum has been limited, with early research concentrating on the physics of the drum. One early study was conducted by Charles Henzie who discussed the concept of ‘stroke length’ (Henzie, 1960). The ‘stroke length’ was defined as the distance between the stick at the top of its arc and the drum’s surface, and this was used to control the strength of strikes on a drumhead. Henzie concluded simply that there was a direct correlation between the amplitude and duration of a snare drum sound. More theoretical work, such as vibration analysis of percussive instruments, has been carried out by Thomas Rossing (Rossing, 1982), (Rossing et al., 1992), (Fletcher and Rossing, 1998), (Rossing and Fletcher, 2004), (Rossing, 2005). Rossing has summarised much of his work in his recent book “Science of Percussion Instruments” (2005). Rossing notes that “relatively little material has been published on the acoustics of percussion instruments” (Rossing, 2005, p.1).

Chapter 2 reviews scientific research on membranophones. Rossing suggests the lack of scientific research could be because “the sounds of percussion instruments change so rapidly with time, their study and analysis require equipment that wasn’t widely available until quite recently.” (Rossing, 2005, p.vii) or it could be that “percussion has been slow to develop and be utilized in Western Art music; hence, the lack of Western scientific interest in these instruments” (Kvistad, 2000, p.v). The lack of research into the tuning of cylindrical drums with two heads may also be down to the fact that some, including Rossing, class them as instruments of indefinite pitch. James Blades notes, however, that the tom drum does possess a pitch (Blades, 1992, p.370). This can readily be seen in the spectrum of the sound produced by an arbitrarily tuned tom drum as shown in Figure 1.2. Much like timpani, a hemispherical drum with a single membrane, shown in Figure 1.3, the pitch and waveform of the drum will change depending on how and where the drum is excited. However, it is significant that the timpani is tuned to a definite pitch corresponding to a note on the musical scale whereas there is doubt as to whether popular drums can, or should, be tuned to pitch. In this thesis the opinions of expert scientists and musicians will be discussed and evaluated.

The standard approach to tuning the drum is by alteration of the tension of the drumhead; however, the tuning status is evaluated with respect to the pitch and timbre. Similarly, the scientific method of tuning a guitar, for example, is to determine the pitch produced and give feedback as to whether the note produced is either too high, too low, or correct, given a particular tuning reference. Although it is the tension of the guitar string that is being altered to produce the desired note the tension itself is relatively unimportant. The same can be said of the tom drum in tuning. The actual tension of the heads is less important than the resultant sound and response. Unlike a guitar, where only frequency is important in tuning, the acoustic drum is more complex, requiring both frequency spectra and attack and decay profiles be manipulated in order for the drum to be considered in tune. This is due, in part, to the significant effect the two heads have on the sound produced by the drum. The current research scientifically investigates methods that provide quantifiable feedback to musicians on the frequency spectrum and waveform envelope of the drum in order to achieve a desired tuning.

Tuning cylindrical drums is considered something of a 'dark art' amongst many drummers and there is a lack of scientific understanding of the tuning process or a definition of in-tune. No suitable closed-loop system for tuning drums has been marketed and it is common to find drummers who are unable to tune their drum kit properly and have a lack of understanding about how their drums should be tuned (Toulson et al., 2008).

As a popular subject, much has been written on drums, although most of the work is not of a scientific nature as the following chapters will discuss. Chapter 3 discusses the literature to date on drum tuning. Here the majority of literature is of a popular or journalistic nature, and this thesis discusses experimentation to put scientific fact to these subjective opinions. There seems to be no clear-cut method of tuning or

Figure 1.1: Photograph of a tom drum.

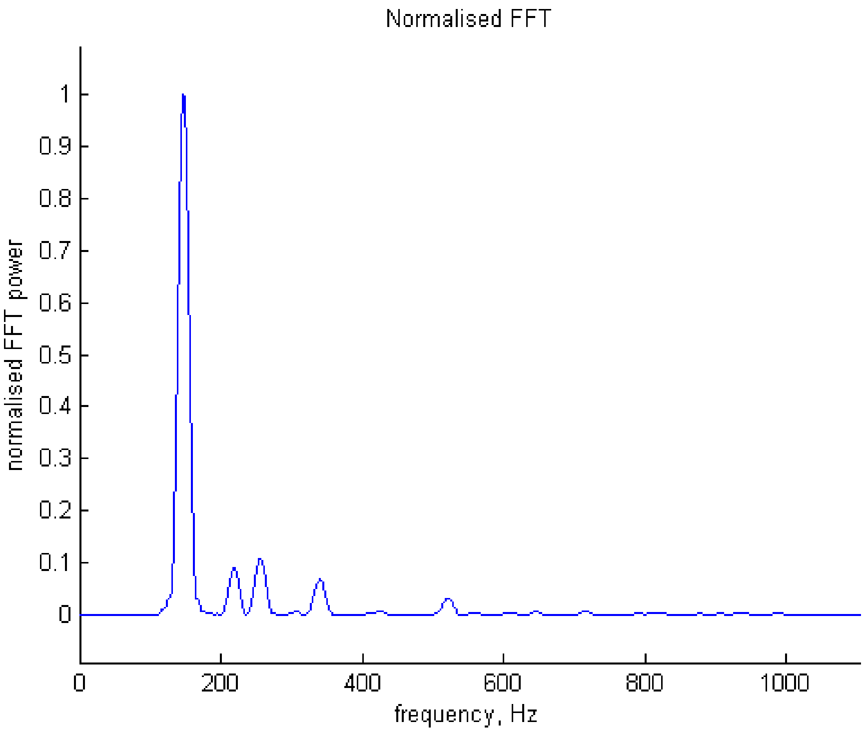


Figure 1.2: Frequency spectrum of an arbitrarily tuned 30-cm tom drum struck in the centre.

controlling the sound produced by a drum, nor a clear definition of what an 'in tune' drum should sound like. There are various methods to get to a state where the drum 'sounds good'. It is this subjectivity that makes the drum so difficult to analyse scientifically. Yet without some consistent basis for analysing drums there will always remain flaws in practical experiments on the acoustic drum. Without understanding how the drum was tuned, or why the drum was in tune, the tuning of the drum will always be an unquantified variable in experiments.

Whatever the reason for a lack of previous research, percussive instruments are now being actively researched. Worland (2010), for example, has performed modal research on the tuning of a single drumhead. There has been research into the classification and automatic transcription of snare drum sounds (Tindale et al., 2004*b*), (Tindale, 2004) through to research on how percussionists hit their instruments; the movement strategies and expressions played (Dahl, 2000), (Dahl, 2003), (Dahl and Friberg, 2007). This indicates that now there is both the technology and need to further investigate membranophones.

The current research aims to further the scientific knowledge of drum tuning with respect to how musicians currently choose to tune their instruments, thus providing new information on how drums are tuned in a musical setting, as opposed to tuning to an 'ideal' or theoretical basis.

1.2 Aims, objectives and framework

The conceptual framework for this research is to generate new knowledge on the subject of drum tuning that is of merit to both scientific and research communities, working to bridge the gap in the understanding of acoustic drums. The research investigates the tuning of cylindrical drums with both heads in place. The aim of the research is to evaluate a quantifiable tuning method by analysing a drum's free vibration under natural excitation.

Figure 1.3: Photograph of a timpani.

The overall objective of this thesis is to provide understanding towards a quantifiable and deliberate methodology for tuning acoustic drums. This has been produced by first reviewing scientific literature on acoustic drums, and reviewing popular literature on the subject of tuning drums. This review highlights the gap between the scientific knowledge of the acoustic drum and the application of knowledge - the tuning of cylindrical drums by percussionists.

Experimental procedures have been designed and tested in order to be able to fully investigate these knowledge gaps and to answer research questions through observation and analysis of experimental data.

This knowledge has been used to develop further experiments in order to provide further evidence and understanding. With further questions and gaps in knowledge clearly identified in order for future research to be performed rather than spreading the scope and content of this thesis too widely.

The focus of drum tuning in application is to produce a desired sound. Therefore, the analysis methods used to generate new knowledge should focus on the desired output of the tuning, that is the sound produced by the drum. Although physical response of the drum or its component parts may be of interest to the scientific community, they do not help bridge the gap between scientific and musical understanding of how a drum is tuned. The signal analysis methods used in this research provided quantifiable data for use in scientific research, and visual feedback to aid with drum tuning, rather than being a suitable method for one community or the other, for example holography or interferometry are useful from a scientific standpoint, but less relevant to musicians, likewise many percussionists make use of the Tama Tension watch to aid with drum tuning, however it is less useful as a scientific tool.

Initial experiments performed on mode shapes produced by a drum, as seen in Appendix B provided useful information on mode shapes and frequencies; however they did not provide a type of information that aided drum tuning. Direct analysis of the sound produced by the drum produced consistent and expected results during testing, and a greater degree of information and feedback in a shorter time-frame than would have been possible with other methods.

1.3 Scope of the thesis and contributions to knowledge

Popular literature suggests that a standard drum tuning method exists and attempts to define such a method can be found in many drum tuning guides, for example those by Gatzen (2006), Johnson (1999), Nicholls (2003*c*) and Ranscombe (2006*a*).

There is scope for research on the tuning of cylindrical drums which avoids subjective terminology and instead focuses on the objective acoustic (scientific) response of the instrument with relation to tuning options.

The current research addresses:

- The tuning of cylindrical drums with two heads in place.
- The acoustic response of the drum as measured by microphone and software analysis techniques.
- The physical tension of the drumhead as measured by the Tama Tension Watch.
- The relative tuning of the batter and resonant drumheads.
- The tuning of a drum kit with a range of drums for different genres.
- Values of decay time for a drum where damping materials have been added.

Related questions which are outside of the scope of the thesis include:

- Non-cylindrical membranophones, for example timpani.
- The effect of the drum shell design on the timbre and spectrum of a drum.
- The effect of the type of drumhead on the timbre and spectrum of a drum.

- The effect of the presence of snare wires on the timbre and spectrum of a drum.

This thesis aims to produce one definition for in tune, namely that a uniform frequency response around the perimeter of the head is a preferable aspect for tuning. The research also explores the possibility of tuning to musical ratios. Here there is scope for future research on whether certain musical modal ratios are preferable to others.

Due to the subjectivity of popular music and the desire to produce a variety of sonic effects there are often a variety of tuning methods for musical instruments. For example, it is possible to state that EADGBE is the standard tuning for a guitar, for many people it is the only tuning system they use, making use of a variety of sound effects in their sonic approach to produce a variety of sounds. Other guitarist use EADGBE less often, as one of a number of tunings. Likewise, with a modern drum kit there are different methods and focuses for achieving a desired sound.

The research shows that it is possible to produce a uniform response for the (11) mode around the perimeter of the drumhead and that the (01) mode is consistent for the drum as a whole, regardless of which head is excited. The research proves that it is possible to manipulate the ratio between modes, in particular tuning (01) and (11) to a more harmonious relationship. These factors can be combined to produce a standard method for tuning drums.

The main findings of this thesis are that:

- The drum can be tuned in a quantifiable manner so that the (11) mode is identical around the perimeter of the drumhead. This was applied to cylindrical drums with either a single or both heads in place.
- When the tuning of the drumhead to a uniform response around the perimeter was achieved via the quantative method used a smooth decay profile was observed.
- The (01) mode exists for the drum as a whole and will be excited regardless of

whether it is the batter or resonant head which is hit. It was observed to remain within 1% regardless of which head was struck and differences in membrane type for the two heads. This is expected given the acoustic theory by Rossing (2005, pp.26-30) outlined in Section 2.2.

- The modal ratios present in a drum with both heads in place are subject to the tuning of those heads. Careful tuning and head choice can be used to manipulate those ratios, and it has been proven that the (01) and (11) modes can be tuned such that they form the ratio 1:1.5.
- The knowledge outlined above can be applied to individual drums and a whole drumkit to provide a consistent tuning methodology.

1.4 About this thesis

It has been noted that there has been little research on cylindrical percussion instruments with much of the academic research performed being of a largely theoretical or observational basis with little output of interest to musicians. Gatzen states that:

> "As much as I like to talk about the technical aspects of drum physics I find this type of information confusing to most drummers. Practical information is far more effective..."
>
> Gatzen (2006)

The current research will make use of both current scientific knowledge and popular understanding of drum tuning to provide further knowledge on the tuning of the instrument that is of merit to both the scientific and musical communities.

Chapters 2 and 3 review the scientific literature and popular understanding on the tuning of cylindrical drums.

Chapter 4 discusses past research on membranophones, and outlines the novel method used in the current research for analysing the sound produced by an acoustic drum.

Experimental procedures and results which answer the specific knowledge gaps identified in Section 4.3 are discussed in Chapters 5, 6 and 7. These chapters explore the issues regarding achieving a uniform frequency response around the perimeter of the drumhead and the tuning of the batter and resonant drumheads in order to achieve a more desirable frequency profile. They also discuss tuning the drum kit as a single instrument, and controlling the attack and decay profiles.

A critical evaluation of the current research, and conclusions drawn can be found in Chapter 8. These conclusions include the fact that a uniform response around the perimeter is achievable, that the ratios between frequency components in the drum spectrum can be manipulated into a more harmonious relationship, and that there is a strong coupling between the batter and resonant drumheads resulting in a consistent fundamental frequency in the drum spectrum not dependent on which head is struck.

Future work highlighted throughout the research is outlined in Chapter 9. The current research indicates a wide scope for potential future research. This is not limited to the fields of science and technology, but also has applications in the fields of psychoacoustics or music.

Chapter 2

Previous research and analysis of percussion instruments

2.1 Acoustic terminology with respect to percussion instruments

In order to perform research on the acoustic drum it is first necessary to understand the prior scientific knowledge. This chapter clarifies the scientific terminology, provides an outline of the theoretical understanding of the drums, highlighting the limitations of experimentation, and finally discusses the psychoacoustic implications of considering the drum as an 'unpitched' instrument and the relevance of this to drum tuning.

When considering the sound produced by any instrument, it is important to have clear definitions for pitch and timbre. Pitch is related to prominent components of the sound's frequency spectrum, while timbre is related to the strength of partials in the signal as discussed by Howard and Angus (1996, p.112). Two instruments may produce the same pitch yet the timbre of the instrument can be radically different.

2.1.1 Loudness

The percussion family are amongst the most powerful instruments in an orchestra, with a bass drum being capable of having a whole spectrum peak power output of about 25 Watts compared, for example, to a flute which typically gives a peak power of 0.06 Watts (Sivian et al., 1931). Rossing (2005, p.23) gives the peak acoustical power of the bass drum as 20 W, or a sound pressure level (SPL) of 122 dB at a distance of 1 metre in a free field. The sound pressure level and the term ‘loudness’ should not be confused. Whereas the SPL can be measured, loudness is subjective. Loudness was first evaluated by Fletcher and Munson (1933) who described loudness as “the magnitude of an auditory sensation”. Due to the nature of the human ear, very low and very high frequencies will not appear to be as loud as those from the frequency bands where our ears are most sensitive, despite these sounds having the same SPL. This effect can be seen in the equal-loudness contours of the human ear (Fletcher and Munson, 1933) where loudness contours are shown with relation to SPL and frequency, although there was later debate as to the accuracy of these curves (Robinson and Dadson, 1956). The International Organization for Standardization (ISO) has revised its standard curves creating a new set of curves standardised as ISO 226:2003 (ISO, 2003), further discussed by Suzuki et al. (2003).

Although it is useful to have an understanding of the term loudness, loudness itself is not a significant factor in this study. Instead discussion tends towards focusing on the strength of impact on the drumhead as opposed to how ‘loud’ a drum sounds.

2.1.2 Pitch

For harmonic waveforms, the pitch is closely related to the frequency of repetition of the waveform. However, this does not explain the pitch of non-harmonic waveforms. The American National Standards Institute (ANSI) states that pitch is:

> "That attribute of auditory sensation in terms of which sound may be ordered on a scale extending from low to high. Pitch depends primarily upon the frequency content of the sound stimulus, but it also depends upon the sound pressure and the waveform of the stimulus."
>
> (ANSI, 1994)

Complex waveforms can be modelled as a sum of sine waves with different amplitudes and frequencies. The complete profile of frequency power defines the frequency spectrum of the waveform (Croft et al., 2001, p.707). A musical instrument produces notes that contain a fundamental frequency and higher-frequency partials. Harmonic tones are produced when these partials are integer multiples of the fundamental frequency.

Pitch is a subjective measurement, as opposed to the quantifiable value of frequency and the perception of pitch and its relation to frequency and musical notes are more fully discussed by Howard and Angus (1996). As pitch is a subjective measurement determined by a person's perception it is subject to similar misinterpretations as is common with optical illusions, for example Shepard tones (Howard and Angus, 1996, p.228) and the "missing fundamental", perception of a fundamental frequency that is not present in the sound (Everest, 2001, p.69), (Rossing, 2005, p.9). Further demonstrations of auditory illusions have been given by Deutsch (2010). The perception of the pitch of church bells has been investigated by Hibbert (2008) who notes that one issue with measuring pitch perception is the variation in results between listeners, stating "there is no absolute value for the pitch of a sound independent of a particular listener's ability to judge it".

Pitch perception is usually explained with reference to place or temporal theory. It is known that the basilar membrane carries out a form of frequency analysis, whereby different frequency components stimulate different places on the membrane. Howard and Angus (1996, p.120) discuss the following three methods as possibilities for determining the value of f_0 via place analysis:

- The brain locates the fundamental, f_0, component directly.
- The brain determines the minimum difference between frequency components.
- The brain determines the highest common factor of the component frequencies.

Since a tone with components at 200/300/400/500 Hz has a pitch corresponding to 100 Hz, the first hypothesis can be discounted. As the same pitch is heard with components at 100/300/500/700 Hz, the second hypothesis is also untrue. The third is generally accepted. Experiments by Schouten (1940) on slightly inharmonic tones indicate that pitch relates to the approximate highest common factor.

Temporal theory, as discussed by Howard and Angus (1996, p.128-132), "relies on the timing of neural firings in the organ of Corti which occur in response to vibrations of the basilar membrane". These firings are phase-locked to the vibration.

There are issues with both temporal and place theory. For example, place theory does not adequately explain the accuracy of pitch perception, the perception of pitch of non-harmonic sounds, perception of higher frequencies not resolvable on the basilar membrane, or pitches where all components are below 50 Hz (Howard and Angus, 1996, pp.124-128). Temporal theory cannot explain pitch perception where f_0 is greater than 5 kHz where phase locking no longer occurs (Howard and Angus, 1996, p.133). Models for pitch perception of complex tones combine both theories (Howard and Angus, 1996, p.133).

Schneider et al. (2005) note two types of listener in experiments on brain asymmetry and pitch perception, with some listeners predominantly perceiving a fundamental frequency while others focus on the higher partials. Miyazaki (2004) discusses listeners with absolute pitch, "the ability to identify the categories of musical pitch", and relative pitch, "the ability to perceive the pitch relationship in the musical pitch context such as musical scales and tonality". Miyazaki (2004) concludes that "absolute pitch may even be incompatible with relative pitch that is essential for music". Stevens (2004) discusses the role of culture and musical experience in the perception of pitch and the musical scale noting that “perception of mistunings by native Western listeners was influenced by both general musical acculturation and musical sophistication”. These studies indicate the extent to which listeners perceive pitch differently.

The current research concentrates on tuning method for cylindrical drums which are often regarded as being ‘unpitched’, for example by Rossing (2005, p.26). An overview of ‘pitched’ and ‘unpitched’ instruments, and their differences and similarities, is therefore necessary in order to understand the role of pitch in percussion acoustics. However, this terminology contradicts many other popular publications which indicate that cylindrical drums can be tuned and pitch can be chosen, for example by Johnson (1999, p. 6).

Rossing (2005, p.1) explains that drums which have an easily identifiable pitch include timpani and tabla, whereas conga drums, tom-toms and snare drums do not. It can be seen that those drums which are classed as instruments with a definite pitch have frequencies which are close to being harmonics of a fundamental frequency. This corresponds to Malu and Siddharthan’s views that “unless a majority of overtones in a particular sound are harmonic, the waveform will not be periodic and will not have a discernible pitch.” (Malu and Siddharthan, 2006).

According to Rossing, we “describe percussive sounds as having a ‘high’ or ‘low’ pitch even if they do not convey an identifiable pitch, but it would be more correct to describe this as high or low range or tessitura” (Rossing, 2005, p.1). However, some definitions indicate that the fundamental frequency is the most prominent attribute of pitch, and all instruments exhibit fundamental frequency characteristics. The current research, however, clearly shows that several prominent frequencies are observable; most notably the fundamental frequency and second partial.

The subject of perceived pitch is discussed extensively in the current research, as many percussionists talk about the pitch of their drums, of each drumhead, the shell, and of different areas of the drumhead. Often, in popular literature, the term pitch is used in a more casual sense than would be the case in a scientific context, so the current research makes a clear distinction between frequency response and pitch.

2.1.3 Timbre

Timbre is most often defined by what it is not, with McAdams and Bregman (1979) describing timbre as the “multidimensional wastebasket category for everything that cannot be qualified as pitch or loudness” whilst Egozy (1995) states:

> “The term musical timbre loosely refers to a sound’s color or textural quality. It is often described by the somewhat unsatisfying definition: that which distinguishes two different sounds of the same pitch, amplitude and duration.”
>
> Egozy (1995)

Timbre can be defined as:

> “that attribute of auditory sensation which enables a listener to judge that two non-identical sounds, similarly presented and having the same loudness and pitch, are dissimilar”
>
> (ANSI, 1994)

Johnson (1999, p.3) refers to timbre, with respect to percussion, as “the overall character of the drum, the distinct quality of the sound given by its overtones. The fact that one drum is ‘brighter’ vs. ‘warm’ is the timbre”. A single drum can produce a wide variety of timbres. Tindale (2004) developed timbre recognition algorithms to successfully recognise several different percussion sounds and stroke types.

The fact that pitch can be analysed as distinct frequencies present at any moment in time makes it simpler to analyse than timbre which is often a very descriptive way of describing sound. It is easier to scientifically justify that the drum produces the note ‘A’ than it is to say that the drum sounds ‘dark’ or ‘dry’.

2.1.4 Envelope

In many instruments waveform envelopes have four distinct sections: attack (A), decay (D), sustain (S), and release (R). This is called the ADSR envelope and is shown in Figure 2.1. The attack is the onset of the sound from zero amplitude until a maximum amplitude. The decay is then a period where the sound quickly drops to the sustained level. The sustain is the near-constant level following the decay where the note continues. The release is how quickly the note ends after excitation stops. Further discussion on wavetable synthesis and the ADSR envelope with respect to percussion can be found in Emsen et al. (2002) and Matapersad (2009). Due to the nature of percussion the envelope can usually be described as only having attack and decay, causing it to have an AD envelope as shown in Figure 2.2. The current research is predominantly interested in the attack and (20 dB) decay of cylindrical drums.

2.2 Vibrational characteristics of membranophones

2.2.1 Modes of vibration and circular membrane theory

The distinctive timbre of a membranophone is produced by complex vibrations producing inharmonic overtones (Rossing, 2005, p.2). The physics of acoustic drums can be partially described using circular membrane theory based on Bessel functions. Bessel functions are solutions to Bessel's equation and have been more fully discussed by Rossing and Fletcher (2004, p.69) in "Principles of Vibration and Sound".

Rossing (2005, p.6) discusses how each mode represents a resonant frequency based on the displacement of the membrane and can be defined by the pattern of nodes and antinodes on the membrane surface. Membranes do not vibrate in modes which have frequencies that are integers of the fundamental frequency. The standard terminology used by Rossing for describing the vibrational modes is (mn) where the vibrational mode has (m) nodal diameters and (n) nodal circles. The (01) mode is the fundamental

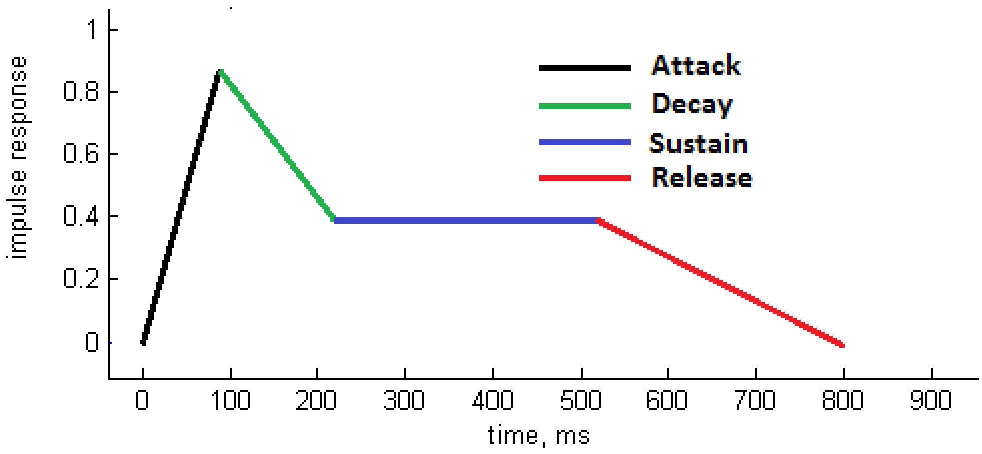


Figure 2.1: Attack, Decay, Sustain, Release (ADSR) envelope.

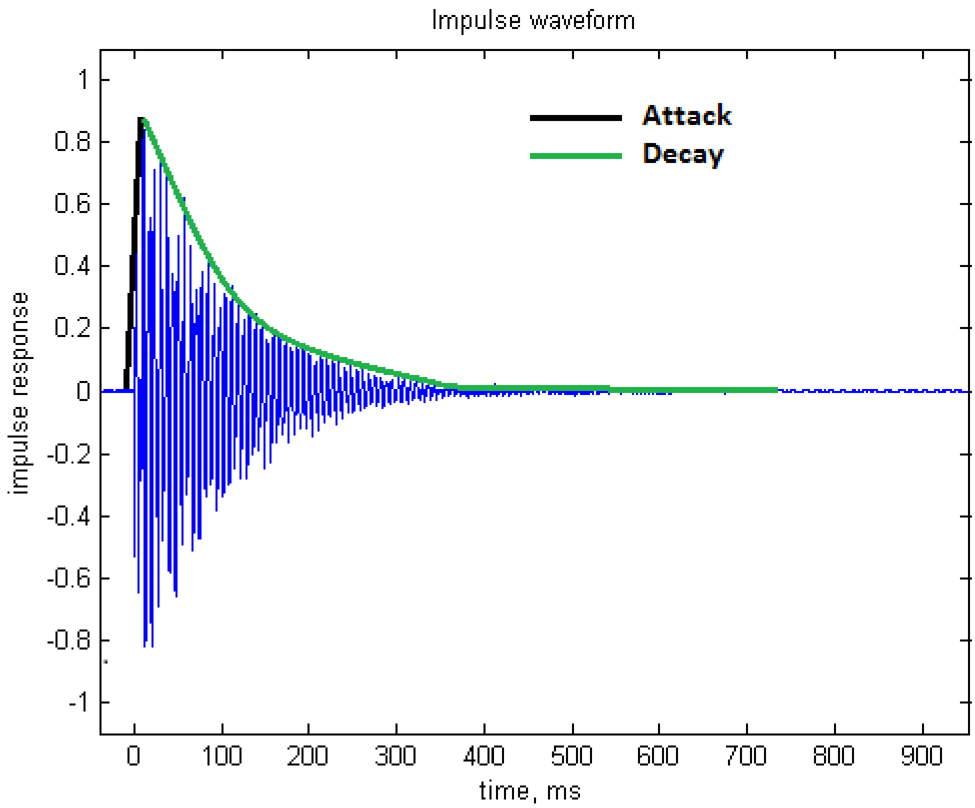


Figure 2.2: Attack and Decay (AD) envelope superimposed over a drum waveform.

mode and displaces most air. The (11) mode has a smaller displacement and is 1.59 times the frequency of the fundamental mode (Rossing, 2005, p.6). Figure 2.3 shows the first twelve modes of an ideal membrane. Russell (2006) has provided animated representations of the first four modes of an ideal membrane to aid the understanding of the motion of the membranes.

Fletcher and Rossing (1998, p.70) define an ideal membrane as one with no stiffness, with its oscillations depending on a restoring force supplied by externally applied tension. The mode frequencies of a real membrane are affected by air loading, bending stiffness, and stiffness to shear (Rossing and Fletcher, 2004, p.70). Whereas, in general, air loading lowers the modal frequencies, bending stiffness and stiffness to shear raise the modal frequencies, although should be noted that where the volume of air is confined, the axisymmetric modes will be raised in frequency (Rossing and Fletcher, 2004, p.70), (Fletcher and Rossing, 1998, p.75). Fletcher and Rossing (1998, p.75) note that the modal frequencies are most affected by air loading for thin membranes. In this thesis an ideal membrane refers to a circular membrane of uniform physical properties, which is perfectly flexible and is without air loading.

The vibrational modes of the ideal membrane are related to Bessel functions and the modal frequencies of a membrane are linked by the ratio of its tension T in newtons to its mass per unit area σ. The frequencies of the vibrational modes of an ideal membrane are given by:

$$f_{mn} = \frac{j_{mn}}{2\pi a}\sqrt{\frac{T}{\sigma}}$$

where j_{mn} is the nth root of the mth Bessel function, a is the membrane radius, T the membrane tension and σ the mass per unit area (Dahl, 1997), (Rossing and Fletcher, 2004, pp.69-70). The wave equation for an ideal membrane is more fully discussed by Rossing et al. (1992) and Rossing and Fletcher (2004, pp.69-70).

Worland (2010), citing Morse and Ingard (1986, pp.209-213), describes the analytical solution for the spatial part of the normal modes:

$$\Psi_{mn}(r,\theta)\sim J_m(k_{mn}r)\left\{\begin{array}{c}\cos[m(\theta+\phi_{mn})]\\ \\ \sin[m(\theta+\phi_{mn})]\end{array}\right\},$$

where $\Psi(r,\theta)$ is the displacement of the membrane as a function of the angular co-ordinates r and θ. J_m are Bessel functions, k_{mn} is found by $k_{mn} = w_{mn}\sqrt{\frac{\sigma}{T}}$ subject to the nth circular node $J_m\ (k_{mn}R)$ being equal to zero at the perimeter of the membrane where $r = R$. Angles ϕ_{mn} define the orientation of the modes containing nodal diameters. For $m = 0$ only the cosine solution is used (Worland, 2010). These equations define the patterns seen in modal analysis of a single membrane, as shown in Figure 2.3, later in Figure 4.6 and in a YouTube video demonstration by Russell (2009).

Rossing notes that “a membrane can be thought of as a two-dimensional string” (Rossing, 2005, p.6). The membrane is restored to its original state by tension from the edge of the membrane and the membrane can be tuned by changing tension. The vibrational modes of a membrane contain nodes and antinodes. An antinode is a “point, line or surface in a standing wave where some characteristic of the wave field has maximum amplitude” (ANSI, 1994) as opposed to a node where the wave field would have “essentially zero amplitude” (ANSI, 1994).

Mei (1969) has calculated mode shapes and frequencies of a circular membrane with arbitrary tension, whilst Worland (2010) investigated the (11) mode in drum tuning under non-uniform tension, where the (11) mode splits into two orthogonal modes. Worland (2010) discusses “frequency splitting”, where the (11) mode in a drum with a single head splits into two distinct frequency peaks. He states that:

> “Under ideal circumstances, the (11) mode produces a single frequency and occurs with its nodal diameter oriented in any direction.”
>
> Worland (2010)

This frequency splitting is also noted in experiments performed on a kettledrum by Rhaouti et al. (1999), along with the presence of beat frequencies when these split frequency peaks occur.

2.2.2 Coupled membranes

For cylindrical drums with two heads the acoustic characteristics diverge from the ideal membrane theory (Argo, 2002). This is due to the fact that the two heads interact through the drum shell and the mass of air within the drum causing a change in boundary conditions. Toms, the kick drum and the snare drum are cylindrical drums and therefore the vibrations of the drumheads are more complex than that of a single membrane. Argo (2002) claims that it is the individual resonances of the two heads, which vibrate at different frequencies, that causes a complex sound to emerge. Although the drumheads may have different modal behaviours for the higher modes of vibration it has been observed that the fundamental frequency will be consistent for both drumheads (Toulson et al., 2008).

Coupled heads have two normal modes of vibration, one in which the heads move in phase, and another where they move out of phase (Rossing, 2005, p.27), (Rossing, 2001). These modes are either asymmetrical or symmetrical, depending on whether the two heads are in the same mode but out of phase or in phase with each other respectively (Tindale, 2004). In Figure 2.4 Rossing shows that the modes of the snare drum display radial motion from the vibrations of the drumheads and enclosed air, as well as the up-and-down motion of the shell. Coupling between the heads can be seen in the (01) and (11) modes and shell motion is opposite to that of the drumhead at about 1% of the amplitude of batter head motion (Rossing et al., 1992). Rossing et al. (1992) also note a weak coupling between the (02) modes. Mode shapes for the 35-cm tom drum used in the experiments in this thesis can be seen in Appendix B. It will be seen that the (01) mode is most strongly excited by impact in the centre of the drumhead and the (11) mode by an impact around the perimeter of the head, as shown in Figure 2.5 and Figure 2.6. Where the drum is perfectly tuned it is hypothesised that there will be one mode of one frequency for the (01) mode, and that the (11) mode will also have one frequency. As asymmetry is introduced into the drumhead, the single (01) mode will be maintained, however the (11) mode will degenerate into two orthogonal (11) modes, each with different a frequency.

It is interesting to note the modal frequencies given by Rossing and shown in Figure 2.4; however, unlike those modal ratios shown in Figure 2.3, these frequencies can be manipulated by tuning the membranes.

Zhao (1990) used a two-mass model to describe the interaction between the two heads. The first mode of vibration of the snare drum was modelled mathematically. This model was for the snare drum without the snare wires activated.

Argo (2002) found that if two heads are tuned to the same fundamental frequency then partials will destructively interfere. Argo goes on to state that if the drum is slightly 'out of tune' more partials will be present:

> "Tuning can be achieved different ways with two heads. If both are the same, a harmonically consistent sound is created no matter the tension. If the bottom head is tuned lower or higher than the top head, the sound has many more harmonics [sic] available. The harmonics from the upper head are more apparent, so the tuning of the lower head can either add lower or higher harmonics to the mix."
>
> Argo (2002)

Research into the coupling between the two heads of a Japanese drum, a wadaiko, has been performed by Suzuki and Hwang (2008). The wadaiko is a barrel-shaped drum, rather than cylindrical, and their research concludes that "depending on the tension ratio of the membranes, the frequency and amplitude ratios of the coupled resonances change".

Theoretical research to date has focused on single-headed toms, and research into the interaction of the two heads on the drum response is very limited. Therefore further

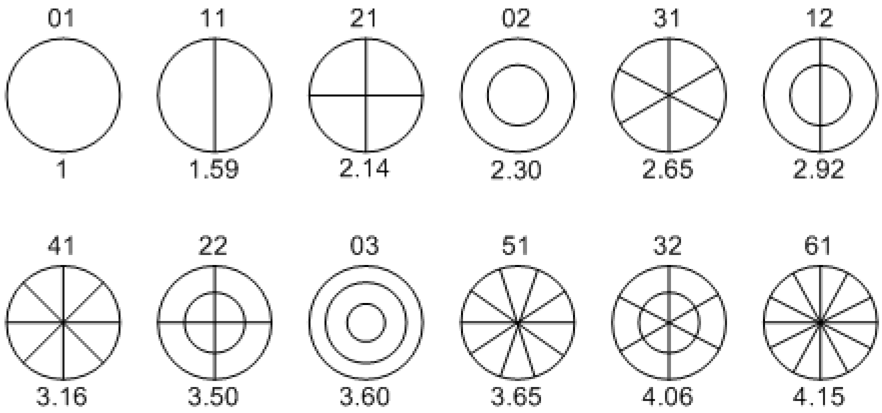


Figure 2.3: Vibrational modes of a membrane, showing radial and circular nodes and the customary mode designation. The number below each diagram gives the frequency of that mode compared to the fundamental (01) mode (from Rossing, 2005, p.6).

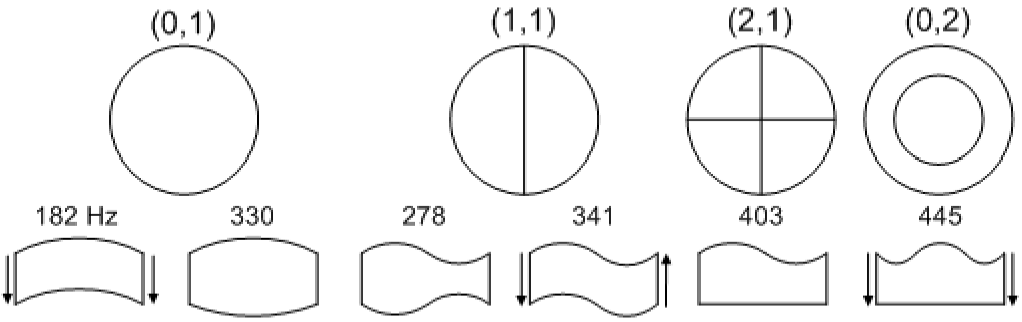


Figure 2.4: The six lowest resonances observed in a snare drum include two mode pairs based on the (01) and (11) membrane modes (from Rossing, 2005, p.28).

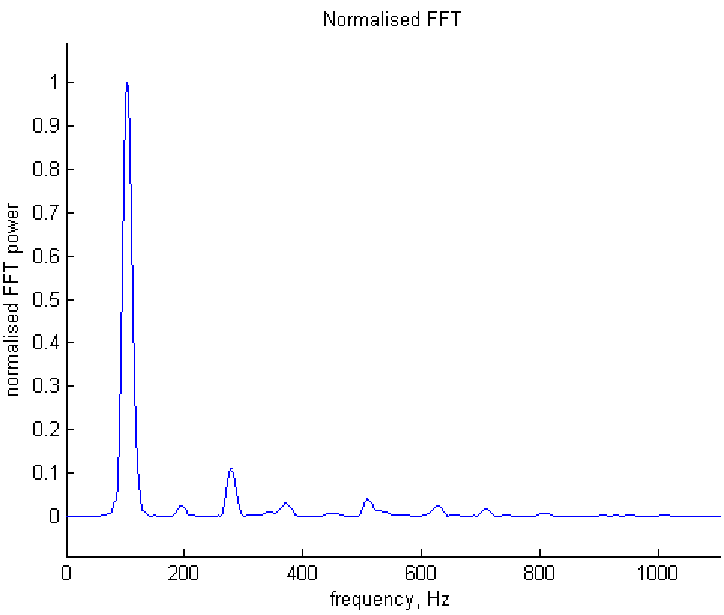


Figure 2.5: (01) membrane mode visible as a single 103.1-Hz peak in the spectrum when the drum is excited in the centre of the head.

research and investigation is required.

2.2.3 The drum shell

The vibrations in a drum shell are complex, as highlighted by Fletcher and Rossing:

> "The whole subject of shell vibration is so complex that we can outline only a few of the simplest cases and we restrict these to those that are relevant to musical instruments."
>
> (Fletcher and Rossing, 1998, p.92)

The drum shell is a hollow cylinder which is very thin compared to its depth and diameter. In the majority of the modes of the drum, the motion of the shell is significantly lower than the motion of the drumheads. There are, however, several modes where shell motion is appreciable.

Rossing states that there are two types of modes in a shell, extensional and inextensional modes. In an extensional mode elastic forces would cause a line drawn on the shell to change length during vibration (Rossing, 2005, p.83). The potential energy due to the change in shape of the shell and the kinetic energy present are proportional to the thickness h. The modal frequencies of the shell are independent of h. However, in an inextensional mode the potential energy is proportional to h^3 with the frequency being proportional to h. The lowest extensional mode and lowest two inextensional modes of a ring are shown in Figure 2.7. A drum shell can be considered to be a series of ring shaped elements and further discussion can be found in "Science of Percussion Instruments" (Rossing, 2005, pp.83-86).

It is far more complex to calculate the modal frequencies for higher modes of vibration with the bending and stretching of the shell also requiring consideration. It is worth noting that the cylindrical shell of a drum is not free at both ends and the shell can be constrained in a variety of ways, further complicating the model. A drum gripped

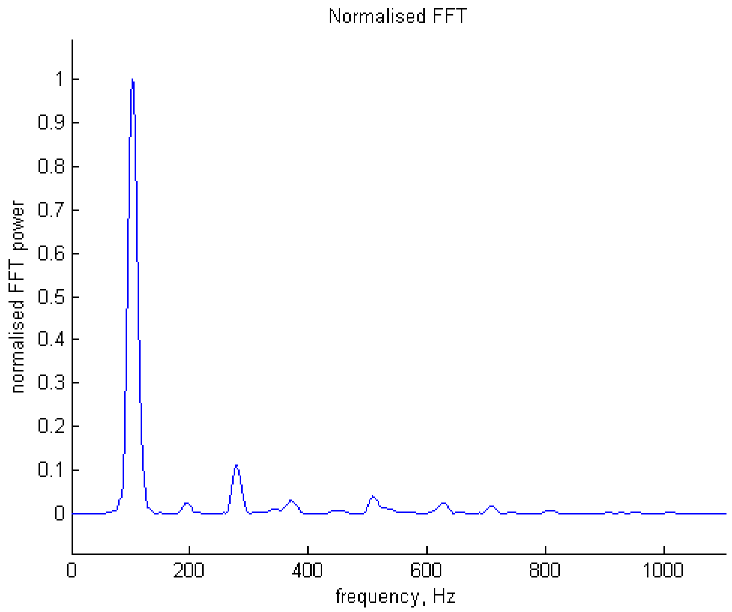


Figure 2.6: (11) membrane mode visible as a single 196-Hz peak in the spectrum when the drum is excited near the edge of the head.

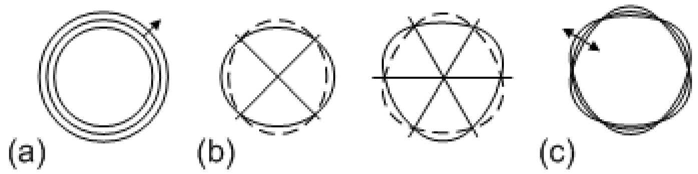


Figure 2.7: Vibrations of a ring: (a) Lowest extensional mode; (b)(c) Lowest two inextensional (flexural) modes (from Rossing, 2005, p.83).

by a stand can produce different decay rates from the same drum supported by a mount attached to the rims due to vibrations transmitted through to the supports. In vibrational modes where the shell moves in an opposite direction to the drumheads these factors become significant (Rossing, 2005, p.28). The energy changes in a snare drum are not just energy turned into the sound radiated, but also mechanical energy by vibrations lost through the supports. In fact, when the drum is supported on a drum stand the (01) and (02) modes of the snare drum decay faster than when it is supported by elastic cords (Rossing et al., 1992). Rossing et al. (1992) records the (01) mode for a drum supported by elastic cords as decaying at 35 dB/s when stuck in the centre, as opposed to 70 dB/s when supported by a drum stand.

Fletcher and Rossing (1998, p.95) state that, from a musical perspective, “cylindrical shells occur mainly as relatively rigid supporting structures for light membranes in drums”. Fletcher and Rossing (1998, p.95) note that the lowest extensional mode and nonextensional modes do not contribute appreciably to the sound radiated by a normal drum. Rossing (2005, p.30) notes several modes where the shell motion is appreciable for modes of a complete drum, the lowest of these modes is the (40) mode of the shell vibrating at 874 Hz, much higher than the frequencies of the (01) and (11) modes of the drumheads, which are the focus of this research.

The current research does not consider the variety of drum shell permutations. Indeed, Seymour states:

> “...although head choice and all the other materials used in a drum will affect the tone you’ll get from it, they won’t affect the basic principles of tuning the drum.”
>
> Seymour (2010)

2.2.4 Damping

Damping can be referred to as the rate at which vibrating systems dissipate energy (Hopkin, 2000, p.11). Fletcher and Rossing (1998, pp.53-56) discuss three types of damping for strings: air damping, internal damping and transfer of energy to other vibrating systems. For a drum where two membranes are coupled by a mass of air the damping produced by air loading is appreciable. Section 2.3.1 discusses the role of air loading and membrane stiffness in producing a more harmonic relationship between the (11), (21), (31) and (41) modes in timpani. The internal damping in a string is "a material property independent of the strings radius, length, or tension" (Fletcher and Rossing, 1998, p.55). For a drum, the internal damping would be the material properties of the membrane, independent of its thickness, diameter or tension. The mechanical transfer of energy from the drum to its surroundings has already been discussed in Section 2.2.3, where it was noted that modal decay rates of a snare drum are affected by whether it is rested on a drum stand or supported by elastic cords.

When choosing a drum kit there are a variety of methods of supporting drums, a variety of sizes, and physical properties which affect the damping of the system. However, when tuning a drum it is unusual to have further control over these variables and instead materials are often added to the drumhead in order to alter the properties of the drumhead to produce a desired decay rate or to minimise unwanted harmonics. These added materials can either be masses added at discrete locations around the drumhead, such as MoonGel (RTOM Inc., 2010), or 'damping rings' that add a mass around the perimeter of the drumhead, such as O-rings (Remo, 2010*b*). This is often referred to as damping the drums, and it is this addition of materials to the system which is the focus of the research in Section 7.3.

2.2.5 Head/membrane types and grades

The drumheads play an important role in the sound produced, as discussed in Appendix A.3. Deviations from the ideal membrane theory have been briefly investigated by Argo (2002) whilst Lewis and Beckford (2000) have investigated how changing the batter head of a snare drum affects the sound produced.

Different batter heads can help shape the timbre of the sound. Lewis and Beckford (2000) note how the spectrum differs between drumheads, with an Evans Genera Coated HD Dry drumhead producing a 'dark' sound due to it having less higher-frequency content, whereas a Remo Ambassador produced a 'brighter' tone due to more high frequencies.

Wheeler (1989) notes that the difference in thickness between the resonant and batter head can pose problems for researchers. Striking a drumhead at different distances from the centre will excite different frequencies as observed by Argo (2002). Argo also observed that as the tension on the drumhead decreases more modes become apparent.

2.2.6 Snare mechanisms

The snare mechanism on a snare drum has a significant effect on the sound. The snare wires are coupled with the snare head. This coupling is dependent on both the mass and tension of the snare head and the nature of the snares (Rossing, 2005, p.28).

If a snare drum is struck with sufficient force the snare wires will break contact with the resonant head and then return to strike the snare head producing the characteristic snare drum sound (Rossing, 2005, p.28), (Rossing et al., 1992). According to Rossing the snare tension is optimum when the impact between the snares and the snare head is greatest, i.e. they are moving at a maximum speed in opposite directions when they come into contact. There is also an ‘activation time’ for the snare wires in the drum due to the snare wires being on the bottom head and the drum being struck on the top head.

Blades (1992, p.370) discusses the effect of snare wires, quoting Forsyth (1955) and Piston (1955) who suggest that the pitch rises by as much as an octave whilst the snare wires are engaged. This seems to be a large rise in pitch, but the psychoacoustic properties of pitch, rather than frequency, may mean that many of the modal frequencies present in the drum are maintained, while the strength of individual frequencies are altered by the interaction with the snare wires, for example by the wires physically damping the (01) mode allowing higher modes to be more prominent.

Wheeler (1989), however, notes that the fundamental pitch of the snare drum does not change regardless of whether the snare wires are engaged or not although he does note that engaging the snare wires causes the length of the drum sound to decrease. Wheeler suggests that perhaps this shortened duration coupled with an increase in the amount of higher frequencies produced whilst the snare is engaged causes a psychoacoustic effect which causes people to hear a higher pitch.

It is interesting that many researchers use pitch and frequency interchangeably within their research. The contradicting statements by Blades (1992, p.370) and Wheeler (1989) indicate that there is still a wide scope for research on percussive instruments, both with respect to the frequency analysis and pitch perception of acoustic drums. Although this study focuses on the analysis of the frequency components produced when a drum is struck, research into the affect of the snare wires on the drum spectra is outside the scope of this thesis.

Initial experiments show that the fundamental frequency of the drum can change when the snares are activated, although these experiments did not rule out the possibility that the fundamental frequency can remain consistent in specific cases. Figure 2.8 shows the difference between the spectra produced by a snare drum with snare drum wires engaged and disengaged. One possible explanation for a rise in pitch when snare wires are activated is that engaging snare wires can increase an already very taut resonant head tension, causing the fundamental frequency to rise.

2.2.7 Pitch glide

Fletcher and Bassett (1978) discuss the tendency for the frequency components of a bass drum to change with time, concluding that “for a hard blow (large amplitude of vibration) the frequency starts higher and then decreases rapidly as the amplitude decreases”. Further research was performed on tom drums by Dahl (1997) and it was noted that a frequency shift occurs with a large stroke force.

Rossing explains that nonlinearities in membranes can cause a change in pitch over the duration of the sound (Rossing, 1982). This is due, in part, to percussive instruments vibrating with a relatively large amplitude. A simplistic model of the drumhead would would be that the tension varies during each cycle, hence a sort of frequency modulation would be expected. When a membrane is struck hard enough to produce a large amplitude the drumhead deflects further and the average tension of the head increases. This, in turn, causes the frequency to increase. Thus as the sound of a drum stroke decays the amplitude of vibration decreases, causing a slight drop in pitch with Dahl (1997) observing a change in fundamental frequency of up to 20 Hz although she notes that this “is usually perceived as a characteristic part of a strong impact rather than a glide in pitch”.

This ‘pitch glide’ is more prominent in drums tuned to a low tension where it takes less force to increase the tension of the drumhead. Figure 2.9 shows the shift in frequency spectrum, causing an increase in the perceived pitch of the drum, when the drum is struck with greater force.

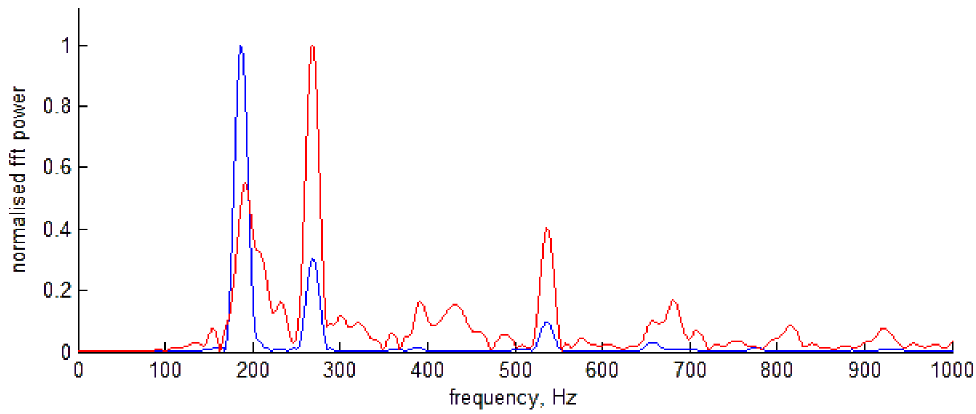


Figure 2.8: A comparison of the spectra of a 35-cm snare drum with snare wires deactivated (blue) and activated (red).

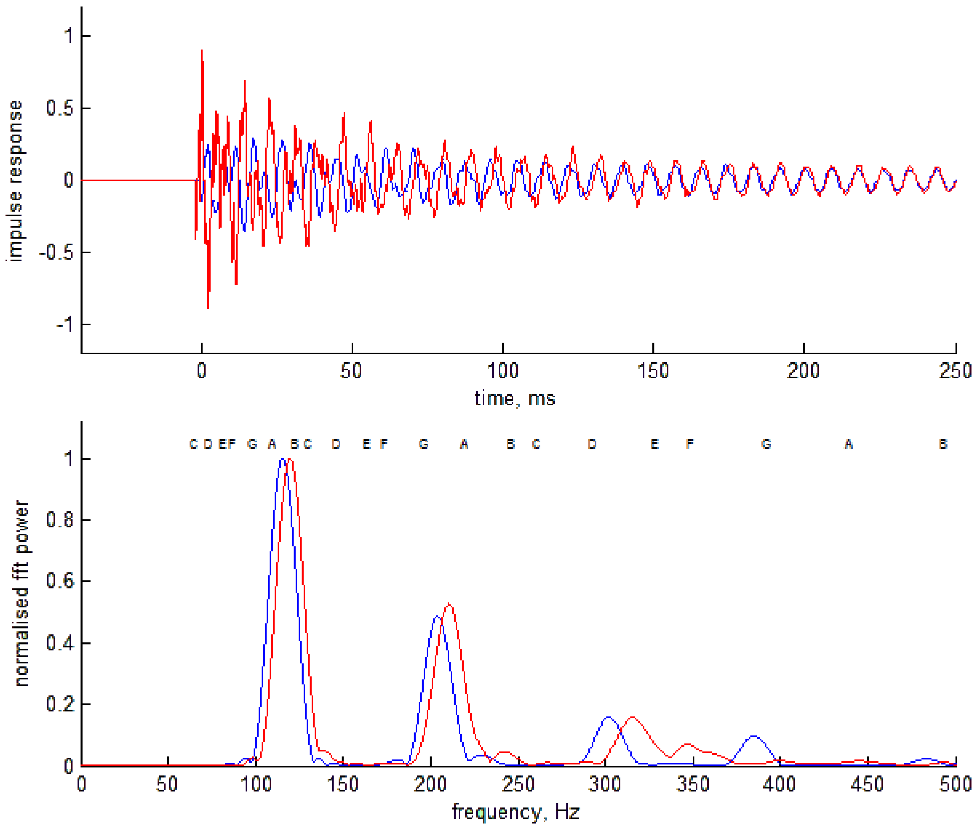


Figure 2.9: The pitch change present when a drum is struck with minimal force (blue) and an increased force (red).

2.2.8 Stroke and gesture effects

There are two main methods used by percussionists to strike a drum, either by using their hands, or by using another object such as a drumstick (Young and Fujinaga, 2004). The cylindrical drums in a modern drum kit (the toms, kick drum and snare) are all usually struck by a drumstick, although occasionally struck by a beater made of another material such as felt or by a brush made of an array of small metal, plastic or wooden sticks. The kick drum is struck by a beater often made of felt but occasionally of wood or rubber.

The drum is rarely hit in the same place with consistent force. Fletcher and Bassett (1978) concluded in their research on the kick drum that "the amplitude of each of the components (and thus the timbre of the sound) changes depending on the strength of the blow and the position on the membrane where the blow is applied". Research has been performed by Henzie (1960) and Tindale (2004) which indicates how different strokes provide a variety of results.

Henzie (1960) carried out experiments on how amplitude affects the duration of snare drum tones. Henzie concluded that the theory that greater amplitude of stroke length results in longer tone is partially correct but cases exist where greater amplitude does not result in a corresponding increase in duration. Henzie noted that this was due to the drumstick not leaving the surface of the membrane quickly enough, thus damping the drum.

It was observed by Dahl (2003) that the number of higher modes excited increased with playing strength, along with a decreased spectral slope for frequencies above 1 kHz. Dahl also observed a change in contact time between the drumstick and drumhead at different playing levels, with a contact time of 5.5 ms for a strong stroke and 8 ms for a softer stroke.

Tindale (2004) has shown that the way the drum is hit has an effect on the sound produced by successfully classifying a variety of strokes on the snare drum. This classification was achieved by recognising the ‘timbre’ of the snare drum. The seven different stroke types classified were rimshot, brush stroke, and five different stroke locations between the centre and the edge of the drumhead. Investigation into rim shots and brush strokes is outside the scope of this research.

It is interesting to note that Tindale (2004) concluded that different sizes of analysis window did not have any major effect on the overall recognition rate of stroke type and classification of stroke location data was successful with small window sizes of less than 2048 samples. The research also indicates that there are significant differences in the timbre produced by a drum struck at different locations with high recognition rates for the seven strike locations (Tindale, 2004).

2.3 The perceived sound of percussion

2.3.1 Percussion instruments traditionally classed as being ‘pitched’

The design of timpani, as described in Appendix A.2, helps change the inharmonic modes of the ideal membrane closer to a harmonic series. This is due to the mass of air in the drum lowering the frequency of vibrational modes especially those of low frequency, whilst the stiffness of the membrane raises the frequency of higher overtones (Rossing, 2005, p.7). Furthermore the air inside the kettle has its own resonances, which interact with the membrane (Rossing, 2005, p.7). A more in-depth scientific analysis of the timpani can be found in “The Physics of Musical Instruments” (Fletcher and Rossing, 1998, pp.584-598).

Table 2.1 shows how the ratios to the principal mode vary between an ideal membrane and timpani. Fletcher and Rossing (1998, p.595) note that it is the (11) mode of the drum which is often identified as the pitch of the drum, rather than the fundamental (01) mode. It is clear to see that the (11), (21), (31) and (41) modes of the kettledrum have frequencies that are closer to harmonics than that of the ideal membrane. Rossing states that the frequencies f_0, $1.5f_0$, $1.99f_0$, $2.44f_0$, where f_0 is the fundamental frequency, are close enough to a harmonic series of f_0, $1.5f_0$, $2f_0$, $2.5f_0$ to give the instrument a strong sense of pitch. It is interesting to note that the series is made up of partials with a missing fundamental frequency at $0.5f_0$ and some timpanists claim to be able to hear such a note when playing lightly (Rossing, 2005, p.8). Although not discussed it would be interesting to know the position of impact where this missing fundamental is most often heard. Tronchin (2005) speculates that this missing fundamental is often not perceived "because the intensity and duration of the harmonics are insufficient to enable the ear to grasp the harmonic spectrum".

As the (11), (21), (31) and (41) modes are almost harmonic of the $0.5f_0$ fundamental frequency it is preferable to excite these modes more strongly than the inharmonic (01), (02) and (03) modes. Timpanists will not strike the head centrally, exciting the (01) mode, and instead strike the drum somewhere between the edge and the centre to excite the pseudo-harmonic modes. Rossing suggests that this distance is approximately a quarter of the way from the edge to the centre (Rossing, 2005, p.8).

Pearl (2010) provide an overview of timpani tuning and suggest tuning the drum by lightly striking the head 5 cm from the edge, which would minimise the excitation of the (01) mode. Wessels (2010) notes that when tuning a timpani it is necessary for the drumhead to "sustain the same pitch at each tension rod". Wessels discusses listening to the "fundamental pitch (not the overtones)" of the drum, however notes that it is helpful to mute the centre of the drum, this indicates that Wessels considers the (11) mode to be the source of the pitch of the timpani, and that this frequency mode is focused upon when tuning. Blades (1992, p.349-358) discusses how it is necessary, when tuning, to test the pitch both at and between each tuning point, noting that timpanists make use of the second and third partials when tuning, describing one method for tuning as follows:

> "The timpanist utilizes the harmonics when tuning, principally the first harmonic above the nominal note, i.e. the fifth. The procedure is that of hum-

> ming the nominal and the fifth above(or other harmonics) into the drumhead at the playing spot. ...It is when the drum responds with a singing tone to the humming of these notes, that the timpanist regards the instrument as well tuned."
>
> Blades (1992, p.355)

Montagu (2002, p.120) however remarks on "the general lack of perception of pitch on percussion instruments, and this may have combined with the common difficulty for the untrained ear to recognise accurately the pitch of low notes" when discussing how composers have used timpani in the past. This seems to indicate that the distinction between 'pitched' and 'unpitched' instruments with regards to the percussion family is not so obvious as has been previously considered.

The Indian tabla conveys a strong sense of pitch. It uses a different method to that of timpani for forcing the inharmonic modes closer to a harmonic relationship. Instead of air loading, the drumhead is loaded with a paste. This paste is made up of starch, gum, iron oxide or other materials (Rossing, 2005, p.15).

There has been significant research performed into the acoustics of Indian drums by Raman (1935), recognising the first five harmonics of the drum being produced by the initial nine normal modes of vibration, with several modes of vibration having the same frequencies (Rossing, 2005, p.16). Malu and Siddharthan theoretically calculated the partials produced by the initial 14 normal modes and produced a table showing theoretical and actual data for the ratios of the Indian tabla (Malu and Siddharthan, 2006). They derived theoretical ratios for a continuously loaded tabla as $1.07f_0$, $2f_0$, $3f_0$, $4f_0$ and $5f_0$. Sathej and Adhikari (2009) present a mathematical model for Indian drums consisting of a membrane of non-uniform density, providing experimental, analytical and numerical values for vibrational modes of the dayan and bayan drums.

2.3.2 Cylindrical drums

The tom drum is classed as a drum of indefinite pitch by Rossing (2005, p.26). This is at odds with the views of expert musicians such as Steve Perkins who states that "with tuning, I like to do it melodically with a xylophone or marimba - I want to be able to make a melody out of the toms." (Rhythm Magazine, 2004*e*, p.72) and Geoff Dugmore who suggests that drummers should "tune the kit to the key of the song". Although the tom is classified as an instrument with an indefinite pitch that does not mean that its pitch is indeterminate (Blades, 1992, p.370). The indefinite pitch of the drum was investigated by Rossing. The inharmonic series of modes are displayed in Table 2.2 which also shows one method drummers use to force their drums into being closer to a harmonic series by adding patches of material to load the membrane. This indicates that although the tom and snare drums have weak harmonic profiles it is possible to tune the drum to behave as a more harmonic instrument.

It is apparent that cylindrical drums are often regarded in scientific literature as unpitched, though many studies clearly show well-defined partials. These may be inharmonic and so not add to the musicality of the instrument. However, sufficient evidence is available to show that such instruments can indeed have a chosen pitch and this can be manipulated by tuning as will be shown through this thesis. This is further evidenced by professional drummers such as Steve Perkins (Rhythm Magazine, 2004*e*, p.72), Gatzen (2006) and Brian Chase (Budofsky, 2009, p.56) who tune their drums to specific notes and keys. It can thus be envisaged that scientific analysis will aid the development of advanced methods for tuning and controlling the sound of an acoustic drum.

Mode	Ideal Membrane f/f_{11}	Kettledrum f/f_{11}
01	0.63	0.85
11	1.00	1.00
21	1.34	1.51
02	1.44	1.68
31	1.66	1.99
12	1.83	2.09
41	1.98	2.44
22	2.20	2.67
03	2.26	2.79
51	2.29	2.89
32	2.55	2.99
61	2.61	3.08

Table 2.1: Frequency ratios of an ideal membrane (without stiffness and air loading, as defined in Section 2.2.1) and a kettledrum (Rossing, 2005, p.8).

Mode	No Dot f/f_{01}	14cm Dot f/f_{01}
01	1	1
11	2.16	2.06
21	3.14	3.10
02	3.58	3.39
31	4.02	4.04
41	4.78	4.95

Table 2.2: Modal frequency ratios of a 30-cm tom with and without centre dots (patches of material) (Rossing, 2005, p.26).

Chapter 3

Tuning percussion instruments

3.1 Existing literature on drum tuning

The scientific knowledge of the acoustic drum has been discussed in the previous chapter. It is apparent that there are significant gaps in the scientific knowledge of the acoustic drum as a musical instrument. One of the most significant gaps involves the tuning of the musical instrument. It is debatable as to whether the data provided by researchers is indicative of all cylindrical drums or their drum on a particular day tuned in a particular way. In order to bridge the gap between scientific research and the ‘real world’ it is necessary to have scientific knowledge of how the instrument is used. It is also of benefit to the scientific community to be able to analyse acoustic drums which have been tuned in a methodical and scientific way. In science it is not enough to say ‘this was the case’; it is continuously necessary to expand on why this is the case. Scientific understanding of the ‘why’ in drum tuning is lacking. The current state of knowledge regarding drum tuning shall now be discussed.

It is apparent from the literature review that there is a wealth of knowledge on drum tuning within the musical community. This knowledge has not been translated into rigorous scientific research, with few key scientific papers on the subject discussing drum tuning.

3.2 Defining 'in-tune'

There are many methods of tuning a drum, and many ideas as to what constitutes a well-tuned drum, particularly those methods described by Ranscombe (2006*a*, p.95-96), (Ranscombe, 2006*b*, p.87-88). Some methods discuss tuning by achieving a uniform tension across the drumhead; others discuss achieving a uniform pitch. These methods can vary greatly and opinion is divided on the methodology used.

> "To properly play a drum head on a tom drum, the tension across the head in all directions must be approximately the same. By varying this tension, the drum's apparent pitch also changes."
>
> Argo (2002)

From a popular standpoint Nicholls, author of The Drum Handbook, states that drum tuning is incredibly subjective and goes on to say:

> "... drums are an instrument of non-specific pitch, with no absolute reference. You "tune" them until they sound right."
>
> Nicholls (2003*c*, p.120)

However even after stating that a drum has no specific pitch Nicholls (2004*a*) notes in a review of Aquarian drumheads that it was possible to get a "very clear note".

Obtaining the 'right sound' however can be difficult. Sullivan (1997) comments that when tuning timpani "even the best drum will not sound good if the differential tension adjustments around the counterhoop are not done with skill". The same can be said of tom, snare and kick drums. Tuning is of critical importance for achieving a desired drum sound.

With such a diverse range of ideas on drum tuning it is important to focus on one ideal and use that as a scientific standard. The focus of the current research is the tuning of cylindrical drums to a certain pitch and achieving a uniform tone around the head. The current research notes four predominant aspects of drum tuning: the pitch of the drum, clearing the drumhead, tuning the two heads relative to each other, and the envelope. All four aspects combine to make 'tuning' and it is apparent that some drummers place more value on one aspect of tuning the drums than another. Particular attention in the current research will be paid to the common attributes that drummers who tune to pitch describe as important.

3.3 The importance of drum tuning

There are many expert musicians who consider the tuning of the drum kit to be critical in making the drums sound good. Dave Passera, for example, states that "good heads, well tuned, are the basis of your sound." (Nicholls, 2003*a*, p.81). Many professional drummers such as Matt Sorum (Rhythm Magazine, 2004*b*, p.62) and Nick McBrain (Rhythm Magazine, 2004*c*, p.60) have clear ideas on the importance of drum tuning and how they tune their drum kits. However, it is very apparent that this knowledge has not yet been transferred into scientific knowledge through empirical research.

Novice musicians, however, often do not understand the importance of tuning their instruments, often choosing to replace drums, at a considerable cost, rather than replacing drumheads and correctly tuning their instruments (Nicholls, 2003*a*, p.81). Part of this reluctance may be due to the difficulty in tuning drums with Schroedl (2002, p.5) describing the drums as being "much more difficult and challenging" to tune than, for example, a guitar.

There are many types of drumhead, as discussed in Appendix A.3: single-ply, double-ply, varying thickness etc. The continuing production of such a wide range of drumheads is not purely a marketing exercise targeting drummers of different genres. There are significant and audible differences amongst different head types. These differences are always described in a very subjective manner. For example, drumheads are often described using adjectives such as "bright", "dry", "punchy" and "ringy" (Aquarian Drumheads, 2010), (Nicholls, 2004*a*), (Nicholls, 2004*b*). However, even without the added complexity of being able to choose different drumheads for any given shell, a pair of drumheads on a single shell presents many complexities and permutations that require further academic research.

> "A guitar player has all these different pedals and can change his sound, so why can't we? We've got a drum key, all we need to do is turn it and we've got a different sound."
>
> Tony Bourke (Rhythm Magazine, 2004*f*, p.24)

The importance of drum tuning in the studio is appreciable; for a recording project lasting 2-3 weeks 15-25% of the entire project can be spent on the drum setup (Toulson et al., 2008). A 'right first time' approach to recording the drum kit makes economic sense, as discussed by mix engineer Chuck Ainlay (Massey, 2002, p.280). Fixing the pitch of the drum via post processing is not always a viable option either, as it is only possible to enhance frequencies present in the original audio signal (Owsinski, 1999, p.32). This means that if the drums are tuned incorrectly then the only post-processing option available is to replace the drum sounds with triggered samples adding to the time of the mixdown process (Toulson et al., 2008). Some guides that discuss recording drums work on the assumption that the drum kit is in tune (White, 2007).

Proper drum tuning is not only essential for studio recording, but also for a live environment, with Brian Chase, drummer for the Yeah Yeah Yeahs, not only tuning his drums every day but also getting to events early to spend extra time tuning (Boxall, 2004, p.51-52). Some drummers such as Tony Bourke (Rhythm Magazine, 2004*f*, p.24) retune their snare drum during a gig in order to replicate the sound of the snare in the recordings of the song being played. The tuning of the snare drum is of particular importance with producer John Leckie stating:

"The two things that identify a record are the vocal and the snare drum"

John Leckie, (Massey, 2002, p.104)

This viewpoint is echoed by Chad Smith of the Red Hot Chili Peppers:

"The snare is the thing that really gives a track its personality"

Chad Smith, (King, 2002, p.15)

3.4 Preparing the drum and seating the heads

Drumheads are seated by adding excess tension to them evenly and then returning them to a normal, playable, state. It is considered critical to apply uniform tension to each tuning rod at this point in order to seat the head evenly (Rhythm Magazine, 2004*g*, p.14). It is recommended by Nicholls (2003*c*, p.122) that preparations at this stage include checking for rattles from the lugs and rubbing a smear of wax around the bearing edge of the shell to ensure optimal contact between drumhead and shell. It is worth noting that drummers often use specific sequences of altering the tension rods. Two tuning methods described by Gatzen (2006) are shown in Figure 3.1. Tuning sequence A involves turning the tension rods at opposite lugs to ensure the head does not slip to one side. Tuning method B is recommended for fine-tuning the drum only and not for seating purposes as it does not require alternating between opposite lugs.

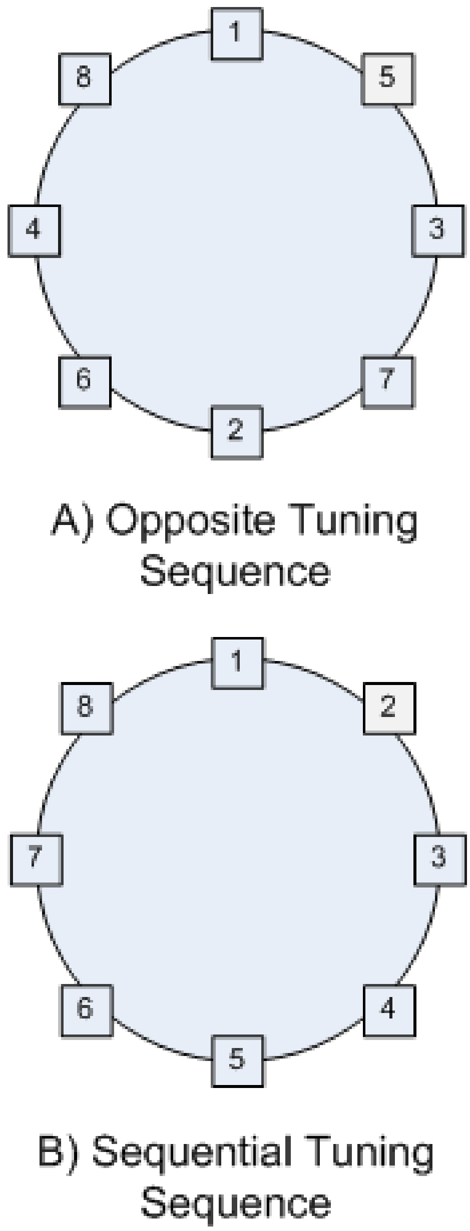


Figure 3.1: Two tuning sequences for a cylindrical drum with 8 tension rods.

3.5 Overview of tuning methods

The terminology used when professional drummers talk about tuning can often be confusing. Drummers will often talk about tuning to a ‘note’ and to ‘high’ or ‘low’ tunings, or leave ambiguity as to whether they are discussing tension or pitch (Rhythm Magazine, 2004*a*, p.80).

Drummers often have their own particular method of tuning the drum (Cannelli, 2001). Nicholls (2003*c*) suggests that there are several steps that need to be taken when tuning a drum. The current research breaks the steps down as follows:

1. Setting the pitch.
2. Achieving a uniform response around the perimeter of the drumhead.
3. Relative tuning of the resonant and batter heads.
4. Envelope control.

3.6 Tuning drums to a specific pitch

At present, the predominant means of a musician tuning an acoustic drum is tuning ‘by ear’; i.e. the drummer listening to the drum and deciding whether it produces the desired sound. This is by far the most effective method currently available but remains extremely difficult, especially for those new to the instrument. Often when tuning ‘by ear’ musicians are focusing on particular frequencies present, for example the fundamental frequency excited in the centre of the drum and also higher partials excited around the perimeter.

Timpani, as discussed in Appendix A.2, are tuned so that each timpani is tuned to a different note on the musical scale (Montagu, 2002, pp.97-101). Some drummers try to tune the toms in a similar manner.

Although it has not been discussed in the scientific literature it appears that some drummers, for example Steve Perkins (Rhythm Magazine, 2004*e*, p.72), Gatzen (2006) and Brian Chase (Budofsky, 2009, p.56) attempt to tune their drums to a specific overall pitch, so that, say, a tom drum, when struck in the centre, will produce a pitch corresponding to a musical note, for example the note G or C. It is also apparent that drummers often tune their drums such that close to the rim a uniform pitch is achieved.

Matt Sorum employs multiple tunings depending on the sound he wants to achieve:

> "I have the toms tuned pretty low for Velvet Revolver shows. In The Cult I went for higher tunings and a bit more of a "note"."
>
> Matt Sorum, (Rhythm Magazine, 2004*b*, page 62)

Once an individual pitch for a drum has been obtained it is then possible to extend this theory further for the whole drum kit, with individual drums each playing a different note on the musical scale. For example, Johnson (1999, p.38) tunes his drum kit to have individual drums each playing a note in the musical scale. Nicholls (2003*c*, p.130) suggests humming a "simple tune or riff as a guide to a nice melodic set of pitches" and goes on to note that:

> "Although the idea with drums is that they are of non-specific pitch so that they will blend in with any key signature, it is still possible to single out the predominant pitches you're aiming for and tune your drums to a specific key to fit a particular tune. Some drummers like to do this, especially when recording. The great jazz-rock drummer Billy Cobham is one of them."
>
> Nicholls (2003*c*, pp.130-131)

The literature indicates that tuning is not merely concerned with the sound of individual drums, but with the kit as a whole. Jose Pasillas uses a seven- or eight-piece drum kit in order to achieve a desired "diversity in sounds, going from really high to really low" (McLachlan, 2002*a*). Geoff Dugmore states that when tuning the aim should be to "tune the kit to the key of the song" (Nicholls, 2003*b*).

Whereas the tuning of many instruments is consistent it appears that many drummers are more flexible with their tuning methods, tuning the drum kit with attention to the rest of the song. Whereas guitarists use effects to alter their sound for a song, drummers tend to use different tuning techniques, with Ryan Vikedal stating:

> "I'm really into different tunings of the kit too. If we're doing a real melodic thing I'll tune the toms to follow the melodic content of the song, and the same with the snare. I'm a big fan of bringing out a different sound from the kit for each different song."
>
> Ryan Vikedal (McLachlan, 2002*b*)

This is at odds with the idea that each drum has one specific 'sweet spot' which is linked to the fundamental pitch of the shell. One manufacturer, Drum Workshop, uses a 'Timbre-Matching' process to stamp all of their drums with a fundamental pitch and this gives a pitch to aim for when tuning (King, 2003, p.60). Nicholls suggests that to do this it would be necessary to strip the shell of all hardware and then suspend it by thread or thin wire. Tapping the centre of the shell should then sound the fundamental note of the shell (Nicholls, 2003*c*, p.123). There is an apparent confusion here between the properties of the individual shell and the tuning of the drum. As discussed previously it is the drumheads themselves that are mostly responsible for the pitch and tuning, with the shell of the drum subtly altering the timbre of the sound:

> "What the shells do is colour the sound. So a metal snare drum sounds a bit different from a wood shelled snare drum. And a maple shell sound fractionally different from your Taiwanese faux-mahogany shell."
>
> Rob Pearson, (Nicholls, 2003*a*, p.81)

In order to more easily hear the pitch of the drum it is sometimes suggested to place a finger lightly on the centre of the head (Rhythm Magazine, 2004*h*, p.14) to prevent motion of the fundamental (0,1) mode (Worland, 2010). Such interference with the surface of the drumhead is not needed if a microphone and analysis tools are used, as in the current research.

3.7 Achieving a uniform response around the drumhead

Unlike a string, the two-dimensional aspect of a circular membrane means that it is possible for there to be significant variation in tension and pitch. In an ideal, theoretical situation, even tension on an evenly seated head - which itself is of equal density and thickness - would create an even frequency spectrum around the perimeter. In real-world situations it can be seen that this is not always the case, something which makes analysing the acoustic response a more reliable method for tuning than measuring tension as discussed in Chapter 5.

Gatzen discusses the importance of an "equal tension" when drum tuning, however he achieves this by listening to the pitch around edge of the drum, making the assumption that if the pitch is equal then the tension must also be equal. It appears that in his DVD he often refers to tension when listening for a uniform pitch rather than actually measuring head tension. On the subject of creating a uniform tuning he states:

> "Equalised tuning is by far the single most important technique I use"
>
> Gatzen (2006)

Many drum tuning guides discuss the importance for a uniform pitch around the perimeter. If the frequency response is not uniform these frequencies interfere causing a beat frequency that can be seen in the waveform (Toulson et al., 2008). Clearing the drumhead, or removing these unwanted frequencies by tuning each point around the perimeter, creates a uniform response which provides a “nice tone that decays with a smooth even note” (Ranscombe, 2006*b*, p.87-88).

Worland (2010) identifies the (11) mode of the drum as being the predominant factor in a drum not sounding in tune and has also noted the presence of audible beats when the drum is out of tune. Worland describes the tuning of a single membrane with respect to mode shapes visible with electronic speckle-pattern interferometry as such:

> “Mode shapes, as seen with ESPI imaging, also appeared generally more symmetric as the tuning was improved. ‘Perfect’ tuning, which presumably would be characterized by fully symmetric mode shapes and the absence of frequency splitting, was never achieved.”
>
> Worland (2010)

3.8 Relative tuning of the drumheads on a cylindrical drum

There has been a lack of scientific research into the relative tuning of both the resonant and batter heads, with significant confusion in terminology being present in popular literature on the subject. This confusion often revolves around ambiguities as to whether a drummer is tuning an instrument to a specific tension, or to a specific frequency response, and whether the intervals between the two heads are measured by number of turns on the lugs of a head, or the perceived musical interval between the two heads. For example, Yard Gavrilovic, drum technician for Steve Gadd, states that he tunes his heads to a “medium low tension” and that with regards to the relationship between the two heads:

> “I get them the same top and bottom then tune the bottom down by about a quarter a turn”
>
> Yard Gavrilovic, (Rhythm Magazine, 2004*d*, p.64)

Rossing et al. (1992) note that, for experimental purposes, "the important tuning criterion was merely that each head have as uniform a tension as possible".

Gatzen suggests that "unisons, 3rds, 4ths and 5ths are good intervals for snare drum tuning". This suggestion is elaborated on by the information provided that a woody sound is produced by tuning to unisons and 3rds, whilst tuning the heads to a 4th or 5th produces a metallic sound (Gatzen, 2006). However, Gatzen does not make it clear in the DVD exactly what he is listening to when he suggests these intervals. Gatzen goes as far as to suggest a tuning range for the resonant head of the snare drum stating:

> "There's a distinct place where the bottom head should be in pitch, and I think it's between about an F# and a B."
>
> Gatzen (2006)

Brian Chase is one drummer who initially chose to concentrate on tuning his batter head to provide a desired stick response, stating that he does not tune his drums "to a specific pitch". However, he goes on to note that he keeps the resonant head of his snare drum a major third or perfect fourth higher than that of the batter head (Boxall, 2004, pp.51-52). Later in his career Chase stated that:

> "For studio situations I'll tune specifically for the song because I want the drums to resonate harmoniously with the rest of the music. I've been lucky in the sense that a lot of our songs tend to be in certain keys. A lot are in E, A, or B, and sometimes G. So I keep my kick drum and my rack tom at E and my floor tom at B. On our new record I think the song "Runaway" is in G minor, so I changed my B to B flat and my E to E flat. There are a bunch of tom fills at the end of the song, and it seems to blend in a nice way."
>
> Brian Chase, (Budofsky, 2009, p.56)

This not only indicates that it is possible to tune drums to a musical scale, but also that even professional drummers are still learning and experimenting with the tuning of their instrument, illustrating the complexities involved.

The literature suggests that if both heads are tuned to the same pitch then a fuller, more open sound will be produced (Johnson, 1999, p.8), (Nicholls, 2003*c*, p.124). It is often stated that there are only three tuning possibilities (Rhythm Magazine, 2004*h*, p.14), these possibilities being the heads tuned to the same pitch, or with either the batter or resonant head tuned higher than the opposite drumhead. There are a vast number of permutations at this stage of drum tuning - as not only can the heads be tuned to the same pitch or one head pitched above or below the other, but also there can be varying degrees of difference in pitch between the batter head and the resonant head. It has often been commented that a musical difference in pitch, for example a major third (Nicholls, 2003*c*, p.123), is likely to produce a harmonic and pleasant sound. Whether the difference in pitch between the two heads is required to correspond to a ratio of musical importance is unknown and there are often ambiguities as to whether it is the (01) or (11) mode that is being focused on. Likewise it has been noted by some that the drum has a descending pitch when struck with Nicholls (2003*c*, p.124) stating this is the case when the resonant head is of a lower pitch than the batter head and Johnson (1999, p.16) stating this occurs when the resonant head is tuned to a higher pitch than the batter. Timbre, as well as pitch, is also affected by the relationship between the two drumheads. For example, it is suggested that if the resonant head is tuned to a higher pitch than the batter head then a much brighter sound with a quicker decay is produced (Nicholls, 2003*c*, p.124). Cannelli (2001) suggests that tightening the resonant head further than the batter head reduces the ring and length of note produced.

Very small changes when tuning the drum will make large differences in the pitch and timbre. One guideline often described is to tune the batter head for the feel of the drum and the resonant head for the pitch or tone (Rhythm Magazine, 2004*h*, page 14), (Johnson, 1999, p.2), (Nicholls, 2003*c*, p.124). The ability to tune the two drumheads independently allows for independent control of the fundamental (01) mode, f_0, and (11) modes, f_1. It is considered in the current research that both heads may be tuned with attention being paid to pitch and tone. Within the tuning ranges available it is possible for there to be musical frequency components present in the batter head spectrum whilst maintaining a batter head tension suitable for providing a desired stick response. High-tempo music usually requires a higher tuning as this produces more stick rebound and a clearer articulation (Nicholls, 2003*c*, p.123).

3.9 Envelope control

The aim of tuning the drum is not exclusively to manage the pitch, but also its envelope. There are many products on the market for damping the drumheads, and many varieties of drumhead produced in order to control the envelope.

Muffling and damping is often limited to the batter head, with the exception of the kick drum, where the vertical orientation of the drumheads makes muffling the resonant head easier. It is suggested by Gatzen (2006) that the muffling the resonant head of a kick drum will also lower the overall pitch.

McLachlan (2003) describes one product, the Min-EMAD, as aiming to "remove unwanted frequencies, retaining the desired attack, resonance and feel". This provides an indication as to what drummers are looking to achieve when tuning their instruments, particularly as the Min-EMAD system dampens the drum at a point near the edge of the drumhead, thus predominantly minimising the higher partials produced.

The choice of whether to dampen the drums is extremely subjective with some drummers such as Frank Tontoh (Rhythm Magazine, 2004*a*, p.80) preferring a more open, resonant sound, while others such as Ian Skelly (McLachlan, 2004*b*, p.46) prefer a more damped sound. It is apparent that drummers are more confident discussing their aims and preferences for controlling the envelope than they are in discussing other aspects of tuning. The importance of proper tuning in order to control the envelope is highlighted by Sorum who states that:

> “I hate noisegates on drums, if you know how to tune drums properly you should be able to leave them wide open and let them sustain and decay naturally. It’s only when they’re badly tuned that they sound terrible and the soundman needs to control them with gates.”
>
> Matt Sorum, (Rhythm Magazine, 2004*b*, p.62).

This importance of careful tuning as opposed to damping is strongly echoed in an article by Rhythm Magazine (2004*i*, p.14) that states that “damping should be a last resort”, “if you damp your drums too much, they will sound dead” and “damping should not be a substitute for careful tuning”. John Bonham, famous for his drum sound, played his drums “completely undamped, and he tuned them high for projection” (Nicholls and Welch, 2003, p.30) and also kept both heads on the kick drum fully intact unlike many of his contemporaries outside of jazz music (Nicholls and Welch, 2003, p.30). In his early career, Ringo Starr also tuned his heads quite high and used no damping except for on the kick drum where he used a felt strip and impact pad (Nicholls, 2004*c*, p.80). Once The Beatles focused on studio recordings in 1966, making use of new technology such as multi-tracking and close miking, Ringo Starr began to dampen his drums more (Nicholls, 2004*c*, p.80). Another example of drummers changing their damping methods to get a desired sound for an individual record is Brian Chase, who states:

> “I’ve always been a purist about tone - as little muffling as possible, open tuning, always put a front head on the bass drum... But this time around it was wallets on the snare and blankets on the kick drum.”
>
> Brian Chase, (Budofsky, 2009, p.52).

This highlights the subjectivity of drum tuning, particularly in regards to the timbre of the instrument, and perhaps also the influence of fashion on the drum tuning process.

There has been little in the way of quantitative research into adding damping materials to the surface of drumheads, materials inside the drum itself, or holes in the kick drum, and many articles in popular tuning literature urge drummers to use damping as little as possible, with Ranscombe going so far as to say that:

> "If your drums are well tuned and with the correct head choices, there really should be no need for additional dampening... no o-rings and absolutely no pillows, towels or other such stuff."
>
> Ranscombe (2006*b*, pp.87-88)

3.10 Drum tuning aids

Many drummers have difficulty learning to tune their drums, with Gatzen suggesting that "drummers simply don't practice tuning enough" and that "for someone seeking information about drum tuning there's really very little out there and the information is really scattered at best". Despite all the problems associated with tuning the acoustic drum, there are very few drum tuning aids on the market. Some commercially successful mechanical aids do exist for assisting the setup of percussion instruments (Neary, 1981), (Hoshino, 1996), but these devices are not capable of specifying whether the resulting setup is actually in tune or not.

It is widely regarded that it can take months or even years of practice before a drummer can effectively tune their drum by ear alone (Tama-Drums, 2010). Gatzen suggests that this can be even more difficult for drummers who do not play other instruments saying:

> "...unless the drummer had experience on a melodic instrument it's ex-

> tremely difficult to develop an ear for pitch, especially from tuning a drum."
>
> Gatzen (2006)

In order to aid drummers in tuning their drums several mechanical solutions have been produced. The Evans Torque Drum Key, shown in Figures 3.2 and 3.3, and the Regal Tip by Calato both attempt to aid drum tuning via setting the torque of tuning rods. Although theoretically a potential solution, uneven head seating, differences in screw tolerances and thread wear make this a less practical solution in a real-world environment (Drumdial-Inc., 2010). For example it is noted by Johnson (1999, p.22) that:

> "If you've spent much time tuning by ear you know that it's not uncommon to have a few lugs that feel loose compared to others. So remember it's the pitch at each lug, not the evenness of lug or head tension/torque that counts."

The Tama Tension Watch (Tama-Drums, 2010), shown in Figure 3.4, and the DrumDial (Drumdial-Inc., 2010) provide an indication of the tension of the drumhead. It has previously been noted that, where ideal membrane theory applies, uniform tension should produce a uniform response around the drumhead. Mechanical devices that measure the drumhead tension provide a rough guide towards the tuning of an acoustic drum, but lack the sensitivity and sophistication needed to aid fine tuning. In his article providing touring tips Erskine (2003) recommends taking a DrumDial on tour to aid drum tuning. Billy Doherty suggests that if you are "uncertain in your drumming" then the Tama Tension Watch is a worthy investment (Reid, 2001).

The Tama Tension Watch uses a spring to push a needle out of the weighted base of the dial (Hoshino, 1996). As the spring pushes the needle the drumhead is moved away from the surface of the base. The dial then indicates the distance between the drumhead and the surface of base. A loose head will exert less pressure on the needle

Figure 3.2: Evans Torque Drum Key.

Figure 3.3: Evans Torque Drum Key in use on a 35-cm tom drum.

allowing it to protrude further from the base and resulting in a lower reading. Whereas a tighter head exerts more pressure on the needle, pushing it further into the base.

Scientific analysis of drums often uses high-tech imaging methods, although many of these experiments concern themselves with the tension of the drumhead to describe the tuning criteria. The current research focuses on analysing the frequency response and waveform envelope of the drum after being struck naturally. The Tama Tension Watch has been used in experiments investigating the moment when a drumstick hits the drumhead (Wagner, 2006) and is used in the current research to gauge tension where appropriate. Displacement is not a measure of tension without knowing the spring constant of the device. Although the Tama Tension Watch is used in this research to indicate tension, there is no specified accuracy for the device. Indeed, the performance of the tension watch is evaluated in Section 5.4 where the frequency response and Tama Tension Watch readings of a drumhead are examined for correlation.

Solutions which rely on methods which alter the engineering characteristics of the system, such as physical contact with the drumhead or removing the drum from the environment and state in which it would be played, will not provide the same consistency in tuning as the use of a microphone performing modal analysis in order to achieve useful data and relay that data back to either scientists or musicians. Thus, it is preferable to analyse frequency response without loading the drumhead (as would be the case with using accelerometers).

Resotune, shown in Figure 3.5, is one electronic device that aids drum tuning. It uses multiple energy sources in the form of loudspeakers to excite the drum and a pair of microphones to receive the signal for analysis by the device software (Roberts, 2005), (Circular Science, 2010*b*). The benefit of this analysis method of is that no physical contact with the drumhead is necessary. The system is limited by the quality of the signal generator and loudspeakers, something that is not an issue when analysing a drumhead under free vibration as used in this research.

Figure 3.4: Tama Tension Watch on a 35-cm tom drum.

Figure 3.5: Resotune electronic tuning device. Image from Circular Science (2010*b*).

The Resotune device has a tuning range of C#0 (17.3 Hz) through to C4 (261.6 Hz) (Roberts, 2005). This device allows for greater accuracy and increased feedback to the musician than previous methods described; however, with a simple LED display, and no feedback regarding the envelope of the signal, it is marketed more as a measurement tool than as a tuning aid (Circular Science, 2010*a*).

It is worth noting at this point that deviations from tuning in an ideal sense, where the response is uniform around the perimeter of the head, are commonplace with tuning manuals making suggestions such as turning one tension rod down in order to produce a "funkier sound" (Rhythm Magazine, 2004*h*, p.14). Current scientific knowledge, along with current tuning aids, do not appropriately consider these deviations in the tuning of the drum. The studies by Worland (2009) on drum tuning and the non-uniform tension of the drumhead attempt to further understanding in drum tuning, but the research was limited to a drum with a single drumhead.

A tuning method and aid which allows for benchmarking previous tunings would benefit musicians in the music studio, with drummers such as Steve Asheim (McLachlan, 2004*a*, p.24) feeling that new drumheads are important when recording. Being able to benchmark these tunings lets one more closely recreate previous drum sounds in future studio sessions.

A drum tuning aid which provides quantitative feedback to drummers could be a potentially useful tool. Electronic musical instrument tuning aids are commercially available and have been accepted by musicians as essential for maintaining accurate instrument tuning. However, existing electronic tuning devices only allow a single fundamental frequency to be detected and evaluated as in tune, such as the device described by Miesak (1984). This data is sufficient for tuning instruments such as guitar and piano which have a strong fundamental frequency. However, more complex sounds such as those from percussion require details of the fundamental frequency, higher partials, relative harmonic strengths and the time-domain envelope in order to tune the drum.

A novel percussion analysis and tuning tool has been developed and patented by Rob

Toulson (Toulson, 2007). The new analysis system is being utilised in this research and, as such, becomes the first ever scientific tuning analysis of percussion instruments by such a method.

It is clear that although many drummers are capable of achieving their tuning aims, terminology is often confused and the scientific basis for tuning has not been adequately explored in prior research. The following chapter outlines research methods for investigating drum tuning via acoustic analysis and defines specific research questions to be answered.

Chapter 4

Methodology and research approach

4.1 The importance of the current research

Significant knowledge gaps in the understanding of percussion instruments, particularly membranophones, have been identified and discussed in Chapters 2 and 3. It is also obvious that the lack of communication between musicians and scientists, regarding percussion instruments, has allowed knowledge gaps and contradictions of theory to develop. Scientific research has been carried out specifically with respect to the acoustic response of the drumhead; however, this knowledge is not often evaluated in a musical context. Likewise, musicians have created a fascinating array of pseudo-scientific theories on tone and timbre of the acoustic drum, its tuning and optimisation. In order to fully understand membranophones and to bring about new knowledge, it is therefore essential to bring together both scientific method and a knowledge of the musicality of the instrument.

There are many possible ways to tune an acoustic drum, in the same way that there are many ways to tune other musical instruments. Most guitarists use the standard EADGBe tuning (Rooksby, 2000, p.142), but no such standard has been formulated for tuning the modern acoustic drum kit. The eventual aim of the current research is to generate the knowledge required to formulate such a tuning method.

The term 'in tune' is used in this study to define being 'at a desired pitch and timbre', in line with the terminology adopted by, amongst others, Ranscombe (2006*a*), as previously discussed in Section 3.2. A systematic tuning method to allow a percussionist to achieve their desired pitch and timbre is therefore beneficial. The aim of this research is not to provide a golden rule which states whether a drum can be classified as in tune, but to provide greater acoustic knowledge and to develop a framework for a systematic method of tuning cylindrical drums. These methods will be defined from the results of quantitative experimentation to generate new tuning options and techniques for percussionists therefore giving this research a practical significance for musicians as well as scientists and engineers. Percussionists at present understand what their desired sound is, but they have no way of identifying via a quantifiable method whether this has been achieved. Such tuning setups often need to be replicated at a later date, for example the next time the percussionist replaces the drumheads on his drum kit, so the ability to benchmark acoustic profiles is a valuable asset. Quantifiable analysis and tuning methods allow for repeatability in tuning setups and can aid novices in learning how to achieve their desired sound.

By setting the foundations for a standardised method of membranophone tuning, further research into modern percussion can be performed in the knowledge that an important factor in the sound of the drum, its tuning, has been taken into account. Not only does this research therefore provide a benefit to those within the scientific community, but it also provides benefit for percussionists of all abilities.

4.1.1 Key knowledge gaps and issues identified by the literature review

Existing research highlights contradictions in the ideal methods for tuning drums. For example, drummers tend to tune their drumheads to a uniform response (discussed as the audible pitch) around the perimeter of the drumhead (Johnson, 1999, p.22), whilst in scientific research the drum is often considered ‘in tune’ if the tension of the head is even (Argo, 2002). It is worth noting that, in practice, a limited number of tension rods around the perimeter of a drum may mean that a uniform tension may not be obtainable. However, here the debate is whether the action (i.e. the drumhead tension) or the reaction (the resulting vibration response) is the key scientific property for analysis. This question is evaluated and discussed as part of the current research.

Many assumptions are made throughout investigations into the acoustic drum and it is debatable as to whether the analysis performed is accurate for all drums, or whether the research is limited to a particular drum analysed on a particular day with an arbitrary tuning setup. It has already been discussed how the model of a cylindrical drum deviates from ideal membrane theory (Argo, 2002) and that research needs to use empirically gathered data to clarify the acoustic theory, particularly when discussing differences between individual drums and drum setups. Modal frequencies for a 30-cm tom drum are noted by Rossing as are the relationships between those frequencies (Rossing, 2005, p.26). Rossing discusses how these ratios are not harmonic, but research described in this thesis does not produce the same modal ratios as Rossing’s on a standard cylindrical drum. For example, Rossing (2005, p.26) notes the frequency ratio for the (01) and (11) modes of a single-headed 30-cm tom as 1:2.16, however a single-headed 30-cm tom drum used in the current research was observed to have the ratio 1:1.89. This implies that there are factors which affect the relationship of the frequencies in the drum that have not previously been investigated and that not all drums respond alike in terms of frequency ratios. This could lead to the suggestion that some drums are naturally more harmonious, that is, they have been manipulated in such a way as to produce frequencies which are closer to being harmonically related than other drums. An alternative suggestion is that cylindrical drums with both a batter and resonant head in place can be tuned relative to each other to be more harmonious than cylindrical drums which have been arbitrarily tuned. This hypothesis is also evaluated in this thesis.

The modal response of a cylindrical drum is affected by head type and tuning, with drum shape and dimensions being significant factors. Data in the reviewed literature is often presented in such a way that it is easy to misinterpret and assume that it is a rule rather than relevant only to a specific experimental setup. It is therefore beneficial to investigate some of the limits of the previous research results that have been published.

4.2 Identifying scientific knowledge gaps

4.2.1 Achieving uniform response around the perimeter of the drumhead

Tuning a drum to a desired pitch can be broken down into two aspects; the overall pitch of the drum when struck in the centre, and the localised pitch of the drum when struck around the perimeter of the drumhead. The current research discusses frequency response rather than perceived pitch to ensure quantitative and objective results.

It has been discussed in Section 3.1 that a uniform head tension or frequency response around the perimeter of the drumhead is necessary for a tuned drum. For example Gatzen (2006) states:

> “Equalised tuning is by far the single most important technique I use”
>
> Gatzen (2006)

Initial investigations also show that uniform frequency response of a drumhead is important in the tuning of the drum. When the drumhead response is uniform, distinct frequency peaks are visible across the frequency spectrum, as in Figure 4.1. These peaks can be observed by exciting the drum at locations around the perimeter of the drumhead. This response profile changes at different locations around the drumhead as the tuning is detuned (by loosening or tightening some of the lugs to remove the uniform response of the drumhead). Although the strong fundamental frequency is always apparent, there becomes less repeatability in higher frequency modes excited around the drumhead as the drum is detuned. The difference in response around the perimeter of the drum causes multiple, complex tones to be excited simultaneously resulting in beat frequency interaction. This effect is also observed and discussed in popular literature by Ranscombe who describes a uniformly tuned drum to exhibit a "nice tone that decays with a smooth, even note" (Ranscombe, 2006*b*) and furthermore by Seymour (2010) who describes a poorly tuned drum as one which 'flutters'. Quantitative experimentation on tuning a cylindrical drum to a uniform response around the perimeter of the drumhead is discussed in this research to develop objective data to support popular theories discussed by percussionists such as Ranscombe and Seymour.

4.2.2 Influence of the resonant head in drum tuning

The two membranes on a cylindrical drum are coupled by a mass of air inside the drum (Rossing, 2005, p.27). The relationship between the two membranes has not been thoroughly investigated to date, although it is generally reported by musicians that the relationship between the two drumheads is a significant factor in tuning (Gatzen, 2006), (Johnson, 1999). Therefore there must be an ideal range for tuning the resonant head with respect to the tension of the batter head. This research aims to investigate the influence of the resonant drumhead tension on the vibrational modes generated, both within and outside the ideal tuning range.

It is apparent that there are similarities in the frequency spectra produced by both the batter and resonant heads. The difference is that the resonant head vibrates with much less power than the batter head. This is to be expected as it is the batter head which is forcibly excited by the drumstick whilst the resonant head is excited by the vibrating air in the drum. Rossing's vibrational analysis of the snare drum illustrates how there are modal pairs for the first two modes, whereas the remaining modes are very closely related to the batter head frequency (Rossing, 2005, Table 4.2, p.29). These mode shapes are shown in Figure 2.4.

It has also been observed that careful tuning of the batter and resonant heads can allow more harmonious frequency ratios. Quantitative analysis of the relative tuning of the batter and resonant drumheads has been conducted and discussed objectively for the first time in this thesis.

4.2.3 Controlling the envelope profile

A significant amount of the scientific knowledge of the sound produced by drums focuses on the frequencies produced. This research, however, also focuses on the relevance of the envelope on the quality of sound. Significant areas of interest include how different tensions and methods of damping affect the envelope, as well as investigating the decay of the frequencies present.

As mentioned in Chapter 3, some percussionists insist that the decay is just as important as pitch, such as Ian Skelly (McLachlan, 2004*b*, p.46) and Brian Chase, (Budofsky, 2009, p.52). It is not only the frequencies that change when the tension of the drumhead is varied. The attack time and the decay of the instrument can also change. These factors are identified as important, for example by Matt Sorum, (Rhythm Magazine, 2004*b*, p.62), but are not scientifically explored in existing literature. For recording drums it may be desired that decay rates are faster to avoid excessive reverberation. For example, dedicated drum booths are often used to absorb some of the sound produced (Robjohns, 2003) (Everest, 1997, p.32). Furthermore, Figure 4.2 shows that higher frequency components of a drum sound decay more rapidly than the lower components when the drum is struck in the centre, whilst Figure 4.3 shows that the second and third partials 'ring' more prominently when a drum is hit off-centre. These particular observation regarding decay rates of individual frequencies are not thoroughly discussed in existing literature and so are evaluated and discussed in this thesis.

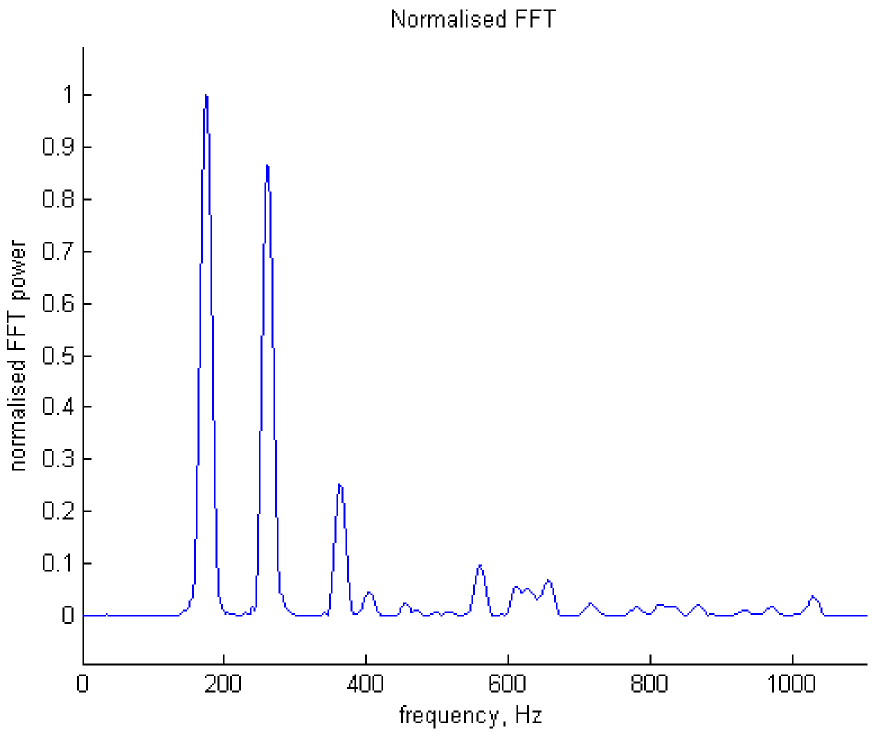


Figure 4.1: The frequency spectrum of an acoustic drum.

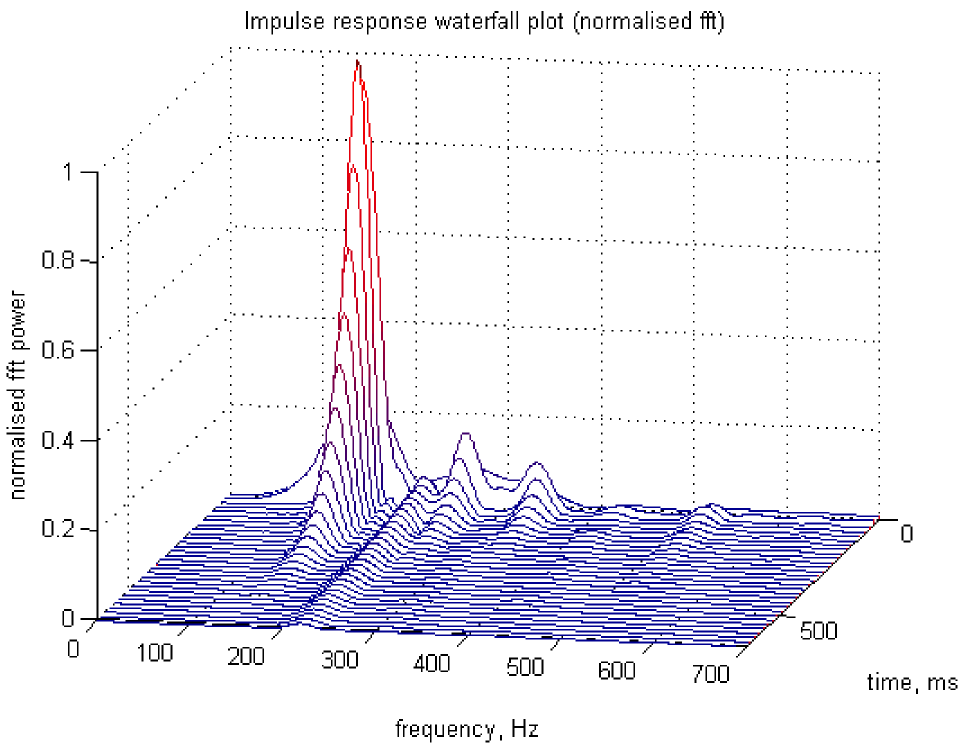


Figure 4.2: Waterfall plot of the frequency spectra of a 30-cm tom drum struck in the centre.

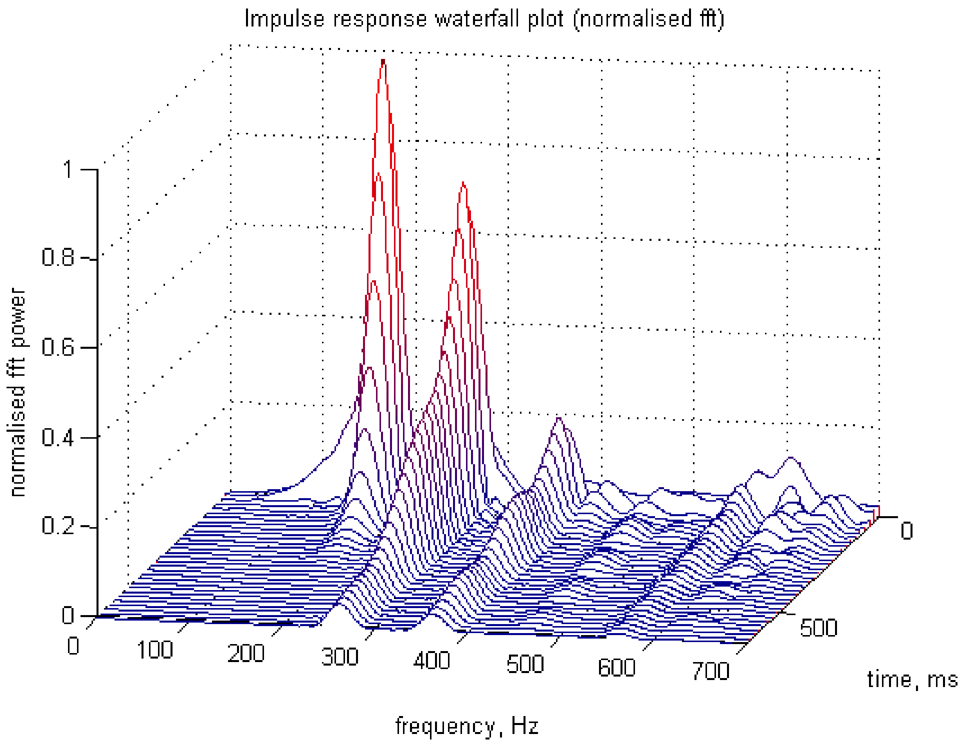


Figure 4.3: Waterfall plot of the frequency spectra of a 30-cm tom drum struck off-centre.

4.2.4 Drum tuning method

Popular literature suggests that a standard drum tuning method exists, indeed there are key texts and articles which attempt to define such a method, for example those by Gatzen (2006), Johnson (1999), Nicholls (2003*c*) and Ranscombe (2006*a*).

There is obviously scope for an educational article on the tuning of cylindrical drums which avoids subjective terminology and instead focuses on the objective acoustic (scientific) response of the instrument with relation to tuning options.

The final component of this research is therefore to create a framework for developing a drum tuning method to assist percussionists in achieving their desired sound.

4.3 Defining research questions

The issues and methodologies discussed in Section 4.2 highlight the following specific research questions:

1. Can frequency response profiles on a drumhead be made uniform?
2. How do the batter and resonant head tensions affect the modes of the cylindrical drum?
3. To what extent can the envelope (decay and attack) of cylindrical drums be adjusted?
4. Is it possible to develop a complete framework for quantitative drum tuning to assist percussionists in tuning cylindrical drums?
5. Can a new framework for quantitative drum tuning bridge the knowledge areas of the popular understanding of drum tuning and the scientific understanding of acoustic drums?

4.4 Benchmarked methods for percussion analysis

Obtaining consistent and reproducible data is of the utmost importance in this research. This requirement is made especially difficult given the sheer number of variables present, not only in the drum, but also in the environment in which the drum is recorded. There are numerous factors which affect how the drum sounds. These include the room the drum is in, how the drum is held in position, how the drum is hit, what is used to strike the drum, where on the head the drum is struck, how the drum is in tuned, whether or not any forms of damping are present and so on. Therefore it is important that the method used to obtain data is thoroughly evaluated. The most significant factors in drum tuning will, in all likelihood, be how the drumhead is excited, and how the heads are tensioned.

4.4.1 The drum setup for experimentation

In his experiments Wheeler (1989) tuned the pitch of his drumhead by using a torque wrench to put equal tension on each of the tension rods. Although this shows that the tuning of the drum was considered it is worth noting that applying equal torque on tension rods does not necessarily mean uniform tension or a uniform frequency response around the perimeter. A number of other research investigations give reference to the drum setup but fail to sufficiently quantify it in scientific terms. For example, Lewis and Beckford's description of how they tuned a snare drum each time they replaced the head is limited to the fact that the drum was "tuned to a medium-tight tension to achieve a 'typical' snare drum sound" (Lewis and Beckford, 2000). This is an example of the use of colloquial terms for drum tuning, rather than using specific scientific benchmarks.

Furthermore to quote Rossing et al:

> "There appears to be no standard practice amongst performers for tuning

> the two heads of a snare drum... For these studies, then, the important tuning criterion was merely that each head have as uniform a tension as possible"
>
> (Rossing et al., 1992)

Here it is not clear whether the uniform tension referred to by Rossing is related to uniform tension around each head, or whether the tension of both heads should be identical. Nicholls, for example, notes:

> "...it's quite common to use a resonant head that is thinner than the batter head, so the two will require different degrees of tension to achieve the same pitch."
>
> Nicholls (2003*c*, p.124)

The type of stick used to strike a drum may produce a difference in the sound produced. For this reason it is suggested that when recording data the same drumstick should be used throughout the experiment. Both Argo and Henzie have noted the differences produced by different sticks, with Henzie's research concentrating on the size of stick (Henzie, 1960) and with Argo noting that a difference exists between nylon- and wood-tipped sticks (Argo, 2002). Argo notes that the wood-tipped stick produced a more prominent (11) mode than the stick with the nylon tip, which produced more higher-frequency components. In the research carried out by Tindale et al. the same sticks were used throughout all experiments, namely Vic Firth Concert wooden sticks (Tindale et al., 2004*b*).

Many stick manufacturers go to great lengths to ensure that sticks sold in pairs are nearly identical. Pro-Mark and Vic Firth both sort individual sticks by weight and then by frequency response before pairing them up (Croft, 2007*a*), (King, 2001). The material the drum shell is made of can also produce an appreciable difference to the tone. Although limited scientific research has been carried out on this subject it is worth noting that this variable exists and may have an influence on any results where drum shells of different materials have been used. Experimentation during the current research will be conducted without varying the drumstick type.

It has been noted that the depth, as well as the diameter of the drum, has an effect on the sound produced. Henzie noted that, when struck equally, the deeper drum appeared to produce a longer tone, whereas the shallower drum produced a greater amplitude (Henzie, 1960). Repeat experiments can be performed on different drums of similar properties in order to make sure that any general conclusions formed are not valid for only one drum. Tindale et al., for example, performed their experiments on three snare drums: a 14" x 6.5" Yamaha drum, a 14" x 6.5" Ludwig drum, and a 14" x 4.5" Gretsch drum (Tindale et al., 2004*b*). These three drums were similar enough for the purposes of their experiments. Where applicable the current research will use a number of different cylindrical drums in order to show that the theories developed relate solely to the tuning method and not to the drum materials and dimensions.

4.4.2 Considering stroke type

Varying how the drum is struck will produce different results. Changing the force used to strike the drum will change the duration of the sound (Henzie, 1960). Likewise, changing the position of the drum stroke will vary which modes are excited, and the extent of that excitation.

Henzie empirically investigated whether changing the distance between the drumhead and drumstick at the top of its arc affected the amplitude and duration of the snare drum. Henzie concluded that a greater amplitude does not always result in a longer sound. Tindale also used manual strokes maintaining consistent stroke length, noting that "although speed, acceleration, and angle of incidence are also factors when striking the drum only the concept of stroke length is used for this study for the sake of simplicity" (Tindale, 2004).

By creating a reference height or stroke length for the drum stroke it is possible to minimise differences in results being caused by the performance of different drummers. This homogenisation may be preferential in order to collect adequate data. In research carried out by Dahl three professional drummers and one amateur drummer were asked to hit the drum with an accented stroke. The research concludes that each drummer strikes the drum differently, this being evident in the preparation of the stroke (Dahl, 2000). The trajectory of the drummers' strokes varied between 10 cm and 38 cm for a normal stroke, and between 41 cm and 70 cm for an accented stroke. This change in stroke length will, at the very least, have an effect on the amplitude and duration of the drum sound (Henzie, 1960) and may, with regards to the current research project, negatively affect the value of any data collected.

Another option for decreasing the impact of the performer on the results would be to use a consistent force mechanism. This was first discussed by Henzie who dismissed a mechanical method involving a motor due to noise issues (Henzie, 1960). Henzie performed preliminary experiments which demonstrated that by maintaining a similar stroke height a high degree of similarity was achievable (Henzie, 1960). Tindale likewise concluded that "the use of experts is important to insure consistency of the data, yet to prevent the homogeny of a stick machine" (Tindale, 2004).

Conversely, Argo argues in favour of a consistent force mechanism and utilises a simple device using a pivot where a rubber band was fixed to a stand and the rubber band holds a drumstick forming a pivot (Argo, 2002). Argo used a rubber band due to pliability and to emulate a drummer's wrist action when striking the drum. The stick was held at 45 degrees above parallel and allowed to fall onto the drumhead at an angle of 45 degrees below parallel. Wheeler also performed research on the snare drum using a mechanical striker to minimise any variables cause by a human player (Wheeler, 1989) and a similar method was used by Lewis and Beckford to measure the tonal characteristics of snare drum batter heads (Lewis and Beckford, 2000).

The current research uses manual strokes as a method of obtaining data for analysis.

Initial trials showed that it is necessary to keep stroke height of the impact consistent throughout experiments to ensure reproducibility of results. It is important, as recognised by Argo (2002) and Henzie (1960), that only individual strokes are recorded and that any implement used to strike the drum only makes contact with the drumhead once for any given data sample.

The position of the drum stroke also has an effect on the drum sound. Tindale et al. (2004*a*) successfully produced a system able to classify snare drum sounds from five locations, centre, near-centre, halfway, near edge and edge. This shows the importance of using the same hit location throughout an experiment. Initial analysis shows that although the low frequencies present in the signal stay consistent over the length of a drum sound the relative amplitudes of those frequencies changes.

The varying types of drumstick impact are noted here, but the present research is concerned with analysing the drum's free vibration once excitation has occurred. As such any excitation method that allows free vibration to occur is sufficient, and in general the force magnitude of excitation should not influence the frequencies and vibrational modes which are excited during free vibration (Thomson, 1993, p.17-25). In the present research, standard drumstick impacts are used to analyse response profiles and wherever possible the impact force is kept consistent by maintaining a consistent stroke height throughout experiments.

4.4.3 Microphones and electronic equipment

A wide variety of drums and recording equipment have been used in past research. Initial experimentation shows that it is no longer necessary to have cutting-edge equipment in order to obtain adequate data. Although it may be preferable to use high-end audio equipment, such as the Neuman U-87 microphone and Mark of the Unicorn 896 soundcard combination used by Tindale et al. (2004*a*), other less expensive equipment can be used. Tindale et al. used a comparatively low-budget microphone in the form of a Shure SM57 microphone in other research (Tindale et al., 2004*b*) although no mention was made as to whether one microphone was preferable to the other. The soundcard used recorded at a resolution of 16 bits at a sample rate of 44100 Hz (Tindale et al., 2004*b*), (Tindale et al., 2004*a*). This indicates that the soundcard was adequate even though the Mark of the Unicorn 896 soundcard can record at a resolution of 24 bits and a sample rate of 192000 Hz. Instead it appears that the key to useful data instead lies in careful design of the experiment and microphone position.

The microphone position is of particular importance when analysing the sound produced. When recording a drum it is common for a microphone to be positioned near the rim. This practice has been followed by others carrying out research with short distances between the microphone and the struck head being the norm. Ono et al. (2009) performed analysis on the wadaiko drum with the microphone placed on the resonant head, as shown in Figure 4.4. Tindale used a microphone 6 cm from the batter head and angled downwards toward the drum at 20 degrees (Tindale, 2004), but in the same year Tindale et al. positioned a Shure SM57 microphone 2.5 cm above the edge of the drum and angled down at 30 degrees (Tindale et al., 2004*b*). When a Neuman U-87 microphone was used the microphone was suspended perpendicularly over the drum and placed near the edge of the drum (Tindale et al., 2004*a*). The microphone position and strike locations used by Tindale et al. (2004*b*) are shown in Figure 4.5. In the present research, similar to Tindale's method, data has been sampled to 16-bit resolution at 44100 Hz using an Edirol UA25 soundcard and a Shure Beta 57A microphone.

Another variable in the sampling of data is the environment the drum is recorded in. Although initial experimentation showed that adequate results are obtainable from an ordinary room, in order to minimise the presence of unwanted sound it is preferable to use a well sound-proofed and acoustically treated room for final experimentation. All experimentation after the initial investigations was carried out in the Audio and Music Technology Studios at Anglia Ruskin University.

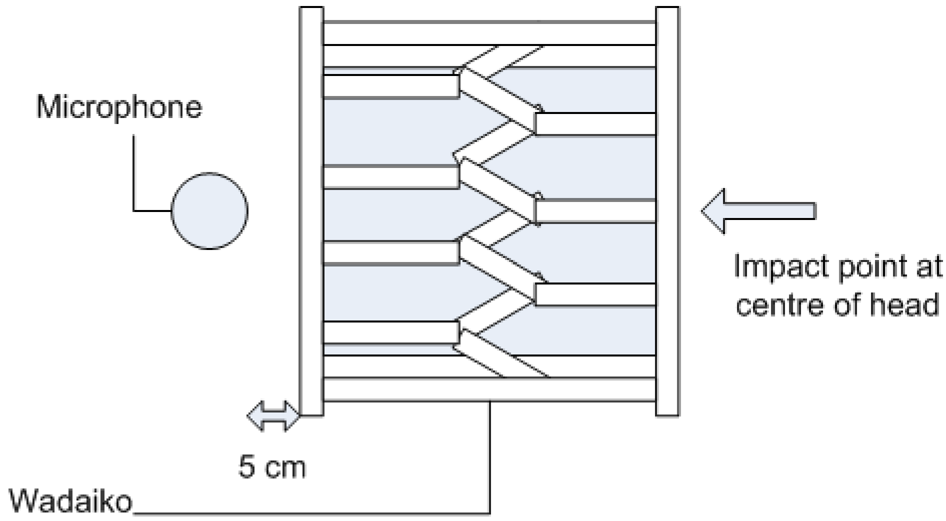


Figure 4.4: Positions of microphone and strike location used by Ono et al. (2009).

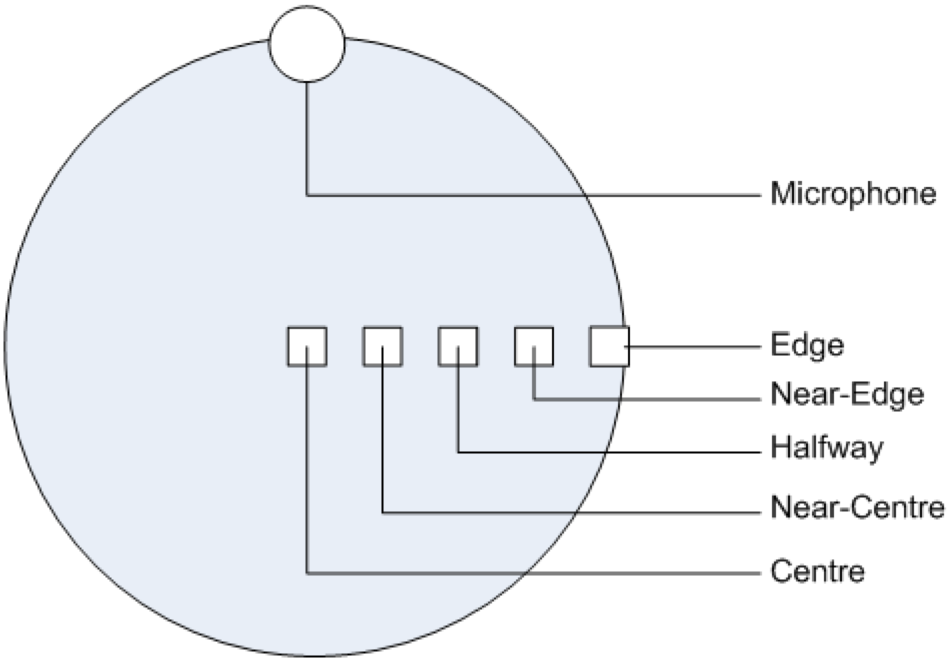


Figure 4.5: Positions of microphone and strike locations used by Tindale et al. (2004*b*).

4.4.4 Data capture and analysis

A certain degree of processing is often applied before analysing the recorded data. This is usually in the form of normalising the signal. In order to determine the point where the drum impact started, Tindale (2004) applied a gate function with a threshold of -60dB to the recorded data and determined the onset of the drum signal to be the zero crossing immediately previous to the point that reached threshold of the gate function.

There must be a long enough sample to convey the drum sound. This could be set to an arbitrary amount of time such as the one second used by Argo (2002). A specific number of data samples, for example 512, 1024 or 2048, was used by Tindale (2004). Alternatively the sample could be set to a time to drop below an arbitrary sound pressure level or where the signal drops below a level related to the maximum amplitude of the drum sound, as used by Henzie (1960).

In their research into snare drum batter heads Lewis and Beckford made use of a Fast Fourier Transform (FFT); however, they noted that one limitation of their research was that they were not able to measure the decay characteristics of the tone (Lewis and Beckford, 2000).

Initial investigations were also necessary to determine which peaks should be considered important. In his investigations Argo determined that any peak amplitude of a value of 5% of the largest peak or above should be considered important (Argo, 2002). The current research limits itself to the first two frequency peaks present in the spectra, i.e. the first (01) and (11) modes.

The Short-Time Fourier Transform (STFT) is a method to determine the frequency content of a signal over a period of time. However the drum signal has short-duration high-frequency components and long-duration low-frequency components making the STFT less than ideal. Another possible method of analysis is wavelet analysis. The wavelet transform is similar to an STFT providing spectral and temporal representations of the drum signal. Tzanetakis et al. have used wavelet analysis in automatic drum transcription of low-frequency and medium-high-frequency sounds (Tzanetakis et al., 2005). Tzanetakis found that there was negligible difference between using the wavelet transform and filter methods describing the differences as “statistically insignificant” (Tzanetakis et al., 2005). Tzanetakis notes that the Discrete Wavelet Transform (DWT) is preferable to the STFT for the classification of drum sounds due to the fact that it gives higher time resolution for higher frequencies (Tzanetakis et al., 2001).

It is not just the analysis of the sound produced which can produce information about the drum. Rossing et al. (2004) notes several methods for studying the modes of vibration in a drum such as holographic interferometry, experimental modal testing and physical modelling. Optical holography, in particular, has been successfully used by Rossing to display the major modes of many percussive instruments (Rossing, 2005). Optical holography involves creating holograms to capture a two-dimensional recording that is capable of reproducing a three-dimensional image. Optical holography using digital imaging techniques has become a popular method for studying vibrations (Rossing, 2005, p.110). Worland (2009) uses a similar method called electronic speckle pattern interferometry (ESPI) which is used to image the mode shapes of the drumhead. This requires the drumheads to be driven rather than analysed under free vibration. Worland used a speaker and function generator to drive the drumheads.

Acoustical holography has been successfully used by Fushimi et al. (2002) to analyse violin plate vibration using BEM-based acoustical holography to reconstruct and visualize distributions of sound pressure and particle velocity in a violin. Kwon et al. (1997) visualized sound fields on a jing, a type of gong used in traditional Korean music, by using planar acoustic holography to reconstruct mode shapes. Sullivan (2008) explains the design and construction of a near-field acoustic holography device which was tested on a vibrating drumhead, but this research focuses predominantly on the apparatus used rather than the analysis results.

4.5 The chosen research approach

4.5.1 The method for excitation and response measurement

Drumhead response has been evaluated in detail for single-headed drums by, amongst others, Rossing (2005), Worland (2010) and Bridge and Keshavan (2007). As discussed in Chapter 2, the vibrational modes of a single drumhead are described by Bessel functions as shown in Figure 4.6.

The response of a drumhead depends on where the drumhead is hit. This is because different modes of vibration are excited by impacts at different locations on the drum, as defined by the mechanical theory for experimental modal analysis (Ingard, 1988, p.131). An experiment to observe mode shapes can be seen in Appendix B and the frequencies at each mode compared to values obtained through the analysis software used in this thesis. It was observed that the first two frequency peaks observed in the spectra produced Chladni patterns for the (01) and (11) modes respectively.

The literature research has shown that for drum tuning, the drum response is regularly evaluated by excitation at two points, at the centre of the batter drumhead (predominantly used for tuning the fundamental response and envelope profile of the drum) and by excitation around the perimeter of the drum (to allow a uniform response to be achieved around the drumhead). For this reason these two locations of excitation will be discussed predominantly throughout this research. Furthermore it will be seen that these two locations for excitation are chosen because they individually excite certain frequency modes associated with fine tuning of the cylindrical drum; the centre excitation predominantly excites the fundamental (01) mode (as shown in Figure 4.6) whereas the edge excitation predominantly excites the (11) vibration mode. Therefore the (01) mode will be used to evaluate the tuning of the fundamental response and the envelope, whereas the (11) mode will be used for evaluation of the uniform response of the drumhead.

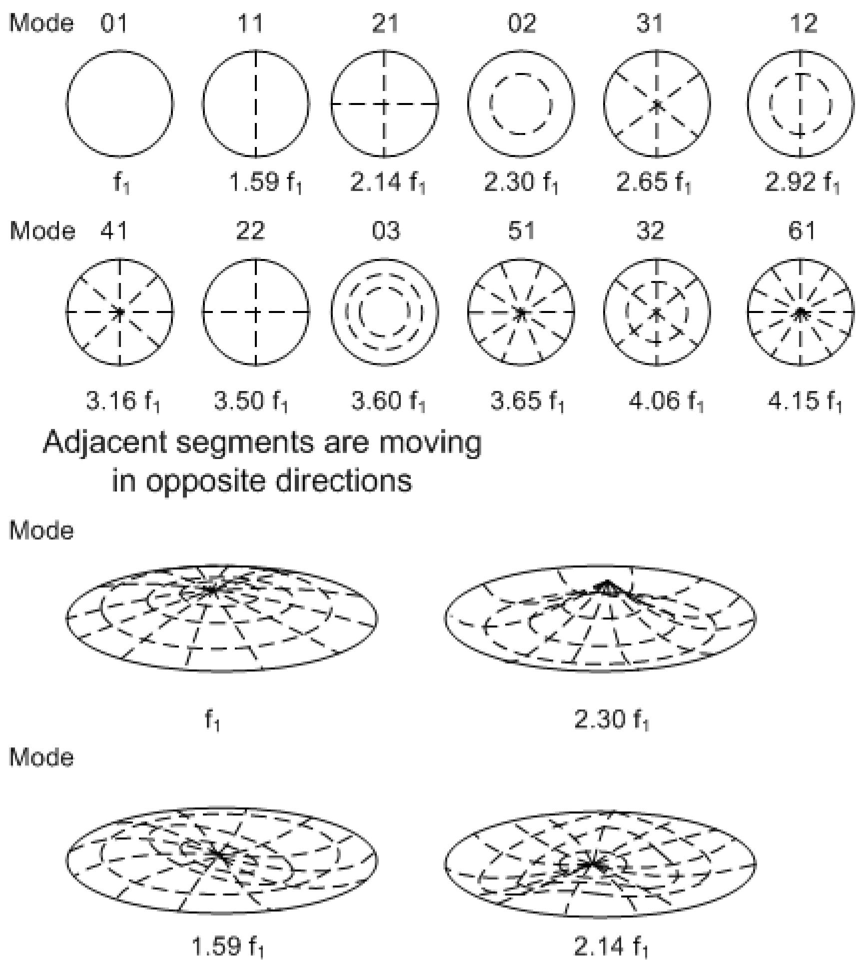


Figure 4.6: Vibrational modes and frequency ratios of a single taut membrane (Rossing, 2005, p6).

Figure 4.7 shows the waveform and frequency spectrum of a drumhead impulse when the vibration is excited, by impact from a standard drumstick, and the response measured by a dynamic microphone positioned at the centre of the drumhead. The drum used here is a 7-ply birch shell measuring 12" in diameter and 9" in depth (30.5 cm x 22.9 cm). The drumheads used were arbitrarily chosen as Evans EC2 on the batter head and a standard Tama resonant head. In Figure 4.7 it can be seen that the drumhead has been tuned to 147 Hz, which corresponds to D3 on the musical scale. This fundamental frequency is described by vibration mode (01), however, we will simplify this terminology in our research and refer the fundamental mode simply as f_0. Where a distinction needs to be made between the frequency present when the batter head or resonant head is struck f_{0B} will be used to denote the fundamental from the batter head and f_{0R} will be used for the fundamental from the resonant head.

If the same drum with the same tuning setup is excited and analysed at the perimeter of the drum, the fundamental mode is not particularly evident, as shown in Figure 4.8. Here we see a second partial at 220 Hz. This is vibration mode (11); however, we will simplify this terminology in our research and refer to this second frequency component simply as f_1. Where a distinction needs to be made between the frequency present when the batter head or resonant head is struck f_{1B} will be used to denote f_1 from the batter head, and f_{1R} will be used for f_1 from the resonant head.

It is no coincidence that in this example the frequency f_1 (220 Hz) relates to the musical note A3; the drum used to generate the data shown in Figure 4.7 and Figure 4.8 was tuned specifically to give the observed modal response and the method for achieving this level of fine tuning will be discussed throughout this thesis.

The present research will show that the fundamental mode, f_0, relates to a combination of the membrane tension and the motion of the mass of air inside the drum. This frequency is predominantly dependent on the size of the drum and the tension of the two drumheads (the batter and resonant or 'top' and 'bottom' heads). Adjustment of either the batter or resonant drumheads will alter the fundamental frequency. The

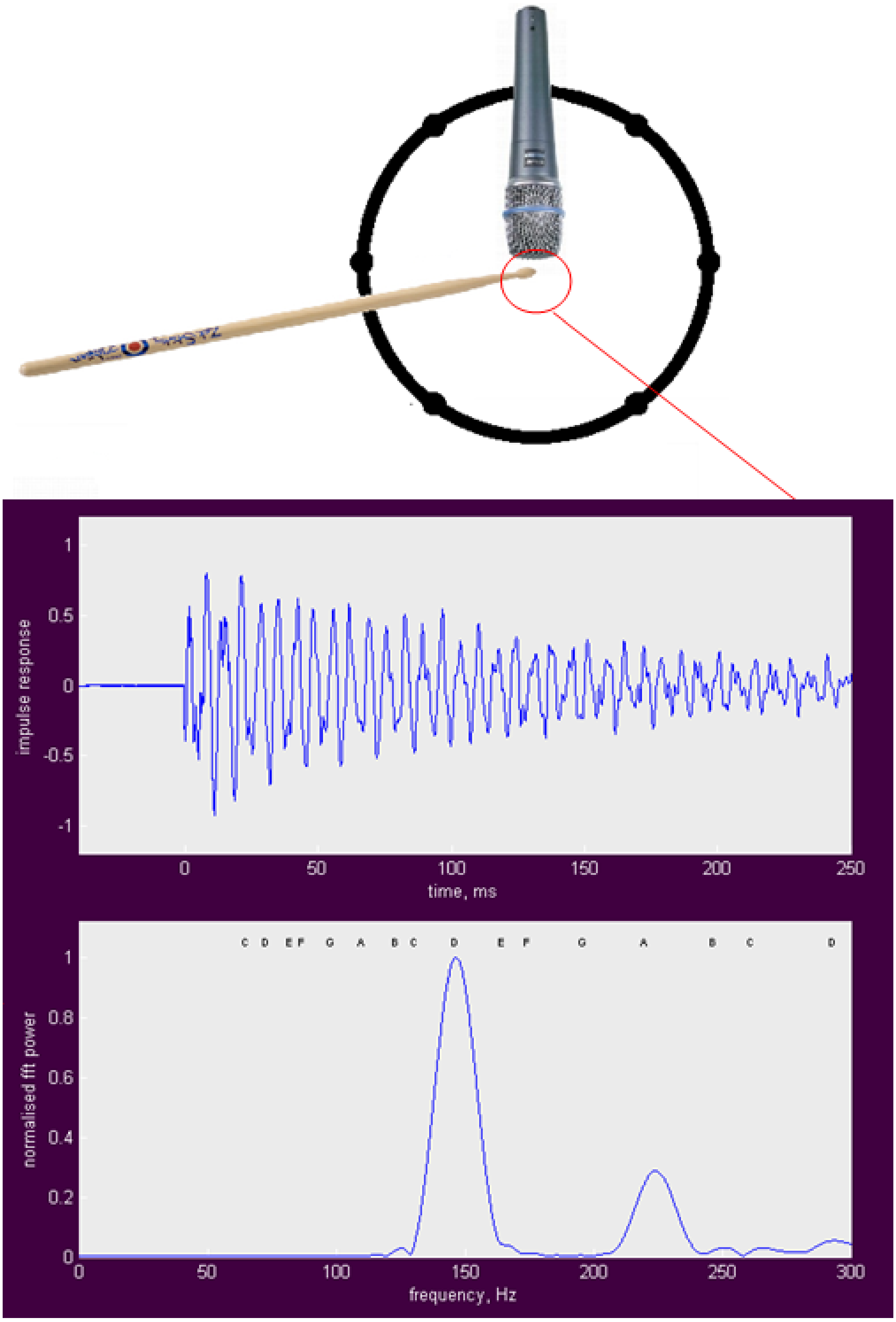


Figure 4.7: Centre impulse and response for a drum tuned such that f_0 = 147 Hz.

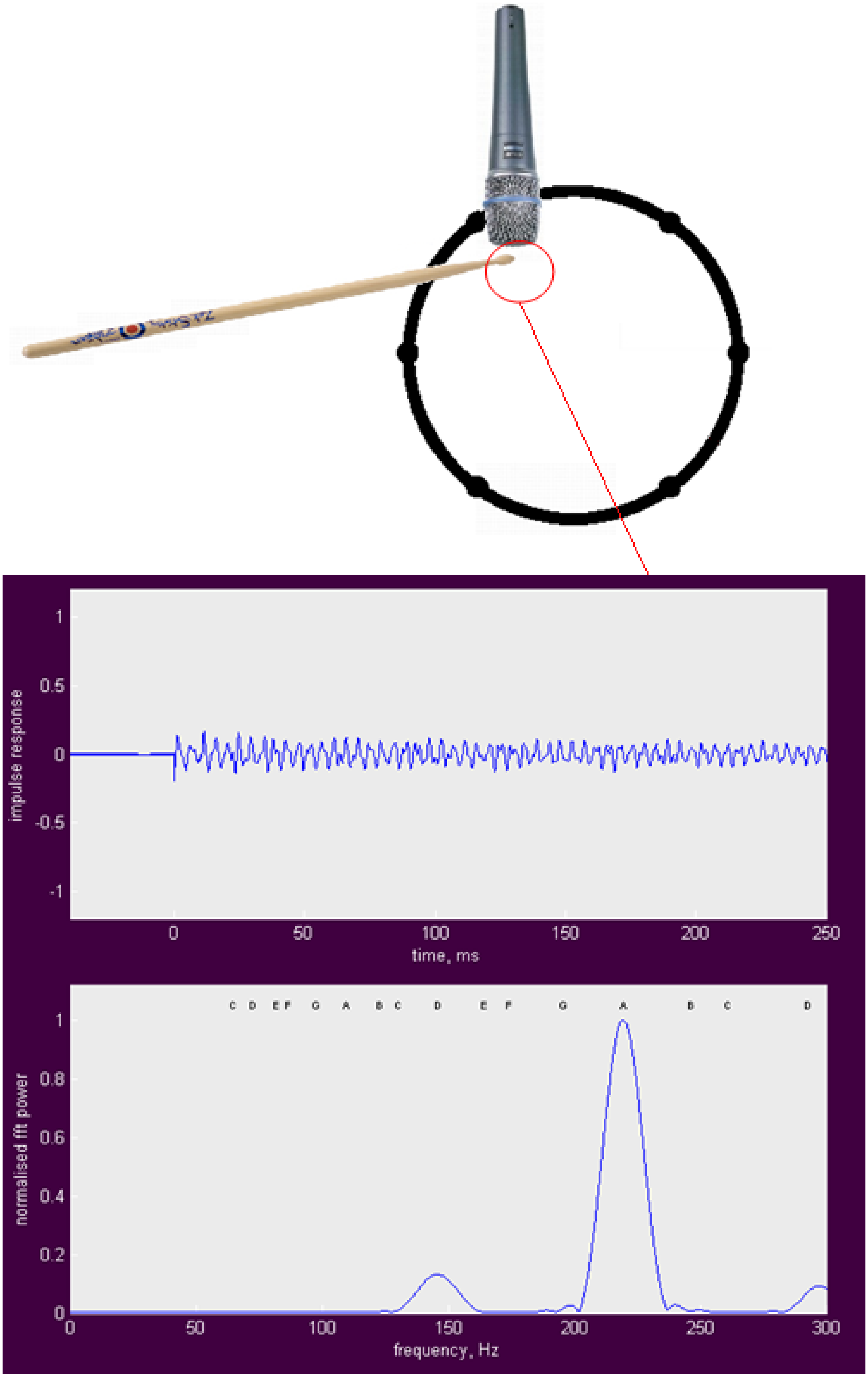


Figure 4.8: Edge impulse and response for a drum tuned such that f_1 = 220 Hz.

frequency f_1, however, is seen to be dependent on the dimensions and tension of that head alone, so adjustment of the opposite head has little influence. It is therefore possible to adjust the relative tension of the two drumheads and hence independently alter the frequencies f_0, f_{1B} and f_{1R}.

Furthermore, it will be shown that excitation and analysis at a location between the centre and the edge will excite both f_0 and f_1 a similar amount, as shown in Figure 4.9. Thus, it is indeed possible to tune a drum to have more than one chosen musical mode, resulting in a rich musical tone.

4.5.2 Waveform analysis method

The waveform analysis method used in this research is developed by an experimental process in order to deduce the required resolution for analysis in both the time and frequency domain. This deduction process has allowed the following waveform analysis method to be developed and shown to perform to a desired level accuracy and resolution.

As this research is predominantly interested in the first two modes of vibration, the analysis will rarely require extending above 500 Hz; this therefore allows the standard compact disc audio sampling frequency of 44100 Hz to be used. Given that the Nyquist criterion for a 500-Hz signal would be satisfied by a sampling frequency of 1000 Hz, this represents a 44 times oversampling ratio. CD standard 16-bit resolution analysis has also been adopted, though this is scaled to the range of -1 to +1. A sampling frequency of 44100 Hz was also used by Tindale (2004) and Tzanetakis et al. (2005), with Tindale also using 16-bit resolution whilst Argo (2002) felt that a 4400-Hz sampling frequency was adequate.

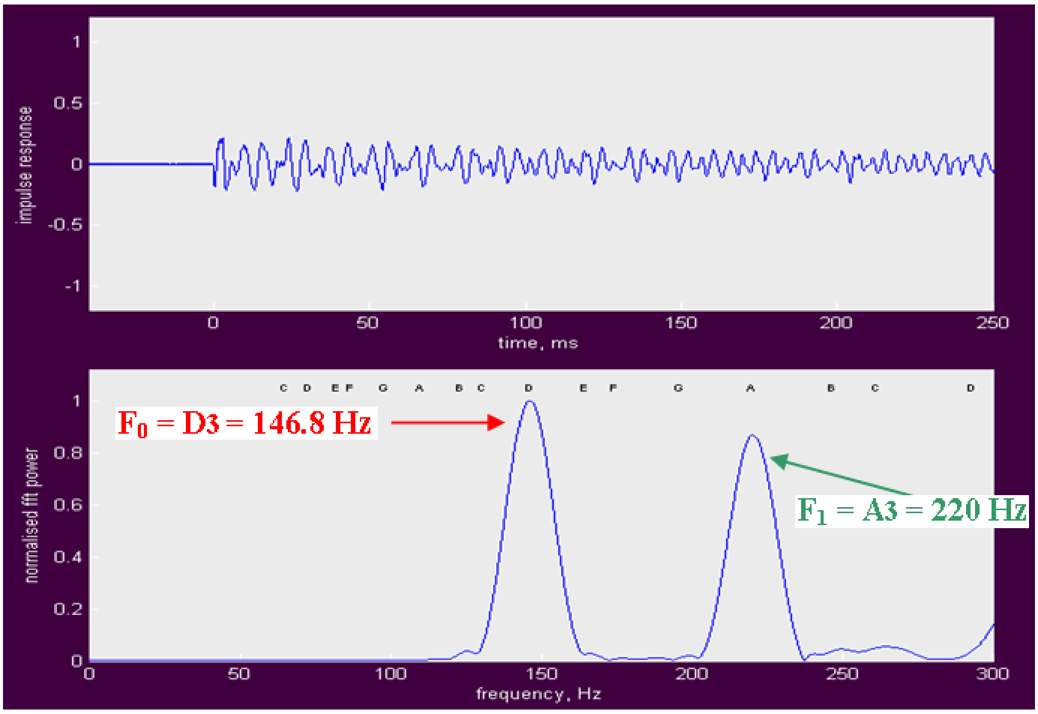


Figure 4.9: f_0 and f_1 excited simultaneously.

Using bespoke software developed in Matlab (MathWorks, 2010*a*), an impulse response can be acquired whenever the membranophone is excited. For each analysis a 2-second audio file (i.e. 88200 samples) is captured. The onset of the response is determined by finding the first instance of a threshold exceedance of half the amplitude of the maximum data reading. Historical capture is also used to ensure that the 2000 samples (45.4 ms) prior to the threshold exceedance are displayed and available for analysis. These time frames have been shown sufficient in the current research to allow capture and analysis of the waveform data, as shown in Appendix C and discussed further below.

A Fast Fourier Transform (FFT) of a windowed section of the time-based data is calculated in order to evaluate the waveform's frequency spectra. The FFT is performed by the built-in Matlab FFT algorithm (MathWorks, 2010*b*). Tindale (2004) used 512, 1024, and 2048 data sample window sizes and Argo (2002) used 4096 samples for his window size, whilst Wheeler (1989) used a window size of 110 ms and Dahl (1997) used a window size of 160 ms. A number of window positions and sizes have been considered when designing the analysis method for this research, such as those windows for analysis shown in Figure 4.10. Here it can be seen that the fundamental frequency component of the spectrum is more prominent when a 5000-sample analysis window is used, although with 5000 data samples a broad frequency peak is obtained, the width of this peak narrows as the sample rate is increased; however the presence of the fundamental frequency is less clear as with a larger window there is an increased weighting towards the higher frequencies. As the drum sound decays the signal to noise ratio increases, and as such a larger window will also have a higher signal to noise ratio than the smaller window. The f_1 frequency was recorded as 261.43 Hz for a 5000 sample window, and 261.26 Hz for both the 10000 and 20000 sample window sizes.

The chosen window size and position is a unique property of the current research and has not previously been evaluated in such detail. The chosen frequency analysis

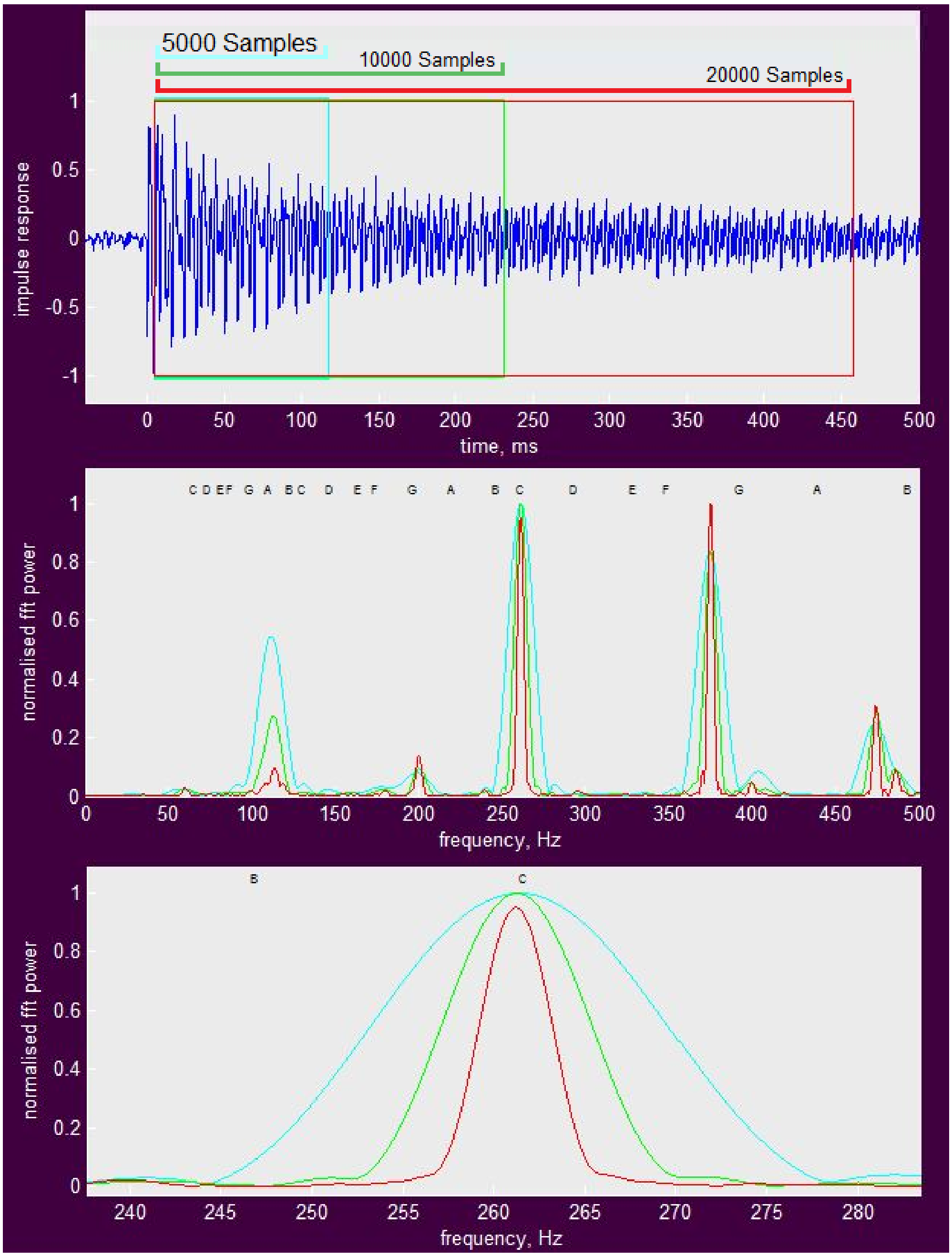


Figure 4.10: Different analysis windows and their spectra:- 5000 samples (blue), 10000 samples (green) and 20000 samples (red).

window attempts to capture data given the following circumstances:

- A large window allows frequency data to be analysed to a higher frequency resolution (Weeks, 2006, p.213), so as large as possible an analysis window is desired.
- The vibrational modes in a cylindrical drum signal tend to decay at different rates, so a window which is too large may be weighted unfairly to those frequencies which have a longer decay time (which tend to be timbral characteristics of the drum shell and are hence not directly associated with drum tuning). As seen in Figure 4.10, the first vibration mode is evident from the first (blue) analysis window, but is less prominent in the longer, 10000-sample (green) and 20000-sample (red), windows.
- During the initial impulse of the drumhead, the drum stick is in contact with the drumhead and so causes loading and tensioning. It is not until a few milliseconds later, when the drumstick has released contact that the drumhead exhibits free vibration. A short delay after threshold exceedance and prior to windowing is therefore desired.

The chosen window function used in this research takes the above points into account. The chosen window starts 200 samples after threshold exceedance and contains 5000 data samples. At a sample rate of 44100 Hz, this window therefore takes data from the period 4.5 ms - 117.9 ms after threshold exceedance, as shown in Figure 4.11.

The windowed data is processed with the Matlab Hanning window function (MathWorks, 2010*c*) to reduce the effects of spectral leakage, given the finite data window (Oppenheim and Schafer, 1989, p.448).

The Matlab FFT function allows any number of frequency bins to be computed. For a time signal of N samples, the standard FFT algorithm computes a Discrete Fourier transform (DFT) with $N/2$ bins spread over 0 to Fs/2 Hz, where Fs is the sampling

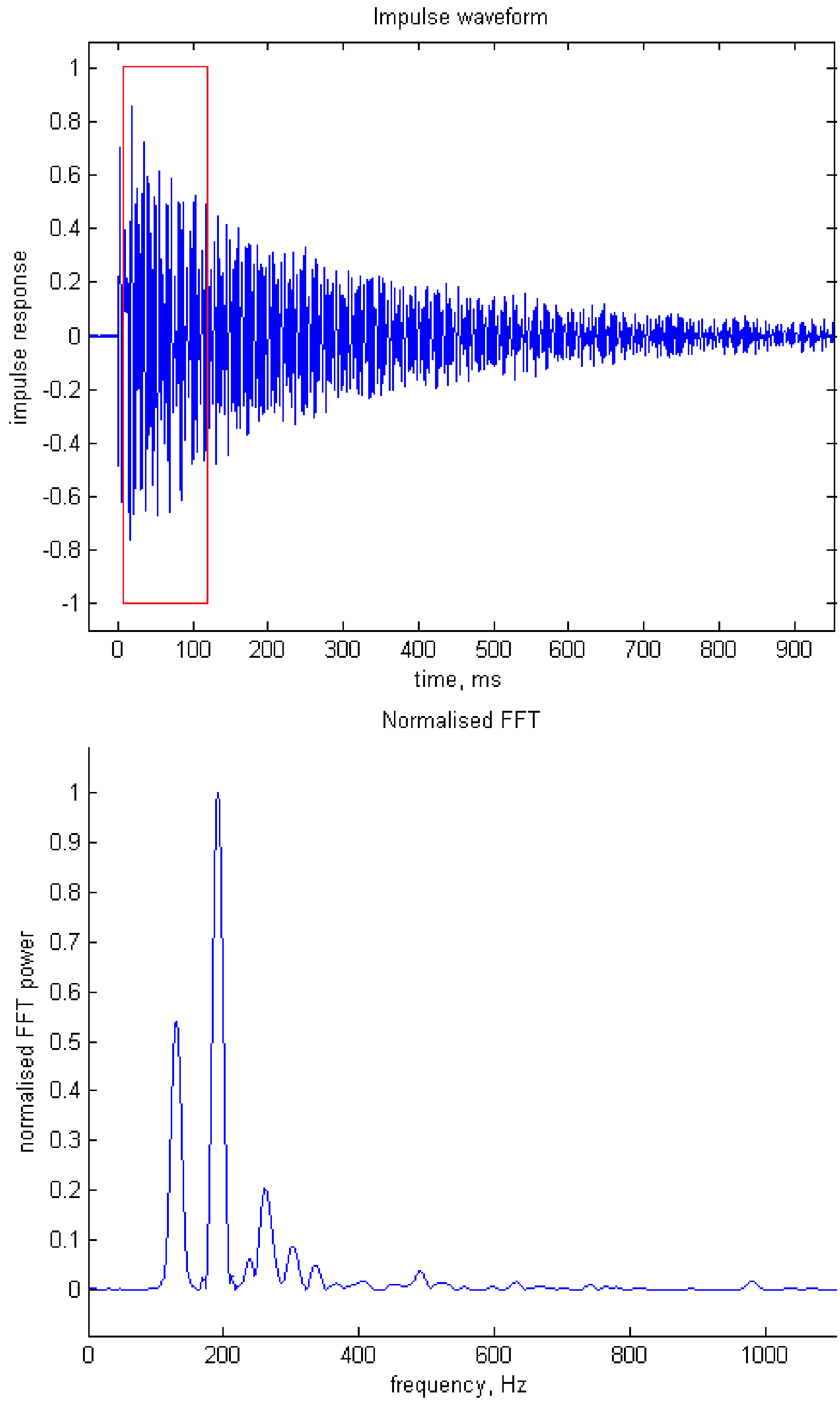


Figure 4.11: The FFT analysis window used in the current research and resultant normalised frequency spectrum.

frequency (Proakis and Manolakis, 1992, p.440). It is noted that although the execution time for the FFT function is fastest for powers of two the current research does not require real-time analysis and as such the window length is not limited to $N = 2^m$ samples (MathWorks, 2010*b*). The Matlab FFT uses the Cooley-Tukey decomposition (Cooley and Tukey, 1965) to compute an N-point DFT when N is composite, i.e when $N = N^1 N^2$, and uses Rader's algorithm (Rader, 1968) where N is a prime number (MathWorks, 2010*b*).

The Matlab FFT function allows higher bin numbers (i.e. $> N$) to be used to effectively interpolate the Fourier transform to give a greater level of detail. This is done by the method of zero padding which effectively increases the time domain data to the desired number of DFT bins by padding zeroes after the time domain data as discussed by Weeks:

> "When we zero-pad a signal in the time-domain, we get a smoother looking frequency resolution...so adding zeroes means that there will be more frequency domain points. The analysis frequencies, as a result, become finer since they are closer together."
>
> Weeks (2006, p.214)

However it must be noted, as also discussed by Weeks, that zero padding "does not actually add any new information" to the DFT, it simply smooths the chart and interpolates the data points for us. However this can be particularly useful for finding interpolated frequency peaks at precise frequency values.

The Fourier transform used in this research is based on a N=5000 sample waveform, sampled at 44100 Hz and converted to a 2^{19} point DFT. The value of 2^{19} (which equals 524288) allows frequency data to be interpolated and plotted at 0.0842 Hz intervals. This method allows for frequency analysis of 0.1 Hz where a single frequency peak is present. A broad peak is produced when a 5000-sample window is used, leading to poor discrimination of frequency peaks within 8.82 Hz, therefore where asymmetry is introduced to the membrane a 20000-sample window is used.

It is desired in the current research to perform frequency analysis to intervals of 0.1 Hz. Given that fine alterations to percussion tuning can be observed at this level of detail, the chosen Fourier transform method achieves this sufficiently. There is scope to investigate further the use of zero padding and oversampling to achieve higher-resolution spectra for percussion analysis. However, the current capture and analysis methodology has been tested with pure sine waves and has been shown to display and determine peaks to an accuracy of 0.1 Hz over the range 50 - 500 Hz with further testing being outlined in Appendix C with the data from experimentation shown in Appendix D. The methodology for generating frequency spectra from time-based data is therefore shown to be sufficient for the analysis conducted in this research.

Following calculation of the Fourier transform, the DFT absolute magnitude is calculated from the real and imaginary components and normalised against the maximum frequency peak. This gives a frequency spectrum with a maximum peak at the normalised power value of 1, as shown in Figure 4.10 and Figure 4.11.

In addition, and prior to spectral analysis, the captured waveform data is high-pass filtered to remove any unwanted rumble, DC offset or other unwanted low-frequency components. In the current research this is performed using a 5th-order Butterworth filter with a 30-Hz cut-off frequency, and is implemented by the Matlab Butterworth filter function (MathWorks, 2010*d*). This processing method has been used in analysis of musical instruments previously, for example by Taguti and Tohnai (2001) who used a 4th-order Butterworth filter with a cut-off frequency of 80 Hz.

4.6 Outside the scope of the current research

Initial investigations have identified questions which are considered to be outside the scope of the current research. Although these shall be discussed further in the future work section of this thesis it is useful to mention these questions now.

Identified research topics outside of the scope of this research include:

1. The effect of the drum shell design on the timbre and spectrum of a drum.
2. The effect of the type of drumhead on the timbre and spectrum of a drum.
3. The effect of the presence of snare wires on the timbre and spectrum of a drum.

Chapter 5

Achieving uniform frequency response around the drumhead

5.1 Uniform response in literature

It has already been discussed in Section 3.1 that a uniform frequency response around the drumhead should be achieved in order for an acoustic drum to be considered in tune. It is considered in this research that the (11) mode is the predominant mode that is perceived when tuning the drumhead. The (11) mode degenerates into two orthogonal (11) modes with different frequencies as the drum is detuned, described by Worland (2010) as a lower frequency, f_-, and higher f_+ frequency. The hypothesis explored presently is that these mode pairs can be tuned in such a way as to converge so that $f_- = f_+$ creating a uniform frequency for the (11) mode of the drum, f_1. The current research shows that a uniform response, when excited around the perimeter of the drumhead, is indeed possible and quantifiable.

It has been noted in the methodology that the fundamental frequency and second partial are the predominant frequencies produced by a drumhead. These two frequencies, the (01) mode, f_0, and the (11) mode, f_1, are the most powerful modes produced by simple excitation, with the fundamental mode being the predominant frequency produced when the drum is struck at or near the centre of the head. The (11) mode becomes most prominent when the drumhead is excited around the perimeter, and it is this frequency that is of most concern to expert musicians when they tune the acoustic drum by ear. This chapter concentrates on the second partial, f_1, or (11) mode of the drum. Where degenerate mode pairs are discussed for the (11) mode, the lower frequency will be denoted as f_{1-}, and the higher frequency as f_{1+}.

As the f_1 mode degenerates into f_{1-} and f_{1+} beat frequencies will be present in the drum waveform. 'Clearing' the drumhead to minimise this beating is one tuning method employed by percussionists. As beating occurs when $f_{1-} \neq f_{1+}$ it is possible to define a 'cleared' drumhead as one where beat frequencies are minimised, thus a cleared drumhead should exhibit a consistent f_1 where $f_{1-} = f_{1+}$.

The literature review has highlighted the fact that although much is known about the theoretical behaviour of an ideal membrane, little empirical evidence on the subject of drum tuning exists. Despite significant knowledge and discourse amongst expert musicians on the subject of drum tuning, there is no single scientifically determined standard for tuning an acoustic drum. Popular literature suggests that a uniform response profile is an important aspect of drum tuning with Gatzen (2006) saying that "equalised tuning is by far the single most important technique" that he uses.

This chapter focuses on answering whether a cylindrical drum can be tuned to have a uniform response around the perimeter of the drum. The current research will define the importance of uniform frequency response over that of uniform tension via observation and analysis of drum setups involving either equal tension or equal frequency response. The sound of a drum that has been purposefully 'detuned', i.e. with asymmetry introduced to the drumhead, has been recorded and the results are also discussed.

In a study of single-headed tom drums Worland notes in his conclusion that:

> "The practical conclusion of this study is that the splitting of the (1,1) mode

under the twofold perturbation appears to be the largest contributor to the sound of a drum not being in tune with itself."

Worland (2010)

5.2 Experimental method

The general data capture method for experiments is described below. The actual method for impacting and recording the sound of a drum is arbitrary in practice, though key emphasis is placed on a repeatable and consistent approach.

The drums used in the experiments were 30-cm and 35-cm tom drums from a Gretsch Catalina Club Jazz kit, with Aquarian Classic Clear resonant heads. Additional experimental data can be seen in Appendix D. The 30-cm tom used an Evans EC2 batter head, whilst the 35-cm tom used an Aquarian Modern Vintage batter head. Each drum was rested on a standard drum stand with a Shure BETA 57A microphone held securely 10 cm above the drum angled toward the location of the drum stroke. The drum was struck approximately 5 cm from the edge at 10 locations - one at each lug and also at points equidistant between lugs. A consistent stroke height of approximately 5 cm was used, as shown in Figure 5.1. As the experimental modal analysis used is concerned with the free vibration of the drumhead precise excitation was not necessarily a significant factor in achieving reliable results.

Where experiments were performed with both resonant and batter head in place the resonant head was tuned to a desired, uniform response before fine tuning the batter head.

Worland (2010) and Rhaouti et al. (1999) discuss the occurrence of mode splitting in circular membranes. Where frequency splitting occurs then two peaks will be observable in the spectrum. However as the peaks converge the limitations of the FFT used for analysis become apparent and whereas a smaller number of samples are

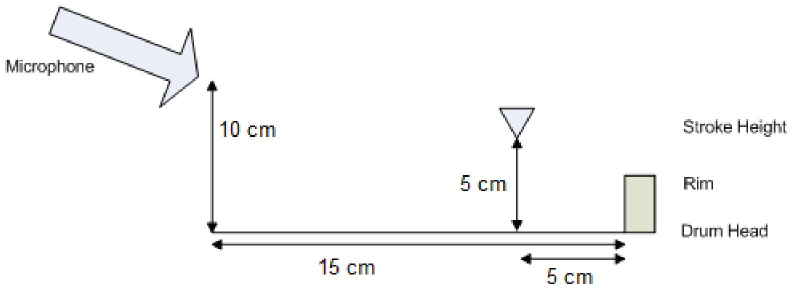


Figure 5.1: Experimental setup for investigating frequency response around the perimeter of a drumhead.

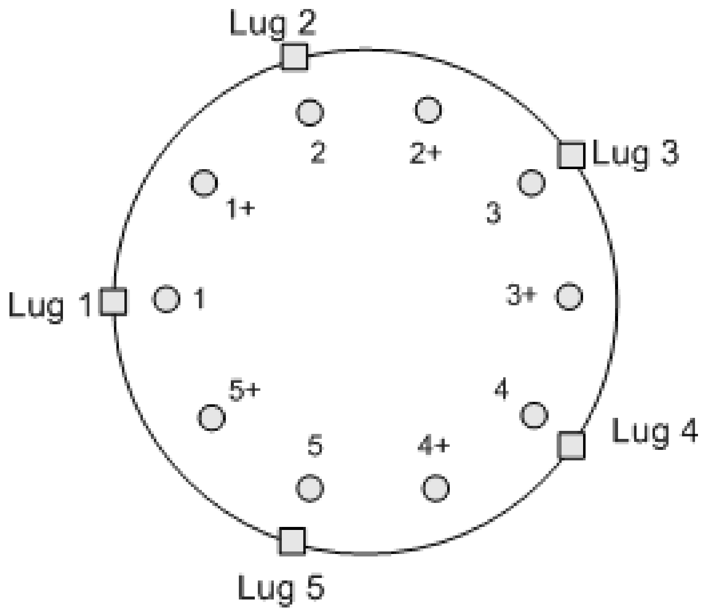


Figure 5.2: The tuning sequence and stroke locations used on a 5-lug tom drum.

adequate for analysis of a cleared drumhead, larger window sizes are needed to accurately determine split-frequency peaks f_{1-} and f_{1+}.

As discussed in Section 4.5 it is necessary that a suitable analysis window is chosen. It can be seen from Figure 5.3 that, where the drumhead has been cleared, window sizes of 5000, 10000 and 20000 data samples provide similar results for peak frequencies, within a tolerance of 0.5%. However, when compared with analysis of a drum where frequency splitting is present it can be seen in Figure 5.4 that a higher resolution is required to accurately determine frequency peaks for the f_1 frequencies.

5.3 'Clearing' the drumhead

It is possible to 'clear' a drumhead by making small adjustments of less than a quarter of a turn to each tension rod (lug) in response to analysis of the frequency spectra for each data reading. Here a uniform frequency response around the perimeter of the drumhead is achieved via analysis of the f_1 mode. A drum which has been set up so that it exhibits a consistent frequency for f_1 can be seen from the results in Table 5.1, Table 5.2 and Table 5.3 which show the peak frequencies when the response was analysed at locations around a cleared drumhead. The drumhead was struck at 10 locations around the perimeter of the drumhead and analysed using a 5000-sample window. The locations struck were at each lug (1, 2, 3, 4 and 5) and halfway between one lug and the next (1+, 2+, 3+, 4+ and 5+), as shown in Figure 5.2.

The results in Table 5.1, Table 5.2 and Table 5.3 show that it is indeed possible to tune a drumhead so that each location near the edge of the drumhead has an equal and single identifiable f_1 frequency peak as can be seen in Figure 5.5, which relates to the data in Table 5.2. Table 5.1 shows that a uniform response chosen to be 164.8 Hz $\pm$0.4 (0.24%) can be achieved with a single drumhead, with the results for the frequency at each lug shown in Figure 5.6 which has been filtered just to show f_1. Table 5.2 and Table 5.3 show the uniform frequency achieved at 220 Hz $\pm$0.5 (0.22%)

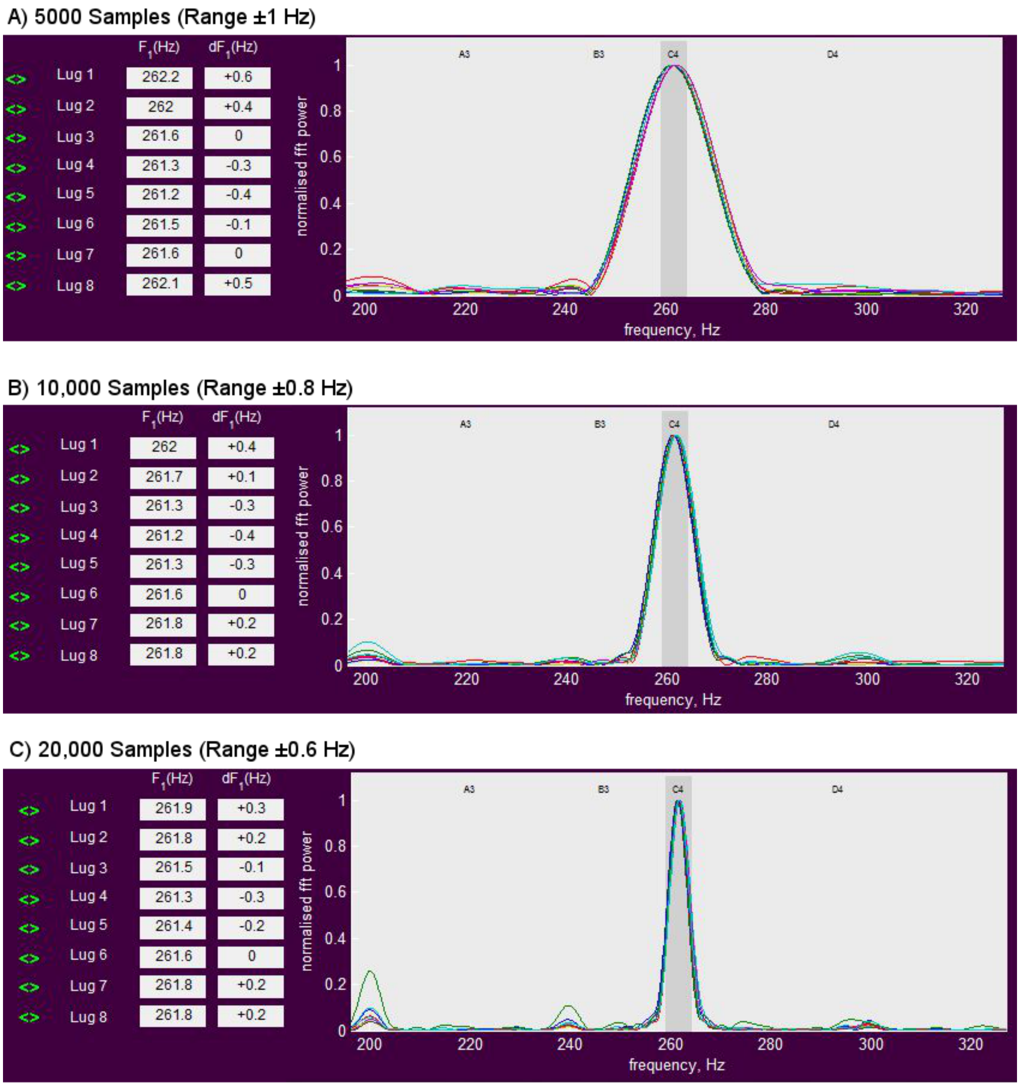


Figure 5.3: Frequency peaks of 8 drum impacts at 8 locations around the perimeter of a cleared drum. Analysed with A) 5000 samples, B) 10000 samples, and C) 20000 samples.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	164.9	164.8	165.0	165.1	164.9	164.9	165.0	165.2	164.9	165.0

Table 5.1: The average f_1 frequency present around a drumhead on a 30-cm tom drum tuned to 164.8 Hz with a single head.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	220.5	220.1	219.7	220.0	220.3	220.5	220.4	219.9	220.0	220.3

Table 5.2: The average f_1 frequency present around a drumhead on a 30-cm tom drum tuned to 220 Hz with both heads.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	175.7	175.5	175.4	175.1	175.0	175.5	175.8	175.1	174.8	175.3

Table 5.3: The average f_1 frequency present around a drumhead on a 30-cm tom drum tuned to 175 Hz with both heads.

and 175 Hz $\pm$0.8 (0.45%) with both drumheads, shown in Figure 5.7 and Figure 5.8 respectively. These frequencies were specifically chosen to correspond to notes on the musical scale E3 (164.8 Hz), F3 (174.6 Hz) and A3 (220 Hz).

Figure 5.9 shows the waveform of a drumhead with a uniform f_1 frequency response. Here it is possible to see that a smooth, 'beat free' decay is present. It is thought that much like the tuning of a timpani, the removal of 'beating' from the waveform is advantageous and necessary in the tuning of a cylindrical drum.

The experimental analysis used shows that when the drumhead has been 'cleared', f_1 is consistent around the drumhead, as shown in Figure 5.6, Figure 5.7 and Figure 5.8. Here it can be seen that f_1 is virtually identical at each point to an accuracy of $\pm$0.5 Hz, and that a smooth decay, see Figure 5.9, is present. This is a novel method for quantifying that a drumhead is in tune by exhibiting a uniform response. This has been shown successfully here on both a drum with a single head and on a drum with both a batter and a resonant head. The response of a drum not uniformly tuned is discussed in Section 5.5 with non-uniform response and uneven decay shown in Figure 5.16, which has been filtered with a 5th-order Butterworth filter applied to $0.5f_1$ to $1.5f_1$ so as to only show the f_1 frequency.

5.4 Investigating the relationship between tension and frequency response

Many experiments in scientific literature, such as those performed by Rossing et al. (1992), consider an even tension to be necessary for a tuned drum. The assumption that drumhead tension and the resulting frequency response are as closely related in the real world as in ideal theory has produced commercial applications such as the Tama Tension Watch (Tama-Drums, 2010) described in Section 3.10. The Tama Tension Watch provides an indication of the tension of a drumhead and requires careful positioning in order to gain repeatable results, the aim being to create a uniform ten-

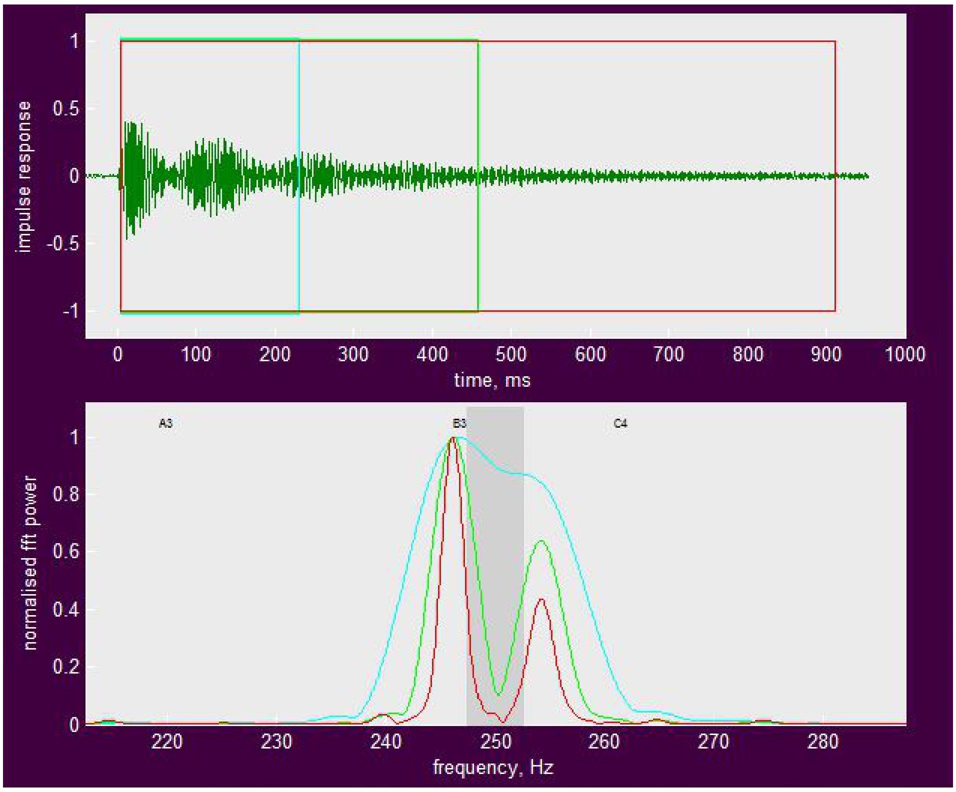


Figure 5.4: Frequency splitting shown when 10000 (blue), 20000 (green) and 40000 (red) data samples are used (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$).

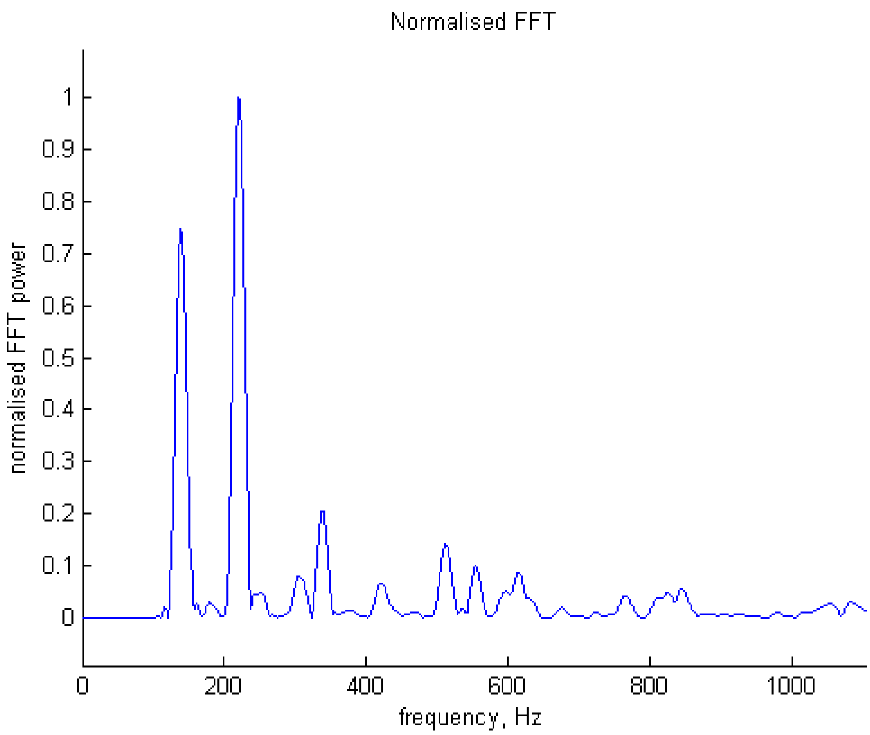


Figure 5.5: Normalised FFT of the sound produced by a drum with uniform frequency response struck at the edge.

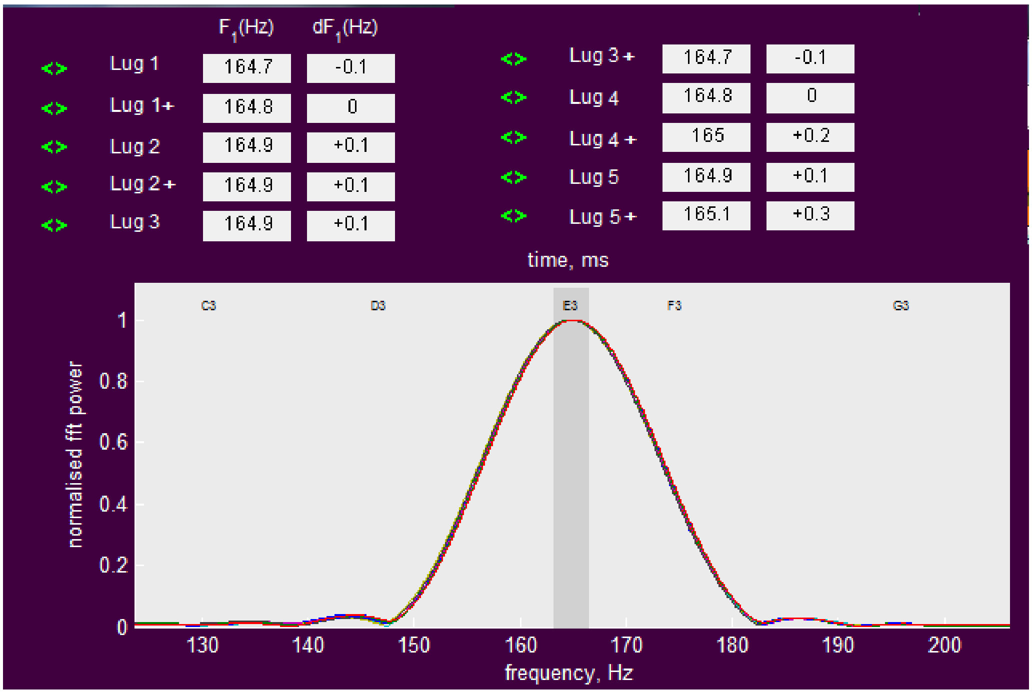


Figure 5.6: Uniform frequency (164.8 Hz) for f_1 for a 30-cm tom drum with a single drumhead (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$, 5000-sample window).

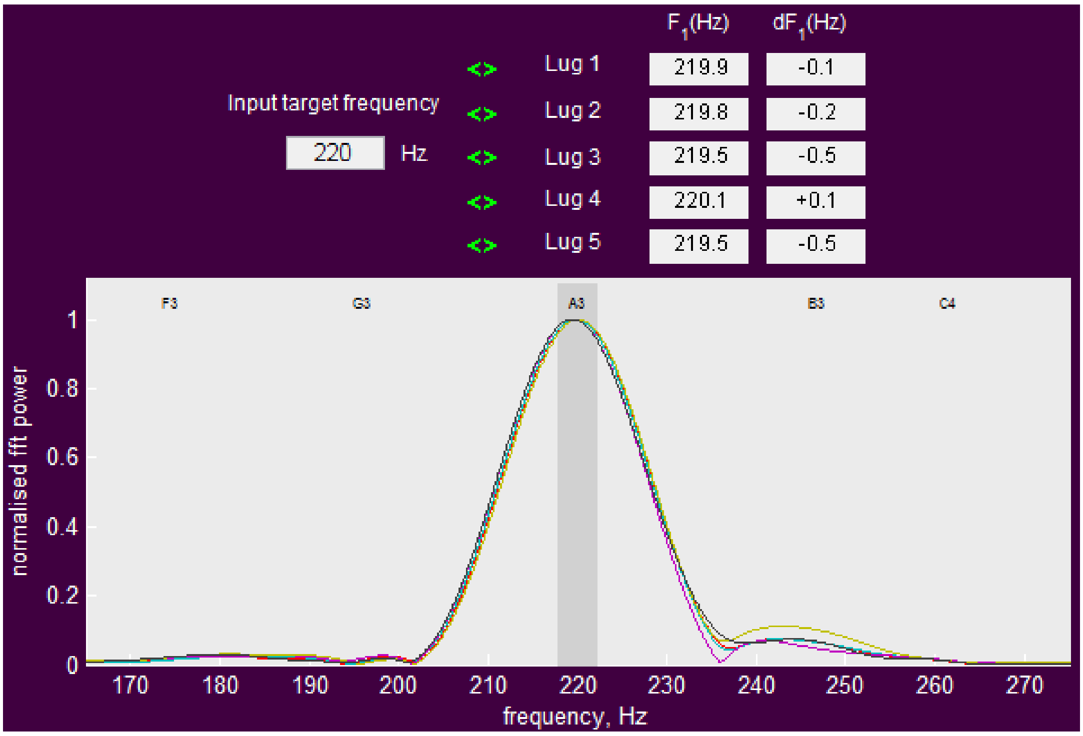


Figure 5.7: Uniform frequency (220 Hz) for f_1 for a 30-cm tom drum with both drumheads (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$, 5000-sample window).

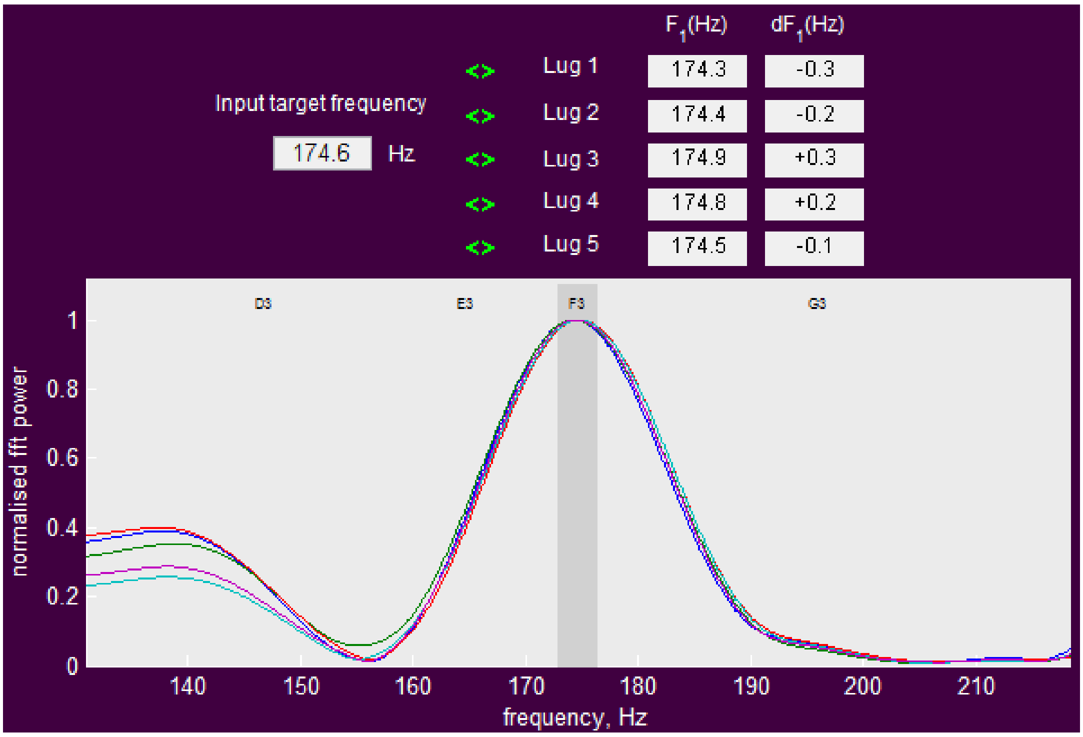


Figure 5.8: Uniform frequency (174.6 Hz) for f_1 for a 30-cm tom drum with both drumheads (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$, 5000-sample window).

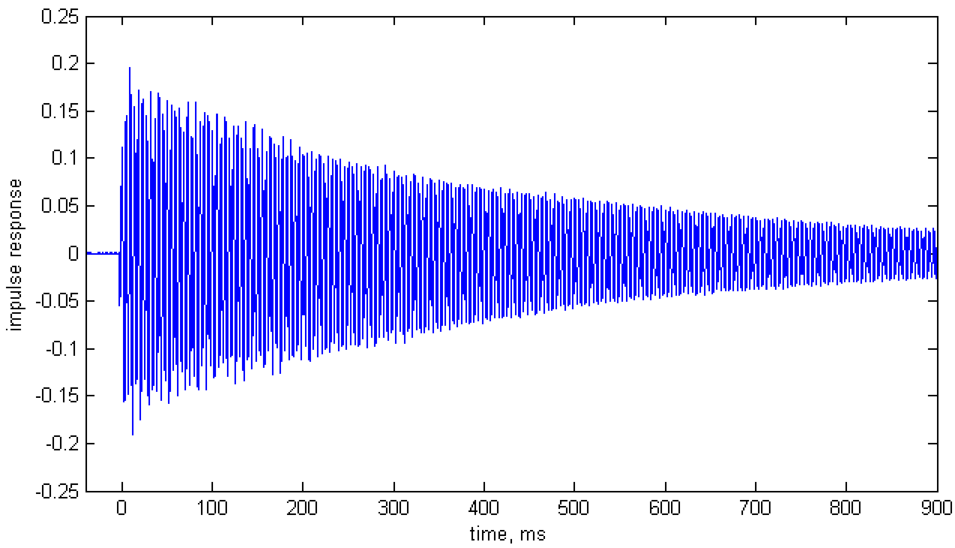


Figure 5.9: Example waveform produced when a uniform frequency for f_{1B} and uniform frequency for f_{1R} are achieved for a 30-cm tom drum.

sion as the supposed requirement for an in-tune drum. Although there are no scientific units of measurement on the scale of the device the Tama Tension Watch was used to gauge the tension of a drumhead with uniform frequency response, and the results are shown in Table 5.5 and Table 5.6. Where the tension is discussed in this thesis the units listed represent numbers on the scale of the Tama Tension Watch and are referred to as Tama units (TU). A 5000-sample window was used for analysis.

Tables 5.5 and 5.6 indicate that uniform frequency response does not necessarily mean a uniform tension around the head as measured by the Tama Tension Watch. In fact, there is a 19.3% increase in the measured tension over the lowest tension in Table 5.5 with a f_1 frequency of 220 Hz $\pm$0.5 (0.22%) and a 14.6% increase in Table 5.6 with a f_1 frequency of 175 Hz $\pm$0.8 (0.45%). This variation in results is significant when compared to the variation in f_1 achieved by tuning to an even frequency response. By choosing to balance the tension around the drumhead at each lug it can be seen that a uniform head tension does not necessarily correspond to uniformly balanced peak frequencies, as shown in Table 5.7 where the tension at each lug is even (57 TU). The variation between lugs is observed to be $+5$ TU (8.8%), whereas the frequency variation is 4.1 Hz.

It is worth noting that even though it is possible to create a uniform tension at each lug, (i.e. at locations 1, 2, 3, 4 and 5 as shown in Figure 5.2) it does not necessarily follow that a uniform tension between the lugs is maintained (tension varies by 8.8% between the lugs). Likewise, nor does it follow that a uniform response will be achieved by balancing a drumhead by analysing its tension (f_1 was observed to change by 2.1%). The waveform produced by a strike near the rim of a head with uniform tension can be seen in Figure 5.10. Unlike the waveform of the drumhead with a uniform frequency response, beat frequencies can clearly be seen indicating that $f_{1-} \neq f_{1+}$. This unwanted beating and frequency splitting indicates that the drum does not fulfil many percussionists' criteria for in-tune, as discussed in Section 3.7.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	164.9	164.8	165.0	165.1	164.9	164.9	165.0	165.2	164.9	165.0
Tension (TU)	49	55	49	52	48	53	46	52	50	53

Table 5.4: The average f_1 frequency and tension around a drumhead on a 30-cm tom drum tuned to 164.8 Hz with only a single head.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	220.5	220.1	219.7	220.0	220.3	220.5	220.4	219.9	220.0	220.3
Tension (TU)	57	63	61	65	65	68	64	63	59	58

Table 5.5: The average f_1 frequency and tension around a drumhead on a 30-cm tom drum tuned to 220 Hz with both drumheads.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	175.7	175.5	175.4	175.1	175.0	175.5	175.8	175.1	174.8	175.3
Tension (TU)	49	53	48	53	48	55	53	55	52	51

Table 5.6: The average f_1 frequency and tension around a drumhead on a 30-cm tom drum tuned to 175 Hz with both drumheads.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz)	197.0	196.7	192.9	193.0	195.9	196.9	196.4	193	193.2	196.2
Tension (TU)	**57**	61	**57**	60	**57**	62	**57**	60	**57**	58

Table 5.7: The average f_1 frequency and tension across a drumhead on a 30-cm tom drum with uniform Tama Unit readings.

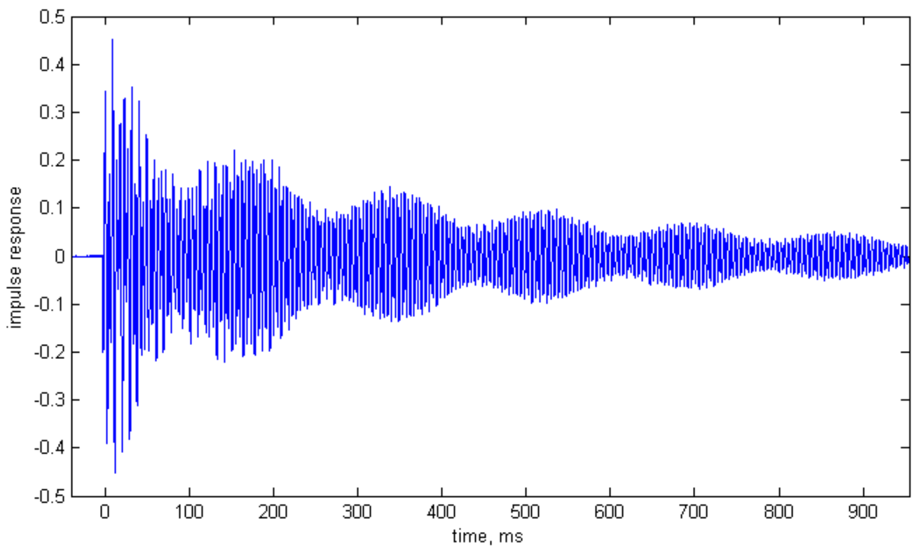


Figure 5.10: Waveform produced by striking a point around the edge of a drumhead with uniform tension.

There are several explanations for the disparity between uniform head tension and uniform response. These include:

1. The head was not seated correctly causing an uneven tension to arise.
2. The head was not of uniform thickness or density.
3. The readings on the device were inaccurate or the device was not correctly calibrated.

It can therefore be seen that it is preferable to measure and analyse partials in the spectrum as opposed to drumhead tension. Tuning a drum by acoustic analysis is therefore shown to provide a more accurate and reliable method of 'clearing' a drumhead than the tension-measuring mechanical tuning aids that are commercially available.

5.5 Identifying anomalies in the tuning setup

Experiments have shown that there are clear fluctuations in the envelope of a 'detuned' drum, as also observed by Worland (2010). That is, the drum has been altered in such a way as to no longer meet the tuning criteria of many musicians, i.e. the drum has been detuned so that the (11) mode degenerates causing the f_1 frequency to split, ($f_{1-} \neq f_{1+}$), introducing beating into the envelope of the waveform.

When two opposite tension rods are altered a $1/8th$ of a turn at a time, from 0 turns to 0.75 turns, the f_1 frequency peaks observed at each lug changes, as shown in Table 5.8. Figure 5.11 which shows the effect of having tension rods, in this case tension rod numbers 1 and 5, loosened in $1/8th$-turn increments with a 20000-sample window being used to analyse results. The drum was a 35-cm Gretsch tom drum with 8 lugs, it was initially tuned to a uniform frequency response and it is noteworthy that frequency splitting occurs as the drum is detuned, and that opposite locations on the drum tend to have similar frequency responses, as shown in Figure 5.12. This is due to the degeneration of the two perpendicular (11) modes caused by the introduction of asymmetry in the drumhead.

It can be seen that detuning opposite tension rods by just 0.75 turns has a significant result on the spectrum, introducing frequency splitting in the f_1 modes. The change in frequency, Δf, can be seen in Figure 5.11, where Δf increases as the change in tension around the drumhead increases. As one tension rod is altered the frequencies begin to split, and this splitting increases as changes in the tension of the head at a single point. The split between f_{1-} and f_{1+} frequencies reaches a maximum of 15.6 Hz at lug 2 at 0.75 turns out of tune, a difference of over a semitone at 243 Hz (13.6 Hz). The difference between f_{1-} and f_{1+} can be seen in Table 5.9 and frequency splitting can be seen at locations where both f_{1-} and f_{1+} are excited. At locations 1 and 5 f_{1+} is not excited and at locations 3 and 7 f_{1-} is not excited; this is due to the presence of perpendicular nodal lines as described in Section 2.2.1 and further discussed by Worland (2010) and Fletcher and Rossing (1998, pp.70-76). When the drum is struck at points between the nodal lines both f_{1-} and f_{1+} are seen in the spectrum, as shown in Figure 5.13.

Figure 5.14 shows the waveform produced when a single lug is altered by one turn and here it can be clearly seen that the smooth decay of the drum sound is no longer present. The absence of a smooth decay causes an audible 'beating' effect as seen in Figure 5.14 and is comparable to the uneven decay observed when the drumhead was tuned to a uniform tension, measured by the Tama Tension watch, as in Figure 5.10.

Figure 5.15 shows the f_1 frequency produced by a tom drum struck at each lug. In Figure 5.15a a uniform f_1 frequency of 220 Hz (A3) can be seen at all locations. Figure 5.15b shows the same tom tuned to produce a non-uniform f_1 frequency and it can be seen that f_1 at tuning lugs 2 and 5 are within a tolerance of 1% of the desired frequency (220 Hz), whereas lugs 1 and 4 are tuned high and 3 and 6 are tuned low. This non-uniform tuning creates an uneven decay profile for the drum, as shown in

Tuning	Tension Rod	1	2	3	4	5	6	7	8
0 Turns	Frequency (Hz)	261.8	261.6	261.3	261.2	261.5	261.7	261.8	261.8
0.125 Turns	Frequency (Hz)	258.5	**261.0**, 257.1	260.2	257.5	258.3	258.2	260.6	258.5
0.25 Turns	Frequency (Hz)	252.8	252.8	257.3	256.8, **252.5**	252.8	257.9, **252.8**	257.8	253.1
0.375 Turns	Frequency (Hz)	246.2	254.2, **246.2**	253.8	254.0, **246.0**	246.2	254.3, **246.3**	254.4	254.4, **246.5**
0.5 Turns	Frequency (Hz)	239.6	250.3, **239.6**	250.0	249.6, **239.1**	239.4	250.2, **239.6**	250.3	250.3, **239.7**
0.625 Turns	Frequency (Hz)	233.2	246.4, **233.1**	245.9	245.8, **232.7**	233.1	246.5, **233.2**	246.5	246.7, **233.5**
0.75 Turns	Frequency (Hz)	227.4	242.7, **227.1**	241.7	241.8, **226.8**	227.3	242.9, **227.4**	242.9	243.0, **227.5**

Table 5.8: f_1 frequencies around the batter head of a 35-cm tom where tension rods 1 and 5 are detuned in $1/8th$ turn increments. Where two frequencies are present in the spectrum these are denoted as f_{1+}, f_{1-} with the stronger frequency in bold.

Tuning	Tension Rod	1	2	3	4	5	6	7	8
0 Turns	Frequency (Hz)	0	0	0	0	0	0	0	0
0.125 Turns	Frequency (Hz)	0	3.9	0	0	0	0	0	0
0.25 Turns	Frequency (Hz)	0	0	0	4.3	0	5.1	0	0
0.375 Turns	Frequency (Hz)	0	8	0	8	0	8	0	7.9
0.5 Turns	Frequency (Hz)	0	10.7	0	10.5	0	10.6	0	10.6
0.625 Turns	Frequency (Hz)	0	13.3	0	13.1	0	13.3	0	13.2
0.75 Turns	Frequency (Hz)	0	15.6	0	15.0	0	15.5	0	15.5

Table 5.9: The difference between f_{1+} and f_{1-} frequencies observed around the batter head of a 35-cm tom where tension rods 1 and 5 are detuned in $1/8th$ turn increments.

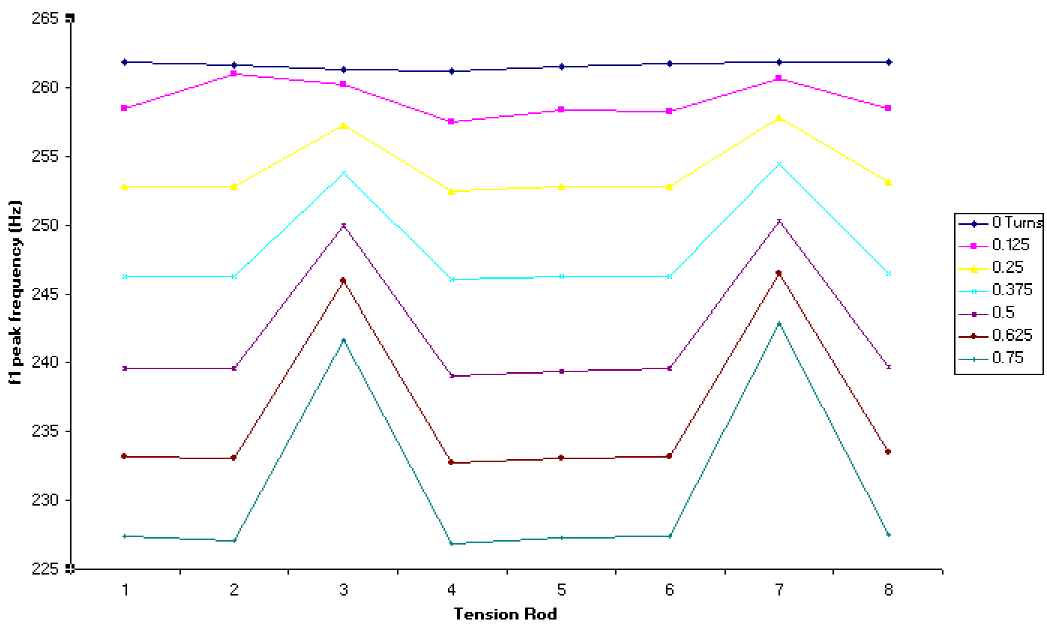


Figure 5.11: The peak frequencies around a drumhead as the head is detuned over 0.75 turns at tension rods 1 and 5. Here only the f_1 frequency of highest amplitude is plotted.

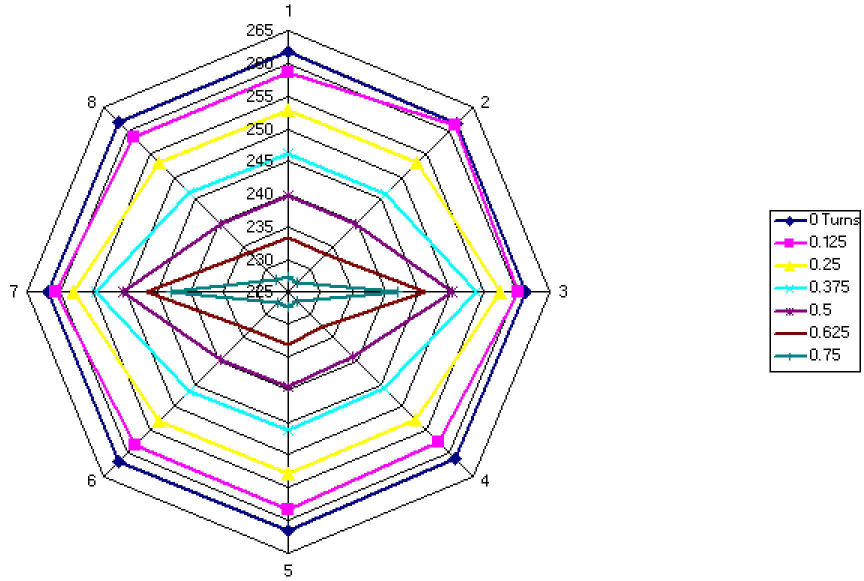


Figure 5.12: The peak frequencies around a drumhead as the head is detuned over 0.75 turns tension rods 1 and 5. Here only the f_1 frequency of highest amplitude is plotted.

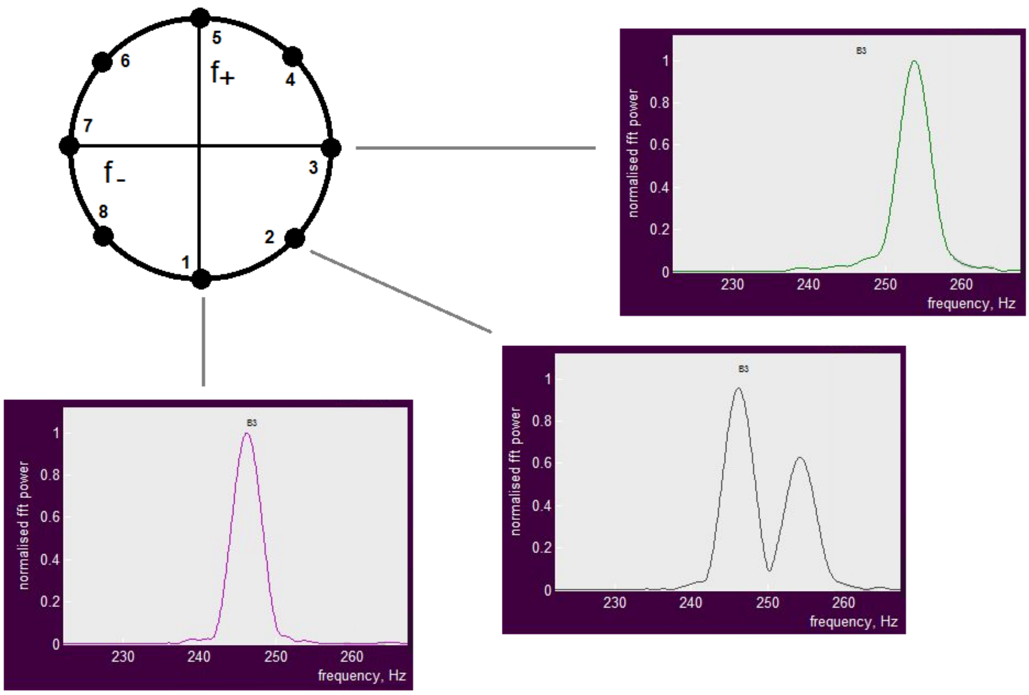


Figure 5.13: Orthogonal (11) modes, f_{1+} and f_{1-}, present in the spectrum, with both modes apparent when the drum is struck at a lug between these nodal lines.

Figure 5.16 and Figure 5.17. In Figure 5.16 the two peaks are at 233.0 Hz and 245.9 Hz, creating a beat frequency of 12.9 Hz ($f_{1+} - f_{1-}$). This is beating is visible in the waveform, where 2 beats occur over 155 ms, $1000/155 * 2 = 12.9$ beats. In Figure 5.16 the two peaks are at 227.1 Hz and 242.7 Hz, creating a beat frequency of 15.6 Hz, visible in the waveform, where 4 beats occur over 245 ms, $1000/245 * 4 = 16.3$ beats.

As has been seen in Figure 5.9, Figure 5.10 and Figure 5.14 the envelope of the waveform changes as the drum is tuned. A drumhead with an uniform frequency response will produce a smooth decay curve, whereas as the drum becomes less well tuned the drumhead begins to 'beat'. The current research shows that a well-tuned drum will minimise beat frequencies. When the drum is tuned only a single predominant frequency peak is present around the edge of the drum. However, as the drum is detuned this main peak frequency splits into 2 peaks, as has also been observed by Worland (2010) and discussed in Section 3.7.

Figure 5.18 highlights the waveform envelope and beating from Figure 5.10. The beating in the envelope is highlighted by the red line. Figures 5.16 and 5.17 shows clearly visible beating occurring as the f_1 frequencies diverge.

This correlates with Gatzen's observation that:

> "You are more able to hear a single pitch the more even your tuning is becoming"
>
> (Gatzen, 2006).

It is possible to define a 'cleared' drumhead as one which has a uniform peak frequency response when excited around the perimeter. The waveform of the drum will exhibit a steady decay with no beat frequencies present. A cleared drumhead therefore means a lack of beating in the waveform.

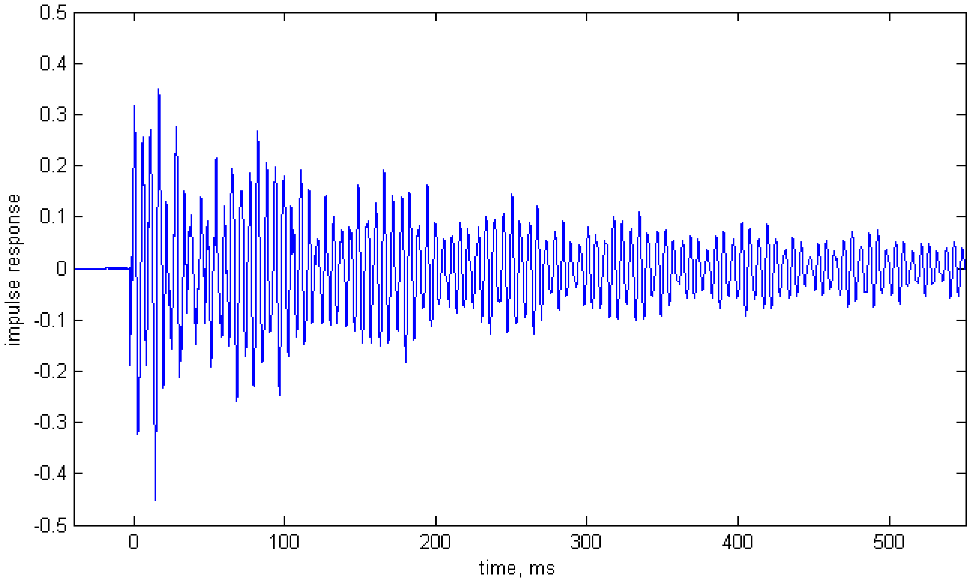


Figure 5.14: Waveform showing visible beating in a drum with one lug altered by one whole turn.

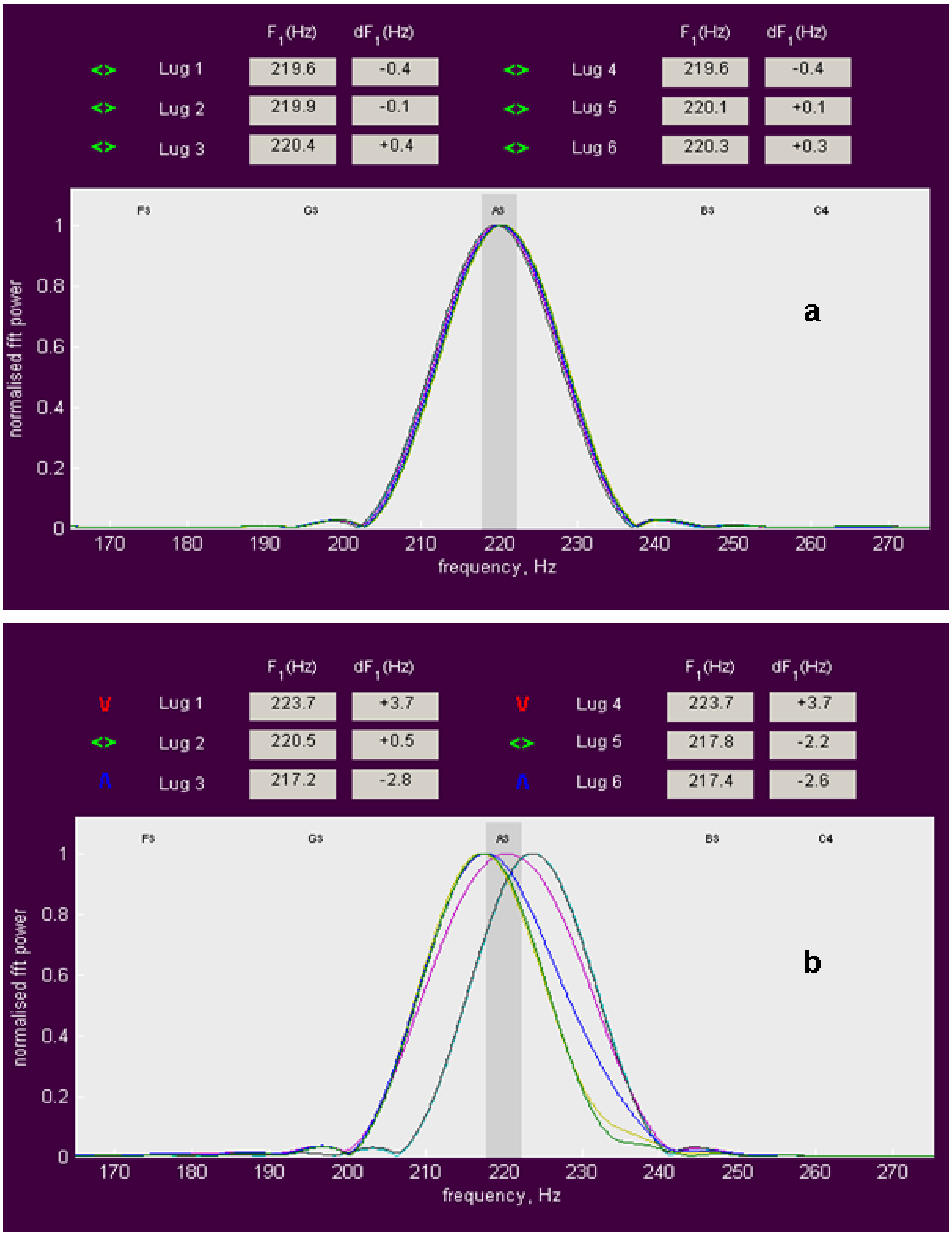


Figure 5.15: Analysis of the f_1 frequency for (a) a uniform response and (b) a non-uniform response (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$).

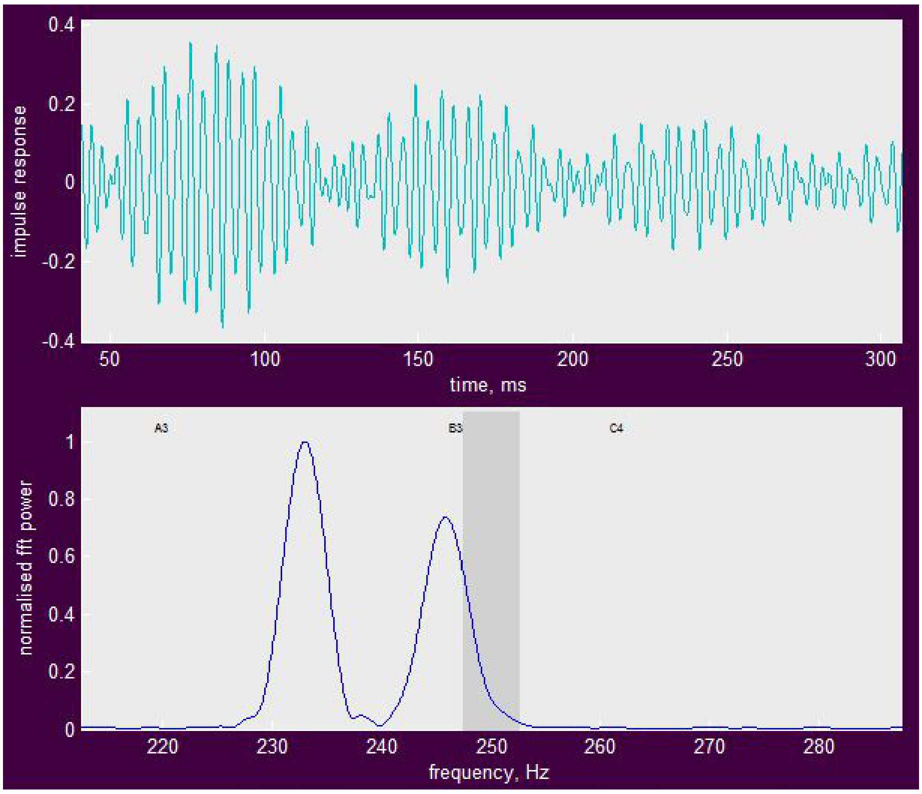


Figure 5.16: Analysis of the f_1 frequency peaks for a non-uniform response, where lugs 1 and 5 have been detuned 0.625 turns (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$).

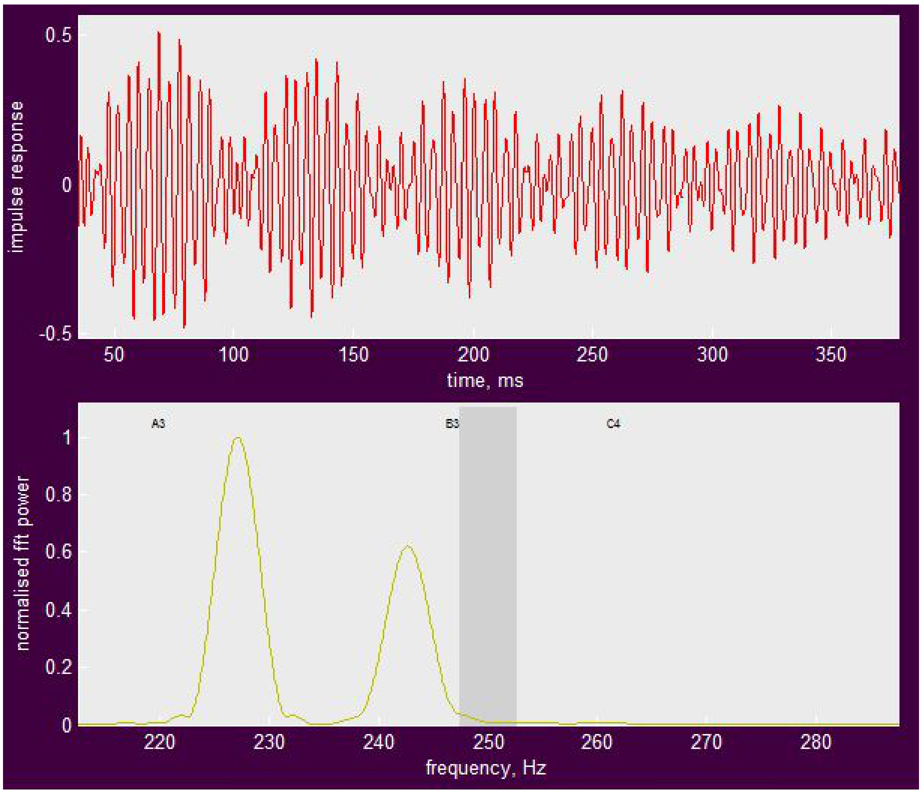


Figure 5.17: Analysis of the f_1 frequency peaks for a non-uniform response, where lugs 1 and 5 have been detuned 0.75 turns (5th-order Butterworth filter applied to band $0.5f_1$ to $1.5f_1$).

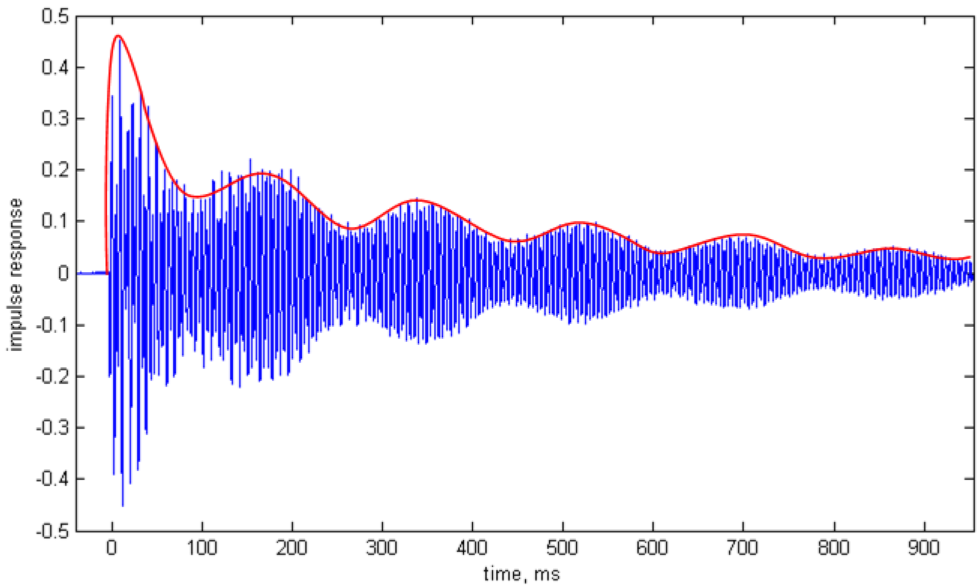


Figure 5.18: Waveform of the batter head of a drum with ‘beating’ visible.

5.6 Reflections and conclusions

The current research shows that uniform frequency responses for the f_0 and f_1 frequencies are achievable for cylindrical drums. This has been shown for a tom drum with only the batter head in place, and with both batter and resonant heads. It has also been shown in this chapter that it is indeed possible to tune the f_1 frequency to a musical note. This will be discussed further in the following chapter where the relationship between the f_0 and f_1 frequencies is further investigated.

The current research shows that with respect to achieving an even consistent decay of the drum waveform, it is preferable to tune the drum to a uniform acoustic response via microphone analysis techniques than to tune the head until it reaches a specific tension. That is not to say that the tension of the drumhead is unimportant, indeed with respect to the batter head it is still important to many drummers who may tune the drumhead to provide a desired drumstick response. However, the method of scientifically tuning to a uniform frequency response produces a drum sound consistent with the qualitative descriptors used by percussionists. For example, Ranscombe (2006*b*) states that a drum should produce a sound with a "nice tone that decays with a smooth, even note".

It has been shown that even small differences in the tuning of the drum can introduce beat frequencies, providing more evidence towards choosing a uniform response when tuning a drumhead in order to produce a drum sound which has a smooth decay. These beat frequencies occur through the splitting of the (11) mode into two orthogonal modes f_{1-} and f_{1+}.

Chapter 6

Manipulating partials via alteration in tension of the resonant and batter heads

6.1 The relationship between batter and resonant heads

As shown in Chapter 5 the f_1 frequency present when a cylindrical drum is struck can be altered. The literature review has highlighted significant gaps in scientific knowledge regarding the relationship between the batter and resonant heads.

It has been discussed in Chapter 2 how some percussive instruments have a definite sense of pitch due, in part, to their nearly harmonic frequency ratios. For example Rossing (2005, p.8) notes that the modal frequencies for a timpani have the ratio 1:1.5:1.99. How this affects the sense of pitch of a musical instrument is discussed in Section 2.3 and a more thorough description can be found in Howard and Angus (1996, pp.119-136). On a single-headed tom drum Rossing (2005, p.26) observed a ratio of 1:2.16:3.14. Given that more harmonic frequency ratios are preferable, it would certainly make sense that a drum with two heads, and therefore more variables to alter, should allow for more adjustment of modes than a single drumhead.

This chapter demonstrates that via manipulation of the drumheads, and hence the alteration of the f_0 and f_1 modes, the ratios of the frequencies in a two-headed cylindrical drum can be made similar to that of a timpani.

In a drum with a single head these frequency ratios remain relatively fixed for each particular setup. However, it could be argued that a key reason for having a second, coupled drumhead on a cylindrical drum is in order to allow greater manipulation of the sound produced by the drum, that is, its pitch and timbre. This chapter tests the novel hypothesis that the alteration of one or both drumheads can produce pronounced differences in the ratios between the frequencies produced.

6.2 Experimental method

The current research focuses predominantly on the f_0 and f_1 modes. As the research is interested in both of these modal frequencies the drum is hit in such a way as to excite the f_0 and f_1 frequencies simultaneously.

For each tuning a series of excitations are recorded. These are recorded independently at both the batter and resonant heads using an impact from a drumstick. It should be noted that the microphone placement is maintained at 10 cm from the head being struck. The strikes are located midway between the centre and the edge of the drum at locations at and between each lug as discussed in Section 4.5.

The drum is tuned arbitrarily to a uniform response and with a fundamental frequency deemed to be mid-range for the drum. Each drumhead is then raised or lowered in turn until all possible permutations have been achieved, as shown in Table 6.1. That is, the drum is recorded at an initial state, the batter head raised, recordings retaken and analysed, the resonant head lowered, results obtained for that tuning, and so on for all tuning options listed.

Investigations will focus first on the 30-cm tom drum, and then on to other drums to prove or disprove the hypothesis that the f_0 and f_1 modes can be tuned to more musical ratios.

In the case study, the 30-cm tom drum was initially tuned so that f_0 was 147 Hz. This frequency was arbitrarily chosen because it allows for a wide range of both higher and lower tunings.

The drumhead was altered by 0.5 of a turn, a 180-degree rotation of the drum key, on each lug for each set of results, until the permutations displayed in Table 6.1 had each been recorded and analysed. That is, each head was either tuned to their original state (Normal), up half a turn on the drum key for each lug (High), or down on by half a turn on the drum key for each lug (Low).

The drumheads used were in good condition and were an Evans Genera G2 coated head as the batter head and an Aquarian classic clear head as the resonant head.

6.3 Raw data and commentary

The initial spectrum of the drum for both heads is shown in Figure 6.1, with f_0 and f_1 frequencies being the predominant frequencies present. It can be seen in Figure 6.1 that f_{0B} and f_{0R} are close compared to the difference between f_{1B} and f_{1R}, where f_{0B} and f_{1B} are measured by analysing strikes on the batter head and f_{0R} and f_{1R} are measured by analysing strikes on the resonant head.

The average frequencies for batter and resonant impacts are shown in Table 6.2. Ten readings were taken to obtain these averages with one being at each lug hit point as described in Figure 5.2. The raw data for these readings can be found in Appendix D. It can be seen that, with the exception of the repeated readings at tuning five, the readings for each tuning are within 1% of each other.

Tuning	Batter Head	Resonant Head
T1	Normal	Normal
T2	High	Normal
T3	High	Low
T4	Normal	Low
T5	Low	Low
T6	Low	Normal
T7	Low	High
T8	Normal	High
T9	High	High
T10	Normal	Normal

Table 6.1: Tuning permutations used in the experiment.

Tuning	f_{0B} (Hz)	f_{1B} (Hz)	f_{0R} (Hz)	f_{1R} (Hz)
T1	147.2	219.4	146.7	279.9
T2	168.9	275.4	167.9	287.5
T3	152.0	267.9	151.5	232.2
T4	124.2	191.5	123.5	224.0
T5	98.9	134.1	98.5	206.6
T5b	99.9	139.7	99.8	206.5
T6	120.5	165.4	121.1	256.8
T7	137.3	180.9	136.6	302.3
T8	167.5	259.9	166.4	305.3
T9	189.8	310.7	191.0	327.16
T10	145.5	218.3	146.4	279.9

Table 6.2: Average frequencies for batter and resonant impacts on a 30-cm tom drum.

As the tuning of the drum is altered, the three frequencies f_{0B}, f_{1B} and f_{1R} vary. The range of f_0 frequencies that the 30-cm tom drum can be tuned to is shown to be almost an octave - 99 Hz to nearly 190 Hz. The tuning range of a drum being determined by the lowest tuning causing slackening of the drumhead (observed in tuning T5) to the breaking tension of the drumhead (not observed in this research). The frequency f_{1B} rises over an octave during the tuning process, going from 98.5 Hz to 310.7 Hz. Scientific pitch notation would make this a change from nearly G2 (98 Hz) to approaching D#4 (311.1 Hz).

Figure 6.1a shows the spectrum produced by the batter impact of the drum, with Figure 6.1b showing the spectrum produced by the resonant side impact. It is visible in both the figures that the drum is tuned so that f_{0B} is 147.2 Hz with an f_{1B} of 219.4 Hz and an f_{1R} of 279.9 Hz. This is also shown in Table 6.2.

As the batter head tension is raised for tuning 2 it can be seen that each frequency rises, as shown in Figure 6.2. It is, however, the f_{1B} reading that has the most prominent increase in frequency, rising 56 Hz (25.5% increase) from one quarter turn of the drumhead whilst f_{0B} only rises 21.7 Hz (14.7% increase), f_{0R} rises 21.2 Hz (14.5% increase), and f_{1R} rises 7.6 Hz (2.7% increase). This proves that the ratio of frequencies can be changed via manipulation of the tension of the drumhead due to the decoupling of the (11) modes, f_{1B} and f_{1R}.

In tuning 3 the resonant head is then lowered in tension, showing a large drop in f_{1R} (55.3 Hz, 19.2% decrease), whereas f_{1B} drops 7.5 Hz (2.7% decrease), and the f_0 frequency drops 16.9 Hz for the batter head (10.0% decrease), and 16.4 Hz on the resonant head (9.8% decrease). Figure 6.3a shows the batter head frequency response while Figure 6.3b shows the resonant head frequency response. This was the only point in the experiment where the frequency of the batter head, f_{1B}, dropped below that of the resonant head, f_{1R}.

The closeness of these frequency changes for f_{1B} and f_{1R} may be coincidental, and further experimentation and statistical analysis would be required to draw any conclusions as to how much change is observed when tension rods around a head are altered by 180 degrees. It is clear that changing the tuning of one head significantly affects the f_1 frequency of that head. Other higher modes are also affected, although the effect on the higher modes of the opposite head is weaker due to less air coupling between the heads. Changing the tension of the batter head will cause a greater change in f_{1B} than in f_{1R}, whilst altering the tension of the resonant head will have a greater effect on f_{1R}. It was observed that the f_0 mode, where the coupling between the two heads is strong, negates the significance of the change to one head, causing f_{0B} and f_{0R} to remain close. This trend continues throughout the results shown in Table 6.2.

The replication of results at T5, is due to the slackness of the heads requiring slight alteration in order to achieve reliable results across the head indicating that for this drum, the lowest batter head tension had been reached at 0.5 turns down. Likewise the number of high-frequency peaks found in the resonant head when it was tuned 0.5 turns up, along with the high tension of the head suggest that the upper limit of the resonant head had also been found in this particular setup.

It is also interesting to note that on the tuning T2, where the batter head was increased whilst the resonant head remained at its initial tension, and T8, where the batter head was tuned to its initial setting whilst the resonant head tuning was increased, similar fundamental frequencies are produced, but the f_1 frequency for both the resonant and batter heads are significantly different. This can be seen in the T4 and T6 tuning pairs, where one head was set at the initial setting and the opposite head was tuned down.

Figures 6.1 to Figure 6.10 show the frequency spectra for a single drum hit at each stage in the experiment. It can be seen how the frequency peaks shift as the drum is tuned. It is also interesting to note how the relative strengths of the higher modal frequencies change as the drum is tuned with more pronounced high frequencies present in the spectrum when the resonant head is tuned up, and a stronger f_0 frequency present when either the resonant or batter head was tuned high.

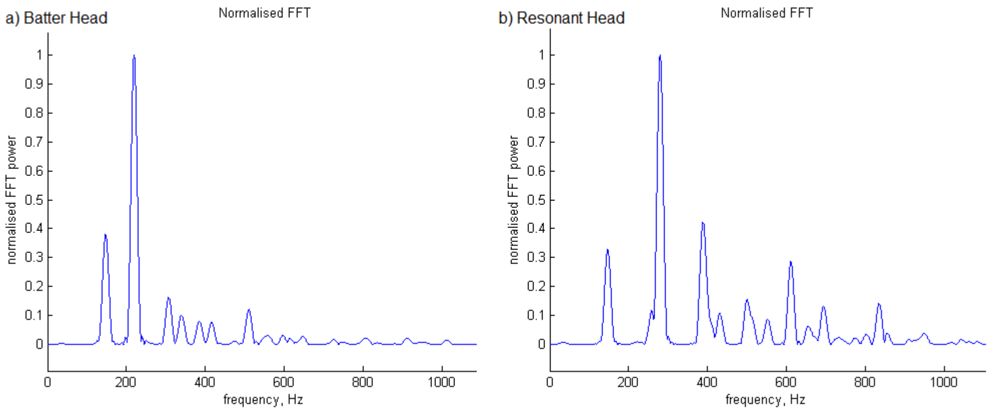


Figure 6.1: (a) Batter and (b) resonant head spectra for both heads at initial tuning (Normal, Normal).

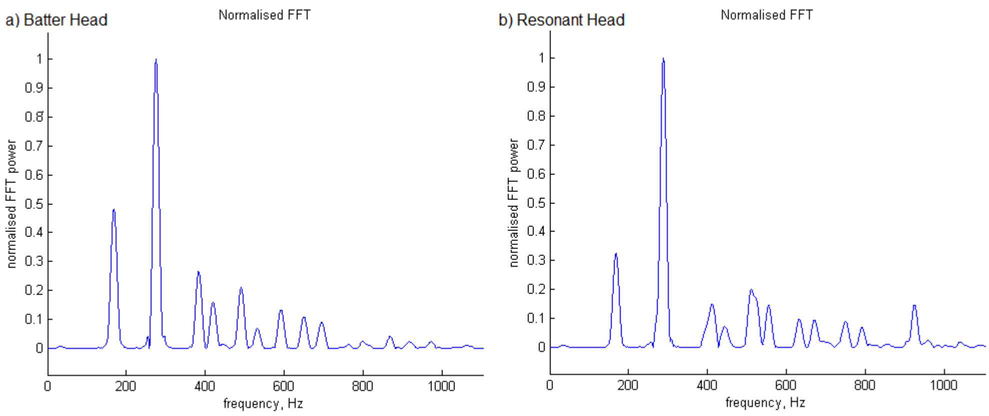


Figure 6.2: (a) Batter and (b) resonant head spectra for both heads at tuning T2 (High, Normal).

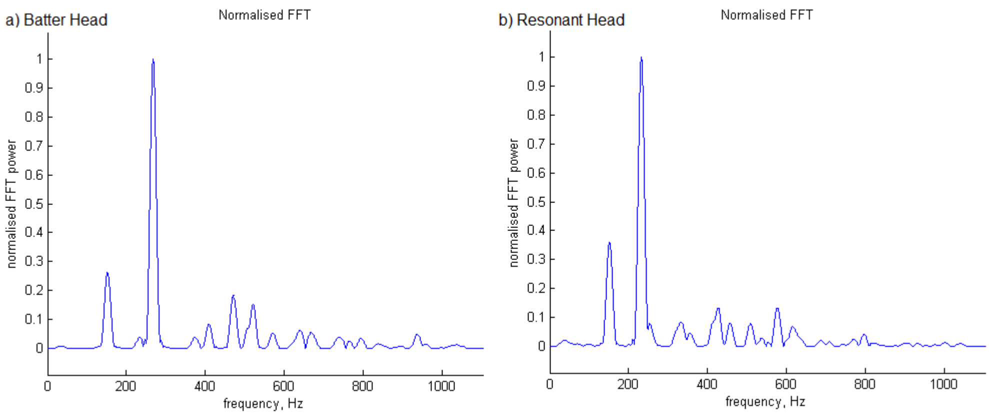


Figure 6.3: (a) Batter and (b) resonant head spectra for both heads at tuning T3 (High, Low).

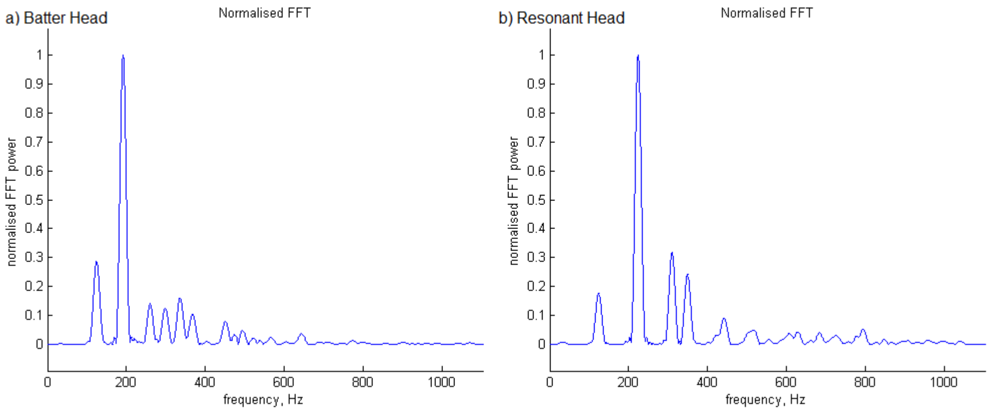


Figure 6.4: (a) Batter and (b) resonant head spectra for both heads at tuning T4 (Normal, Low).

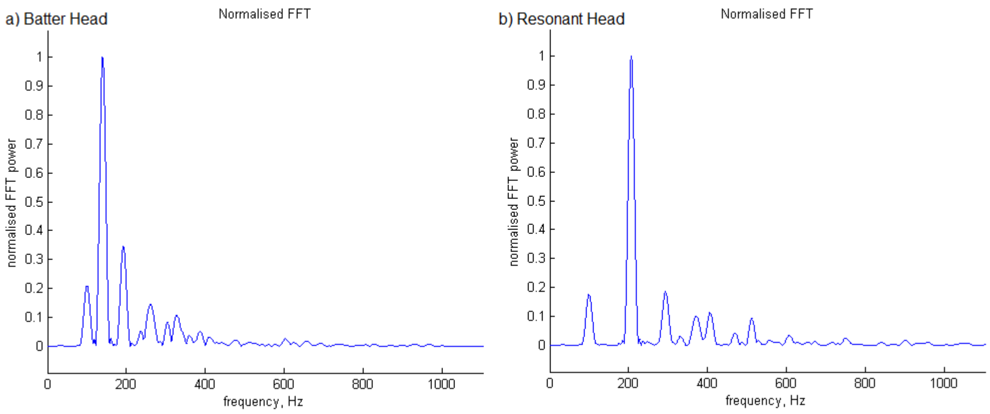


Figure 6.5: (a) Batter and (b) resonant head spectra for both heads at tuning T5b (Low, Low).

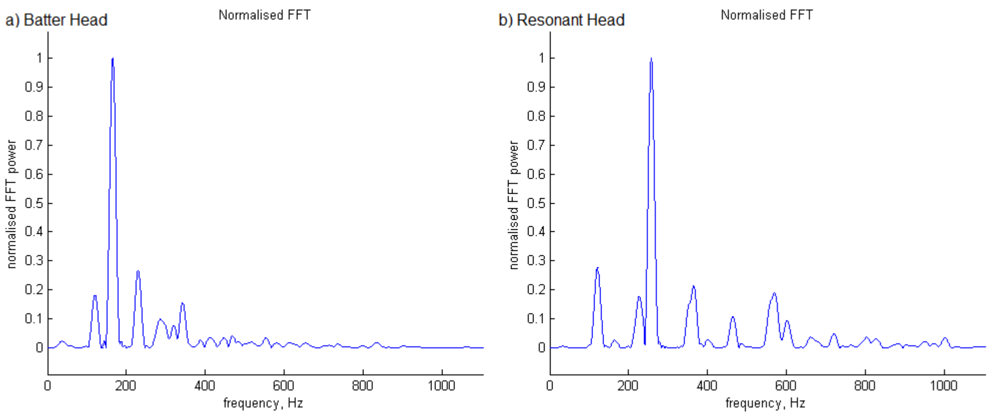


Figure 6.6: (a) Batter and (b) resonant head spectra for both heads at tuning T6 (Low, Normal).

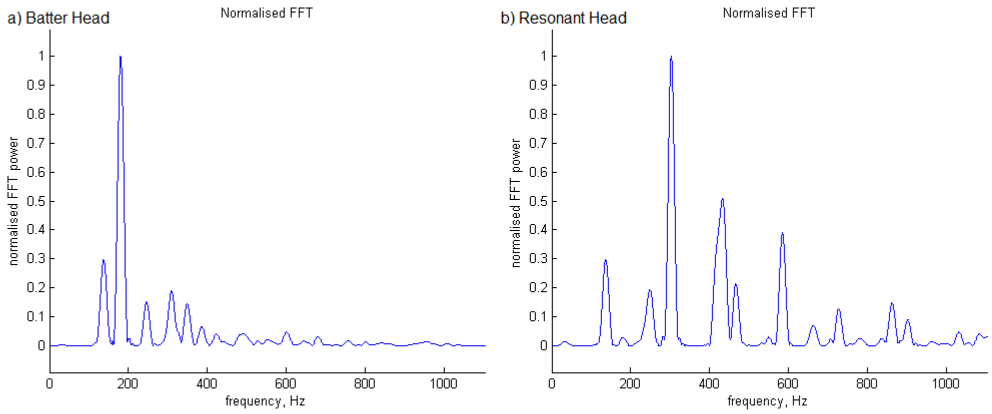


Figure 6.7: (a) Batter and (b) resonant head spectra for both heads at tuning T7 (Low, High).

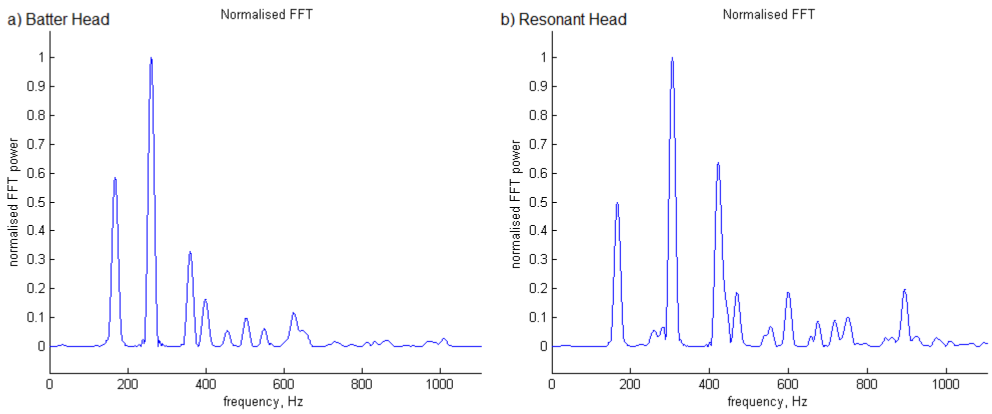


Figure 6.8: (a) Batter and (b) resonant head spectra for both heads at tuning T8 (Normal, High).

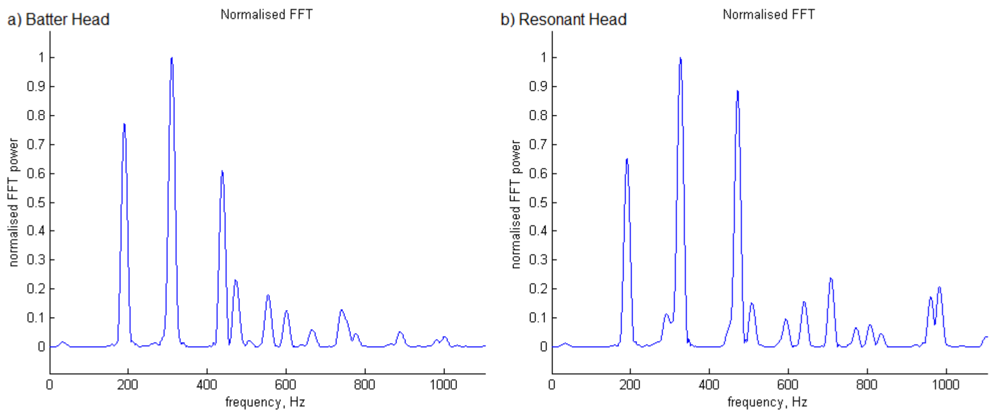


Figure 6.9: (a) Batter and (b) resonant head spectra for both heads at tuning T9 (High, High).

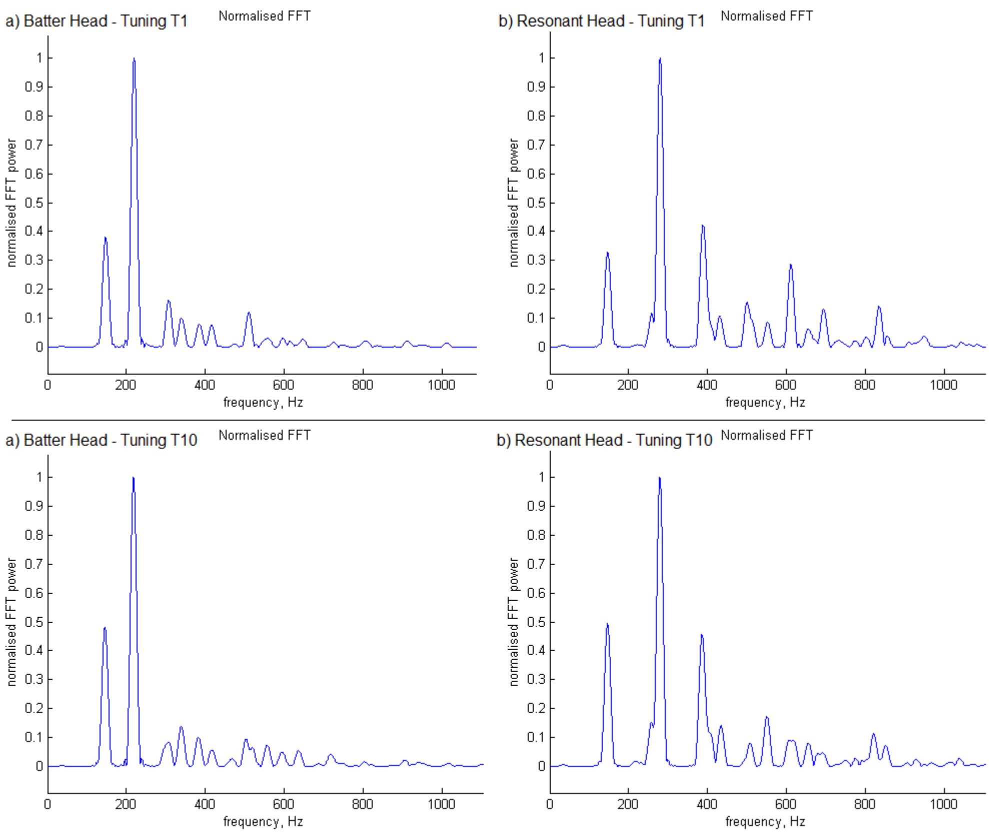


Figure 6.10: (a) Batter and (b) resonant head spectra for both heads at tuning T10 and at T1 (Normal, Normal).

Figure 6.10 shows both the T1 and T10 tunings, having gone through every permutation and back towards the initial setup. The frequency spectrum in tuning T10 is very similar to that of the initial tuning T1.

6.4 Discussion of results

6.4.1 Comparing f_{0B} and f_{0R}

Table 6.3 shows that f_{0B} and f_{0R} are nearly identical. In each case it can be seen that the difference between f_{0B} and f_{0R} is less than 1% (varying between -0.6% and 0.7%), and we can conclude that f_0 measured on the batter head and f_0 measured on the resonant head are virtually the same. f_{0R} can be considered equal to f_{0B}, as such the focus for this chapter is on f_{0B}, f_{1B}, and f_{1R}.

f_{0B} and f_{0R} are nearly identical due to the first (01) mode, where the heads move in the same direction, occurring at the f_0 frequencies listed. In the (01) mode the effect of the large movement of the mass of air in this mode causes strong coupling between the two heads. This corroborates the theory outlined in Section 2.2 and further discussed by Rossing (2005, pp.26-30). The small difference between the readings for f_{0B} and f_{0R} are within the frequency resolution associated with the measurement method, but higher resolution analysis methods and a consistent excitation method could be used to further investigate f_{0B} and f_{0R} in order to verify whether the oscillation frequencies are exactly the same. Given that many drums have drumheads of different weight on the batter and resonant heads (which could affect damping factors and subsequently oscillation frequency) and usually have a hole inside the drum shell, a small deviation between f_{0B} and f_{0R} could be expected.

It is important to note that although there is a second (01) mode, which occurs when the heads move in opposite directions, this (01) mode occurs at a higher frequency and is not evaluated in this thesis. It is the first (01) mode which is observed as f_{0B}

and f_{0R}. The observed difference in results between f_{0B} and f_{0R} could be due to limitations in the analysis software, holes present in the shell, i.e. the shell is not an airtight cylinder, or the differences in head properties for the batter and resonant heads.

6.4.2 Evaluating the ratios

It is seen in Figure 6.11 and Figure 6.12 that the frequency ratio of f_{0B}, f_{1B} and f_{1R} can be manipulated, with the resonant head in particular displaying a large change of ratio from the initial tuning (+0.3 and -0.37 from the initial ratio) as shown in Table 6.4. These significant alterations in frequency ratio clearly show how versatile the tuning options for a cylindrical drum are when both drumheads are present. Lines of best fit for the points plotted in Figure 6.12 have different gradients, indicating that shell dimensions and/or head choice play an important role in being able to achieve certain ratio combinations. The results show that manipulation of f_{0B}, f_{1B} and f_{1R} can be achieved; however, simultaneous control over all three modes presents difficulties with f_{1R} dependent on the chosen frequencies for f_{0B} and f_{1B} along with head choice and shell type. The result for two heads tuned low on a 35-cm tom falls substantially away from the rest of the data, this may be due to microphone picking up the f_0 mode and f_{1R} mode, with the f_{1B} mode being masked by these two modes at low frequencies.

Tuning 3, batter head high, resonant head low, shows the possibility for the f_{1B} frequency to be above that of f_{1R}. Although for the majority of tunings this does not occur it is worth noting that there may be times where drummers tune their drums in such a way that f_{1B} is greater than f_{1R}, as reported in Chapter 3.

Tuning	f_{0B} (Hz)	f_{0R} (Hz)	$f_{0B} - f_{0R}$ (Hz)	Difference between f_{0B} and f_{0R} as a percentage (%)
T1	147.2	146.7	0.50	0.3
T2	168.9	167.9	1.00	0.6
T3	152.0	151.5	0.50	0.3
T4	124.2	123.5	0.70	0.6
T5	98.9	98.5	0.40	0.4
T5b	99.9	99.8	0.10	0.1
T6	120.5	121.1	-0.60	-0.5
T7	137.3	136.6	0.70	0.5
T8	167.5	166.4	1.10	0.7
T9	189.8	191.0	-1.20	-0.6
T10	145.5	146.4	-0.90	-0.6

Table 6.3: Table comparing f_{0B} and f_{0R} for arbitrary tunings.

Tuning	f_0 (Hz)	f_{1B} (Hz)	f_{1R} (Hz)	f_{1B}/f_0	f_{1R}/f_0	Change in f_{1B}/f_0 with respect to T1	Change in f_{1R}/f_0 with respect to T1
T1	147.2	219.4	279.9	1.49	1.90	0	0
T2	168.9	275.4	287.5	1.63	1.70	0.14	-0.20
T3	152.0	267.9	232.2	1.76	1.53	0.27	-0.37
T4	124.2	191.5	224.0	1.54	1.80	0.05	-0.10
T5	98.9	134.1	206.6	1.36	2.09	-0.13	0.19
T5b	99.9	139.7	206.5	1.40	2.07	-0.09	0.17
T6	120.5	165.4	256.8	1.37	2.13	-0.12	0.23
T7	137.3	180.9	302.3	1.32	2.20	-0.17	0.30
T8	167.5	259.9	305.3	1.55	1.82	0.06	-0.08
T9	189.8	310.7	327.2	1.64	1.72	0.15	-0.18
T10	145.5	218.3	279.9	1.50	1.92	0.01	0.02

Table 6.4: The changes in frequencies and frequency ratios over a variety of tunings. Also shown are the changes in ratios with respect to the initial tuning T1.

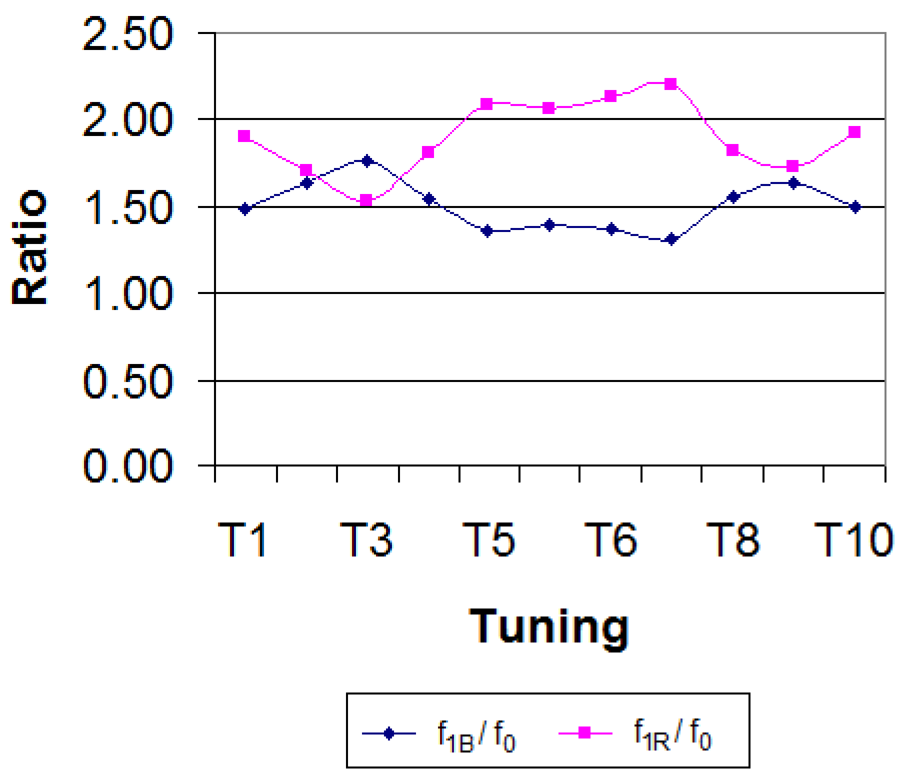


Figure 6.11: f_0/f_1 ratios plotted for each tuning permutation of a 30-cm tom.

6.4.3 Comparing the ratio differences between results for a tom drum with one or two heads

For a tom drum with a single head the f_1/f_0 ratios observed are all very close compared with the range of ratios available when tuning a drum with two coupled drumheads. Table 6.5 shows several tunings for a 30-cm tom drum, three with a single head and three with both heads. This indicates that an aspect of tuning lies in the careful manipulation of the drumheads relative to one another. A single-headed drum would have a relatively fixed f_{1B}/f_0 (i.e. a grouping near one point on the graph shown in Figure 6.12). Two drumheads allow for a range of f_0, f_{1B} and f_{1R} ratios to be tuned.

6.4.4 Reflecting on the hypothesis

It has been shown in the experiments above that the modal ratios of a cylindrical (two-headed) tom drum are not fixed and can be altered to a range of frequencies. These ratios can be set or chosen, tuning the drum.

Much like the harmonic frequency ratios present in a string (1:2:3:4...), it can be shown that the drum can be tuned in such a way that f_{0B}, f_{1B} and f_{1R} are nearly harmonically related.

Sullivan states that:

> "Timpani sound spectra show a fairly close approximation of their musical relevant partial frequencies to a harmonic series with missing fundamental"
>
> Sullivan (1997)

It is this series of partial frequencies that gives timpani its clarity of pitch and the data implies that the ratios can be manipulated and therefore a cylindrical tom drum can be tuned to have a similar frequency ratio to that of a timpani drum of 1:1.5:2.

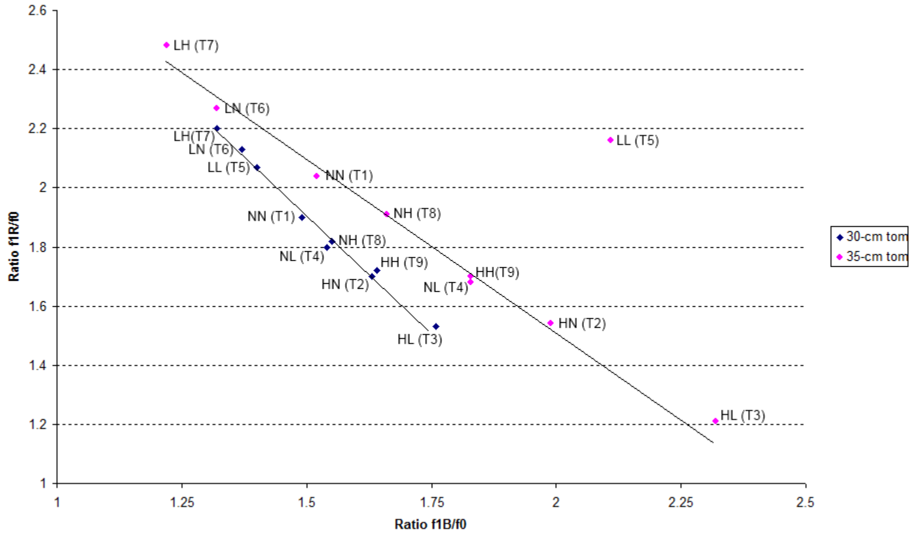


Figure 6.12: The f_0/f_1 ratios for each tuning permutation of a 30-cm tom (blue) and a 35-cm tom (pink).

Head	f_{0B}	f_{1B} (Hz)	f_{1B}/f_{0B} (Hz)
Single	88.2	165.0	1.87
Single	103.7	196.2	1.89
Single	116.4	219.8	1.89
Both	99.9	139.7	1.40
Both	124.2	191.5	1.54
Both	152.0	267.9	1.76

Table 6.5: Table comparing f_{0B} and f_{1B} for six arbitrary tunings.

It is perhaps this relationship between f_{0B} and f_{1B} that percussionists are alluding to when they suggest that they tune these modes a fifth apart, a musical fifth being a ratio of 3:2.

If it is, as implied by the data, the case that the drums can be tuned so that f_0, f_{1B} and f_{1R} can be tuned to the ratio 1:1.5:2, then this can be proven by testing it.

6.5 Testing the theory

Table 6.6 shows the f_{0B}, f_{1B} and f_{1R} frequencies for four drums, in each case tuned to a ratio close to 1:1.5:2. These ratios were chosen to closely correspond to those of a timpani. These ratios can be observed for a range of drum sizes and head types. The 25-cm, 30-cm, and 35-cm tom drums were 9-ply mahogany drums made by Gretsch, whereas the 32.5-cm tom drum had a 6-ply birch shell and was made by Tama. The 25-cm tom drum had Gretsch (Evans) standard batter and resonant heads. The 30-cm tom drum had an Evans EC2 batter head and Aquarian Classic Clear resonant head. The 32.5-cm Tama drum had a Remo pinstripe batter head and Tama standard resonant head. The 35-cm tom drum had an Aquarian Modern Vintage batter head and Aquarian Classic Clear resonant head.

Figure 6.13 and Figure 6.14 show the spectra of the drums described in Table 6.6. Here it can be seen that each of the drums has a ratio close to that of timpani, i.e. where f_{0B}:f_{1B}:f_{1R} is close to 1:1.5:2.

It is interesting to note during the experiments a frequency ratio of 1:1.54:1.99 was achieved where the 35-cm tom was tuned so that f_{0B} was 105.8 Hz, f_{1R} was 163.2 Hz and f_{1B} was 211 Hz. The spectrum for this tuning is shown in Figure 6.15.

Drum Diameter (cm)	f_0 (Hz)	f_{1B} (Hz)	f_{1R} (Hz)	f_0/f_{1B}	f_0/f_{1R}
25 cm	181.0	281.1	365.0	1.50	1.95
30 cm	174.2	260.9	333.7	1.50	1.92
32.5 cm	109.9	165.0	225.2	1.50	2.05
32.5 cm	130.7	196.3	269.2	1.50	2.06
35 cm	77.6	116.5	157.1	1.50	2.02

Table 6.6: Toms tuned such that f_0:f_{1B}:f_{1R} approaches 1:1.5:2.

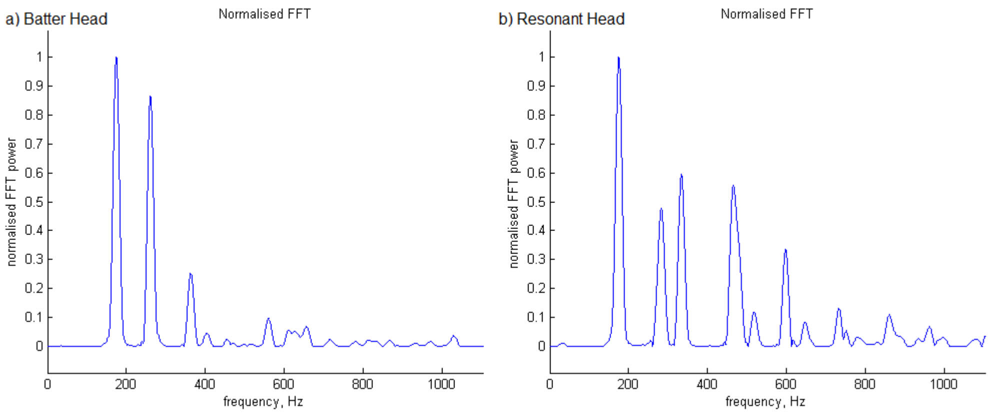


Figure 6.13: (a) Batter and (b) resonant head frequency spectra for a 30-cm tom drum.

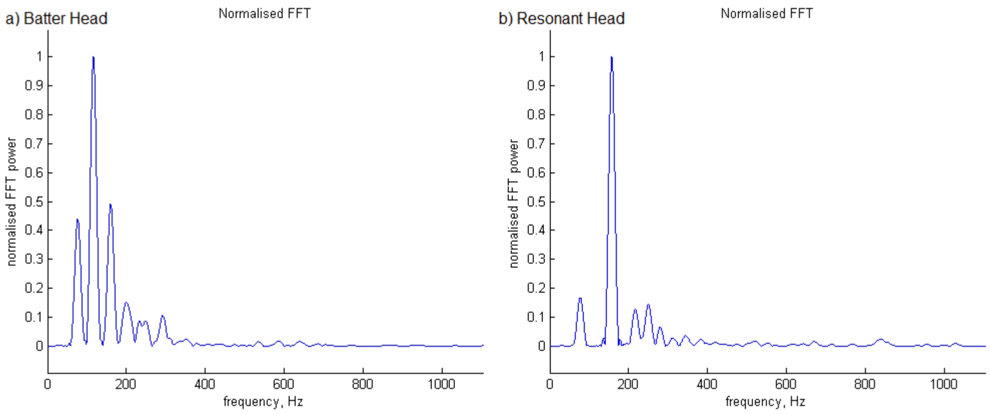


Figure 6.14: (a) Batter and (b) resonant head spectra for a 35-cm tom drum.

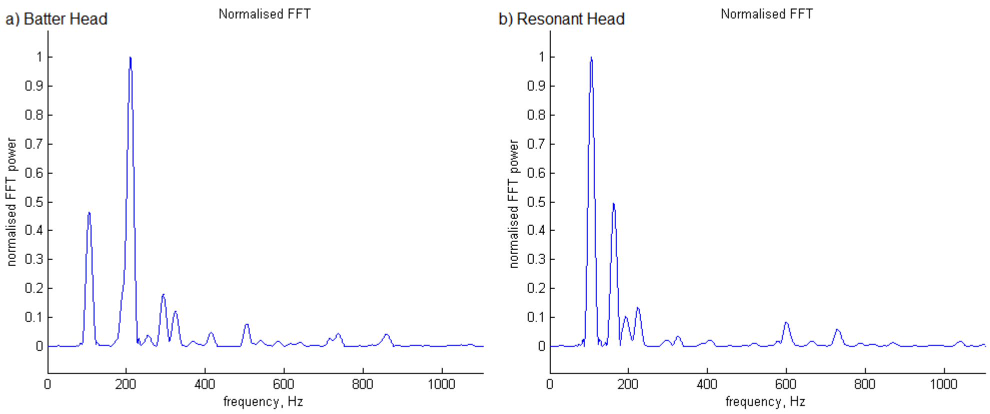


Figure 6.15: (a) Batter and (b) resonant head spectra for a 35-cm tom drum.

6.6 Reflections and conclusions

The research has shown that the frequency ratios present in the tom drum spectrum can be altered significantly. This change in modal frequency ratios by changes in tuning has not previously been shown for a cylindrical drum. It has been shown that these alterations can be made with a definite target frequency and frequency ratio in mind, in this case a ratio of 1:1.5:2. This level of control over the tuning of the drumhead has not previously been shown in a scientific context and allows for greater understanding of the way that percussionists tune cylindrical drums. There is, however, scope for future research to provide further knowledge on the relationship between the batter and resonant heads.

It has been observed in this chapter that f_{0B} and f_{0R} are very close and consistent independently of which head is struck. The deviation between the two heads was observed to be less than 1%, as discussed in Section 6.4.1. This is due to the strong coupling between the heads caused by the mass of air inside the drum shell. The tuning implications of this significant coupling has not been explored previously and it is this coupling that allows the variation of modal ratios to occur. Although some coupling occurs between the f_1 modes, as indicated by the tendency for the f_{1B} frequency to change slightly as tension of the resonant head is altered, the f_{1B} and f_{1R} modes are not subject to the same strong coupling effect as the f_0 mode. Although this weaker coupling prevents independent movement of the f_1 modes it is not so strong as to prevent manipulation of the frequency ratios for f_{0B}, f_{1B} and f_{1R}.

Considerations for future research include the use of alternative methods to further test the relationship between the f_0 and f_1 modes and investigation into the role of higher modes of vibration in drum tuning. Further analysis to determine whether f_{0B} and f_{0R} are identical or whether there is indeed a small deviation between f_{0B} and f_{0R} could also be performed. These issues are discussed further in Chapter 9.

Cylindrical drums with two coupled heads provide a wide range of tuning options.

Chapter 5 shows that an even response is preferable, and this chapter shows how the relationship between the frequencies f_{0B}, f_{1B} and f_{1R} can be manipulated. The knowledge gained for tuning individual drums to provide a desired frequency response gained from Chapter 5 and Chapter 6 can be applied to a the drum kit as a whole, and will be discussed further in Chapter 7.

Chapter 7

Tuning cylindrical drums for performance and production

7.1 Introduction

It has been seen in Chapters 5 and 6 that an individual drum can be tuned so that the response is uniform around the perimeter of the drumhead and that the relationship between the fundamental, f_0, frequency and the f_{1B} and f_{1R} frequencies can be manipulated in a way as to provide a musical relationship between these modes.

Uniform response provides a smooth decay rate, minimising any unwanted 'beating'. It is considered in this research that a smooth decay is preferable with regards to determining how 'in-tune' a drum is, as argued by Ranscombe (2006*b*) and Seymour (2010).

The relationship between the batter and resonant head also indicates there are tuning permutations where the drum produces more frequencies which correspond to notes on a musical scale, and tunings where they do not. It has also been shown that modal response profiles tending towards those associated with pitched percussion, such as timpani, can be achieved with cylindrical drums.

Fine tuning the drum can be considered to be the manipulation of the heads until the four aspects of drum tuning previously discussed have been achieved. These four aspects are listed below:

1. Setting the pitch.
2. Achieving a uniform response around the perimeter of the drumhead.
3. Achieving the desired relationship between the resonant and batter heads.
4. Controlling the decay times of the drum sound.

By manipulating the drumheads so that a uniform response is achieved, and tuning the heads so that f_0, f_{1B} and f_{1R} produce frequencies that correspond to notes on the musical scale, these four criteria for tuning an individual drum are met. The smooth decay of the signal of a tuned drum can be seen in Chapter 5 and will be further discussed along with further discussion on the ability to control the decay by adding damping.

This chapter will discuss two key elements with respect to performance and music production:

- Tuning f_0 for all the drums in a drum kit
- Controlling envelope and decay profiles

In this chapter it is assumed that fine tuning is done by the methods discussed in Chapters 5 and 6.

7.2 Tuning f_0 for the whole drum kit

7.2.1 The drum kit and tuning to pitch

A modern drum kit is usually made up of a kick drum, snare drum, a number of tom drums and cymbals. Other percussive instruments are sometimes also included, for example cowbells and wood blocks. Although these other instruments complement the sound of the rest of the kit the current research is concerned only with the kick drum, snare drum and tom drums.

The kick drum, snare drum, and tom drums are often hit in or close to the centre of the drumhead. As discussed in Chapter 4, excitation near the centre causes f_0 to be the predominant frequency present in the spectrum. Each individual drum in the drum kit can be tuned such that each has its own distinct pitch as discussed in Chapter 3.

As has previously been discussed, given the complexity of pitch and the drum spectra it is hard to clearly know what exactly drummers mean when they say they tune a drum to 'A' or to 'B flat', and this is particularly true when they are talking about tuning individual heads in relation to each other as discussed in Chapter 6. Here it can be reasonably thought that given the fundamental frequency is the predominant frequency produced when the drum is stuck in the centre, and that for playing rather than tuning purposes the drum is usually struck either at the centre of the head or close to it, that these notes are most likely to be the perceived pitches of each drum when the drummer is focusing on the fundamental f_0 frequency of the drum.

7.2.2 Tuning ranges

The modern drum kit does not have one standard tuning, so it is possible to tune the drum kit to produce a variety of different timbres and pitches, although there is a limit to the tuning range of the drum, and therefore the drum kit as a whole.

> “For a given depth and diameter, a drum has a very definite range of pitches over which it sounds good. If you tune the drums too high or too low, the sound will be compromised.”
>
> White (2007)

The tuning of the drum kit as a single instrument adds to the confusion with regards to drum tuning. It is not enough to tune each drum until it sounds good, it is generally necessary to tune each drum so that it sounds good as part of the kit as a whole.

Tuning the drum kit as a whole is almost exclusively discussed in literature with respect to ‘high’ or ‘low’ tunings. However the musicality of each drum is seen as important by many with Cannelli (2001) stating “The secret is to get each drum tuned so that it has a full tone”.

Understanding the tuning range of a single drum, and the frequencies present in the drum sound, allows recording engineers a more precise method for manipulating drum sounds. For example in the article ’Drum Magic’, White (2007) suggests boosting the 70-90 Hz region of the kick drum sound, whilst reducing the 150-200 Hz region. A more rigorous understanding of why these ranges were chosen is often lacking, and it can be seen that the 70-90 Hz often corresponds to the f_0 mode of a kick drum, with higher partials in the 150-200 Hz region. If the precise tuning of the drum is known then a more selective equalisation filter (EQ) can be applied.

Due to percussionists’ desire for a suitable stick response related to the head tension when playing the drums, the batter head has a limited range where it provides both suitable pitch and stick response.

Liberty DeVitto (Nicholls, 2001), mentions the compromise between the sound of the drum and the response of the drum whilst Bob Gazten (Gatzen, 2006) discusses how each drum has a range of pitches that it can be tuned to.

Each drum in the modern drum kit has a different size and a different tuning range. Although it may be possible to tune, say, 30-cm, 35-cm and 40-cm toms all to produce the same f_0 frequency it is unlikely that this is going to produce a desired result when tuning the kit as a whole. It has been shown in the previous chapter that an individual drum can be tuned to a wide range of frequencies, with a degree of control not only over the f_0 frequency but also over f_{1B} and f_{1R}. This chapter shows the possibility for a drum kit to be tuned to a range of frequencies where f_0 corresponds to a note on the musical scale.

7.2.3 Tuning range for a drum kit

Given the previous research performed in Chapter 6 it can be hypothesised that it is indeed possible to tune an entire kit in such a way that the pitch of each drum corresponds to a note on the musical scale.

To prove this hypothesis a standard drum kit, shown in Figure 7.1, was taken and tuned in such a way that each drumhead has f_0 aligned to a musical frequency. Arbitrarily the following frequencies were chosen: 73.4 Hz, 87.3 Hz, 103.8 Hz, 123.5 Hz, 146.9 Hz within a tolerance of $\pm$0.4 Hz. These correspond to musical notes three semitones apart, namely D2, F2, G#2, B2 and D3, the results of which can be seen in Figure 7.2. Figures 7.2 and 7.3 are filtered at $1.5f_0$ in order to clearly show the f_0 frequency of each drum.

The drum kit shown in Figure 7.1 and tuned to the tunings shown above was a Tama Superstar Series kit (7-ply birch/basswood) made up of the following drums:

- 20 x 18 inch (diameter x depth) kick drum (50.8 cm x 45.7 cm)
- 12 x 9 inch tom drum (30.5 cm x 22.9 cm)
- 13 x 10 inch tom drum (33.0 cm x 25.4 cm)
- 16 x 16 inch tom drum (40.6 cm x 40.6 cm)

- 14 x 5.5 inch snare drum (35.6 cm x 14.0 cm)

The drums used Tama standard resonant heads and Evans EC2 coated batter heads with the exception of the kick drum and snare drums which used Remo Pinstripe batter heads.

To further prove the hypothesis the drum kit was tuned to produce higher frequency values for f_0 as shown in Figure 7.3. Although this is not necessarily the full range for each drum, which would be determined at the drumhead being completely slack through to the breaking tension of the head, it is indicative of the range over which a single drum kit can be tuned. This range, shown in Table 7.1, indicates that a variety of tunings can be achieved where the f_0 for each drum corresponds to a musical frequency within a tolerance of $\pm$0.4 Hz.

7.2.4 Suggested ranges for different genres

Drum kits are often sold in 'Rock', 'Jazz' or 'Fusion' kit sizes. Each drum in a rock kit will be larger than in a jazz kit. It has previously been discussed that larger drums produce lower pitched sounds, and it is often considered that low tunings are associated with 'rock' genres whereas jazz drummers prefer higher tunings. More investigation is required on what is considered a 'jazz' tuning or a 'rock' or 'pop' tuning and how such tunings differ from each other. It is expected that such research would focus more deeply on music performance and psychoacoustic fields. As an example of kit ranges, Gretsch have three kits in their 'Catalina Club' series referred to as 'Jazz', 'Mod' and 'Rock', with the 'Mod' kit being marketed as a versatile kit (Gretsch, 2010). The kit configurations are shown in Table 7.2 and it can be seen that each drum from the rock kit is larger than that of its jazz counterpart, with the 'Mod' kit having drum sizes between the jazz and rock kits and as such would be considered a 'Fusion' kit. It is worth noting that although the size of the kick drum and tom drums can differ significantly a 14-inch snare drum is considered standard across drum kits with the depth of snare

Figure 7.1: Tama Superstar Series drum kit which was tuned to two different tunings.

Drum	Low (Hz)	Low (Note)	High (Hz)	High (Note)	Range
20” Kick	73.3	D2	87.6	F2	3 semitones
16” Tom	87.4	F2	110.1	A2	4 semitones
13” Tom	104.0	G#2	139.0	C#3	5 semitones
12” Tom	123.1	B2	174.5	F3	6 semitones
14” Snare	147.2	D3	220.2	A3	7 semitones

Table 7.1: Tuning range for each drum.

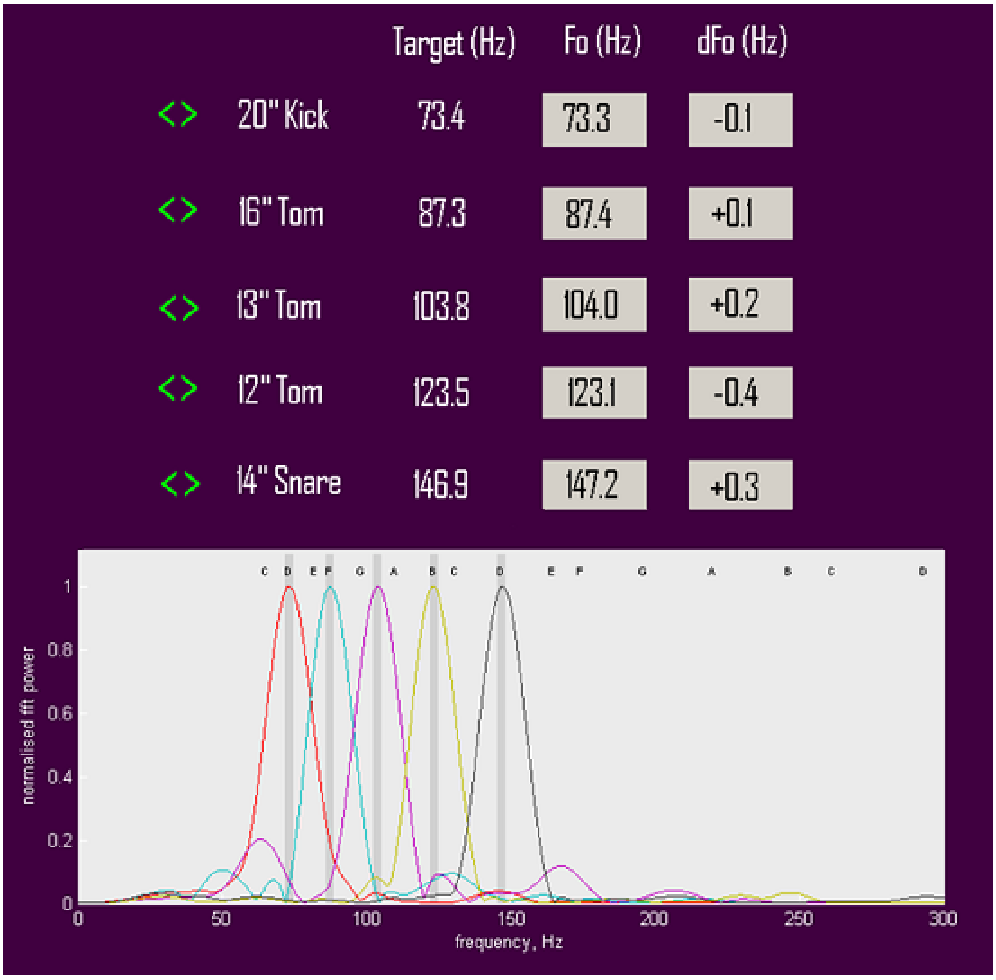


Figure 7.2: Drum kit tuned to a low tuning range, with each f_0 corresponding to a musical frequency (with a filter applied at $1.5f_0$).

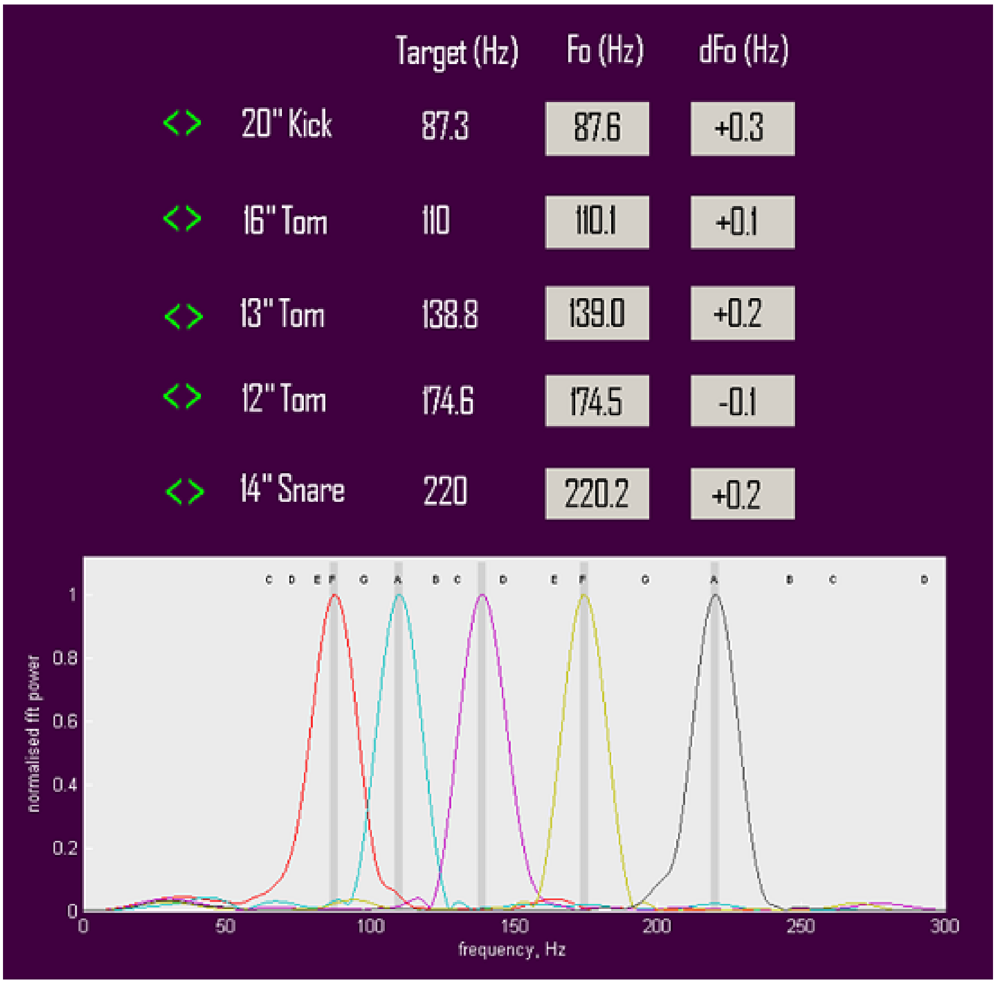


Figure 7.3: Drum kit tuned to a high tuning range, with each f_0 corresponding to a musical frequency (with a filter applied at $1.5f_0$).

drums differing by only one or two inches.

Through experimentation, a range of tunings were evaluated for a single drum kit. These are considered ‘benchmarks’ so the frequencies obtained can be used as targets for percussionists to aim for when tuning similar drum kits. The fundamental frequencies shown in Table 7.3 show that it is possible to create appropriate musical intervals between each drum in order to produce a more melodic feel to the drum kit, which many drummers have indicated as a preferable condition for tuning, for example Brian Chase (Budofsky, 2009, p.56), Steve Perkins (Rhythm Magazine, 2004*e*, p.72) and Gatzen (2006).

As can be seen from the breakdown in Table 7.4 through to Table 7.9 a drum kit can be tuned over a range of frequencies. These examples are shown to be achievable with the kit described in Section 7.2.3. These results have been tested and are indicative of how a single drum kit can be tuned for a range of musical styles and purposes. Each tuning shows that it is possible to make slight alterations in the kit tuning in order to incorporate the addition of another drum, such as moving from a 4-piece to a 5-piece kit. Throughout the range of tunings a ratio of $f_{1B} = 1.5 f_{0B}$ has been maintained to produce a stronger sense of pitch as discussed in Chapter 6.

Figure 7.4 shows a 6-piece Gretsch Catalina Club kit tuned to the values in Table 7.10. These values are shown graphically in Figure 7.5. By comparing Table 7.10 with Tables 7.8 and 7.9 it can be seen that further drums can be incorporated into an existing drum setup. In this case, a ‘jazz’ tuning has been maintained with the additional drums being added to the setup, and by transferring to an entirely different kit in the case of the 6-piece Gretsch Catalina Club kit.

Drum	Jazz	Mod	Rock
Kick	18 x 14	22 x 20	24 x 18
Floor Tom	14 x 14	16 x 14	16 x 16
Rack Tom	12 x 8	12 x 8	13 x 9
Snare	14 x 5	14 x 6.5	14 x 6.5

Table 7.2: Diameter and depth in inches for three Gretsch drum kits.

Kit Type	Snare Drum	Rack Tom	Rack Tom 2	Floor Tom	Kick Drum
4 Piece Rock Kit	196	123.5	n/a	77.8	51.9
5 Piece Rock Kit	196	123.5	92.5	73.4	51.9
4 Piece Pop/Fusion Kit	196	146.8	n/a	92.5	55
5 Piece Pop/Fusion Kit	196	146.8	110	87.3	55
4 Piece Jazz Kit	207.7	164.8	n/a	98	61.7
5 Piece Jazz Kit	207.7	164.8	130.8	98	61.7

Table 7.3: f_0 frequencies for each drum over a variety of tunings.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	51.9	G#1	77.8	D#2
Floor Tom	77.8	D#2	116.5	A#2
Rack Tom	123.5	B2	185.0	F#3
Snare Drum	196	G3	293.7	D4

Table 7.4: 4-piece rock kit tuning.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	51.9	G#1	77.8	D#2
Floor Tom	73.4	D2	110.0	A2
Rack Tom 2	92.5	F#2	138.6	C#3
Rack Tom 1	123.5	B2	185.0	F#3
Snare Drum	196	G3	293.7	D4

Table 7.5: 5-piece rock kit tuning.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	55.0	A1	82.4	E2
Floor Tom	92.5	F#2	138.6	C#3
Rack Tom	146.8	D3	220.0	A3
Snare Drum	196	G3	293.7	D4

Table 7.6: 4-piece pop/fusion kit tuning.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	55.0	A1	82.4	E2
Floor Tom	87.3	F2	130.8	C3
Rack Tom 2	110	A2	164.8	E3
Rack Tom 1	146.8	D3	220.0	A3
Snare Drum	196	G3	293.7	D4

Table 7.7: 5-piece pop/fusion kit tuning.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	61.7	B1	92.5	F#2
Floor Tom	98	G2	146.8	D3
Rack Tom	164.8	E3	246.9	B3
Snare Drum	207.7	G#3	311.1	D#4

Table 7.8: 4-piece jazz kit tuning.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	61.7	B1	92.5	F#2
Floor Tom	98	G2	146.8	D3
Rack Tom 2	130.8	C#3	207.7	G#3
Rack Tom 1	164.8	E3	246.9	B3
Snare Drum	207.7	G#3	311.1	D#4

Table 7.9: 5-piece jazz kit tuning.

Figure 7.4: Gretsch Catalina Club drum kit which was tuned to a ‘jazz’ tuning.

Drum	f_0 (Hz)	f_0 (note)	f_{1B} (Hz)	f_{1B} (note)
Kick Drum	61.7	B1	92.5	F#2
Floor Tom 2	98	G2	146.8	D3
Floor Tom 1	123.5	B2	185.0	F#3
Rack Tom 2	146.8	D3	220.0	A3
Rack Tom 1	174.6	F3	261.6	C4
Snare Drum	207.7	G#3	311.1	D#4

Table 7.10: Jazz tunings for a 6-piece drum kit.

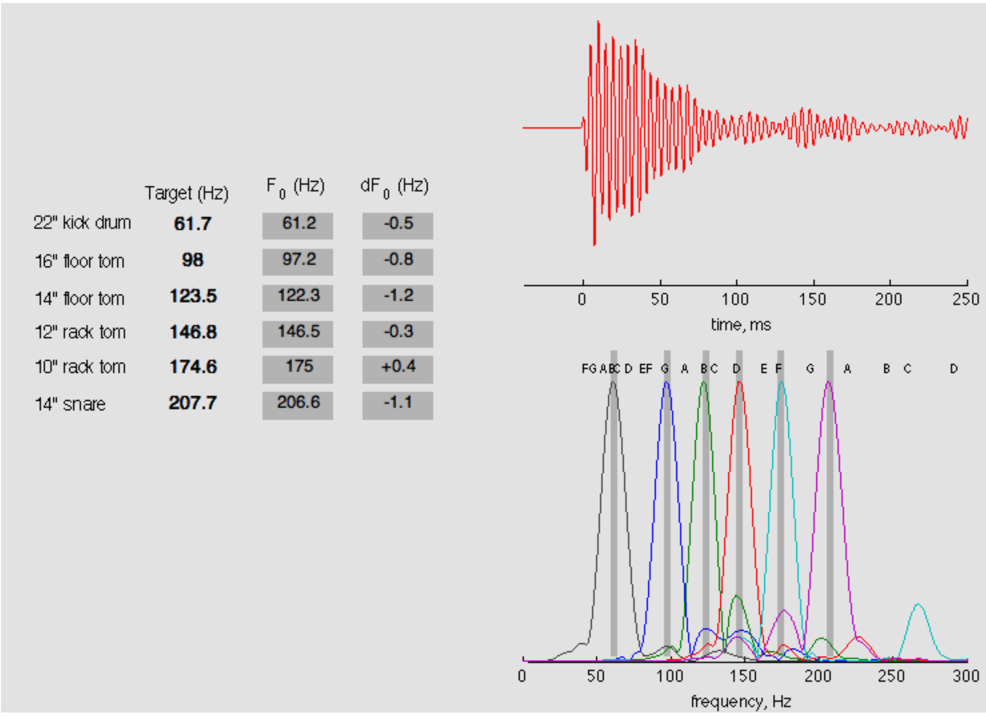


Figure 7.5: Drum kit tuned to a low tuning range, with each f_0 corresponding to a musical frequency (with a filter applied at $1.5f_0$).

7.2.5 Discussion of results

By applying the methods from Chapters 5 and 6 to tuning the drum kit as a whole it is apparent that the drum kit can be tuned in much the same way as more melodic musical instruments. It has been shown to be possible to tune f_0 and f_{1B} to a range of musical frequencies, whilst maintaining a ratio of 1:1.5 as described in Chapter 6.

Further investigation into tuning the kit as a whole to specific fundamental frequencies is necessary to gain further understanding on the qualitative descriptors applied to drum kits and drum tunings. This could be done using the software used in this research and carried out using listening tests and interviews with professional musicians.

7.3 Envelope profile and decay rate

7.3.1 Methods for manipulating envelope profile

Controlling the envelope profile of a drum sound is an aspect of drum tuning whereby a desired decay rate is achieved through a variety of methods. In particular the decay of the drum sound, especially the higher frequencies, is of considerable importance to many drummers. Although some drummers such as Simon Phillips (Keefe, 2007), Darrin Mooney (Le Roc, 2004) and Frank Tontoh (Rhythm Magazine, 2004*a*) are comfortable with allowing their drums to ring, that is certainly not the case for all drummers, with Ranscombe noting:

> “One of the biggest villains in tuning drums is the obsession many drummers have with eliminating ring. In live situations in particular - even when miked - some ring is healthy, as long as it’s even and not discordant. ”
>
> Ranscombe (2006*c*)

There are four main ways to control the envelope profile of a drum:

1. Applying damping to the drumhead.
2. Fine tuning the drum.
3. Mounting/suspension of the drum.
4. Head choice.

The focus in the current research is on tuning any standard drum kit, and here it is assumed that the drumheads and mounting of the drums have already been chosen by the drummer. This leaves two options available for a musician to alter the envelope. The drum can either be manipulated via fine tuning until a desired envelope is achieved, or additional damping material can be added to the drumheads. Manipulation of tuning in order to achieve a desired envelope may adversely affect frequency response and pitch, so may not be an ideal method in all scenarios. Likewise loading the drumhead with additional materials may risk unbalancing the drumhead, making it difficult to achieve a uniform frequency response around the head.

Although some drummers may chose to focus solely on adding damping materials to alter the sound, and others on fine tuning whilst avoiding damping, it is most common to find a mixture of both techniques being used. Cigarette cartons, towels, duct tape and a variety of other materials have all been used by professional drummers in the past.

The potential of using both tuning and damping materials to provide a desired drum sound provides a wide range of possibilities for manipulation of attack and decay profiles and whilst discussing damping methods an article in Rhythm magazine states:

> “damping should not be a substitute for careful tuning”
>
> Rhythm Magazine (2004*i*, p.14)

There are many damping methods available to drummers, from damping built into the head (Evans Drumheads, 2010*a*) and Mylar rings (Remo, 2010*b*) which theoretically dampen the head evenly, through to Moongel which can be applied at distinct locations (RTOM Inc., 2010).

Ranscombe (2006*c*) argues that experimenting with a variety of drumheads in order to obtain a desirable sound is preferable to the addition of damping materials to the drum stating:

> "Rather than sticking muffling devices on, try changing the type of head. The choice of heads for snare drums is almost endless and you should be able to find a batter head that will work for you regardless of what style you play."
>
> Ranscombe (2006*c*)

It is apparent that it is possible to significantly alter the profile of the drum once a head has been selected and tuned. However the compromises made by manipulation via tuning, or via adding damping materials is not necessary if the correct drumheads are chosen. Cindy Blackman experiments with a variety of drumheads to obtain the desired drum sound, stating:

> "I'm pretty set on the way I'm tuning but I go through different drumheads to try and find different sounds and to make sure I have the best sound I can."
>
> Cindy Blackman, (Keefe, 2008)

7.3.2 Example data

It can be shown that damping materials and changes in drum tuning affect the attack and decay rates of the drum waveform. The attack time of the signal can be defined as the period from onset of the stroke through to the maximum amplitude of the signal, with the decay time being the time taken for the signal to decay by a specific amount. In this chapter, damping is measured by evaluating the time taken for the RMS of the signal amplitude to decrease by 20 dB - i.e. by a factor of 10.

The decay is analysed by normalising the waveform against its peak value, so that maximum the signals amplitude occurs at a value of 1. The RMS signal is calculated using a 1000-sample window incremented at 200-sample steps. The RMS signal is plotted in red on the waveform signal. These signals are also converted to decibels and plotted together. The maximum RMS value is found and the line of best fit for the RMS decay to the value (RMSmax-20) is calculated. The gradient of this line is then used to calculate the 20-dB decay time (Dt-20).

Figure 7.6 shows the decay time for a 30-cm tom drum, and proves that decay can be manipulated by the use of damper rings. The overall 20-dB decay in this example was reduced by 984 ms from 1272 ms to 288 ms. Damper rings add mass to the perimeter of the drum, therefore much of the damping causes a reduction in the decay time of the higher overtones of the drum rather than the f_0 fundamental.

Figure 7.7, a waterfall plot, shows how different modal frequencies do not decay at the same rate. In this example Moongel damping was applied and it can be seen that although the modal frequencies do not decay at a uniform rate in Figure 7.7a, where although the f_0 frequency decays after approximately 400 ms, the higher modes are still prominent. The addition of damping causes a more uniform decay of the modes, with f_0 continuing to decay at around 400 ms, but with the higher frequency components decaying within a similar timeframe.

Figure 7.8 shows that by splitting the analysis into separate filtered bands a more quantifiable method of determining the decay rates for percussive instruments can be obtained, splitting the decay rates into frequency bands focusing on the fundamental f_0 mode, the f_{1B} mode, and then grouping of the higher frequency ranges.

Figure 7.9 shows how tuning can be used to manipulate the envelope of the drum. Here, with the same 30-cm tom drum, significantly different decay rates are found with the only alteration being the tuning of both heads down half a turn on each tension rod. Table 7.11 shows the difference in attack and decay times for a 30-cm tom drum over the tuning ranges outlined in Section 6.2. In this example the attack time ranged from 10.4 ms to 19.1 ms over a variety of tunings. The 20-dB decay of the drum varied between 171 ms and 384 ms. Decay times are affected by relative tuning of the two heads; however the current results do not allow any specific conclusions to be drawn.

7.3.3 Discussion of results

It has been shown that the attack and decay profiles of the drum can be manipulated via both damping and tuning. Quantifiable values for attack and decay can be obtained, but the current research has not empirically provided any definitive ranges of attack and decay rates for the tom drum. Some drummers prefer to over-dampen their drums, reducing decay time significantly, and others allowing a very open sound where the drum is free to resonate.

Whilst the current research indicates that frequency response is controllable over a range of heads, head choice is often linked to the timbre of the sound produced when a drum is struck, as indicated by the qualitative descriptions ascribed to different drumheads in marketing literature. For example, Aquarian Drumheads (2010) describe their range of drumheads using terms such as “focused attack” or “deeper tone”. It is therefore suggested that head choice plays a crucial role in controlling the attack and decay profiles. This requires further investigation as discussed in Chapter 9

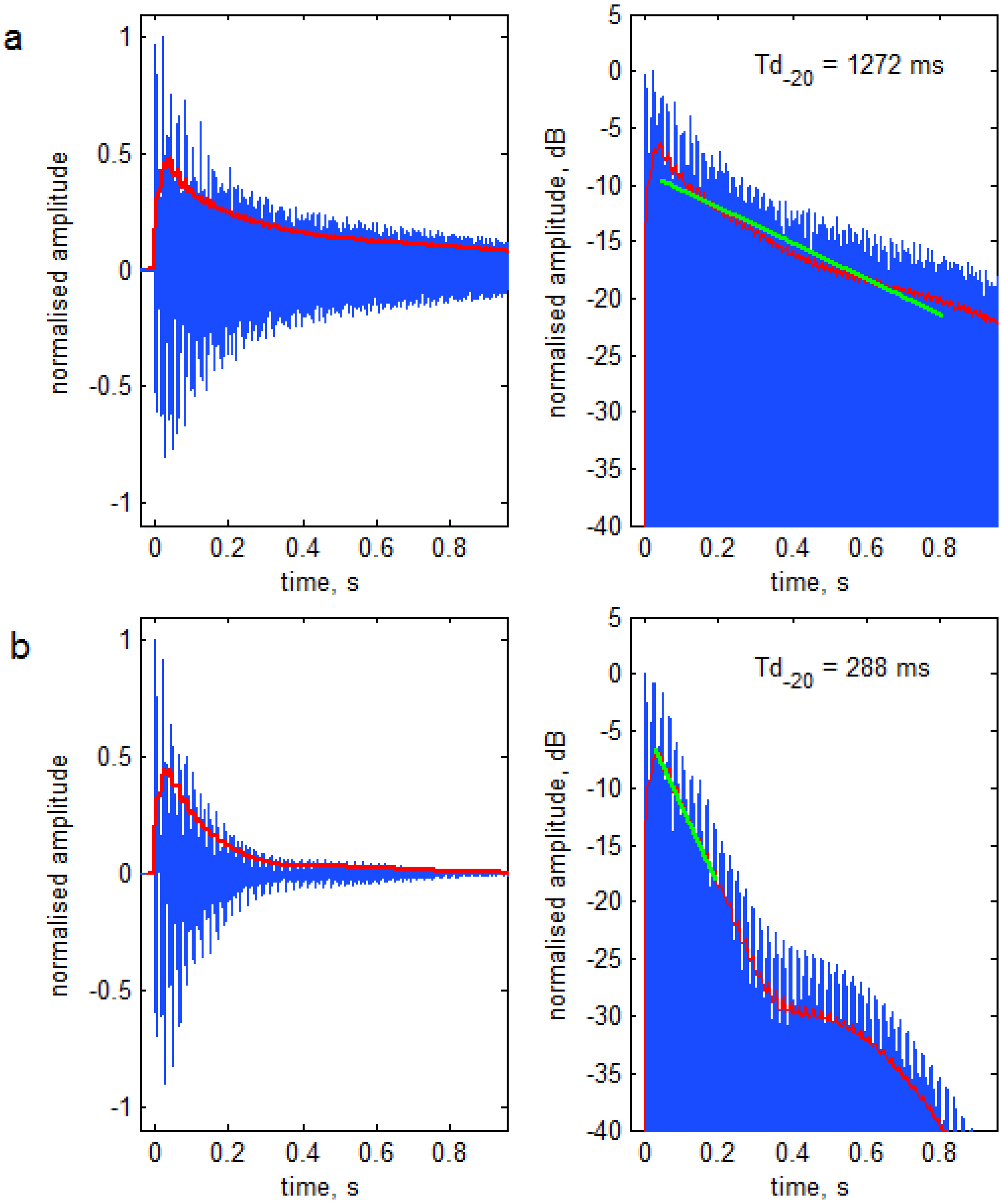
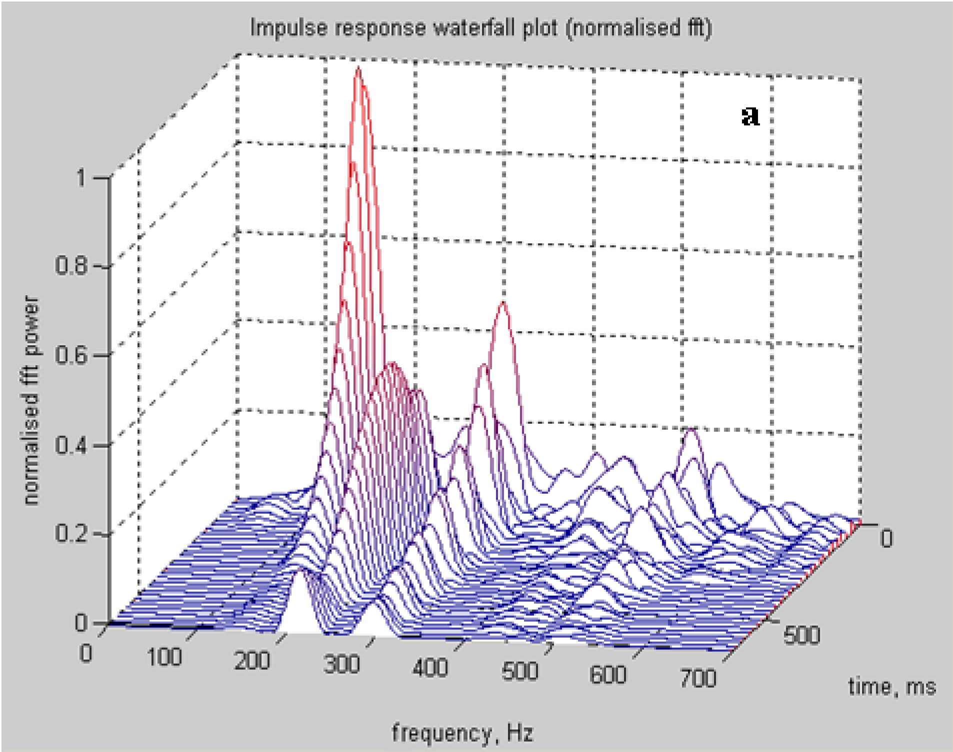


Figure 7.6: Decay profiles of a 35-cm tom drum, (a) without damping (20-dB decay time = 1272 ms) and (b) tom damped with Evans O-Ring (20-dB decay time = 288 ms). Normalised waveform amplitude (blue) RMS amplitude (red) on both linear and decibel axes. Line of best fit for calculation of the 20-dB decay time is also shown in green.

Tuning	f_{1B}/f_{0B}	Attack (ms)	Dt-20 (ms)
T1	1.49	13.5	203
T2	1.63	11.7	191
T3	1.76	12.7	244
T4	1.54	19.5	208
T5	1.40	12.7	384
T6	1.37	11.4	171
T7	1.32	10.4	198
T8	1.55	11.9	231
T9	1.64	10.9	265

Table 7.11: Attack and decay times for batter impacts in the centre of a 30-cm tom drum.



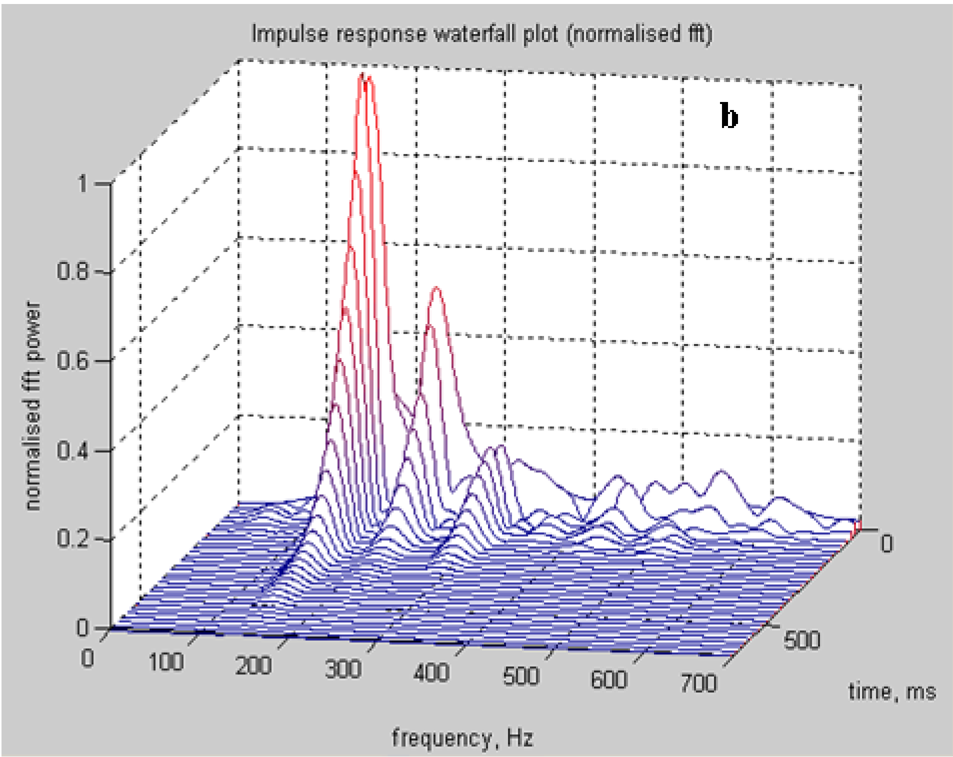


Figure 7.7: Waterfall plot showing how a 30-cm tom drum decays, (a) without damping and (b) with damping.

7.4 Summary

This chapter has shown that the methodologies applied in Chapters 5 and 6 can be extended to the drum kit as a whole, and that musicians are in charge of the musicality of their instrument as a whole, being able to select which frequencies their drums are tuned to for the f_0 and f_{1B} frequencies.

This chapter has also shown that drummers can control the timbre of their instrument, through both damping methods and tuning methods to create desired attack and decay profiles.

Although future work is needed on both the subject of tuning a drum kit as a whole, and on the attack and decay profiles produced, it is expected that such research would require considerable input from the fields of psychoacoustics and music performance. It is suggested that listening tests and interviews with musicians could be employed to further bridge the gap between the qualitative descriptors applied by musicians and drum manufacturers and the quantifiable data of frequency and attack and decay profiles.

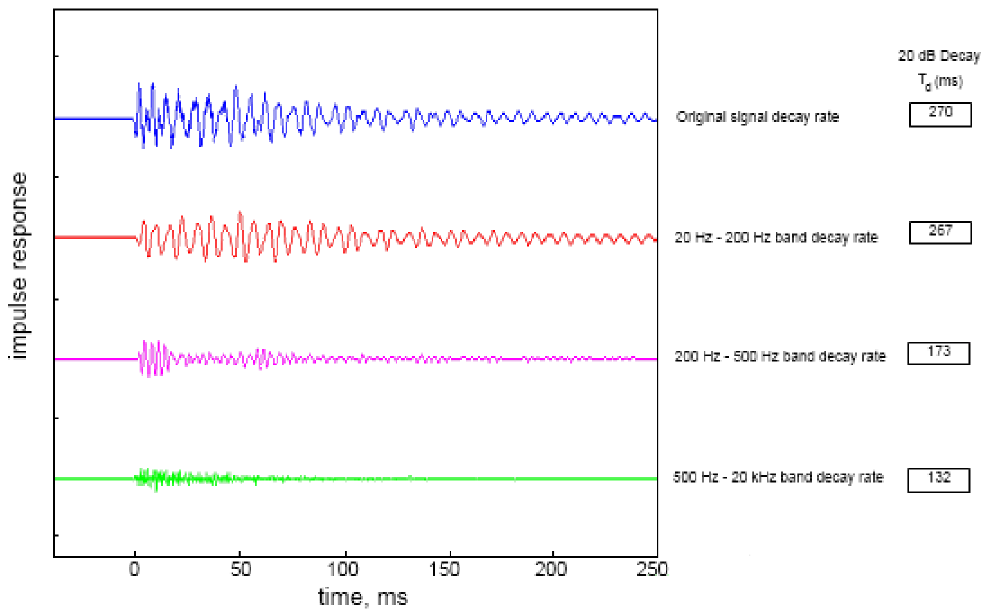


Figure 7.8: Split band analysis showing the different decay rates for each frequency band.

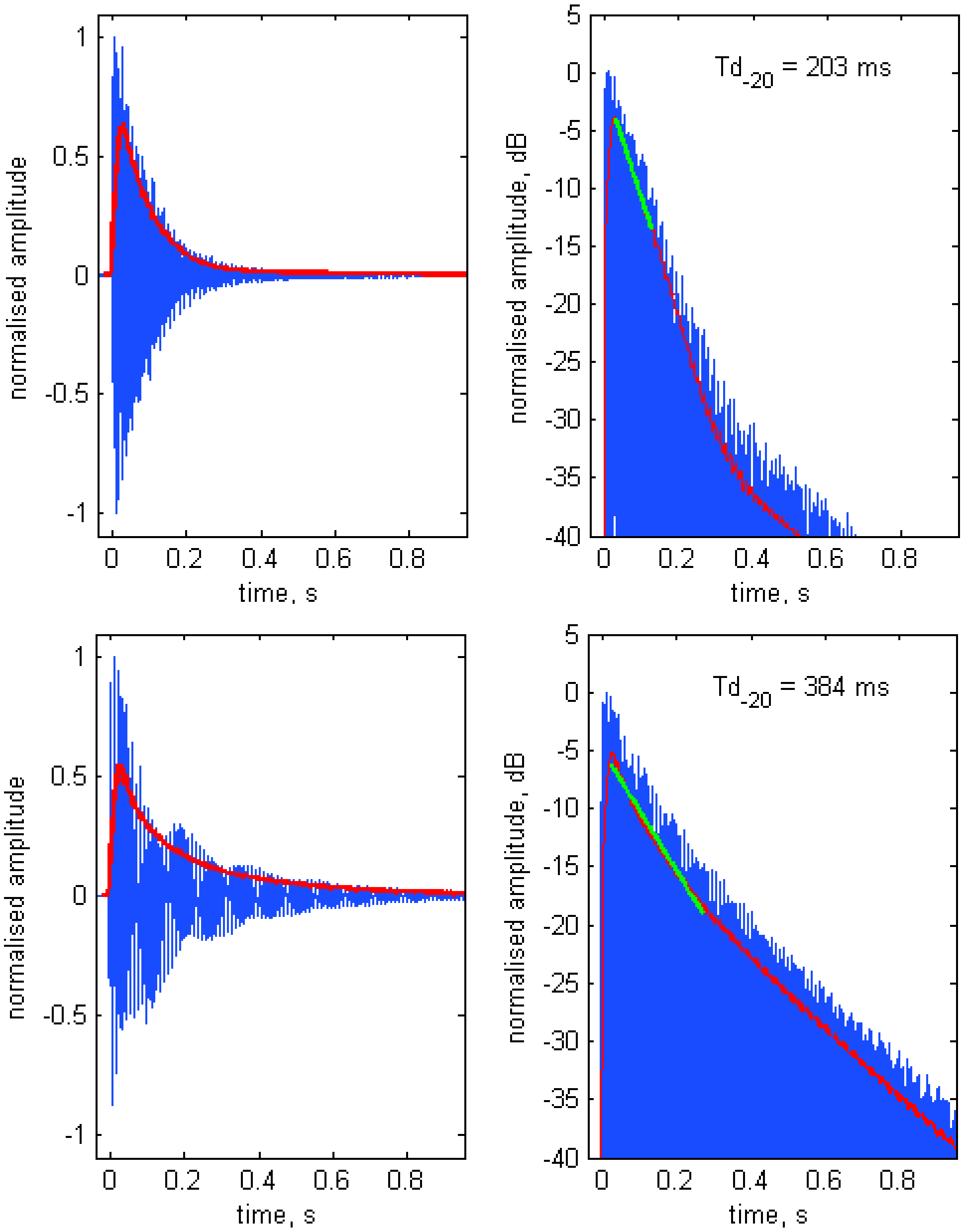


Figure 7.9: Waveforms of a 30-cm tom drum at two different tunings, with both heads tuned to a mid-range (top) and both heads tuned low (bottom).

Chapter 8

Discussion and conclusions

8.1 Discussion of the current research

The current research has brought together both scientific and popular knowledge on the subject of drum tuning to further the understanding of how expert musicians choose to tune cylindrical membranophones. In the scientific literature reviewed in Chapter 2, there was little discussion of how a drum is tuned in a musical context, whereas Chapter 3 indicated that although expert musicians were able to discuss drum tuning at length they were not necessarily capable of providing scientific information regarding the methods they employed. In order to further the understanding of drum tuning it has been necessary to employ acoustic analysis to bridge the gap between the scientific knowledge and musicians' knowledge.

The current research has produced a greater understanding and clarification of drum tuning methods and has, for the first time, generated scientific knowledge with particular respect to cylindrical drum tuning. The analysis methods employed allow for further academic research on the tuning of the instrument.

This chapter summarises the achievements of the current research. Namely, that it is possible to tune a drum to a chosen, uniform frequency response to a quantified accuracy, where both the fundamental frequency and second partial can be tuned to correspond to a note on the musical scale where $f_{1B} = 1.5f_0$. The research shows that the manipulation of the ratios between the frequencies of these (01) and (11) modes can be achieved through alteration of the relative tensions of the two drumheads. Furthermore, it has been shown that these ratios can be maintained over a a range of frequencies for each individual drum in a drum kit. The research performed also notes the effect of tuning on the envelope, i.e. that as a drum is detuned the (11) frequency mode degenerates, and beating is introduced into the envelope. Finally the research investigates the practice of adding damping materials to the drumhead to provide additional control of decay rates of modal frequencies.

8.2 Drum tuning methodologies

The current research has provided knowledge on the drum tuning methodologies employed by professional drummers. This knowledge can be broken down into providing answers for the questions described in Section 4.3.

8.2.1 Research question 1: Can frequency response profiles on a drumhead be made uniform?

This research has shown that there is a difference between uniform frequency response and uniform head tension, as measured by the Tama Tension Watch, when an acoustic drum is tuned. Although some drummers discuss getting an “even head tension”, they lack the means of reliably measuring head tension. Although only an indicator of head tension, the Tama Tension Watch shows that it is not always the case that a uniform head tension produces a uniform frequency response. This, along with the reviewed literature, indicates that although terms such as ‘even tension’ are often used when discussing drum tuning, expert musicians actually tend to focus on achieving a uniform f_1 frequency around the perimeter of the head. The current research has shown that uniform head tension and uniform pitch do not necessarily coincide and that a uniform frequency response exhibited around the perimeter of the drumhead is achievable and a desirable state for a tuned drum.

Frequency mode shapes have been discussed by Rossing (2005) and Worland (2010), but they have not discussed the response of the drumhead at different strike locations as performed in the current research. Past research has focused on the overall response of the drum as opposed to the specific response of the drum when excited in particular locations.

It is these specific responses which are observed when tuning the drum as a musical instrument. It has been clearly shown in Chapters 5 and 6 that an overall view of the behaviour of the drum can be obtained by comparing results from multiple strike locations. This research focused on the (01) mode (f_0) when the drum is struck in the centre and the (11) mode (f_1) when the drum is struck around the perimeter. In the current research, multiple strike locations are used to determine whether the drum produces a uniform frequency response around the perimeter. The results show that a drum can be accurately fine-tuned to provide a uniform response around the perimeter, whilst, with only small changes of drum tuning, a frequency split occurs causing the drum to fall out of tune and beat frequencies to appear.

Frequency splitting and the beats in the response waveform indicate that a drumhead is not cleared or in tune. More specifically, asymmetry has been introduced into the drumhead and two orthogonal (11) modes of different frequencies are produced. Understanding of these factors in combination with the analysis techniques used in this thesis can be used in a drum tuning framework. The analysis software used in this thesis is capable of providing visual feedback to aid the tuning process. Where frequency splitting occurs, plots of the (11) mode for each hit location are superimposed, providing a visual indication of which tuning rod needs to be altered in order to bring the drumhead into tune with itself, as shown in Section 5.5. Given that minimisation of beating in the envelope and frequency splitting in the spectrum are desired attributes, the current research shows that it is possible to achieve these aims by using feedback from the spectra and envelopes. This alters this aspect of drum tuning from an audible process of tuning 'by ear', a skill which may take many years to develop, to a visual process where quantified feedback is provided to aid and speed the process of drum tuning.

This research shows that a uniform frequency response for the f_0 and f_1 modes is achievable to a high degree of precision (less than 1% difference in values of f_1 when excited and measured around the perimeter of the drumhead). The research concludes that uniform frequency response profiles on a drumhead can be evaluated scientifically via signal analysis.

The analysis software can be used for quantitative drum tuning and this aspect has produced publishable results with abstracts being accepted for the 'Reproduced Sound Conference 2010' and 'The Art Of Record Production Conference 2010'. These abstracts can be found in Appendix F and Appendix G respectively.

8.2.2 Research question 2: How do the batter and resonant head tensions affect the modes of the cylindrical drum?

Confused terminology with regards to tuning heads to each other has been apparent throughout the literature review. Rossing et al. (1992), for example, state that the drum was considered in tune if the heads were of equal tension, whereas Bob Gatzen (2006), in his drum tuning guide, stated that he tuned his drumheads to various intervals such as unisons, thirds, fourths and fifths.

Through experimentation a greater understanding of which frequency modes drummers refer to when discussing drum tuning has been obtained. The current research concludes that expert musicians tune with attention paid to the overall fundamental frequency of the drum f_0, and the second partial excited in each head, f_{1B} and f_{1R}.

The fundamental frequencies for each head, f_{0B} and f_{0R}, are very close at all times, within 1% as shown in Table 6.3. In the (01) mode the effect of the large movement of the mass of air in this mode causes strong coupling between the two heads. However, less air coupling is observed for the f_{1B} and f_{1R} modes meaning that these can be tuned almost independently of each other. It is noted that f_{0B} and f_{0R} are similar despite differences between the drumheads used in the research. Whilst it is expected that striking the batter head or the resonant head of a drum with near-identical heads will produced similar values for f_{0B} and f_{0R}, it is noteworthy that this singular f_0 mode is maintained despite significantly different head choices for the resonant and batter drumheads.

Further to this it has been shown for the first time that the control of the ratios f_{1B}/f_0 and f_{1R}/f_0 is possible in order to produce specifically tuned peak frequencies. The ratios for f_{1B}/f_0 ranged between 1.32 and 1.76 whilst the ratios for f_{1R}/f_0 ranged from 1.53 to 2.20, this indicates how versatile the tuning options for a cylindrical drum are when both drumheads are present. By having a higher tension on the resonant head, it is possible to adjust the ratio f_{0B}:f_{1B}:f_{1R} to close to 1:1.5:2, giving a clearer sense of pitch, similar to that of timpani. Similar variation in ratios was not seen in tunings for a drum with a single head. The level of control available in tuning the drumheads relative to each other has not previously been discussed in a scientific context. The research provides quantifiable data which relates to discussions in popular literature regarding tuning the drumheads to be musically related to one another.

The research concludes that manipulation of the relative batter and resonant drumhead tension profiles affects not only the frequency modes of the cylindrical drum, but also the ratio between those modes. This thesis pays particular attention to the f_{0B}, f_{0R}, f_{1B}, and f_{1R} modes, and notes that these can be manipulated to produce musical frequencies.

8.2.3 Research question 3: To what extent can the envelope (decay and attack) of cylindrical drums be adjusted?

It has been shown in Chapter 7 that it is possible to manipulate the envelope of the drum signal, via both tuning and damping. The current research, however, agrees with experts such as Ranscombe (2006*b*) that correct head choice minimises the need for alteration of the envelope of the drum sound through tuning or damping.

Quantifiable values for the attack and decay profiles of cylindrical drums have been determined via the software used in this thesis. Understanding of the different decay rates of individual resonant frequencies is of use to percussionists who desire a smooth and controlled decay, as discussed by Ranscombe (2006*b*) and Seymour (2010). In particular, musicians are concerned with 'benchmarking' sounds, and achieving repeatable tuning setups. There is still much research to be conducted with respect to decay times, however, a method for analysing and quantifying decay times has been described, so this could be of immediate value to musicians and music producers.

It has previously been discussed that a smooth decay of the signal is desirable and the visual feedback used in this research indicates that the presence of beating in the envelope can be minimised through tuning methods. For a simple test setup, the 20-dB decay time was observed to change from 171 ms to 384 ms through tuning, with the attack changing between 10.4 ms and 19.1 ms. This control of attack and decay times through alterations in drum tuning has not previously been evaluated.

Furthermore the effect of damping materials to control the envelope has been evaluated. It can be seen that damping materials are used to shorten the decay of the higher partials, rather than the fundamental frequency. This result was expected as damping materials are rarely applied to the centre of the drum where the (01) mode is most prominent. Arguments could be made towards achieving a decay time that is similar for each partial.

It was noted that the addition of damping produces a larger variation in decay time than alterations in drumhead tuning, although the current research has not determined whether this is a specific or general case. This result suggests that this is one reason why damping materials are often used to control decay times, as opposed to tuning methods which have less effect on the decay time. When a desired decay is achieved through tuning alone it may be the case that the pitch-related factors of drum tuning are no longer achieved.

This research concludes that the envelope profile (decay and attack) of cylindrical drums can be tuned and envelope analysis can be used for quantitative drum tuning methods; however a more detailed study of attack and decay is recommended and discussed in Chapter 9.

8.2.4 Research question 4: Is it possible to develop a complete framework for quantitative drum tuning to assist percussionists in tuning cylindrical drums?

The current research provides example tunings for the drum kit as a single instrument in Chapter 7. It is possible to tune the drum kit to different ranges targeted at different genres of music, for example a low 'rock' tuning, or a higher 'jazz' setting. Although drum kits can be sold as 'rock' or 'jazz' kits, the latter having smaller drums in order to more easily produce higher notes, an individual drum kit can be tuned to be suitable for a variety of musical genres.

Although many drummers discuss tuning their drums melodically, as highlighted by the literature review, this claim had not previously been scientifically evaluated. Together with the research performed in Chapter 6 on the frequency ratios present in an individual drum, it has now been shown objectively that it is possible to produce an increased musicality of the drum kit, something some drummers take great care in achieving.

Through experimentation a range of tunings were created for one drum kit. Each tuning setup tuned the frequencies f_{0B} and f_{1B} to a note on the musical scale. In this research the ratio for f_{0B} and f_{1B} was maintained at 1:1.5 giving a better sense of pitch, similar to that of timpani. These results were saved as a benchmark so the frequencies obtained can be used as targets for percussionists to aim for when tuning similar drum kits.

Further research is necessary to complete a framework of tuning ranges for a wide variety of musical genres, and such research should include envelope analysis in the framework along with information on the frequencies produced by the f_{0B} and f_{1B} modes, as performed in the current research. It would be expected that carefully developed listening tests and artistic input are required to further discuss drum tuning with respect to genre.

8.2.5 Research question 5: Can a new framework for quantitative drum tuning bridge the knowledge areas of the popular understanding of drum tuning and the scientific understanding of acoustic drums?

The current research goes some way towards providing a scientific background and methodology for how expert musicians tune a drum kit. The approach is distinctly different from other such studies, for example by Worland (2010) and Rossing et al. (1992), where the understanding of the drum is approached wholly from an acoustics standpoint.

Musicians have often discussed a desire for ‘evenness’ of pitch when the drum is excited around the perimeter of the drumhead, and the current research empirically shows that a uniform frequency response around the drumhead is achievable, and is necessary for a smooth, beat-free decay. Discussion on achieving this uniform response is often muddled in previous literature, with references to note, pitch and tension often being used interchangeably. This research however concludes that it is indeed uniform frequency response, and not measured tension, that produces the qualitative descriptions used when describing a drum as ‘in tune’. It therefore makes sense for discussion on tuning to be based on acoustic rather than ‘invasive’ analyses which alter the physical characteristics of the drum, i.e. it is preferable to analyse frequency response directly without loading or changing the properties of the drumhead (as would be the case with using accelerometers or when measuring tension).

Furthermore popular literature discusses tuning the drumheads relative to each other, again with terminology such as pitch and tension being used interchangeably, and qualitative descriptions of the drum sound produced by these differences are also stated, for example by Gatzen (2006) who suggests that some relative head tunings sound “woody” while others produce “metallic” sounds. The current research has not attempted to link qualitative descriptions with quantitative data, but has proven that it is indeed possible to alter the relationship of the frequencies in the spectrum by manipulation of the relative tension of the two drumheads. It was shown, as an example, that tuning of three distinct frequencies present in the drum, f_{0B}, f_{1B} and f_{1R} could be manipulated into more harmonious relationships, with musical ratios similar to those of timpani and those described by Gatzen (2006).

Some drummers, such as Brian Chase, discuss tuning their drum kit to a set key with each drum playing a musical note (Budofsky, 2009, p.56). This tuning has not been previously discussed in a scientific context and this thesis shows that it is possible to not only tune an individual drum kit such that f_0 and f_{1B} are notes on a musical scale, but also that an individual drum kit can produce a wide range of such tunings. It is discussed that some tunings may be more appropriate for specific genres of music, and that a single drum kit can cover a variety of tunings appropriate for different styles of music.

This thesis has shown that manipulation of drumhead tension is one method available to drummers for control of the envelope. The other method discussed in this research was the addition of damping materials. Quantifiable data for attack and decay times for the drum sound as a whole, along with split-band analysis to obtain data for the

f_{0B} and f_{1B} frequencies can be used to further understand the response envelope.

The current study uses approaches and methods already employed by expert musicians and provides visual and quantitative information to further the understanding of drum tuning. This quantitative research goes some way towards bridging the knowledge areas of understanding of drum tuning and the scientific understanding of acoustic drums; however, it is recognised that this subject has by no means been fully explored as emphasised by the numerous recommendations for future work in Chapter 9.

8.3 Benchmarking methods and use of the analysis software in further research

8.3.1 Importance in benchmarking for studio and research environments

The analysis techniques used provide quantifiable values for how a drum is tuned at any given time. By keeping a record of these values it is possible to ensure that a benchmark is made so that should a drum go out of tune it can be returned to its initial state. This is of importance in both commercial studio environments, where large amounts of time are spent on achieving a desired drum sound, and also in a research environment where having a clearly defined setting for the drum can allow further analysis and repeatable experiments as discussed by the author and colleagues in the paper ‘The perception and importance of drum tuning in live performance and music production’ (Toulson et al., 2008) which can be found in Appendix E.

Drum tuning plays an important role in music production and the ability to benchmark and retrieve drum tunings may be of significant value during recording sessions, minimising the time taken to achieve desired drum sounds on recording projects. It is hoped that the ability to benchmark tuning setups using the methods described in this thesis will help reduce time and cost in studio environments.

8.3.2 Analysis software

The analysis software used in the current research provides a novel way of tuning drums. Such a method is more readily available than methods such as interferometry, but, clear, accurate results are shown to be obtainable. Due to the relatively low cost potential of the software it is clear that it can not only be applied to future scientific research, but also be used to provide benefits in industry, where it could be used to analyse the behaviour of new products. In a commercial setting a digital drum tuning aid may be a viable product on the marketplace.

The current research tests the software as discussed in Chapter 4 and Appendix C and makes use of the software explicitly to tune drums. The results and observations seen throughout this thesis corroborate other results gained in scientific literature, and the experiences of expert musicians. Together with this thesis, the software provides a scientific method and tuning aid for benchmarking and tuning cylindrical membranophones.

Further development of the analysis software used in this thesis will be outlined in Chapter 9.

8.3.3 Use in future research

Research such as that performed by Worland (2010), who described the tuning of a single membrane with respect to mode shapes visible with electronic speckle-pattern interferometry, could make use of the acoustic analysis used in this research to provide a basis and benchmark for further experimentation. For example, in experiments on a single membrane Worland observes:

> "Mode shapes, as seen with ESPI imaging, also appeared generally more symmetric as the tuning was improved. 'Perfect' tuning, which presumably would be characterized by fully symmetric mode shapes and the absence

of frequency splitting, was never achieved."

Worland (2010)

A uniform frequency response has been shown to be achievable in the current research, and could be of use to provide quantifiable values for the tuning of a drum alongside other methods of analysis such as ESPI.

8.4 Final conclusions

The research has shown that it is possible to provide a uniform response around the perimeter of a drumhead by using signal analysis techniques. The (11) mode, f_1, can be tuned to be consistent around the drumhead (to an accuracy of 0.5%). It can also be seen that whilst the modal ratios of a single head are relatively fixed, the modes of a cylindrical membranophone with two heads can be manipulated in such a way as to alter those modal ratios with f_{1B}/f_0 varying from 1.32 to 1.76 and f_{1R}/f_0 varying from 1.53 to 2.20 for a 30-cm tom drum.

Despite differences in head type, the f_0 frequencies for both f_{0B} and f_{0R} will remain consistent (within 1%) and is independent of which head is struck. This is due to the strong coupling between the heads in the (01) mode of the drum. This coupling enables the drum to be tuned so that the frequency peaks f_0, f_{1B} and f_{1R} can be manipulated in such a way that the modal ratios alter. This is an important aspect in tuning cylindrical drums, and is a significant benefit of having two drumheads on a cylindrical shell. It has been shown to be possible for the fundamental frequency (of both heads) and second partials of each head to be moved close to a ratio of 1:1.5:2, similar to that of timpani, giving a clearer sense of pitch. Each individual drum has a range of notes that it can be tuned to, determined in part by head type and shell size. This thesis proves that a drum kit as a whole can be tuned to provide a series of pitches where f_0 and f_{1B} correspond to notes on the musical scale. It is recognised in this thesis that f_{1R} may also correspond to a musical note, however achieving musical frequencies for f_0, f_{1B} and f_{1R} simultaneously is affected by drum shell and head choice. The musical intervals between drums, along with the frequencies present, can be chosen to tune the drum to a set key, or to be suitable for specific genres.

These aspects of drum tuning have been thoroughly discussed in popular literature, albeit sometimes with misused or confusing terminology, however they have been more fully evaluated in a scientific context for the first time in this thesis. The research has contributed new knowledge bridging the gap between scientific acoustic theory and musicians' knowledge on drum tuning.

Published output from this research can be found in Appendix E, a research paper presented at and included in the Proceedings of The Art of Record Production Conference in 2008. Abstracts have been accepted for presentation and inclusion in the Proceedings of the Reproduced Sound Conference 2010, Appendix F, and The Art of Record Production Conference 2010, Appendix G.

The current research has opened up many opportunities for further scientific and interdisciplinary research. Some of these new research areas will be addressed in the following chapter.

Chapter 9

Future work

9.1 Overview of the current research

The current research has provided a more thorough scientific understanding of how expert musicians tune a drum kit.

The drum tuning method outlined provides an initial quantitative basis for tuning an acoustic drum and has answered the research questions outlined in Section 4.3. The drum tuning method can be used as a starting point for further research into the tuning of cylindrical drums, and further analysis of the sound they produce.

9.2 Higher modes of vibration

It has been suggested by Worland (2010) that the (21) mode also has an effect on the tuning. The higher modes have not been fully discussed during the current research, however future research could investigate the ratios present for the higher modes and whether the relationship between the batter and resonant head can be manipulated to produce more harmonic ratios in the higher modes whilst maintaining that seen in the current research for f_0, f_{1B} and f_{1R}. It is hypothesised that, with the tuning variables used in this thesis, there will be limited control of a higher number of partials. As such, it would be necessary to investigate the role of drumhead properties in determination of higher partials, particularly with popular drumheads which are designed with non-uniform properties, such as in-built damping rings, dots, or 2-ply heads.

Further empirical research on how the resonant head of the drum is affected by changes in the tuning of the batter head, and vice versa, is still necessary in order to fully explain comments by many musicians and scientists on how they tune the two drumheads in relation to each other.

Another consideration with real-world implications is the effect of the snares on the (11) and higher modes of the snare drum.

9.3 Advanced envelope analysis

Further analysis of the importance of the envelope of the drum sound would be desirable. Such research could focus on extracting decay rates of individual modes to provide further understanding on how the addition of damping materials affects each mode. It is also hypothesised that decay rates for each partial could be manipulated to be closer in duration, and that extended ‘ringing’ of higher partials should be minimised to produce a preferable drum sound; however, this thesis has not fully explored this hypothesis and further research involving psychoacoustic listening tests and expert opinion would be necessary.

Analysis of the envelope of tom drums has been discussed in this thesis, but the envelope of the snare and kick drums are distinctly different. Whereas achieving uniform frequency response and tuning to pitch are applicable to all cylindrical drums, achieving a desired envelope may require a subtly different approach for toms, snare and kick drums.

Many drummers attempt to limit the ‘ring’ of the drum when tuning individual drums in bright rooms, away from a live or studio environment and without the backing of other instruments. Future research could investigate to what extent the amount of 'ring' in different environments affects how percussionists tune their instruments with particular attention paid to decay times.

9.4 Variance of head and shell types

It has been stated by Louise King (Rhythm Magazine, 2004*j*, p.16) that the "sound of a drum is said to be 80 percent due to the heads you use", but this does not appear to have been scientifically evaluated in current literature. It is envisaged that any drumhead can be tuned to a uniform response and chosen pitch within a specific range. The specific drumhead will affect the timbre of the sound and therefore affect the envelope and the higher partials of the sound, rather than the fundamental frequency and assumed pitch.

Although the current research has shown that a uniform frequency response can be obtained for a range of drumheads there has been little research on the effect of the drumhead on frequency response and envelope. Lewis and Beckford (2000) performed some research into the role of head type on the spectrum of a snare drum, but this study was limited to 14 drumheads and further investigation is required. Discussion on how two cylindrical shells of any given size or material, with the same head and tuned in the same manner, can produce different sounds has been limited to popular literature and has not been empirically investigated.

In order to further aid novice drummers in their choice of drum kit and head type it is necessary to investigate the differences in tonality produced by different shell and head materials and types. Listening tests on the effect of material type on the timbre of instruments have been performed qualitatively, for example by Yamauchi et al. (2001). Quantitative analysis on different shell materials and shapes of wakaido drums has been performed by Ono et al. (2009), although this study did not link the quantified values to any qualitative information on how the sound altered. These studies indicate that technology and methodologies are available for studying the role of the head and the shell in more detail than has previously been performed. The quantifiable analysis methods used in this thesis could, in combination with listening tests, fully explore the role of the drumhead and shell materials and types on timbre.

9.5 The role of stick response in drum tuning

It has been repeatedly seen throughout the literature review that stick response is an important factor in drum tuning, with drummers such as Liberty DeVitto (Nicholls, 2001) stating the importance of the feel of the batter head. Research into stroke movements has been performed by Dahl (2003) however this research did not take into account the changes in physical response of the batter head through tuning alterations.

> "I always played with my drums tuned down and I never used to get any bounce back from them. I tuned them up recently, against the wishes of my soundman, and I got way more rebound on my sticks. I couldn't believe it. All of a sudden I was able to make fills that I couldn't before, and the kit felt a hell of a lot better."
>
> Nick Jago, (Hopkin, 2008)

Drummers such as John Boecklin (Croft, 2007*b*), Adrian 'Bone' Green (Croft, 2007*c*) and John Tempesta (Croft, 2007*d*) state that beater response is preferable with a hole in the resonant head of the kick drum. This indicates that microphone placement is not the sole reason for cutting a hole in the resonant head. The beater response from the kick pedal is a concern when the head is intact, possibly due to the force with which the drum is struck, along with the large mass of air inside a kick drum, with Adrian 'Bone' Green saying:

> "Playing with a hole in the front of the front kick head really feels better. While on the fast double bass runs it allows me to keep going without having to worry about weird 'bounce back' on the batter head."
>
> Adrian 'Bone' Green, (Croft, 2007*c*)

This factor has been discussed briefly in the current research, but there has been limited research on the limits of drumhead tension and the physical response of the drum.

9.6 Tuning ranges

As discussed in Chapter 7 there is scope for interdisciplinary research to continue on the tuning ranges of the drum kit as a whole. Although the current research shows that it is possible to tune a drum kit to a variety of musical intervals further research could be performed into tuning the kit to a set musical key, along with the potential uses of tuning a kit in this manner in studio and live environments.

Psychoacoustic research could be used to determine quantifiable and scientifically verified tuning systems for drum kits of a variety of tunings, particularly with respect to the qualitative marketing of modern drum kits as being 'jazz', 'rock' or other types.

Research into tuning to genre could also further detail the role of envelope in genre. For example a heavy-metal drummer may prefer a quick decay to allow for clarity of fast strokes, whilst a jazz drummer may prefer a more resonant sound. Although it has often been noted that larger drum kits produce lower pitched tunings, there is scope for further research on how the size of the drums in kit affects the ability to manipulate attack and decay times.

Further research into the perception of the pitch of cylindrical shells tuned so that f_0:f_{1B}:f_{1R} forms the ratio 1:1.5:2 is necessary to fully determine whether a missing fundamental pitch of $0.5f_0$ can be heard.

9.7 Advanced analysis methods and stroke analysis

The current research has made use of signal analysis; however, further results could be obtained by the methods outlined in the literature review, such as electronic speckle-pattern interferometry. Acoustical holography has been successfully used to reconstruct and analyse the sound field produced by a violin plate by Fushimi et al. (2002), and by Kwon et al. (1997) on a jing, a type of gong used in traditional Korean music. However, this method is often overlooked in favour of optical holography in research on membranophones. Sullivan (2008) explains the design and construction of a near-field acoustic holography device which was successfully tested on a vibrating drumhead. By using a variety of analysis methods a clearer understanding of the head and shell vibrations and mode shapes for uniform and non-uniform frequency response profiles could be obtained.

Likewise modal analysis techniques such as those used by Rossing (2001) and Worland (2010), have not been applied to drums with damping materials added to them, such as Moongel which does not provide a uniform damping around the head. These methods could also be applied to further determine whether f_{0B} and f_{0R} are exactly the same or whether, given difference in the batter and resonant heads and hole inside the drum shell, a small deviation between f_{0B} and f_{0R} could be expected. Use of a consistent force mechanism, such as described in the Chapter 4, could also be of benefit and interest in future research. Furthermore, the methodology used in this research could also be extended to other membranophones of indefinite pitch.

9.8 Development of intelligent tuning aids

The research analysis software could be further developed to provide intelligent feedback which could speed the process of tuning drumheads to produce musically related f_0, f_{1B} and f_{1R} frequencies.

In the experiments the f_0 and f_1 frequencies were observed over a large range of tunings. Further research could focus on the differences produced by much smaller variations in tuning, and could allow for a method to more easily find the correct relationship for the drumheads where f_0 corresponds to a note on the musical scale, and where f_{1B} and f_{1R} partials share a musical relationship with f_0.

It is expected that further development of software which provides visual feedback to drummers on how to achieve a desired sound could be a viable commercial product.

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Appendix A

Introduction to membranophones

Acoustic drums are percussion instruments and, more specifically, are part of the membranophone family of instruments. This means that the sound produced by these instruments is predominantly from the vibrations of a stretched membrane. This distinguishes them from idiophones, such as cymbals or marimbas, which produce sound from the vibrations of the instrument itself.

A.1 Cylindrical drums

A cylindrical drum often has two heads, a batter head and a resonant head. On a snare drum the resonant head is also known as the snare head. Drumheads, often made of Mylar, are attached to an aluminium hoop, and rested on the shell of the drum. When tightened onto the shell the plastic of the drumhead moulds to the bearing edge, seating the head. The drumheads are secured by way of a metal rim held in place by metal rods as shown in Figure A.1. Tension rods are used to tune the drum.

In order for the drumhead to be properly seated onto the drum shell the bearing edge has to be uniform. This is the case for most cylindrical drums with the notable exception of the resonant side of a snare drum where there needs to be two slight dips on opposing sides (Nicholls, 2003*c*, p.50). These dips are known as snare beds and they help the snares lie flat across the head.

The rims of a drum are usually made of metal, with wooden hoops occasionally being used. With a metal rim the rim is either moulded or hammered into shape, die-cast or flanged respectively. Die-cast rims tend to be more rigid than their flanged counterparts and, being rigid, the drum tends to go out of tune more easily (Nicholls, 2003*c*, p.66), (Rhythm Magazine, 2004*k*, p.14), (Rhythm Magazine, 2004*c*, p.60). Nicholls (2003*c*, p.66) argues that the rigidity of the die-cast rim causes the shock from rim shots to be evenly transmitted around the rim, causing detuning, whereas flanged rims are more flexible and tend to have localised tuning issues, for example detuning at the lugs where rim shots occur.

The snare drum has seen a variety of uses during its history, from being a military instrument predominantly used for communicating signals and commands to troops (Dobney, 2004) to becoming an integral part of modern Western music. The origins of the snare drum may date back as far as medieval times, from a double-headed drum known as the atambor (Blades, 1992, p.185). James Blades notes that the side drum, from which the modern snare drum originated, was certainly well developed by the 17th century. During its time as an orchestral instrument it has undergone several changes. During the period between 1837 with the invention of rod-tensioned drums (Ward, 1837) and 1912 when the throw-off snare mechanism was developed (Ludwig, 1912), the instrument became smaller and shallower and evolved into what is recognisable as today's snare drum (Dobney, 2000).

Unlike tom drums, a snare drum, shown in Figure A.2, has a snare mechanism attached to the shell, holding snare wires in tension across the resonant head. Striking the batter head causes the lower head to vibrate against the snares (Rossing, 2005, p.28) adding a noise component to the sound. Without this interaction the drum would give a different, tom-like, sound. There is a small time delay between the drum being struck and the snares interacting with the resonant head. This delay is called the activation time and there is no definite mathematical formula to describe the behaviour of the snares (Tindale, 2004). The length of this delay time is not noted by Tindale (2004), and it is unknown how perceptible this delay is. The number of wires on a snare varies, with popular numbers of wires being 12, 16, 20 and 24 (Puresound Percussion, 2010), and the wires are commonly made from coiled steel.

The drumheads and tuning of the drum can be changed to alter the timbre, but the shell also affects the sound of the drum. A wide range of materials can be used for the drum shell, although usually cylindrical drums are made from a range of woods such as mahogany, beech and birch, or plastics such as acrylic. Snare drum shells are also often made from metal. The material also makes a difference to the sound produced. These differences are usually described in literature by adjectives such as dark, bright, mellow, hard or woody, as opposed to by any scientifically quantifiable parameters.

The size and thickness of the shell also have an effect on the sound of the drum. In general the larger the diameter, the lower the pitch. Most snare drums tend to be of similar size with a diameter of 14 inches (35 cm) and a depth of 5 to 7 inches (12.7 cm to 17.8 cm) being popular choices. Tom drums come in a wide variety of dimensions although they are usually deeper than a snare drum.

The kick drum has the lowest fundamental frequency of the drums in a drum kit. It is also often referred to as a bass drum. A kick drum is in many ways similar to a tom drum but it is struck by a beater controlled by a pedal, and is the only drum in the kit that is always struck in the same place. To keep the drum stable, legs are added to the sides which drop down and stop the drum from rolling across the floor and from moving forwards when the drum is struck.

A.2 Timpani

Timpani (or kettledrums) have been used in Europe since 1457 (Montagu, 2002, p.42); however, like the snare drum, they were initially used as a military instrument and it was not until the 17th century that the orchestral timpani appeared (Blades, 1992,

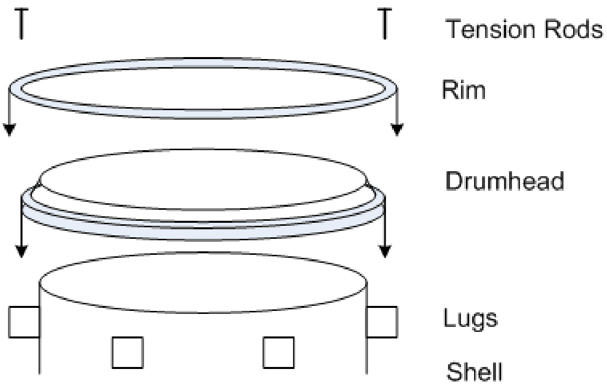

Figure A.1: Drumhead between rim and shell, held in place by tension rods and lugs.

Figure A.2: Photograph of a snare drum.

p.236).

Timpani consist of a single circular membrane stretched over a large bowl (Montagu, 2002, p.4). The bowl is usually made of copper or fibreglass, and can be hemispherical or parabolic. Like the drum the heads of timpani are usually tuned by way of tension rods and are struck by an implement, although they are struck by mallets rather than drumsticks. They may alternatively have a pedal to alter the overall tension of the head. It is usual for more than one timpani to be used to produce the required range of notes. This is similar to the modern drum kit where a kick drum, snare drum and various sizes of tom are used to produce different sounds.

A.3 The drumheads

The drumheads, or skins, are made of a material known as Mylar. Mylar is a polyester film originally made by DuPont(tm) (Remo, 2010*a*). Produced by Remo, who were founded in 1957, Mylar drumheads were created in the late 1950s and were further developed over the decades to come. Another drumhead manufacturer, Evans Drumheads, claims to be the first to have made synthetic drumheads in 1956 (Evans Drumheads, 2010*b*).

Drumheads come in a variety of thicknesses and coatings. The snare drum usually has a coated batter head and a thinner, clear resonant head. Coated heads are rougher than their transparent counterparts, mimicking an animal skin, and provide friction which is useful for brush playing (Nicholls, 2003*c*, p.107). Drumheads also come in either one or two ply, with each ply being 0.2 mm to 0.25 mm thick (Nicholls, 2003*c*, p.108). However, the snare drum also has a thinner resonant head. This thinner skin is often only 0.05 mm to 0.13 mm thick and is chosen to accentuate snare response (Remo, 2010*a*). The choice of heads has an effect on the sound produced, with Rhythm Magazine (2004*j*, p.16) stating that the "sound of a drum is said to be 80 percent due to the heads you use."

The importance of the drumhead can be likened to that of a guitar string, with Rob Pearson stating:

> "It's like the string on a guitar - it's the string that makes the sound; the acoustic body is just a resonating chamber. With an acoustic kit the drum shell is the same except that a taut drum head makes a lot more noise than a taut guitar string."
>
> Rob Pearson, (Nicholls, 2003*a*, p.81)

Appendix B

Analysis of mode shapes

Much of the research on acoustic drums has centered on the vibrational modes of the drumhead. Although much of this research has been carried out for ideal membranes, and drums with only one head, a limited amount of research has been conducted on acoustic drums with both heads in place. Of that research much of it has been conducted by Rossing et al. (1992) using optical holography to observe several modes of drums.

Rossing has noted modal pairs for the (01) and (11) modes, as well as single (21), (02) and higher modes as shown in Figure 2.4 and discussed in Section 2.2.2.

A 35-cm tom drum was struck and analysed using the methods discussed in Section 4.5. Frequency peaks were noted at 125.2 Hz, 212.2 Hz, 325.7 Hz, 366.1 Hz and 417.9 Hz. A signal generator and loudspeaker was then used to displace salt on a drumhead which would produce Chladni patterns at the modal frequencies of a drum. Figures B.1 through to Figure B.4 show these patterns; these images have been manipulated by increasing the contrast and then inverting the colours to more clearly show the modal patterns.

A much weaker mode was also observed at 373 Hz and was not strong enough to adequately displace the salt. The current research concentrates mainly on the first two frequencies present in the spectrum which can be identified as the (01) and (11) modes.

Research, such as that carried by Rossing, often presents modal frequencies and the ratio between modal frequencies for a single, unattached membrane. The current research investigates cylindrical drums with two heads in place and shows that it is possible, through tuning the drumhead, to significantly alter the relationship between modal frequencies as discussed in Chapter 6.

Figure B.1: (01) mode visible at 124.9 Hz.

Figure B.2: (11) mode visible at 212.7 Hz.

Figure B.3: (02) mode visible at 323.8 Hz.

Figure B.4: (12) mode visible at 421.0 Hz.

Appendix C

Evaluation of the software used in this thesis

C.1 Overview of the software

The capture and analysis methodology used in this thesis has been tested with pure sine waves and has been shown to display and determine fundamental frequency peaks to an accuracy of 0.1 Hz over the range 50 - 500 Hz. Further testing has been performed by using the 'expression evaluator' tool in Goldwave, a professional digital audio editor, to produce complex tones with three partials, as shown in Figure C.1. The expression evaluator allows a sound wave to be generated from an equation, for example a simple sine wave can be generated by $sin(2 * \pi * f * t)$.

The expressions used were as follows:

Equation A: $0.3*\sin(2*\pi*t*f)+0.3*\sin(2*\pi*t*f*1.2599)+0.3*\sin(2*\pi*t*f*1.4983)$

Equation B: $0.4*\sin(2*\pi*t*f)+0.2*\sin(2*\pi*t*f*1.4983)+0.1*\sin(2*\pi*t*f*2.0)$

where f is a specified frequency and where t is time.

These tones then had an envelope applied using the 'Shape Volume' tool, shown in

Figure C.2, to produce the waveform shown in Figure C.3. This could also have been applied via a mathematically generated envelope using an exponential decay. To be comparable to a the drum signal, each sample lasted one second with 40 ms silence prior to onset of a generated wave which decays within 600 ms.

C.2 Raw data

Tables C.1, C.2 and C.3 show frequencies calculated by the Goldwave software and those determined by the analysis software used in this research. Table C.2 shows results from waveforms generated from Equation A ($0.3*\sin(2*\pi*t*f)+0.3*\sin(2*\pi*t*f*1.2599)+0.3*\sin(2*\pi*t*f*1.4983)$) whilst Table C.3 shows results from waveforms from Equation B ($0.4*\sin(2*\pi*t*f)+0.2*\sin(2*\pi*t*f*1.4983)+0.1*\sin(2*\pi*t*f*2.0)$)

C.3 Discussion

The 'expression evaluator' tool is used for manipulating and generating audio data, although Goldwave is closed-source proprietary software and as such it is not known precisely how the expression evaluator works. However, it can be seen from Tables C.1, C.2 and C.3 that there is a close correlation between the results gained from the analysis software and the values defined using Goldwave. Figure C.4 shows the example waveform with a 5000-sample analysis window and spectrum of the data used in Table C.3.

It is apparent, through initial experimental analysis, testing on sine waves, and use of specifically generated waveforms that the software used in this research has the resolution necessary to analyse data on cylindrical drums and is fit for the purposes of this research.

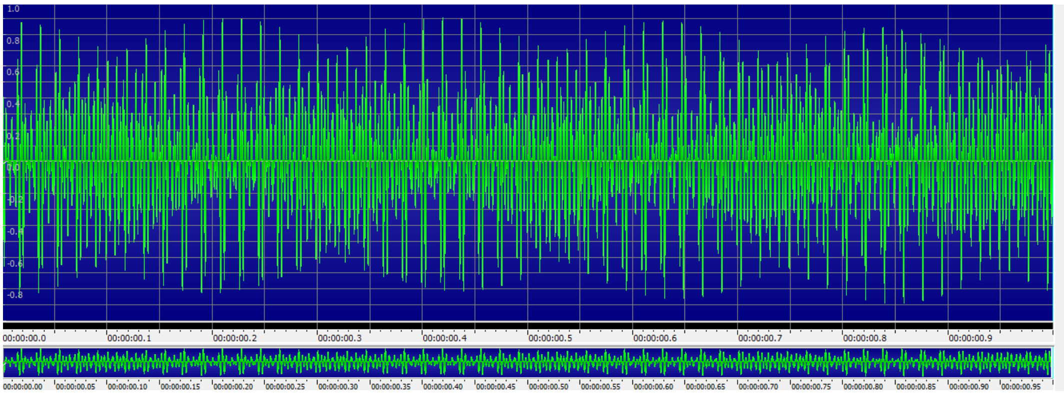

Figure C.1: Waveform produced by Goldwave containing 220.0-Hz, 277.2-Hz and 329.6-Hz frequencies.

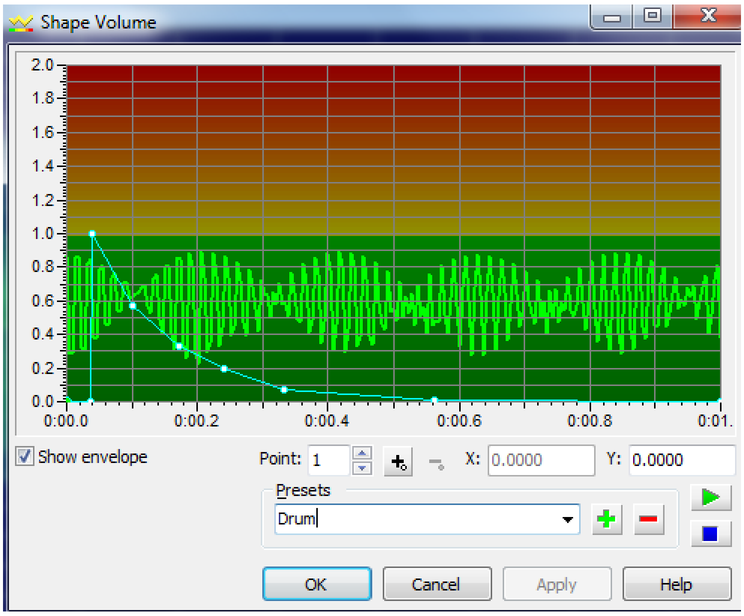

Figure C.2: Envelope applied to waveform produced by Goldwave containing 220.0-Hz, 277.2-Hz and 329.6-Hz frequencies.

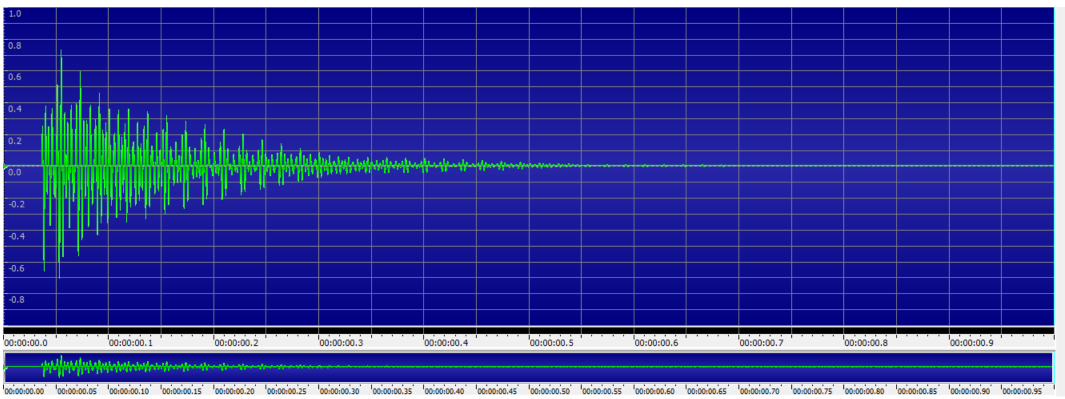

Figure C.3: Waveform produced by Goldwave containing 220.0-Hz, 277.2-Hz and 329.6-Hz frequencies with envelope applied.

Software	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)	Frequency (Hz)
Goldwave	51.9	103.8	207.7	415.3
Percussionizer	51.9	103.8	207.7	415.3

Table C.1: Sine waves analysed by the software used in this thesis.

Frequency	$f1$ (Hz)	$f2$ (Hz)	$f3$ (Hz)	$f2/f1$	$f3/f1$
Goldwave	110.0	138.6	164.8	1.260	1.498
Analysis Software	109.9	138.7	164.9	1.262	1.500
Goldwave	220.0	277.2	329.6	1.260	1.498
Analysis Software	220.0	277.2	329.6	1.260	1.498

Table C.2: Comparison of frequencies determined by Equation A and by the software used in this thesis.

Frequency	$f1$ (Hz)	$f2$ (Hz)	$f3$ (Hz)	$f2/f1$	$f3/f1$
Goldwave	98.0	146.8	196.0	1.498	2.000
Analysis Software	98.0	146.9	196.0	1.499	2.000
Goldwave	196.0	293.7	392.0	1.498	2.000
Analysis Software	196.0	293.7	392.0	1.498	2.000

Table C.3: Comparison of frequencies determined by Equation B and by the software used in this thesis.

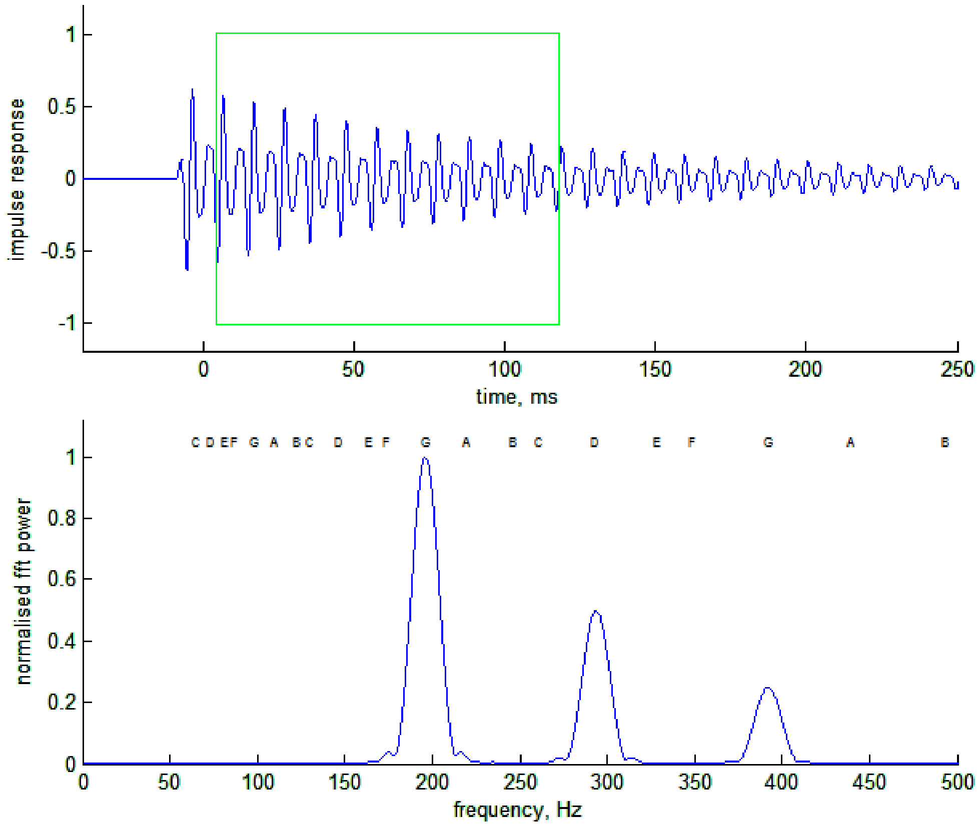

Figure C.4: Waveform and spectrum containing 196.0-Hz, 293.7-Hz and 392.0-Hz frequencies.

Appendix D

Additional experimental data

D.1 Overview

This appendix contains the raw data obtained over the course of the research. The experimental data in this appendix has been gathered from following drums:

- Arbiter Flats 25-cm tom, Evans Hydraulic batter head.
- Arbiter Flats 30-cm tom, Evans Hydraulic batter head.
- Arbiter Flats 35-cm tom, Evans Hydraulic batter head.
- Arbiter Flats 30-cm snare, Remo Weatherking Coated Ambassador batter head Remo Weatherking Ambassador snare head.
- Gretsch Catalina Club Jazz 30-cm tom, Evans EC2 batter head and Aquarian Classic Clear resonant head.
- Gretsch Catalina Club Jazz 30-cm tom, Aquarian Modern Vintage batter head and Aquarian Classic Clear resonant head.

Although there are no scientific units of measurement on the scale of the device the Tama Tension Watch was used to measure the tension of a drumhead are referred to as Tama units (TU).

The data has been analysed using a 5000-sample window and the reported data is provided to supplement and support the data provided in the thesis. Where f_1 frequencies around the perimeter of the drumhead are compared three repeat readings are taken and noted.

D.2 Arbiter Flats drums

D.2.1 Raw data

Three Arbiter Flats drums were tuned to produce f_0 frequencies corresponding to a musical note. Arbiter Flats drums are single-headed drums with no shell and one tuning lug, as shown in Figure D.1. The data experimental data evaluates the mechanics of the arbiter flats drums. Specifically, as a drum with only one tuning point, the Arbiter Flats marketing claim is to be easier to tune, this claim is evaluated presently.

Experimental data was obtained as discussed in Chapter 5, and is displayed in Table D.1 to Table D.4. Repeat readings were taken three times at each location, with the microphone positioned so that it is angled towards the strike location as shown in Figure 5.1. Although only one tuning rod is available (and used as the location for reading 1) other hit locations were chosen around the perimeter at even distances to obtain the same number of readings as performed on a 5-lug, 30-cm tom drum. The Tama Tension Watch is used to gauge tension around the drumhead at each location.

The Arbiter Flats snare drum is the only drum in the Arbiter Flats kit that has a drum shell with drumheads on either side, as shown in Figure D.2. The snare drum continues to use the Arbiter Flats single-lug tuning system. Data for three tunings are shown in Table D.5 through to Table D.10

Figure D.1: 35-cm Arbiter Flats drum.

Figure D.2: Arbiter Flats snare drum.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	271.3	284.4	282.7	270.8	270.3	283.0	283.1	283.0	270.3	270.5
Tension (TU) Reading 1	63	65	65	55	53	64	60	65	67	65
Frequency (Hz) Reading 2	271.4	284.5	282.7	270.8	270.3	283.3	283.1	283.1	270.3	270.3
Tension (TU) Reading 2	63	65	65	55	53	64	60	65	67	65
Frequency (Hz) Reading 3	271.4	284.1	282.7	270.4	270.3	283.4	283.4	283.0	270.4	270.1
Tension (TU) Reading 3	63	65	65	55	53	64	60	65	67	65

Table D.1: f_1 frequencies and tensions around a 25-cm drumhead tuned so that f_0 is equal to 164.8 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	211.7	211.4	224.6	224.3	211.3	211.6	224.6	224.7	223.9	211.4
Tension (TU) Reading 1	61	65	66	61	55	52	54	61	61	64
Frequency (Hz) Reading 2	211.7	212.1	224.1	224.5	211.9	211.6	224.9	224.2	224.2	211.5
Tension (TU) Reading 2	61	65	66	61	55	52	54	61	61	64
Frequency (Hz) Reading 3	211.5	211.6	224.9	224.3	211.4	211.7	225.1	224.8	223.7	211.1
Tension (TU) Reading 3	61	65	66	61	55	52	54	61	61	64

Table D.2: f_1 frequencies and tensions around a 30-cm drumhead tuned so that f_0 is equal to 130.8 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	173.4	173.9	193.6	193.3	173.9	174.5	193.0	192.5	194.1	173.7
Tension (TU) Reading 1	51	64	65	60	54	54	56	65	68	63
Frequency (Hz) Reading 2	174.1	173.9	193.8	193.3	174.0	174.0	193.2	192.7	193.5	173.5
Tension (TU) Reading 2	51	64	65	60	54	54	56	65	68	63
Frequency (Hz) Reading 3	173.9	173.4	193.9	193.8	173.7	174.5	193.3	192.8	193.6	173.7
Tension (TU) Reading 3	51	65	66	60	54	54	56	65	68	63

Table D.3: f_1 frequencies and tensions around a 35-cm drumhead tuned so that f_0 is equal to 110 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	107.8	109.2	109.6	109.7	108.2	108.1	108.7	109.9	109.0	108.2
Tension (TU) Reading 1	41	45	40	35	35	34	32	38	42	42
Frequency (Hz) Reading 2	106.8	109.3	109.5	109.7	108.8	107.8	108.4	108.8	109.0	108.8
Tension (TU) Reading 2	40	45	40	35	36	34	32	38	42	42
Frequency (Hz) Reading 3	107.2	108.9	109.7	109.3	108.4	107.5	108.8	109.2	108.7	108.3
Tension (TU) Reading 3	41	45	40	35	36	34	32	38	42	42

Table D.4: f_1 frequencies and tensions around a 35-cm drumhead tuned so that f_0 is equal to 65.4 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	253.4	253.0	253.1	247.4	247.4	252.9	252.8	247.9	247.0	246.5
Tension (TU) Reading 1	73	73	69	66	60	60	61	63	66	69
Frequency (Hz) Reading 2	253.4	253.0	253.0	247.5	247.3	253.0	252.8	247.4	247.0	246.5
Tension (TU) Reading 2	73	73	69	66	60	60	61	63	66	69
Frequency (Hz) Reading 3	253.3	253.0	253.1	247.5	247.4	253.1	252.8	248.1	247.0	246.5
Tension (TU) Reading 3	73	73	68	66	60	61	62	63	66	69

Table D.5: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 196 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	392.1	392.1	392.6	392.7	392.9	393.2	393.2	393.4	392.9	392.1
Tension (TU) Reading 1	65	62	63	58	60	56	53	56	58	63
Frequency (Hz) Reading 2	392.1	392.5	392.7	392.9	393.0	393.2	393.5	393.7	392.9	392.4
Tension (TU) Reading 2	65	62	63	58	60	56	53	56	58	63
Frequency (Hz) Reading 3	392.2	392.3	392.6	393.1	392.8	393.3	393.6	393.7	393.0	392.5
Tension (TU) Reading 3	65	62	63	58	60	56	53	56	58	63

Table D.6: f_1 frequencies and tensions around the resonant head tuned so that f_0 is equal to 196 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	237.8	238.7	239.0	238.3	236.9	237.5	238.9	238.5	236.9	236.6
Tension (TU) Reading 1	69	70	67	64	59	58	60	61	64	67
Frequency (Hz) Reading 2	237.8	238.6	238.9	238.1	236.9	237.5	238.8	238.5	237.0	236.5
Tension (TU) Reading 2	68	70	67	64	59	59	60	61	64	68
Frequency (Hz) Reading 3	237.8	238.6	238.9	238.2	236.8	237.5	238.9	238.5	237.0	236.4
Tension (TU) Reading 3	69	70	67	64	59	58	60	61	64	68

Table D.7: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 185 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	366.2	366.1	365.1	364.9	365.5	365.6	364.7	364.3	365.2	365.9
Tension (TU) Reading 1	60	59	58	53	55	52	51	50	54	60
Frequency (Hz) Reading 2	366.4	365.9	364.9	364.9	365.4	365.7	364.9	364.6	365.4	365.9
Tension (TU) Reading 2	60	59	58	52	55	52	51	50	54	60
Frequency (Hz) Reading 3	366.2	366.0	365.1	365.0	365.6	365.7	364.7	364.4	365.4	365.9
Tension (TU) Reading 3	60	59	58	53	55	52	51	50	54	60

Table D.8: f_1 frequencies and tensions around the resonant head tuned so that f_0 is equal to 185 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	222.6	225.8	226.6	226.7	222.3	222.8	227.1	227.1	222.9	222.7
Tension (TU) Reading 1	65	67	66	64	57	58	59	60	64	66
Frequency (Hz) Reading 2	222.3	225.8	226.7	226.5	222.4	222.7	226.9	227.2	223.1	222.7
Tension (TU) Reading 2	65	67	66	64	57	59	59	60	65	66
Frequency (Hz) Reading 3	222.4	226.0	226.7	226.5	222.4	222.6	226.9	227.1	223.2	222.8
Tension (TU) Reading 3	65	67	66	64	58	59	59	60	64	66

Table D.9: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 164.8 Hz.

D.2.2 Discussion

The three tunings shown for the Arbiter snare drum: Table D.5 and Table D.6; Table D.7 and Table D.8; Table D.9 and Table D.10 each show decoupling of the (11) modes present in the batter and resonant heads. Here it is important to note that the clear snare head of the drum is thinner than the coated batter head of the arbiter flats snare drum, producing a higher f_1 frequency.

It can be seen that each Arbiter Flats drum can be tuned to produce a musical frequency at f_0 as shown in Table D.11. In each case frequency splitting can be seen, for example in Table D.3 where there are two distinct f_1 frequencies present, one at around 174 Hz and another at around 194 Hz, indicating the drum is not in tune. Figure D.3 shows two clear, distinct f_1 frequencies one at 174.0 Hz (red) and the other at 193.6 Hz (blue). It was also possible to excite both of these frequencies simultaneously when struck near the edge as shown in Figure D.4. The single tension rod system can be used to easily tune a drum to a specific f_0, however it does not offer the level of control to simultaneously clear the drumhead.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	301.2	292.4	293.8	292.7	301.1	301.3	293.2	294.3	292.0	300.2
Tension (TU) Reading 1	37	34	31	38	46	45	45	42	37	42
Frequency (Hz) Reading 2	301.3	292.6	293.6	292.3	300.4	301.2	293.2	294.1	292.6	300.0
Tension (TU) Reading 2	37	34	31	38	46	46	45	42	37	42
Frequency (Hz) Reading 3	300.7	292.9	293.8	292.5	300.5	301.5	293.3	294.1	293.0	300.5
Tension (TU) Reading 3	37	34	31	38	46	45	45	42	37	42

Table D.10: f_1 frequencies and tensions around the resonant head tuned so that f_0 is equal to 164.8 Hz.

Drum	f_0 (Hz)	f_0 (note)
25 cm Tom	164.8	E3
30 cm Tom	130.8	C3
35 cm Tom 1	110	A2
35 cm Tom 2	65.4	C2
Snare Drum 1	196	G3
Snare Drum 2	185	F#3
Snare Drum 3	164.8	E3

Table D.11: f_0 for four Arbiter Flats drums, including two tunings for a 35-cm tom and three for the snare drum.

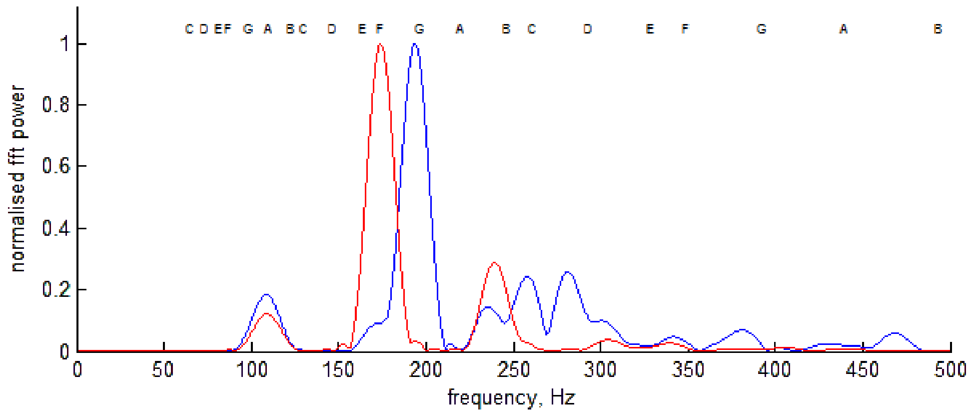

Figure D.3: Frequency splitting of f_1 for a 35-cm tom at 174.0 Hz (red) and 193.6 Hz (blue).

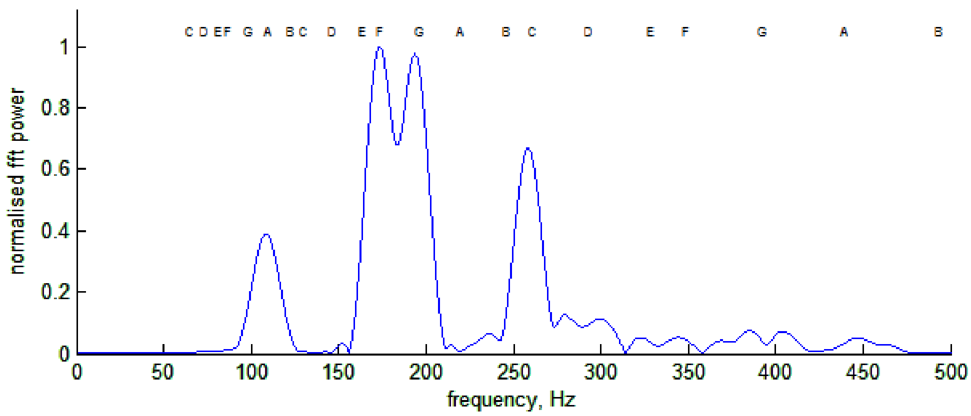

Figure D.4: Frequency splitting of f_1 for a 35-cm tom with both f_1 peaks excited.

D.3 30-cm tom drum (single head) experimental data

D.3.1 Raw data

Experimental data was obtained as discussed in Chapter 5. Tables D.12, D.13 and D.14 show the frequencies and tensions present in a 30-cm tom drum tuned to a uniform tension using the Tama Tension Watch. Tables D.15, D.16 and D.17 show the frequencies and tensions present in a 30-cm tom drum tuned to a uniform frequency using signal analysis techniques. Tables D.18 and D.19 show the effect of detuning a single tension rod on a 30-cm tom drum with a single head. The data in Table D.18 shows the effect of loosening the tension rod of the tom in quarter turn (90-degree) increments, whilst Table D.19 shows the effect of tightening the tension rod in quarter turn increments. Tables D.20 and D.21 show the change in fundamental frequencies f_0 as the drum is detuned.

D.3.2 Discussion

Data for a 30-cm tom drum with only a single head in place indicates that the uniform response is required for tuning a single drumhead in the same way that it is required for tuning a cylindrical drum with both heads in place.

Table D.16 shows that a single drumhead on a 30-cm tom can be tuned to a uniform response, in this case 196 $\pm$0.4 Hz. The effect of detuning the drumhead by increasing the tension of one tuning rod (tuning rod 3) can be seen in Table D.19 which shows frequency splitting occurring at opposite lugs, as illustrated by Figure D.5 and Figure D.6.

Frequency ratios for a 30-cm tom drum with a single head are seen to remain fairly static, with the ratios for f_1/f_0 being 1.87, 1.89 and 1.89 in Tables D.15, D.16 and D.17 respectively.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
f_0 Frequency (Hz) Reading 1	86.5	86.4	86.6	86.7	86.6	86.7	86.6	86.7	86.7	86.7
f_1 Frequency (Hz) Reading 1	162.4	163.3	162.8	160.7	160.7	161.3	163.7	163.7	160.8	160.2
Tension (TU) Reading 1	48	53	48	51	48	53	48	50	48	50
f_0 Frequency (Hz) Reading 2	86.5	86.5	86.6	86.6	86.6	86.7	86.6	86.7	86.6	86.7
f_1 Frequency (Hz) Reading 2	162.3	163.4	162.7	160.7	160.7	161.6	163.4	163.6	160.6	160.3
Tension (TU) Reading 2	48	53	48	51	48	54	48	50	48	50
f_0 Frequency (Hz) Reading 3	86.6	86.5	86.6	86.6	86.6	86.6	86.6	86.7	86.7	86.7
f_1 Frequency (Hz) Reading 3	162.4	163.5	162.6	160.6	160.7	161.3	163.9	163.6	160.8	160.2
Tension (TU) Reading 3	48	54	48	54	48	54	48	51	47	50

Table D.12: The f_1 frequencies and tensions around a drumhead on a 30-cm tom drum with a uniform head tension set to 48.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
f_0 Frequency (Hz) Reading 1	99.1	98.9	98.9	98.8	98.8	98.7	99.0	98.8	99.0	98.8
f_1 Frequency (Hz) Reading 1	186.8	186.1	186.8	187.3	187.4	186.8	186.3	186.1	187.3	187.1
Tension (TU) Reading 1	55	59	55	59	55	60	55	58	55	57
f_0 Frequency (Hz) Reading 2	99.1	98.9	98.9	98.8	98.9	98.8	99.0	98.9	99.0	98.8
f_1 Frequency (Hz) Reading 2	186.7	186.1	186.8	187.4	187.6	187.0	186.1	186.2	187.3	187.0
Tension (TU) Reading 2	55	59	55	59	55	60	55	58	55	57
f_0 Frequency (Hz) Reading 3	99.1	98.9	98.9	98.8	98.9	98.8	99.0	98.9	99.0	98.8
f_1 Frequency (Hz) Reading 3	186.8	186.2	186.6	187.4	187.5	187.0	186.2	186.3	187.3	187.1
Tension (TU) Reading 3	55	59	55	59	55	60	55	58	55	57

Table D.13: The f_1 frequencies and tensions around a drumhead on a 30-cm tom drum with a uniform head tension set to 55.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
f_0 Frequency (Hz) Reading 1	120.3	120.5	120.5	120.7	120.7	120.6	120.9	120.8	121.0	120.5
f_1 Frequency (Hz) Reading 1	230.7	231.3	230.9	229.4	229.3	230.7	231.4	230.4	229.5	229.6
Tension (TU) Reading 1	65	68	65	67	65	68	65	68	65	67
f_0 Frequency (Hz) Reading 2	120.4	120.4	120.5	120.6	120.7	120.5	120.7	120.6	120.8	120.3
f_1 Frequency (Hz) Reading 2	230.7	231.3	231.0	229.4	229.4	230.8	231.4	230.2	229.4	229.5
Tension (TU) Reading 2	65	68	65	67	65	68	65	68	65	67
f_0 Frequency (Hz) Reading 3	120.4	120.4	120.5	120.6	121.0	120.7	120.6	120.5	120.6	120.5
f_1 Frequency (Hz) Reading 3	230.7	231.3	231.1	229.5	229.2	230.8	231.2	230.1	229.4	229.5
Tension (TU) Reading 3	65	69	65	67	65	68	65	68	65	67

Table D.14: The f_1 frequencies and tensions around a drumhead on a 30-cm tom drum with a uniform head tension set to 65.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
f_0 Frequency (Hz) Reading 1	88.2	88.2	88.2	88.1	88.2	88.2	88.2	88.2	88.2	88.2
f_1 Frequency (Hz) Reading 1	164.9	164.8	164.9	164.9	164.9	165.0	164.9	165.0	164.8	165.1
Tension (TU) Reading 1	49	55	48	52	48	53	46	51	50	53
f_0 Frequency (Hz) Reading 2	88.2	88.2	88.2	88.1	88.2	88.2	88.2	88.2	88.2	88.2
f_1 Frequency (Hz) Reading 2	164.9	164.8	165.0	165.1	165.0	165.0	165.0	165.2	165.0	164.9
Tension (TU) Reading 2	49	55	49	52	48	53	46	52	50	53
f_0 Frequency (Hz) Reading 3	88.2	88.2	88.2	88.2	88.2	88.2	88.2	88.2	88.2	88.2
f_1 Frequency (Hz) Reading 3	164.8	164.8	165.1	165.3	164.9	164.8	165.1	165.3	164.9	164.9
Tension (TU) Reading 3	48	55	49	52	48	53	46	52	50	52

Table D.15: The f_1 frequencies and tensions around a drumhead on a 30-cm tom drum with a uniform f_1 frequency of 164.8 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
f_0 Frequency (Hz) Reading 1	103.6	103.5	103.5	103.5	103.6	103.5	103.6	103.6	103.6	103.7
f_1 Frequency (Hz) Reading 1	196.4	196.3	196.3	196.0	196.2	196.2	196.2	196.0	196.2	196.2
Tension (TU) Reading 1	58	63	59	62	57	60	54	59	58	60
f_0 Frequency (Hz) Reading 2	103.6	103.5	103.5	103.5	103.7	103.5	103.6	103.6	103.6	103.7
f_1 Frequency (Hz) Reading 2	196.4	196.3	196.3	196.1	196.3	196.2	196.2	196.0	196.2	196.2
Tension (TU) Reading 2	58	63	59	62	57	60	54	59	58	60
f_0 Frequency (Hz) Reading 3	103.7	103.5	103.5	103.5	103.6	103.5	103.6	103.6	103.6	103.7
f_1 Frequency (Hz) Reading 3	196.4	196.4	196.3	196.0	196.3	196.3	196.2	196.0	196.2	196.2
Tension (TU) Reading 3	58	63	59	62	57	60	55	59	58	61

Table D.16: The f_1 frequencies and tensions around a drumhead on a 30-cm tom drum with a uniform head tension set to 196 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
f_0 Frequency (Hz) Reading 1	116.4	116.4	116.4	116.2	116.7	116.2	116.3	116.4	116.2	116.2
f_1 Frequency (Hz) Reading 1	220.2	220.0	220.0	219.8	219.9	219.5	220.1	219.5	219.6	219.5
Tension (TU) Reading 1	60	65	60	65	65	69	64	67	65	65
f_0 Frequency (Hz) Reading 2	116.2	116.3	116.3	116.2	116.3	116.3	116.2	116.5	116.3	116.4
f_1 Frequency (Hz) Reading 2	220.2	220.2	220.0	219.8	219.6	219.4	220.1	219.7	219.7	219.4
Tension (TU) Reading 2	60	65	60	65	65	69	64	67	65	65
f_0 Frequency (Hz) Reading 3	116.4	116.4	116.3	116.3	116.3	116.3	116.2	116.4	116.3	116.4
f_1 Frequency (Hz) Reading 3	220.1	219.9	220.0	219.8	219.6	219.4	220.0	219.7	219.7	219.3
Tension (TU) Reading 3	61	65	60	65	65	69	64	67	65	65

Table D.17: The f_1 frequencies and tensions around a drumhead on a 30-cm tom drum with a uniform head tension set to 220 Hz.

Tuning	Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Initial	Frequency (Hz)	220.2	220.2	220.2	220.2	220.3	220.2	220.3	220.2	220.3	220.3
Setting	Tension (TU)	61	66	62	65	62	66	62	66	63	65
0.25 turns	Frequency (Hz)	208.5	208.3	208.6	213.7	213.5	212.2	208.2	208.2	213.7	213.6
down	Tension (TU)	60	66	61	65	60	64	57	62	62	64
0.5 turns	Frequency (Hz)	193.8	195.5	194.6	206.8	205.7	208.2	195.8	193.8	206.0	206.3
down	Tension (TU)	59	65	61	64	60	59	49	58	61	64
0.75 turns	Frequency (Hz)	182.2	181.6	181.9	195.2	196.0	195.2	181.4	182.9	196.0	196.0
down	Tension (TU)	59	65	60	63	57	55	42	53	59	63
1 turn	Frequency (Hz)	169.2	169.9	170.1	188.2	188.1	187.5	168.6	169.6	187.7	187.6
down	Tension (TU)	58	65	60	62	57	50	34	46	58	62
1.25 turns	Frequency (Hz)	152.4	152.1	153.1	175.7	175.6	175.0	153.1	174.6	174.7	175.0
down	Tension (TU)	58	64	59	62	55	43	25	42	55	61
1.5 turns	Frequency (Hz)	138.0	137.7	138.5	161.6	161.3	161.2	139.9	160.7	161.0	159.1
down	Tension (TU)	57	63	59	62	53	37	15	36	52	61

Table D.18: f_1 frequencies and tensions around the batter head when tension rod 4 is detuned.

Tuning	Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Initial	Frequency (Hz)	196.0	196.0	196.0	195.9	195.9	196.0	196.0	196.0	196.0	195.9
Setting	Tension (TU)	55	61	57	61	58	63	57	61	56	58
0.25 turns	Frequency (Hz)	203.2	200.5	200.7	203.5	203.6	203.1	200.1	200.0	202.5	203.6
up	Tension (TU)	55	62	58	64	64	66	58	61	56	58
0.5 turns	Frequency (Hz)	212.1	204.4	204.0	211.5	211.0	212.3	203.1	204.1	212.8	211.2
up	Tension (TU)	56	63	60	67	68	68	60	61	57	58
0.75 turns	Frequency (Hz)	222.3	210.0	209.9	221.1	219.5	220.3	207.8	210.5	222.6	219.0
up	Tension (TU)	56	63	62	69	71	71	61	63	58	59
1 turn	Frequency (Hz)	229.3	217.2	216.3	229.1	228.5	228.9	216.2	216.9	230.3	228.4
up	Tension (TU)	56	64	62	73	74	73	63	63	59	59
1.25 turns	Frequency (Hz)	231.3	219.5	219.6	232.8	232.2	232.2	220.0	219.6	232.7	232.1
up	Tension (TU)	57	64	63	73	75	73	63	63	59	59
1.5 turns	Frequency (Hz)	234.5	222.5	223.2	236.4	236.3	236.1	223.8	222.2	235.5	236.2
up	Tension (TU)	57	65	64	74	76	75	64	64	59	59

Table D.19: f_1 frequencies and tensions around the batter head when tension rod 3 is detuned.

Tuning	Initial Setting	0.25 turns down	0.5 turns down	0.75 turns down	1 turn down	1.25 turns down	1.5 turns down
Frequency (Hz)	115.3	110.7	105.6	100.3	95.9	90.3	85.5
Tension (TU)	65	63	61	59	57	55	53

Table D.20: f_0 frequencies and tensions around the batter head when tension rod 4 is detuned.

Tuning	Initial Setting	0.25 turns up	0.5 turns up	0.75 turns up	1 turn up	1.25 turns up	1.5 turns up
Frequency (Hz)	103.2	107.3	109.9	114.0	118.1	120.5	121.5
Tension (TU)	60	62	64	65	66	67	68

Table D.21: f_0 frequencies and tensions around the batter head when tension rod 3 is detuned.

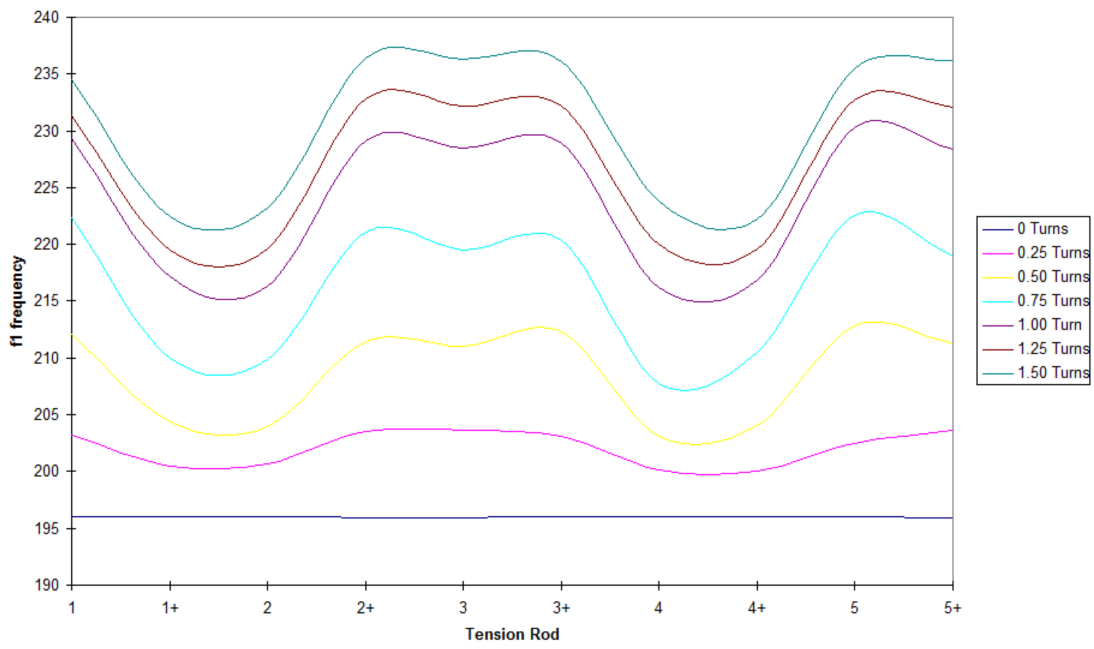

Figure D.5: How detuning a single lug affects the peak frequencies at locations around a drumhead.

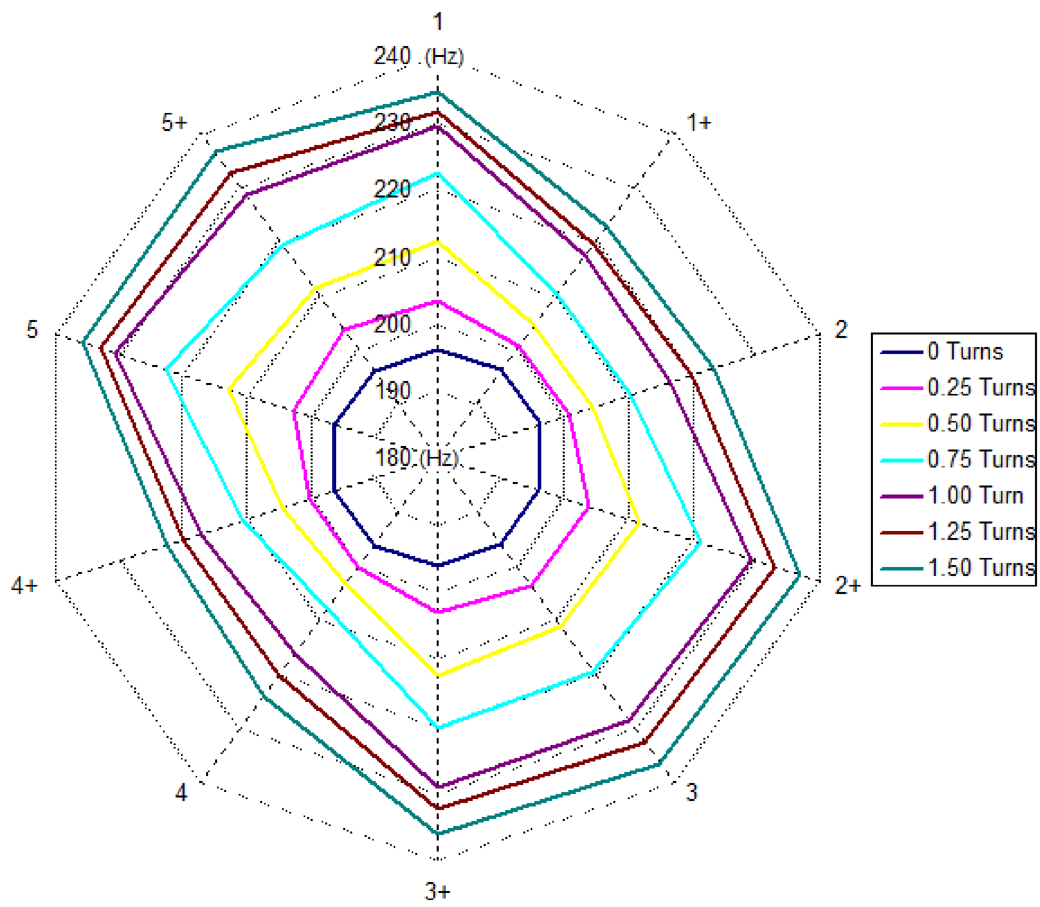

Figure D.6: f_1 remains similar for opposite locations as frequency splitting occurs while a 35-cm tom drum is detuned by altering tension rod 3.

D.4 30-cm tom drum (both heads) experimental data

D.4.1 Raw data

Tables D.22 to D.25 show the frequencies and tensions present around a 30-cm tom drum tuned to uniform tension with both heads in place. Table D.22 provides data for the resonant head, which was kept the same for three variations in tension of the batter head, the data for which can be seen in Tables D.23, D.24 and D.25.

Tables D.26 to D.28 show the frequencies and tensions present around a 30-cm tom drum tuned to uniform frequency with both heads in place. Table D.26 provides data for the resonant head, which was kept the same for two variations in tension of the batter head, the data for which can be seen in Tables D.27 and D.28.

When one tension rod is slowly altered a quarter of a turn at a time, from 0 turns to 1.5 turns, the peak frequency observed at each lug changes, as shown in Table D.29. Figure D.7 which shows the effect of having a tension rod, in this case tension rod number 3, loosened in quarter-turn increments. The drum was initially tuned to a uniform frequency response and it is noteworthy that frequency splitting occurs as the drum is detuned, and that opposite locations on the drum tend to have similar frequency responses, as shown in Figure D.8.

As one tension rod is altered the frequencies begin to split, and this splitting increases as changes in the tension of the head at a single point and the split between frequencies reaches a maximum of 20.5 Hz at 1.5 turns out of tune. Also it can be seen that although lug 3 is detuned, the maximum frequency change (64 Hz) is at position 3+. This is not surprising as position 3+ is located between lugs and is therefore further away from a fixed tuning point than position 3. Figure D.9 shows the waveform produced when a lug is altered by one turn and here it can be clearly seen that the smooth decay of the drum sound is no longer present.

Table D.31 displays the frequencies present for batter and resonant impacts around a

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	228.1	228.0	199.8	200.0	228.5	228.3	228.2	200.2	200.1	200.9
Tension (TU) Reading 1	57	63	57	45	57	63	57	62	57	62
Frequency (Hz) Reading 2	228.1	227.9	199.9	200.0	228.3	228.3	228.2	200.2	200.0	200.8
Tension (TU) Reading 2	57	63	57	45	57	63	57	62	57	62
Frequency (Hz) Reading 3	228.0	228.0	199.9	200.1	228.2	228.2	228.1	200.1	199.9	201.0
Tension (TU) Reading 3	57	63	57	45	57	63	57	62	57	62

Table D.22: f_1 frequencies and tensions around the resonant head tuned so that f_0 is equal to 123.1 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	196.8	196.7	192.9	192.9	195.9	196.8	196.4	193.0	193.2	196.0
Tension (TU) Reading 1	57	61	57	60	57	62	57	60	57	58
Frequency (Hz) Reading 2	197.1	196.6	192.8	193.0	195.8	197.0	196.4	193.0	193.2	196.4
Tension (TU) Reading 2	57	61	57	60	57	62	57	60	58	58
Frequency (Hz) Reading 3	197.2	196.7	192.9	193.0	196.0	197.0	196.5	193.0	193.1	196.2
Tension (TU) Reading 3	58	61	57	60	57	62	57	60	57	58

Table D.23: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 118.6 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	181.8	181.1	177.6	178.0	180.5	181.6	181.9	177.8	177.8	180.8
Tension (TU) Reading 1	53	58	53	57	54	58	53	55	53	53
Frequency (Hz) Reading 2	181.7	181.0	177.6	177.8	180.3	181.7	181.9	177.9	177.9	180.8
Tension (TU) Reading 2	53	58	53	57	53	58	53	56	53	54
Frequency (Hz) Reading 3	181.8	181.2	177.6	177.7	180.3	181.6	181.9	177.7	177.8	181.1
Tension (TU) Reading 3	52	58	53	57	53	58	53	55	53	54

Table D.24: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 113.3 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	222.5	223.0	223.0	222.5	222.2	222.7	223.2	222.9	222.1	222.0
Tension (TU) Reading 1	64	67	64	66	64	67	64	66	64	65
Frequency (Hz) Reading 2	222.4	223.0	223.0	222.5	222.1	222.6	223.2	223.0	222.1	222.1
Tension (TU) Reading 2	65	68	64	66	64	67	64	66	64	65
Frequency (Hz) Reading 3	222.4	223.0	223.0	222.5	222.1	222.7	223.2	222.9	222.1	222.1
Tension (TU) Reading 3	64	68	64	66	64	68	64	66	64	65

Table D.25: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 132 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	247.3	247.3	247.4	247.3	247.0	247.0	247.7	248.1	247.5	247.5
Tension (TU) Reading 1	60	66	66	62	68	68	61	66	66	65
Frequency (Hz) Reading 2	247.1	247.3	247.5	247.1	247.1	247.0	247.5	248.1	247.6	247.2
Tension (TU) Reading 2	60	66	66	62	68	68	61	66	66	65
Frequency (Hz) Reading 3	247.1	246.9	247.1	247.3	247.0	247.0	247.1	248.1	247.4	247.5
Tension (TU) Reading 3	60	66	66	62	68	68	61	65	66	65

Table D.26: f_1 frequencies and tensions around the resonant head tuned so that f_0 is equal to 140 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	220.5	220.0	219.8	220.0	220.3	220.4	220.4	219.9	220.0	220.3
Tension (TU) Reading 1	57	63	61	65	64	68	64	62	59	58
Frequency (Hz) Reading 2	220.5	220.2	219.7	220.0	220.4	220.5	220.5	219.9	220.0	220.4
Tension (TU) Reading 2	57	63	61	65	65	68	63	63	59	58
Frequency (Hz) Reading 3	220.5	220.2	219.6	220.0	220.2	220.5	220.4	220.0	219.9	220.3
Tension (TU) Reading 3	57	63	61	65	65	68	64	63	59	58

Table D.27: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 139.4 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
Frequency (Hz) Reading 1	175.5	175.5	175.5	175.0	175.0	175.6	175.8	175.0	174.7	175.2
Tension (TU) Reading 1	49	53	48	53	48	55	53	55	52	51
Frequency (Hz) Reading 2	175.6	175.4	175.5	175.2	175.2	175.2	175.9	175.2	175.1	175.3
Tension (TU) Reading 2	49	53	48	53	48	55	53	55	52	51
Frequency (Hz) Reading 3	176.0	175.5	175.3	175.2	174.9	175.8	175.8	175.1	174.6	175.3
Tension (TU) Reading 3	48	53	49	53	48	55	53	55	52	51

Table D.28: f_1 frequencies and tensions around the batter head tuned so that f_0 is equal to 125.1 Hz.

Tuning	Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+
0 Turns	Frequency (Hz)	220.1	220.0	220.1	219.9	219.8	220.0	219.9	219.8	220.1	220.0
0.25 Turns	Frequency (Hz)	214.7	216.8	216.7	215.3	214.6	214.6	215.8	216.7	215.7	214.9
0.5 Turns	Frequency (Hz)	204.6	208.7	207.8	207.8	204.6	204.5	207.2	207.3	207.1	204.8
0.75 Turns	Frequency (Hz)	189.4	200.0	200.5	202.3	189.3	187.4	198.9	201.3	203.6	190.8
1 Turn	Frequency (Hz)	183.4	191.2	189.1	190.5	182.3	182.4	192.0	191.2	191.3	183.6
1.25 Turns	Frequency (Hz)	174.1	184.5	183.1	181.2	166.9	169.8	183.2	184.2	184.7	172.5
1.5 Turns	Frequency (Hz)	163.2	176.9	176.5	173.7	159.2	155.9	173.8	176.6	174.1	161.1

Table D.29: f_1 frequencies and tensions around the batter head of a 30-cm tom where tension rod 3 is detuned.

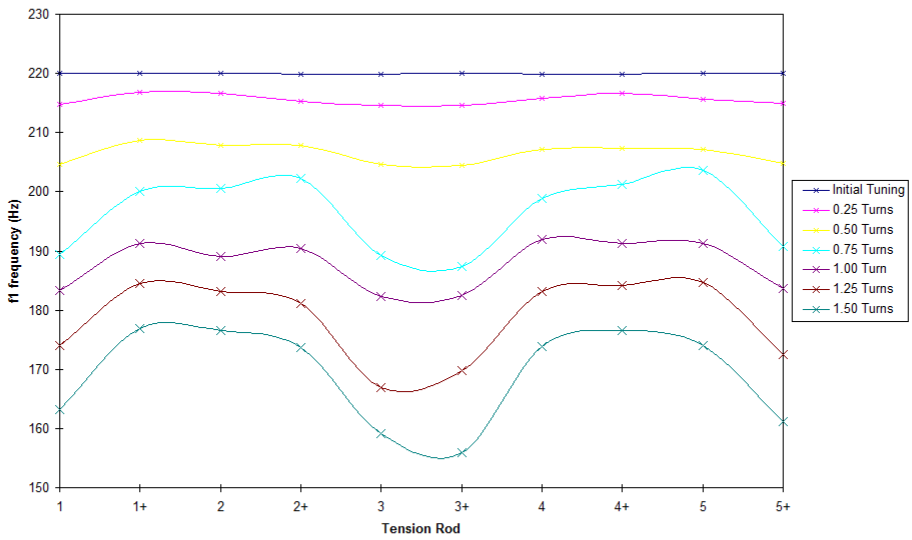

Figure D.7: How detuning a single lug affects the peak frequencies around a drumhead.

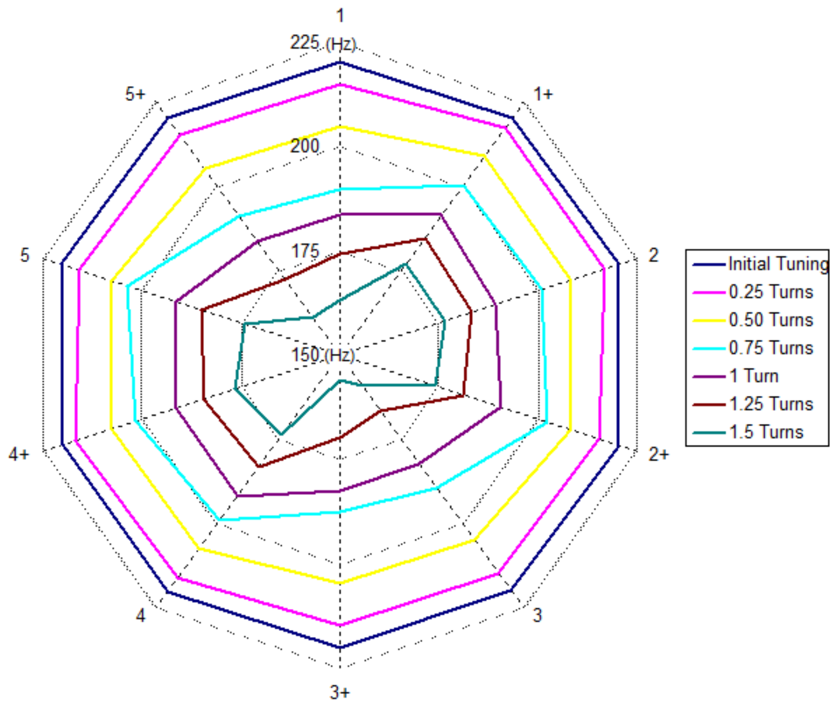

Figure D.8: f_1 similar for opposite locations as frequency splitting occurs while a 30-cm tom drum is detuned by altering tension rod 3.

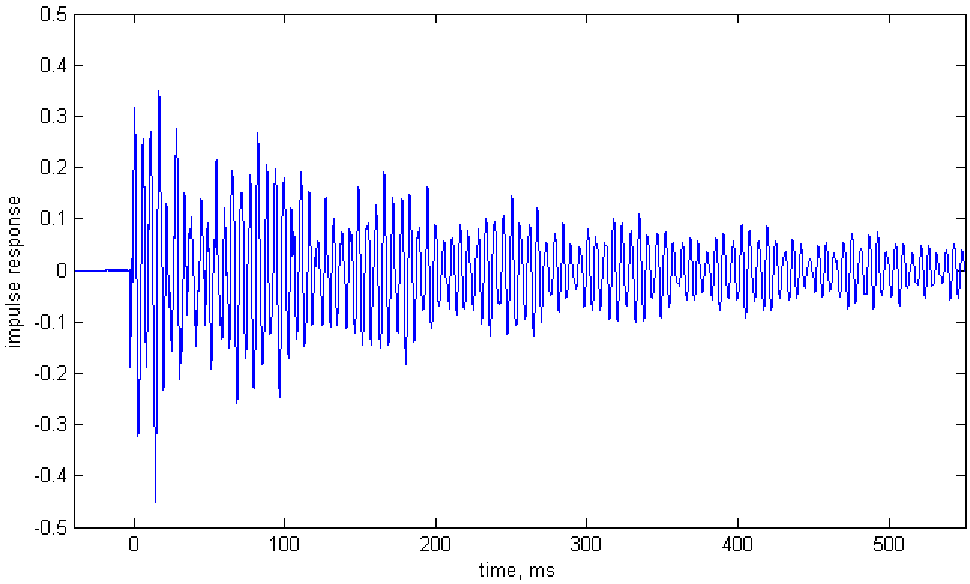

Figure D.9: Waveform showing visible beating in a drum with one lug altered by one whole turn.

Tuning	Batter Head	Resonant Head
T1	Normal	Normal
T2	High	Normal
T3	High	Low
T4	Normal	Low
T5	Low	Low
T6	Low	Normal
T7	Low	High
T8	Normal	High
T9	High	High
T10	Normal	Normal

Table D.30: Tuning permutations used in the experiment.

30-cm tom drum for tuning permutations T1-T10 as outlined in Table D.30. An additional tuning at T5 was required due to excessive slack in the batter head.

D.4.2 Discussion

The raw data in this section has been discussed and evaluated in Chapters 5 and 6 where the data was condensed into average values from the repeat readings shown here.

Tuning	Hit Location	1	1+	2	2+	3	3+	4	4+	5	5+
T1	Frequency f_{0B} (Hz)	147.4	147.1	147.2	147.2	147.4	147.3	147.4	147.2	147.1	147.1
(Batter)	Frequency f_{1B} (Hz)	219.4	219.2	219.3	219.5	219.4	219.3	219.3	219.2	219.6	219.4
T1	Frequency f_{0R} (Hz)	146.7	146.8	146.8	146.6	146.6	146.6	146.6	146.8	146.9	146.5
(Resonant)	Frequency f_{1R} (Hz)	280.2	279.8	279.2	279.6	280.5	280.4	279.8	279.5	279.8	280.1
T2	Frequency f_{0B} (Hz)	168.8	169.0	169.2	169.2	169.2	169.3	169.3	168.9	168.2	168.2
(Batter)	Frequency f_{1B} (Hz)	275.1	275.6	275.7	275.6	275.1	275.1	275.6	276.0	275.6	274.9
T2	Frequency f_{0R} (Hz)	167.4	167.9	168.0	168.0	168.1	167.8	167.6	167.8	167.8	168.0
(Resonant)	Frequency f_{1R} (Hz)	287.5	288.1	287.4	286.8	286.7	287.7	288.1	287.8	287.8	287.4
T3	Frequency f_{0B} (Hz)	151.9	152.0	152.0	152.0	152.0	152.1	152.0	152.0	152.1	152.2
(Batter)	Frequency f_{1B} (Hz)	267.0	268.2	268.8	268.2	266.9	267.2	269.0	269.0	267.7	267.1
T3	Frequency f_{0R} (Hz)	151.3	151.5	151.6	151.7	151.3	151.6	151.6	151.4	151.4	151.4
(Resonant)	Frequency f_{1R} (Hz)	232.1	232.5	232.1	232.2	231.9	232.5	232.7	232.2	232.1	232.1
T4	Frequency f_{0B} (Hz)	124.3	124.4	124.4	124.3	124.2	124.0	124.0	123.9	124.2	124.4
(Batter)	Frequency f_{1B} (Hz)	190.8	191.4	191.4	191.6	191.4	191.6	191.9	192.0	191.8	191.5
T4	Frequency f_{0R} (Hz)	122.6	122.5	122.5	124.0	123.9	123.9	123.9	124.0	123.8	123.6
(Resonant)	Frequency f_{1R} (Hz)	223.9	224.1	224.0	224.2	224.3	224.3	224.0	224.3	223.2	223.2
T5	Frequency f_{0B} (Hz)	98.5	98.8	98.8	98.8	99.1	98.8	98.8	98.9	99.4	99.0
(Batter)	Frequency f_{1B} (Hz)	133.7	134.3	134.2	134.1	134.0	133.9	134.0	133.9	134.3	134.2
T5	Frequency f_{0R} (Hz)	98.0	99.2	99.2	99.3	99.1	98.9	98.4	97.9	97.9	97.7
(Resonant)	Frequency f_{1R} (Hz)	208.9	204.1	203.7	209.8	209.4	203.1	203.6	204.5	209.4	209.8
T5B	Frequency f_{0B} (Hz)	99.9	99.8	99.8	99.9	100.0	100.0	99.9	100.0	100.0	100.0
(Batter)	Frequency f_{1B} (Hz)	139.7	139.9	139.5	139.6	139.3	139.8	139.5	140.1	139.8	140.1
T5B	Frequency f_{0R} (Hz)	99.8	99.8	99.6	99.7	100.1	99.8	99.8	99.6	99.7	99.6
(Resonant)	Frequency f_{1R} (Hz)	206.3	206.2	206.6	206.8	206.8	206.4	206.5	206.6	206.6	206.5
T6	Frequency f_{0B} (Hz)	120.5	121.3	120.9	120.5	120.2	120.2	120.4	120.5	120.2	120.1
(Batter)	Frequency f_{1B} (Hz)	164.9	165.0	165.0	165.9	165.7	165.7	165.1	165.4	165.5	165.8
T6	Frequency f_{0R} (Hz)	120.4	120.1	121.0	120.5	120.8	121.5	121.5	121.6	121.7	121.6
(Resonant)	Frequency f_{1R} (Hz)	256.4	256.5	257.3	257.4	256.8	256.3	256.6	257.1	256.9	256.5
T7	Frequency f_{0B} (Hz)	137.1	137.2	137.2	137.4	137.4	137.4	137.3	137.5	137.7	137.5
(Batter)	Frequency f_{1B} (Hz)	181.2	181.2	180.3	180.6	180.7	181.3	181.3	181.1	181.0	180.6
T7	Frequency f_{0R} (Hz)	136.7	136.7	136.6	136.6	136.7	136.7	136.4	136.5	136.4	136.8
(Resonant)	Frequency f_{1R} (Hz)	301.6	302.1	302.7	303.0	302.4	301.7	302.0	302.7	302.6	302.0
T8	Frequency f_{0B} (Hz)	167.6	167.6	167.6	167.3	167.3	167.5	167.5	167.3	167.4	167.5
(Batter)	Frequency f_{1B} (Hz)	259.9	260.2	260.0	259.6	259.6	260.2	260.3	260.0	259.6	259.6
T8	Frequency f_{0R} (Hz)	166.5	166.5	166.5	166.5	166.5	166.5	166.4	166.5	166.2	166.4
(Resonant)	Frequency f_{1R} (Hz)	304.2	305.6	306.3	306.0	304.7	304.5	305.8	306.3	305.4	304.2
T9	Frequency f_{0B} (Hz)	189.8	190.0	190.0	189.9	189.8	189.7	189.6	189.7	189.7	189.7
(Batter)	Frequency f_{1B} (Hz)	311.6	311.4	310.5	310.0	310.6	311.2	311.2	310.2	309.9	310.5
T9	Frequency f_{0R} (Hz)	190.9	191.1	191.0	190.9	191.1	191.0	191.1	191.1	191.0	190.8
(Resonant)	Frequency f_{1R} (Hz)	326.8	328.2	328.0	326.7	326.1	326.8	328.3	328.1	326.4	326.2
T10	Frequency f_{0B} (Hz)	145.6	145.6	145.6	145.6	145.4	145.4	145.5	145.4	145.5	145.5
(Batter)	Frequency f_{1B} (Hz)	218.0	218.6	218.4	218.2	217.8	217.9	218.4	218.5	218.7	218.2
T10	Frequency f_{0R} (Hz)	146.4	146.5	146.5	145.6	146.4	146.4	146.4	146.4	146.4	146.4
(Resonant)	Frequency f_{1R} (Hz)	279.7	280.9	280.4	279.2	278.8	280.0	281.1	280.5	279.1	278.9

Table D.31: Frequencies for batter and resonant impacts around a 30-cm tom drum over a variety of tunings.

D.5 35-cm tom drum (both heads) experimental data

D.5.1 Raw data

Tables D.32 and D.33 show the frequencies and tensions around a 35-cm tom drum tuned to uniform frequency with both heads in place. The drum was tuned high, and a fundamental frequency of 136.4 Hz (f_{0B}) was observed.

The data in Table D.34 shows the effect of loosening the tension rod of the tom in quarter turn (90-degree) increments. Table D.35 display the frequencies present for the resonant head around the perimeter of a 35-cm tom drum prior to detuning the drum. Table D.36 shows the change in fundamental frequencies f_0 in the drum as it is detuned. The tom drum was purposefully tuned high to allow the full range to be explored as it was detuned.

Table D.37 displays the frequencies present for batter and resonant impacts around a 35-cm tom drum for tuning permutations T1-T9 outlined in Table D.30.

D.5.2 Discussion

Data for the 35-cm tom drum corroborates the data and conclusions drawn from experiments performed on a 30-cm tom drum.

Table D.33 shows that a 35-cm tom drum can be tuned to a uniform response, in this case 220 $\pm$0.5 Hz. The effect of detuning the drum can be seen in Table D.34 which shows frequency splitting occurring at opposite lugs, as illustrated by Figure D.10 and Figure D.11. This closely corresponds with results shown in Chapter 5.

Frequency ratios for a 35-cm tom drum can be altered as shown in Table D.38. The drum was also initially tuned to a frequency ratio of close to 1:1.5:2 as discussed in Chapter 6.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+	6	6+
Frequency (Hz) Reading 1	263.4	263.2	263.3	262.9	262.9	262.8	263.0	263.4	262.8	263.0	262.8	262.9
Tension (TU) Reading 1	74	75	74	75	75	74	75	75	73	72	75	72
Frequency (Hz) Reading 2	263.2	263.3	263.1	262.9	262.8	262.9	263.1	263.4	262.9	263.1	262.9	263.3
Tension (TU) Reading 2	75	76	74	75	75	74	75	75	73	72	75	72
Frequency (Hz) Reading 3	263.2	263.4	269.2	263.1	262.9	262.8	263.2	263.2	262.9	262.9	262.9	263.4
Tension (TU) Reading 3	75	76	74	75	75	74	75	74	73	72	75	72

Table D.32: f_1 frequencies and tensions around the resonant head tuned to a uniform response where f_{0R} is equal to 137.1 Hz.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+	6	6+
Frequency (Hz) Reading 1	220.0	220.3	220.2	220.5	219.8	220.0	220.1	220.3	220.3	220.4	220.0	220.0
Tension (TU) Reading 1	68	66	69	70	67	69	71	67	67	65	67	66
Frequency (Hz) Reading 2	219.9	220.4	220.2	220.3	219.8	220.1	220.2	220.4	220.3	220.2	220.1	220.0
Tension (TU) Reading 2	68	66	69	70	67	69	71	67	67	65	67	65
Frequency (Hz) Reading 3	219.8	220.2	220.3	220.5	219.8	219.8	220.2	220.3	220.4	220.4	220.1	219.9
Tension (TU) Reading 3	68	66	68	70	67	69	71	67	67	65	67	65

Table D.33: f_1 frequencies and tensions around the batter head tuned to a uniform response where f_{0B} is equal to 136.4 Hz.

Tuning	Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+	6	6+
Initial Setting	f_1 (Hz)	220.1	219.9	219.8	220.0	220.0	219.8	219.9	220.0	219.9	220.0	219.9	219.7
	Tension (TU)	68	66	69	70	67	69	71	67	67	65	67	65
0.25 turns down	f_1 (Hz)	216.8	215.9	215.7	212.8	212.1	211.7	212.5	216.3	215.5	213.9	212.2	213.1
	Tension (TU)	67	66	67	67	65	66	70	66	65	66	67	66
0.5 turns down	f_1 (Hz)	211.2	210.1	209.4	206.9	202.3	203.2	211.0	210.3	211.2	211.5	208.6	211.0
	Tension (TU)	66	65	66	65	58	64	69	65	65	64	66	66
0.75 turns down	f_1 (Hz)	190.4	206.7	204.7	205.6	190.2	190.0	208.9	208.3	206.8	207.0	189.9	190.3
	Tension (TU)	66	65	65	62	50	60	67	64	65	64	65	65
1 turn down	f_1 (Hz)	180.0	201.1	198.5	179.1	177.6	177.4	199.0	202.0	198.3	179.9	181.4	181.3
	Tension (TU)	66	64	62	57	41	55	65	63	65	63	65	64
1.25 turns down	f_1 (Hz)	161.8	189.5	189.4	163.3	164.0	163.5	189.0	189.6	189.4	162.4	162.2	162.9
	Tension (TU)	65	62	60	46	21	45	62	62	63	62	65	62
1.5 turns down	f_1 (Hz)	145	170.7	169.2	144.8	144.9	144.3	172.2	169.1	168.9	145.7	145.5	145.3
	Tension (TU)	65	62	60	40	8	35	61	62	63	62	64	62

Table D.34: f_1 frequencies and tensions around the batter head when tension rod 3 is detuned.

Tension Rod	1	1+	2	2+	3	3+	4	4+	5	5+	6	6+
Frequency (Hz) Reading 1	263.3	263.4	263.3	262.9	262.9	262.9	263.0	263.4	262.8	263.0	262.9	262.9
Tension (TU) Reading 1	74	75	74	75	75	74	75	75	73	72	75	72
Frequency (Hz) Reading 2	263.2	263.3	263.2	262.8	262.8	262.9	263.1	263.4	262.9	263.1	262.9	263.2
Tension (TU) Reading 2	74	76	74	75	74	74	75	75	73	72	75	72
Frequency (Hz) Reading 3	263.3	263.4	269.2	263.2	262.9	262.8	263.2	263.3	262.9	263.0	262.9	163.0
Tension (TU) Reading 3	75	76	74	75	75	74	75	74	73	72	75	72

Table D.35: f_1 frequencies and tensions around the resonant head tuned so that f_0 is equal to 137.1 Hz.

Tuning	Initial Setting	0.25 turns down	0.5 turns down	0.75 turns down	1 turn down	1.25 turns down	1.5 turns down
Frequency (Hz)	136.3	135.3	132.7	129.4	124.1	120.2	117.4
Tension (TU)	68	66	64	63	62	60	58

Table D.36: f_0 frequencies and tensions around the batter head where tension rod 3 is detuned.

Tuning	Hit Location	1	1+	2	2+	3	3+	4	4+	5	5+	6	6+
T1 (Batter)	f_{0B} (Hz)	76.5	76.7	76.4	76.5	76.3	76.5	76.5	76.5	76.7	76.7	76.8	76.8
	f_{1B} (Hz)	116.2	116.9	116.2	116.2	115.4	116.2	116.2	116.2	117.1	116.7	116.7	117.3
T1 (Resonant)	f_{0R} (Hz)	76.0	76.1	75.9	76.0	76.1	76.1	76.1	76.6	76.5	76.3	76.3	76.6
	f_{1R} (Hz)	156.2	156.5	156.3	156.5	156.0	154.8	154.7	155.9	156.3	157.0	156.9	156.6
T2 (Batter)	f_{0B} (Hz)	106.2	106.1	105.9	105.8	105.7	105.7	105.7	105.7	105.7	105.8	105.8	105.7
	f_{1B} (Hz)	213.0	211.4	210.5	210.5	210.6	211.8	211.7	211.0	209.9	209.9	210.9	211.2
T2 (Resonant)	f_{0R} (Hz)	105.5	105.6	105.6	105.5	105.6	105.6	105.5	105.6	105.5	105.5	105.3	105.5
	f_{1R} (Hz)	162.6	163.8	163.4	163.2	163.7	163.1	163.0	163.5	163.3	162.8	162.6	163.0
T3 (Batter)	f_{0B} (Hz)	87.2	87.2	87.1	87.2	87.0	86.8	86.9	87.0	86.9	87.0	87.0	87.0
	f_{1B} (Hz)	202.5	201.4	201.1	201.4	202.4	202.7	202.3	201.5	201.0	201.5	202.5	203.0
T3 (Resonant)	f_{0R} (Hz)	86.8	86.9	86.9	86.9	86.8	86.8	86.9	87.0	86.7	86.7	86.7	86.8
	f_{1R} (Hz)	105.1	106.4	106.3	106.4	104.5	104.7	104.8	106.5	106.4	104.9	105.4	105.1
T4 (Batter)	f_{0B} (Hz)	59.1	59.8	60.4	60.1	59.6	59.4	59.6	60.1	60.6	60.5	59.6	59.6
	f_{1B} (Hz)	110.4	110.3	108.2	107.5	109.8	110.6	111.4	109.7	108.8	109.2	110.6	111.1
T4 (Resonant)	f_{0R} (Hz)	59.6	59.6	59.6	59.6	60.0	59.7	59.6	59.3	59.8	59.9	60.0	59.8
	f_{1R} (Hz)	98.7	100.8	101.7	101.4	100.1	99.3	99.6	100.8	101.7	100.7	100.4	99.8
T5 (Batter)	f_{0B} (Hz)	45.5	45.8	45.5	46.2	46.2	47.1	46.3	46.9	46.4	46.4	47.0	46.4
	f_{1B} (Hz)	92.0	97.9	97.3	98.0	95.9	100.8	99.7	100.3	99.3	98.7	100.4	92.0
T5 (Resonant)	f_{0R} (Hz)	46.2	45.8	45.7	46.3	46.7	46.9	47.1	47.1	46.6	46.2	46.9	46.7
	f_{1R} (Hz)	97.7	99.3	101.3	102.2	99.3	98.8	98.8	99.3	102.4	102.1	101.7	99.6
T6 (Batter)	f_{0B} (Hz)	64.8	63.8	64.3	63.9	64.0	64.2	64.7	64.0	64.2	63.7	63.6	64.3
	f_{1B} (Hz)	83.3	84.3	84.3	86.3	85.3	83.8	83.6	84.5	85.5	84.5	84.7	84.1
T6 (Resonant)	f_{0R} (Hz)	63.2	63.4	63.2	63.1	63.3	63.5	63.8	63.6	63.1	63.2	63.5	63.5
	f_{1R} (Hz)	144.3	145.9	145.9	146.1	146.2	144.8	144.8	144.9	145.8	145.9	144.5	144.3
T7 (Batter)	f_{0B} (Hz)	89.4	89.2	89.0	89.2	88.6	88.7	89.5	89.2	89.3	89.2	88.8	89.6
	f_{1B} (Hz)	109.7	109.1	108.4	109.0	109.0	108.7	108.8	108.8	108.8	109.8	108.8	109.0
T7 (Resonant)	f_{0R} (Hz)	88.2	88.2	88.2	88.2	88.3	88.3	88.2	88.1	88.1	88.1	88.4	88.2
	f_{1R} (Hz)	221.6	220.9	220.6	220.5	220.6	220.9	221.1	221.5	221.2	220.7	221.0	220.7
T8 (Batter)	f_{0B} (Hz)	117.0	117.0	116.9	116.9	116.9	116.8	117.0	117.0	117.0	117.0	117.0	117.1
	f_{1B} (Hz)	192.9	193.4	193.6	195.1	195.8	195.2	193.8	193.4	193.6	195.2	195.4	193.9
T8 (Resonant)	f_{0R} (Hz)	116.6	116.6	116.6	116.7	116.6	116.7	116.6	116.6	116.6	116.6	116.5	116.5
	f_{1R} (Hz)	222.9	223.2	223.1	223.1	222.9	223.1	222.7	222.8	223.0	223.1	223.1	222.9
T9 (Batter)	f_{0B} (Hz)	138.6	138.6	138.5	138.5	138.5	138.5	138.5	138.5	138.4	138.4	138.5	138.5
	f_{1B} (Hz)	254.3	253.4	253.0	253.6	254.4	254.1	253.3	253.1	252.5	253.6	254.0	253.9
T9 (Resonant)	f_{0R} (Hz)	138.0	138.1	138.0	137.7	137.8	137.7	137.7	137.7	137.7	137.7	137.7	137.6
	f_{1R} (Hz)	236.9	236.5	235.7	235.0	235.0	236.3	236.5	235.9	234.8	234.9	236.0	236.3

Table D.37: Frequencies for batter and resonant impacts around a 35-cm tom drum over a variety of tunings.

Tuning	f_0 (Hz)	f_{1B} (Hz)	f_{1R} (Hz)	f_{1B}/f_0	f_{1R}/f_0
T1	76.6	116.4	156.1	1.52	2.04
T2	105.8	211.0	163.2	1.99	1.54
T3	87.0	201.9	105.5	2.32	1.21
T4	59.9	109.8	100.4	1.83	1.68
T5	46.3	97.7	100.2	2.11	2.16
T6	64.1	84.5	145.3	1.32	2.27
T7	89.1	109.0	220.9	1.22	2.48
T8	117.0	194.3	223.0	1.66	1.91
T9	138.5	253.6	235.8	1.83	1.70

Table D.38: The change in f_0, f_{1B} and f_{1R} frequencies and frequency ratios over a variety of tunings for a 35-cm tom drum.

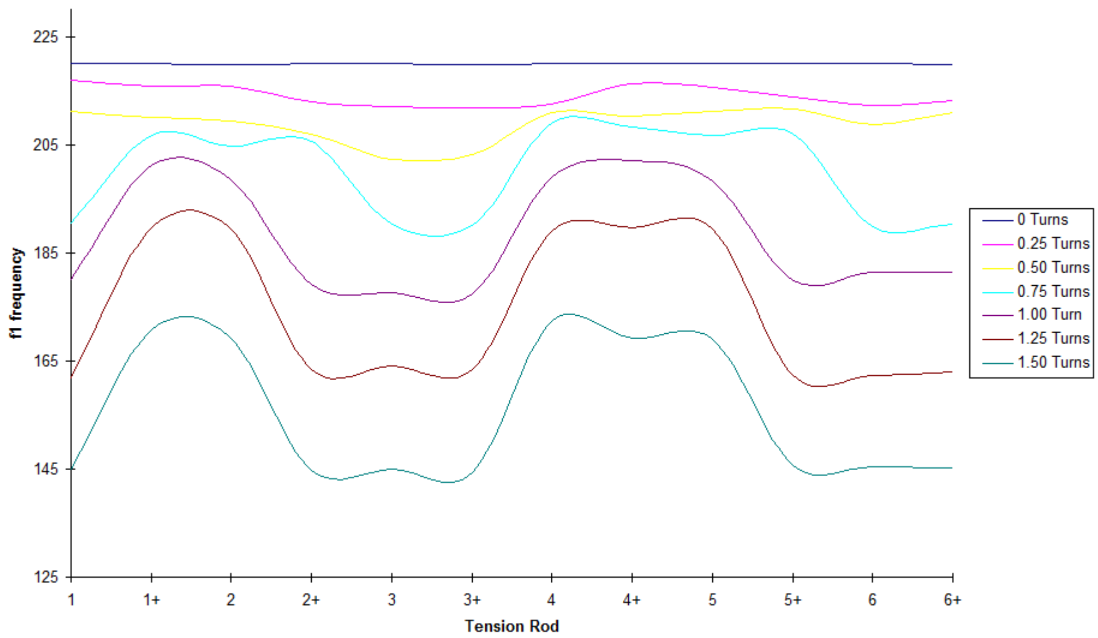

Figure D.10: How detuning a single lug affects the peak frequencies at locations around a drumhead.

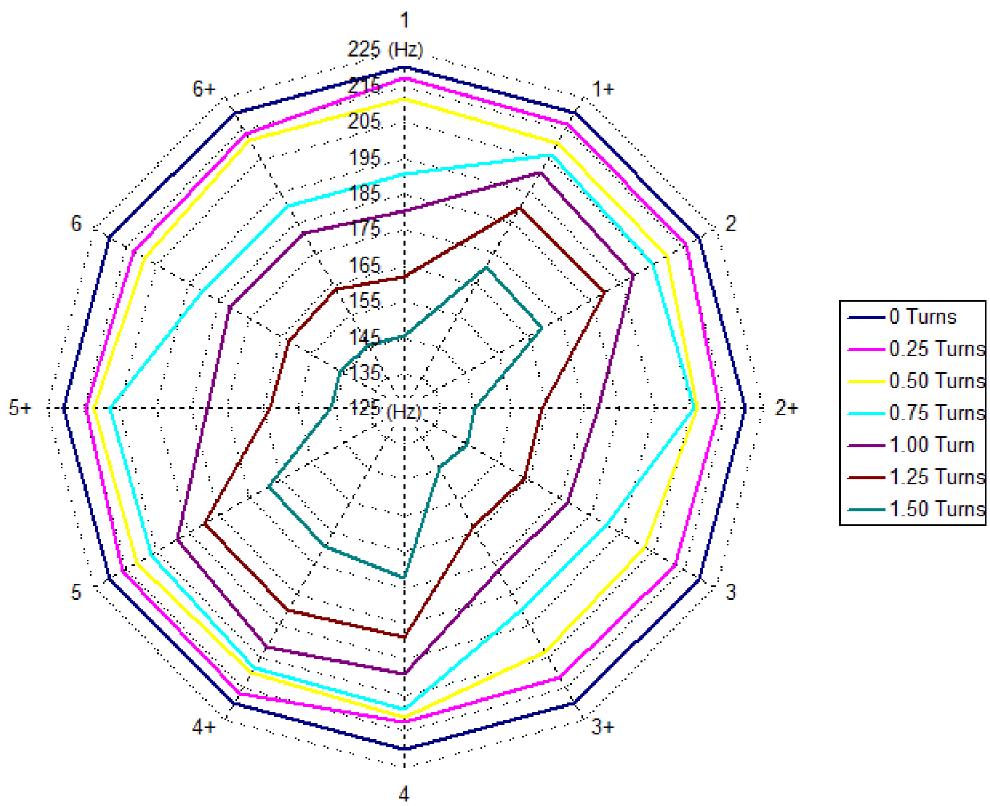

Figure D.11: f_1 remains similar for opposite locations as frequency splitting occurs while a 35-cm tom drum is detuned by altering tension rod 3.

Appendix E

"The perception and importance of drum tuning in live performance and music production"

Research paper presented at and included in the Proceedings of
The Art of Record Production Conference, Lowell,
Massachusetts, November 2008.

The perception and importance of drum tuning in live performance and music production

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Presented at The Art of Record Production Conference 2008

Abstract

Intricate setup and tuning of acoustic drums can have a significant and valuable impact on the quality and contextuality of the instrument when played alone or as part of a music group performing live or in the recording studio. Indeed, many record producers will spend a number of hours achieving the preferred drum sound at the start of a studio project. Similarly, live performances may require an exact drum sound every night, so knowledge and repeatability of drum setups can be a valuable asset. Drum tuning, however, is a rather subjective matter. There is no correct benchmark for 'in-tune' like there is for most other musical instruments, it is very difficult to define why a particular drum setup might sound good when another does not.

A research study has been conducted to assess how performers and producers interpret and value the importance of drum tuning in their specific field or music genre. Research has been conducted by a combination of one-to-one interview, focus group discussion, questionnaire, and through the authors' own experiences of drum performance and recording. This paper presents and discusses the results of the study.

Conclusions of the research show that advanced musicians do have the ability to tune drums by ear, and do greatly value the differences that can be made. Less advanced musicians are aware of the benefits that can be made by knowledgeable drum tuning, but many do not possess the skills to achieve the desired results. Unfortunately, owing to the subjective nature of drum tuning, there is currently no qualified method for educating novice practitioners. Of the music producers interviewed, the importance of drum tuning was high on their agenda, and there is evidence that any technical methods for standardising or benchmarking particular drum setups would be embraced. This paper therefore discusses drum tuning, with particular reference to analysed waveform data, in an attempt to demystify the methods used and provide a first step towards advancing knowledge and further educating performers and producers alike.

1 Introduction

Intricate setup and tuning of popular acoustic drums can have a significant and valuable impact on the quality and contextuality of the instrument when played alone or as part of a music ensemble performing live or in the recording studio. Some record producers will spend a number of hours achieving the preferred drum sound at the start of a studio project. Similarly, live performances may require an exact drum sound every night, so knowledge and repeatability of drum setups can be a valuable asset.

Drum tuning, however, is a rather subjective matter and, in comparison to other instruments, drums are regarded as being “much more difficult and challenging” to tune (Schroedl, 2002). This is predominantly owing to the number of degrees of freedom in the tuning setup. A drum within a standard drum kit setup usually consists of two taught drum heads held on to a drum by a number of tension rods, each of which can individually alter the tuning setup.

At present, there is no standardised benchmark for ‘in-tune’ like there is for most other musical instruments. It is also very difficult to define why a particular drum setup might sound good when another does not. It is generally accepted that there are a number of techniques and setups that allow the drums to be classed as ‘in-tune’. This study, however, does not intend to state which methods or setups are right or wrong, moreover the definition of ‘in-tune’ is regarded as being ‘with the desired sound’. So, the topic of tuning is classed as an issue of being in control of and influencing the resultant sound of the instrument, as also described by Ranscombe (2008).

A research study has been conducted to assess how performers and producers interpret and value the importance of drum tuning in their specific field or music genre. Research has been conducted by a combination of one-to-one interview, focus group discussion, questionnaire, and through the authors’ own experiences of drum performance and recording. This paper presents and discusses the results of these discussions in Sections 2 and 3.

Furthermore, digital signal analysis has been used to quantify a number of acoustic and vibration factors affecting drum setup and tuning. Section 4 uses waveform examples to discuss acoustic properties of the drum and investigates how this knowledge might be used to assist drum tuning and benchmarking preferred sounds. This paper, therefore, attempts to provide a first step towards advancing the technical knowledge of drum tuning setups and further educating performers and producers alike.

2 Drum tuning in music production

2.1 Practical issues with drum tuning

In many recording sessions, the drum setup has a very important role. The setup involves choosing the correct drum kit, choosing and positioning microphones for recording the drum kit, and tuning the drum kit to give the desired sound.

The drum setup process is often the first step in a recording session, as many music producers prefer to achieve a suitable rhythm track before overdubbing lead instruments. From our interviews with record producers, it was expressed that for recording projects lasting 2-3 weeks, the drum setup can account for 15-25% of the entire project, particularly if alterations are required between songs. Record companies are no longer willing to spend large funds on recording projects, so a ‘right first time’ approach makes economic sense, as discussed by mix engineer Chuck Ainlay (Massey, 2003, p280). If the drum setup is correct, the recording session can move swiftly and the mix down process can be simplified. It appears that producers are not willing to cut corners on the drum setup, but assistance to speed up and guarantee the correct setup would be embraced.

Drum tuning can also be a creative tool in the studio, especially to underpin the music genre being recorded. Rock, Metal, Pop and Jazz genres all use subtly different drum setups, and a knowledgeable drum technician can make a big difference in the way the drums sound in context with the rest of the music being recorded.

Other issues encountered in the studio with respect to drum tuning involve dealing with poor quality drum kits, changing drum heads half way through a session, and chasing a desired drum sound that was achieved once before. A producer or artist might want to emulate the drum sound on a previous recording, but, given that there is currently no quantitative method for benchmarking drum sounds, this is very difficult to achieve qualitatively and by ear alone.

2.2 Tuning and maintaining the desired sound

Drum tuning in the studio particularly focuses on the pitch of the drums and the decay time of each drum sound.

Drums for Jazz music are generally tuned higher and with a longer decay than drums for Rock music, so pitch ranges can be suggested for different music genres - as for example by Mike James (2008). Tuning for a particular genre is practiced by the musicians and producers interviewed, but some interviewees also expressed a desire to tune the drum kit to the specific key of the song being played. Producer John Leckie states that

> "The two things that identify a record are the vocal and the snare drum",
>
> (Massey, 2003, p104)

and it has been expressed that it is possible for the pitch of the snare or toms to be at odds with that of the bass guitar or other instruments. So, the specific tuning of the drum kit does have the ability to 'make or break' the recording. It has been expressed by the interviewees and by Toulson (2008) that fixing the drum pitch afterwards in post processing is not always a viable option. It is only possible to enhance frequencies that are evident in the original audio signal (Oswinski, 1999, p), so if the drums are tuned to the wrong pitch, then usually the only post processing option is to replace the drum sounds with triggered samples – again adding time and complexity to the mix down process.

The decay profiles of the drums in a drum kit are also tuned to give the desired sound in context with a song. For example, a slow tempo song might utilise drums with a long decay time to 'fill the space' between the musical notes. However, longer decay times might drown out the music in an upbeat song. It has also been expressed that as well as the overall decay time being a tuneable value, the decay times of the individual frequency components of the sound should all be similar too. For example, a drum sound might have a low frequency fundamental pitch and a high frequency overtone related to the drum shell and its construction. It is not desired for the low tone to decay quickly and the high tone to decay slowly, as this can result in a high frequency 'ringing'. A suggested approach is to achieve a decay time that is similar for all components of the drum sound's frequency spectrum. There are many products available for altering the decay times of acoustic drums; however it is very difficult to quantify the effect of these products by any means other than by ear. It is therefore difficult to quantitatively benchmark drum pitch and decay times for future reference.

3 The performer's perspective

3.1 Advanced and professional musicians

Discussions with professional percussionists indicate that drum tuning is an essential part of their craft. Expert percussionists appear to have a considerably personalised approach to drum tuning, though all ultimately tune by ear to the point where the drum sounds as desired.

Repeatability of sound can be an issue for even expert drummers however. The professionals interviewed expressed that they can always tune a drum kit to a desired sound by ear alone, but they might not be able to achieve exactly the same sound every time, which may or may not be a problem.

The need for professional percussionists to have extra control over their tuning setup is predominantly when in the recording studio or performing on a high profile tour. In the studio it is not uncommon for a difference of opinion between the drummer and the producer on the tuning of the drum. It is noted that a common scenario is where the producer wants a heavily damped (quick decay) sound, but the drummer would prefer a less damped setup. Quantitative benchmarking of sounds would allow more reasoned debate on which particular setups have been successful in the past and which haven't.

Repeatability of sound can be an issue on high profile tours where, for example, the drum sound is required to be as close to that of the artist's recorded work as possible. In this case the drum sound is desired to be consistent on every night of the tour, and some method for achieving this is attempted by the sound technicians. Repeatability and benchmarking also become issues when considering that many percussionists desire to tune their drums to a particular musical scale or the key of a particular song, for example Geoff Dougmore (Keefe, 2008). Currently the only method for this is by ear, using a reference tone or a piano to tune towards.

It appears that expert percussionists are indeed in control of their sound, and their ears are generally accurate enough to allow drum tuning unassisted. Drum tuning is a personal issue that can separate one musician from another, so in many respects a quantitative or standardised method for drum tuning is not essential for these performers. However, it is also felt that a method for recording and benchmarking tuning setups could be embraced.

3.2 Discussions with novice musicians

A focus group session with new drummers (1-3 years playing experience) indicated that tuning by ear is very challenging, and as a result most did not attempt tuning to any particular accuracy, saying they would prefer to concentrate on their playing technique. Drum tuning is difficult by ear, and the introduction of quantitative data could complicate the process further for this cohort. Those interviewed, however, were conscious of the advantages that precise tuning provides and expressed a desire to improve their ability in the future.

Benchmarking of sounds and setups was an interesting concept to the focus group. The opportunity for a new drummer to tune their kit to a ‘Rock’ setting or a ‘Jazz’ setting would be embraced. Indeed, some drummers explained that they only owned one drum kit which might be used for a Rock performance one night, and a Jazz performance the next night. Any assistance in quickly tuning their kit from one genre setup to another would be of benefit. Furthermore, the ability to replicate the drum sound of a favorite musical idol was an area where quantitative benchmarking could provide a unique advantage.

The discussions with novice musicians highlighted that drum tuning is indeed a universally appreciated skill, but one that is expected to be learnt automatically as a result of many years playing and listening. There appears to be no guarantee that this skill will embed with all percussionists, however, and there is no current method to accelerate the process of learning.

3.3 The talented hobbyist and part-time musician

During our investigation a third cohort appeared; those who fell between the classification of ‘novice’ and ‘expert’. Many percussionists are hobbyists who have perhaps played for many years and are quite talented and/or experienced. These musicians may perform and record regularly, but do not make their profession out of music.

Part-time musicians now make up a large number in the global recording industry, self-funding projects and expecting good recordings in a short timeframe. Indeed, many commercially successful musicians are now forced to find extra routes of employment, given the current tightening of recording budgets and record deals in the music industry. Of the percussionists who fall into this group, most would argue to being proficient musicians, but at the same time most were willing to admit a level of inability in drum tuning. These performers are often musicians who have a good ear for tone and quality, but do not have such accurate hearing to perform precise tuning. One such percussionist explained that they apply a ‘twist and hope’ attitude with drum tuning.

In addition, the part-time musicians are often experienced in studio projects and understand the basics of acoustics and recording principles. For this reason it appears that the cohort would be willing to embrace some form of technical assistance in drum tuning.

4 Defining a quantitative approach to drum tuning

4.1 The acoustic behaviour of a drum

The sound of a drum varies dependant on where the drumhead is hit. This is because different vibration modes are excited by impacts at different locations on the drum, as defined by the mechanical theory for experimental modal analysis (Ingard, 1988, p131).

Figure 1 shows the waveform and frequency spectrum of the drum acoustic when the vibration is excited and measured at the centre of the drum head. The drum used here measures 12” diameter and 9” depth; more particular details of the drums used in this research are included in the Appendix. The tuning lugs around the perimeter of the drum can be used to raise or lower the pitch of the drum. In Figure 1 it can be seen that the drum head has been tuned to have a fundamental pitch of 147 Hz, which corresponds to note D_3 on the musical scale. We will refer to this fundamental frequency as F_0.

If the same drum with the same tuning setup is excited and analysed at the perimeter of the drum, the fundamental mode is not particularly evident, as shown in Figure 2. Here we see a second frequency component (or ‘vibration mode’) at 220 Hz. We will refer to this second frequency component as F_1.

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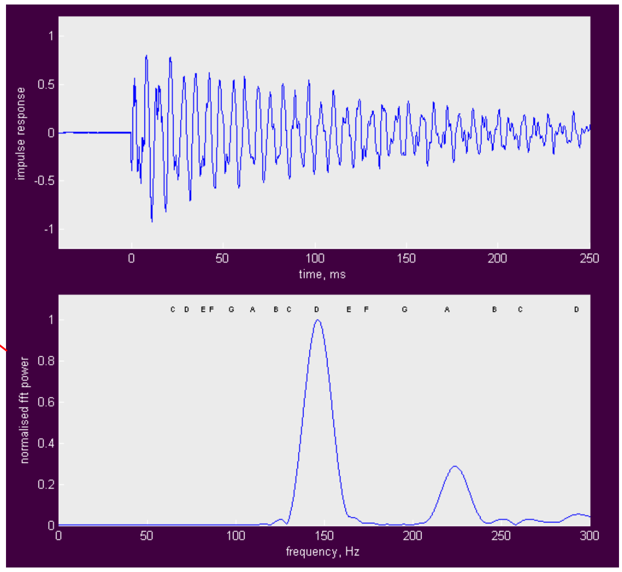
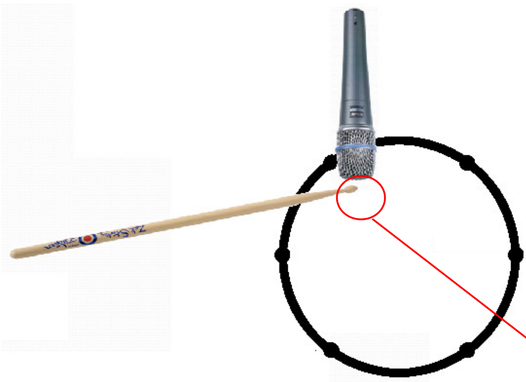


Figure 1. Centre impulse and response.



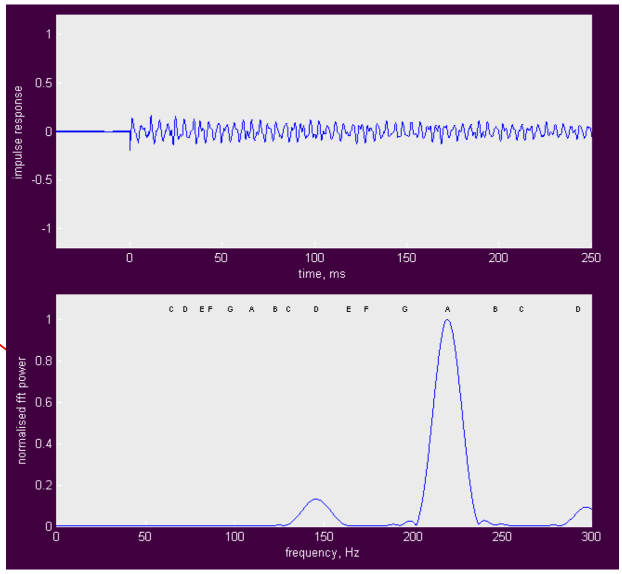


Figure 2. Edge impulse and response.

It is no coincidence that in this example the frequency F_1 (220 Hz) relates to the musical note A_3. The present research has shown that the fundamental mode, F_0, relates to the motion of the mass of air inside the drum. This frequency is therefore predominantly dependent on the size of the drum and the tension of the two drum heads (the batter and resonant or 'top and 'bottom' heads). Here, adjustment of either the batter or resonant drum heads will alter the fundamental frequency.

The frequency F_1, however, is seen to be more localised to be dependant on the dimensions and tension of the batter head alone, so adjustment of the resonant head has little influence. It is therefore possible to adjust the relative tension of the two drum heads and hence independently alter the frequencies F_0 and F_1. So the drum analysed in Figures 1 and 2 has been tuned to give this exact response.

Furthermore, it can be seen that excitation and analysis at a location between the centre and the edge will excite both F_0 and F_1 a similar amount, as shown in Figure 3. So it is indeed possible to tune a drum to have two chosen desired musical modes, and to excite these in unison, resulting in a rich musical tone.

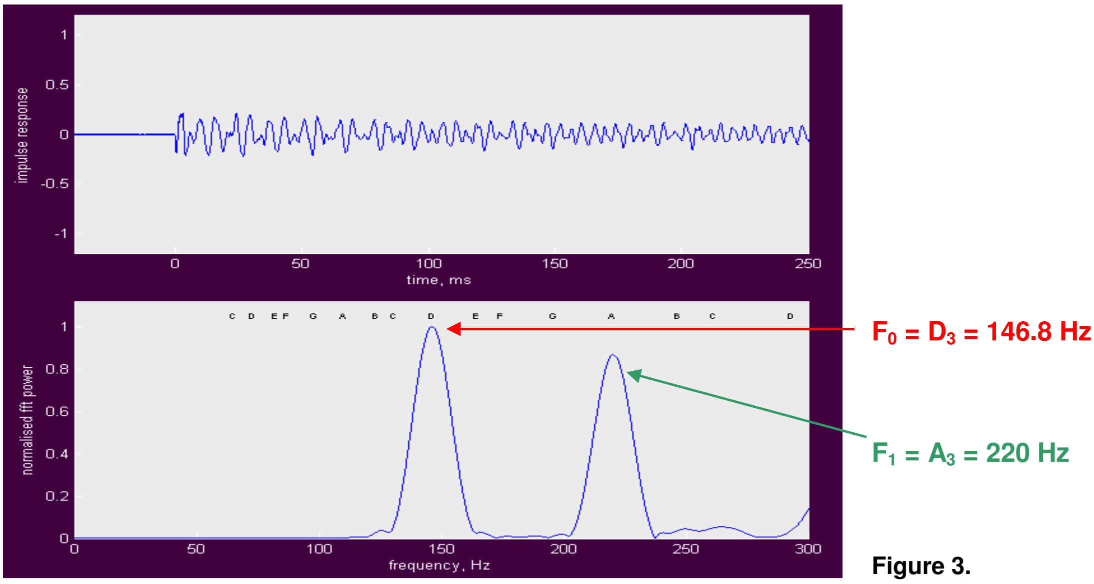


Figure 3.

The mechanical properties of drums and percussion instruments are discussed in detail by Rossing (2000). However, Rossing admits that "relatively little has been written about scientific research on these instruments" to date. Rossing discusses the vibration characteristics and modes of different drums in the popular drum kit; but, even here, little acknowledgement is made to the setup and tuning of the drums under investigation.

4.2 Tuning the pitch of the drums in a drum set

The ability to tune drums to a specified fundamental (F_0) pitch means that performers and record producers can tune an entire drum kit to a musical scale or reference. This type of tuning is performed by ear by a number of professionals who tune drums to specific notes by using a piano as a reference, for example Geoff Dougmore (Keefe, 2008).

The drum kit described in the Appendix has been tuned to give the fundamental tones shown in Figure 4. A descending drum roll on the kit described in Figure 4 will therefore give a musical scale through the following fundamental notes

14" snare → 12" tom → 13" tom → 16" floor tom → 20" kick drum

=

$G_3 \rightarrow D_3 \rightarrow B_2 \rightarrow G_2 \rightarrow E_2$

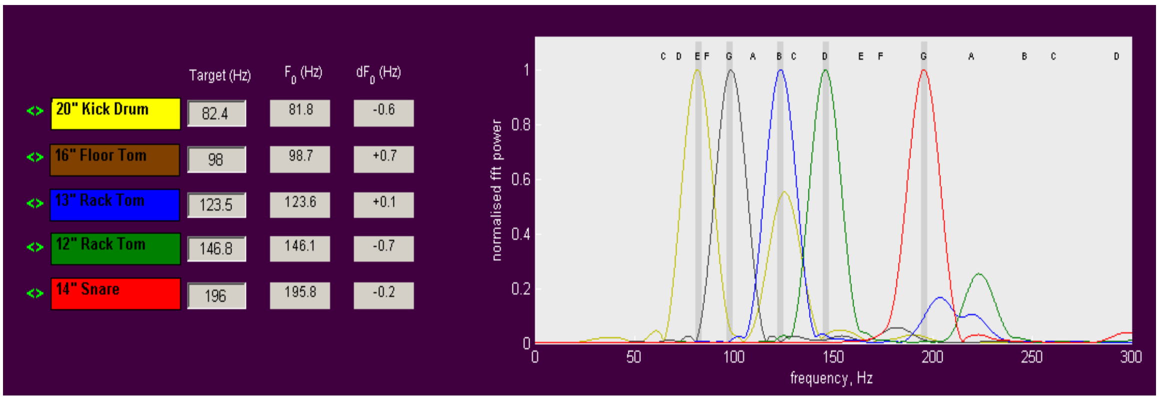


Figure 4.

The musical pitches chosen have been deduced from the outputs of testing and interviews with experienced drummers and recording engineers. This setup is intended to be a 'multi-genre' setup, however it has been observed that, in general, drums sounds associated with Rock drumming tend to be tuned to a lower pitch, whereas those associated with Jazz drumming tend to be higher pitch. The associations between drum pitch and music genre is an area of current and continuing research by the author.

4.3 Attack and decay profiles

As discussed previously, the decay profiles of drum sounds are often debated between musician and producer. Many drummers prefer an open sound with a decay that sustains the tone of the drum. Conversely many producers prefer a damped sound which will not overcrowd the recording. It is felt here that precise tuning of a drum's pitch allows the decay of the response to be in key with the music, so longer decay times can possibly enhance a recording. A second point to note for recording drums is that often producers desire the decay time to be matched to the tempo of the song, so it may be possible to suggest a delay time given the song's BPM (beats per minute).

It is possible to measure the decay time of drum sounds, and suggested standards are to consider the decay time, T_d, for 20 db, 30 db or 40 db reduction. A number of products, such as RTom Moongel (see www.rtom.com) and Evans E-Rings (see www.evansdrumheads.com), do exist for altering the decay profiles of drums. For example, Figure 5 shows that it has been possible to reduce the overall (20 db) decay of a 12" tom from 752 ms to 199 ms by the use of damper rings. Damper rings in general affect the frequency modes at the perimeter of the drum, so here the reduction in decay time is predominantly by a reduction of the decay time of the F_1 mode and overtones.

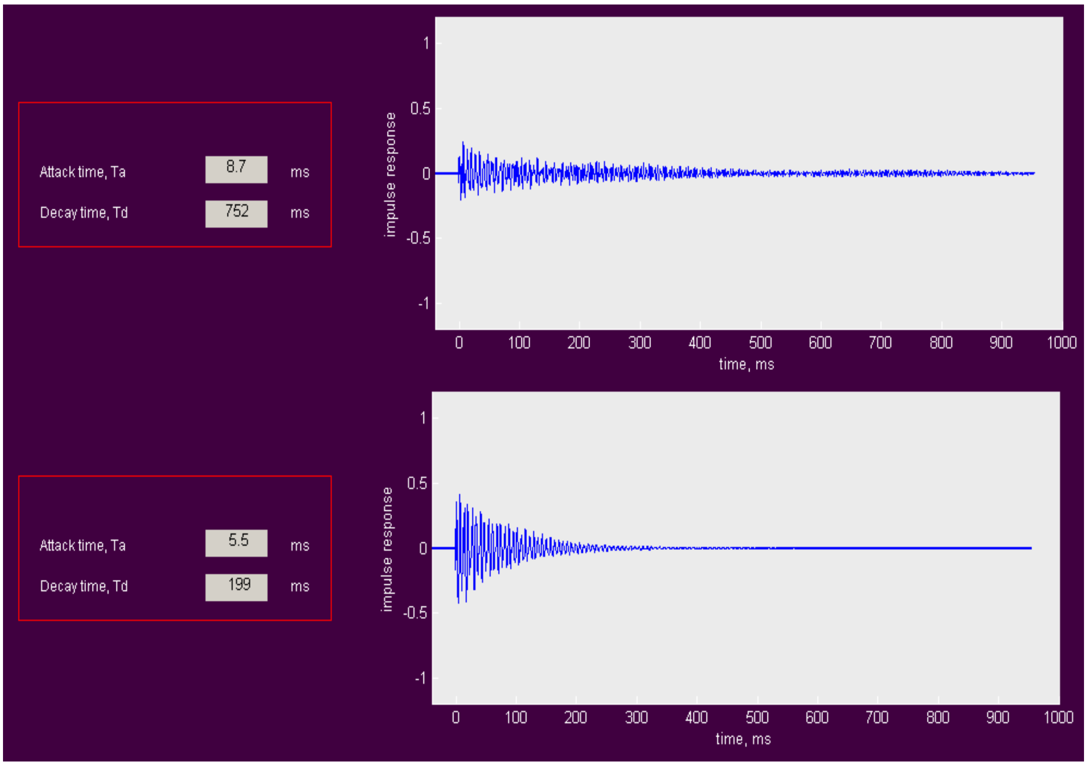


Figure 5.

The attack profile of an impact can also be measured. Here we are interested in the time taken for the signal to rise from its initial onset to its maximum value. In Figure 5 it can be seen that the attack time has reduced from 8.7 ms to 5.5 ms by the addition of the damper ring. Many texts suggest adding some high frequency boost in post processing to enhance the attack of the drum signal, for example Robinson (2006). However, it is suggested that achieving a desired attack profile is an essential task in drum tuning, and it is possible to change the attack time by changing the materials of the drumhead or the drum stick or beater. So, with more precise tuning, the recording can be much closer to the final desired sound, and hence simplifying the mixdown task.

4.4 Other tuning factors

It must be noted that many other factors affect the tuning of a drum kit, including

- drum sizes and dimensions
- the material of the drum shells and tuning mechanisms
- drum head types
- cymbal selection
- drumstick choice

Each drum has its own range of tone that it can be suitably tuned to. For example, a 12" tom can be tuned to have a fundamental within a specific frequency range. But as it is tuned lower and lower, eventually the drum head will go slack and the tone will become poor. At this stage if a lower tone is required, a larger drum should be used. Drums are also made with different depths and of many different materials by many different methods. Similarly, the types of drum heads used have a major impact on the available tuning ranges and attack and decay profiles. Furthermore, the choice of whether to use the same or different heads on the batter and resonant sides of the drum have a major influence. These factors are all under consideration in the current research.

At present, however, this research is predominantly concerned with understanding a particular drum setup and the tuning options available within that setup (the particular setup used here for data analysis is described in the Appendix). Once this knowledge capture is complete it is possible to look at multiple drum setups and consider extra factors, particularly with correlating drum sizes, materials and drum heads to specific tuning options and music genres.

5 Conclusions

It has been seen that drum tuning plays an important role in music production and performance. This is most obvious in recording projects where the drum sound has a major influence on the quality and context of the produced music. In addition, expert percussionists have a passion for drum tuning and see this as a very personal subject, one which often causes debate during the recording process. In these instances a more technical approach to tuning could be embraced to achieve a quantified and more precise sound profile and to capture benchmarks for future reference.

Beginner and part-time musicians admit to being challenged by drum tuning, and benchmarking towards standard 'Rock', 'Pop' and 'Jazz' setups would appear to be of value. A major challenge here however is simplifying any technical procedure to not confuse musicians further.

A quantifiable method for drum tuning has been developed and is being evaluated in the author's current research. Of course, some musicians and producers will not embrace yet another technical method within their artistic field. But, it is felt that, at the technical level where waveform and spectrum analysis are the norm, this approach could be embraced to give the valuable capture, analysis and benchmarking of drum sounds and tuning setups.

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7 Acknowledgements

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Ian Croft and Alex Reeves from Drummer Magazine; Drummers/Tutors Nick France and Steve McLachlan; Pete Whittard and students at The Institute of Contemporary Music Performance, London; Drum Technicians Jay Morris and Oli Perry; Producers/Studio Owners Mick Venning (Orchard Cottage Studios) and Neil Rogers (Half-ton Studios).

8 Appendix

The hardware used for analysis in the figures and examples within are as follows:

Drum shells:

All Tama Superstar Series drum shells (7ply birch/basswood)

20 x 18 inch (diameter x depth) bass drum

12 x 9 inch tom drum

13 x 10 inch tom drum

16 x 16 inch tom drum

14 x 5.5 inch snare drum

Drum heads:

Evans EC2 coated batter heads

Tama standard resonant heads

Microphone:

Beyerdynamic Opus 67 Dynamic

Appendix F

“Clearing the drumhead by acoustic analysis method”

Accepted for presentation and inclusion in the Proceedings of the Reproduced Sound Conference, Cardiff, November 2010.

Clearing the drumhead by acoustic analysis method

Reproduced Sound Conference 2010

Abstract submitted by:

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and

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Abstract

The tuning of acoustic drums can have a significant effect on the success of a recording project. One popular method involved in drum tuning is to 'clear' the drum head, to ensure an even response by tapping the drum head around the perimeter of the drum and checking that a consistent sound is achieved at all locations. This technique is discussed in a number of popular texts and magazine articles, but to date has not been evaluated in a scientific context.

This paper uses modal analysis techniques to investigate the effect of clearing a drum head. It is shown that it is indeed possible to quantify how uniform the drum head tuning is via simple acoustic analysis and that, while many expert musicians have the ability to tune drums by ear, an intelligent tuning aid can provide significant benefits to those who are still learning their trade, be it as a musician or a record producer.

Biography

Phillip Richardson is investigating acoustic behaviour and tuning methods for drums and membranophones for his PhD at Anglia Ruskin University, Cambridge. Phillip is in his final year of study and is currently preparing to submit his thesis. Phillip's first degree is a BSc (Hons) Audio and Music Technology, also from Anglia Ruskin University.

Dr Rob Toulson is Director of The Sound and Audio Engineering Research Group at Anglia Ruskin University. Rob lectures on Electronics and Audio and Music Technology pathways, he is also an active musician and record producer.

Appendix G

“Fine tuning percussion - a new educational approach”

Accepted for presentation and inclusion in the Proceedings of The Art of Record Production Conference, Leeds, December 2010.

Fine tuning percussion - a new educational approach

The Art Of Record Production Conference 2010

Abstract submitted by:

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Submitted for the following conference stream:

3. Music production and education - a site of resistance?

Abstract

A number of skills and techniques involved in music technology are rarely taught in a formal manner. Originally, ear training and listening skills were assumed to be acquired automatically as practitioners gain knowledge and experience in their field. However, in recent years, well developed education methods for assisting and accelerating ear training have proven successful.

A related skill, which has no current formal education method, is the practice of drum tuning. The tuning of acoustic drums can have a significant effect on the success of a recording project, however, this is a largely subjective matter and drum tuning is often considered something of a 'dark art' amongst emerging drummers. One popular method involved in drum tuning is to 'clear' or 'equalise' the drum head, to ensure an even response by tapping the drum head around the perimeter of the drum and checking that a consistent sound is achieved at all locations. This technique is discussed in a number of popular texts and magazine articles, but to date has not been evaluated in a scientific context. Thus, no formal or quantifiable method of educating a technician in clearing the drum head has previously existed.

This paper uses modal analysis techniques to investigate the effect of clearing a drum head. It is shown that it is indeed possible to quantify how uniform the drum head tuning is via simple acoustic analysis; i.e. with a drumstick and a microphone. The effect of clearing a drum head with respect to the tension of the head, as opposed to the audible response, is shown to be ineffective in a number of cases, indicating that the drum head should indeed be tuned by analysis of the audible response rather than to the exact tension of the drum head itself. Furthermore, a drum head with a non-uniform response can be seen to exhibit beat-frequencies, producing an uneven profile to the drum response decay envelope.

It is apparent that while many expert musicians have the ability to tune drums by ear, an intelligent tuning aid provides significant benefits to those who are still learning their trade, be it as a musician or a record producer. The visual feedback produced by the novel and bespoke analysis software used in this paper can help musicians and producers make more informed choices with regards to their drum sound. Furthermore, the developed methods for drum tuning allow the development of a standardised education method for assisting and accelerating the learning of this skill.

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ACOUSTIC ANALYSIS AND TUNING OF CYLINDRICAL MEMBRANOPHONES

Phillip Giles MacGillivray Richardson