ACOUSTICAL STUDIES OF THE MARIMBA

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Abstract

An experimental striking apparatus was used to produce repeatable marimba tones across a range of experimental parameters. These parameters – including mallet choice, striking force, and bar position – were varied to produce different tones which were then analyzed. Insight was gained as to how these variables affect tone and timbre. Harmonic characteristics for an ideal marimba were isolated by identifying the waveforms of two instruments, one considered of high quality by local percussionists while the other was considered inferior. The amplitudes of odd harmonics were found to have a strict dependence on the marimba resonators, while the even harmonics did not. Vague musical adjectives, such as "bright" and "dark," were quantified with concrete waveform analysis. Experiments involving striking position were found to agree with struck bar theory. This paper reports the experimental techniques and the subsequent analysis used to characterize these marimba acoustics.

Introduction and Theory

Today, the marimba is one of the most commonly played percussion instruments. Its warm, distinctive tone color sets it apart from other percussive instruments such as the snare drum or the glockenspiel. This uniqueness gives excellent cause to study the physical characteristics of marimba tone and timbre. Our goal was to characterize the acoustical properties of the marimba – to strictly quantify what percussionists (and musicians in general) relegate to the realm of elaborate adjectives such as "mellow," "darkly resonant," or "thickly warm toned." Further, we wanted to explore observable harmonic phenomena to gain insight into how variable parameters affect tone color. Throughout all of these tests and analysis, pertinent theory was referenced.

The marimba is a relatively new addition to the recognized canon of western musical instruments. Used by Latin American peoples for centuries, the marimba begin to migrate north during the early 1900s. Clair Omar Musser, one of the marimba's earliest developers and progenitors, began forming novelty orchestras of nearly 100 marimbists in the late 1930s. These orchestras were soon touring the world and with this exposure, composers began writing parts for this new instrument; the marimba was soon absorbed into the orchestral percussion arsenal.

The marimba is currently employed in nearly every playing medium imaginable: concert halls, jazz clubs, church services, and drum corps shows; each medium and style requires a distinctly different sound. A drum corps marimbist must project with piercing brilliance while a Sunday morning Bach prelude would be performed intimately with a warm, dark tone. We endeavor to characterize and quantify these sounds.

The marimba typically includes 3 ½ to 5 octaves of tuned bars; a 5 octave instrument extends from C_2 to C_7 (f = 65.4-2093 Hz). These bars can be made of carved rosewood (preferred for its beautiful sound), lower grade padouk wood, or synthetically molded and carved fiberglass (chosen for durability). The bars are generally graduated in width from about 4.5 cm in the upper octaves to 6.4 cm in the low register. When struck, these bars vibrate with transverse standing waves, seen in Figure 1.[1] As the harmonics ascend (f_i, i = 1,2,3...), the standing wavelengths decrease proportionately. All of these transverse waves have nodes and anti-nodes. The dashed lines of Figure 1 locate the nodes of the first seven modes of transverse vibration. We hypothesized that exciting the bar by striking it with a mallet would emphasize all of the harmonics whose anti-nodes corresponded to the position of mallet impact. This is predicted by theory: to emphasize a particular partial, the bar should be struck at a point of maximum amplitude for that mode.[2] This technique has long been qualitatively known to marimbists (i.e. playing near the nodes de-emphasizes the fundamental). However, we wanted to quantify this and test it across many positions and harmonic responses.

Directly beneath each marimba bar is a resonator tube. This resonator tube has a metal plate in the bottom of the tube and obeys the physical laws for standing waves in a pipe closed at one end. In this case, the physical length of the resonator tube is L'. The effective length of the tube due to the end correction is L=L'+.6R, where R is the radius of the tube. The equation of resonant frequency for a pipe closed at one end is,[3]

$$f_n = n\frac{v_s}{4L}, \quad n = 1, 2, 3... \qquad \text{(Eq.1)}$$

where v_s is the speed of sound in air and only the odd harmonics are present. This can be rearranged to give the physical length of a tube needed to resonate a certain frequency.

$$L' = n\frac{v_s}{4f_n} - .6R \qquad \text{(Eq.2)}$$

Marimba resonators are designed to resonate with the fundamental (f_1). Eq.2 then reduces to,

$$L' = \frac{v_s}{4f_1} - .6R \qquad \text{(Eq.3)}$$

Thus, a resonator's length is determined by the note it must resonate; a resonator tube is tuned to a certain note with a fundamental frequency f_1 by adjusting its length L' as per Eq.3.

Contrary to the intuition of many musicians, the resonator tubes do not sustain the tone of the struck note. Instead, the resonators serve to amplify the fundamental. Given a finite amount of energy imparted to the bar of a resonator system, some of the energy escapes by amplifying the fundamental instead of sustaining the note. Thus, the decay time of a note with a resonator should be less than that of an note without a resonator (see Figure 2). However, as seen in Figure 2, given a high enough background noise, a resonating note can be interpreted to have a longer decay time.

Given the odd harmonic dependence of resonance noted in Eq.1, and the fact that the resonators amplify as opposed to sustain, we hypothesized that the amplitude of the odd harmonics would not be affected by the absence of the resonator.

Using different mallets while playing the marimba greatly changes the tone. This is why an experienced percussionist carries around a large bag full of whacking implements. For some literature a "dark" tone is desired, whereas in other literature a "bright" sound is appropriate. The piercing or penetrating power of a mallet is also a fundamental characteristic.

The range of human hearing extends from roughly 20 Hz to 20 kHz. This range is particularly well matched to human speech since the majority of vocal energy lies between 100 Hz and 10 kHz. While the frequency range of musical sounds span the full range of human hearing, most of the energy of musical sounds is restricted between 100 Hz and 3 kHz.[4] Further, the range of highest sensitivity for human hearing is between 2 kHz and 3 kHz.[5] This becomes particularly important when taken in context of the author's experience. When practicing with very "bright," penetrating marimba mallets, the author has experienced a piercing, yet unidentifiable shrillness in the tone of the bar. At times, the volume of this shrillness was enough to cause discomfort. The source of this discomfort will be explored further in the analysis.

Experimental Apparatus and Procedure

Consulting the aforementioned theory, we formulated five experimental foci utilizing these concepts: repeatability, bar composition, resonator function, mallet harmonic response, and timbral dependence on bar position. It became clear that in order to perform meaningful experiments, we would need a repeatable way to produce marimba tones. For this, a striking apparatus was created (Figure 3). The complete experimental apparatus included this striking apparatus, rubber bands, one M 250 model Musser 4 1/3 octave rosewood marimba, one M 150 model Musser 4 octave rosewood marimba, eight marimba mallets, a PC fitted with a sound card, a snare drum stand, several crotales,[6] a triangle, a tape recorder, various audio tapes, and experimental duct tape. The eight types of mallets used were: Jason's White, Van Sice, Jason's Yellow, Balter Red, Malletech White, Musser Good Vibes, Jason's Concerto Blue, and Musser Red Ball. The striking apparatus was constructed using wood, screws, eye hooks, epoxy glue, dowel rods, and standardized rubber bands (tested for consistent spring constants). The intent of building this apparatus was to create a machine which could consistently and accurately reproduce proper mallet technique. Enough flexibility was incorporated into the design so that we could adjust the intensity of a stroke by manipulating rubber band position and type. Also, mallets could be easily exchanged without disrupting to the system. In creating a pivot point around a mostly frictionless axis, the mallet was capable of being cocked at a measurable and repeatable angle with the help of a fixed protractor.

The striking apparatus was used in every section of the main experiment. It was crucial that the apparatus be experimentally quiet, consistent, flexible, and reliable. Without these qualities, the experiment would have no consistency from trial to trial.

A computer fitted with a sound card and the Spectra Plus spectrum analyzer program facilitated the data acquisition portion of the experiment. The program includes a series of display options: harmonic spectrum, 3D plot, spectrograph, and time series. The spectrum mode, which plots relative amplitude versus frequency, was used most often. A microphone was attached to the “mic in” port at the rear of the computer. With this setup, we were able make a direct line-in digital recording of the trials. Before this setup was finalized, however, a frequency response experiment needed to be performed on potential recording media. The goal of this was to determine whether audio tapes would be adequate media for recording the trials.

Two crotales were tested in this preliminary experiment. A microphone was input to the audio tape deck, which recorded the sound of the strike. Attaching the “line out” of the tape deck to the “line in” of the sound card on the computer made it possible to record a digital copy of the same strike on the computer. In this way it was possible to directly compare the two methods of data acquisition with no experimental variation. It was found that the audio tape picked up at most four distinct harmonics, whereas the direct line in was capable of distinguishing at least a dozen or more peaks. Not only did the audio tape resolve very few peaks, but the ratios of the amplitudes of these peaks were inconsistent with the digital recording. Since the analysis for this experiment would require a high level of consistency and sensitivity, it was quite obvious that acquiring data on tape would not be a reasonable method for our purposes. Thus, it was decided that the computer equipped with the microphone was a necessary component for the data acquisition process.

The computer, microphone, and striking apparatus were all transported to the percussion studio located in the Fine Arts building. The striking apparatus was mounted on the snare drum stand so that it could be consistently positioned and kept at an optimum height equal to that of the marimba bars. The microphone was mounted in a standard position between the two rows of bars, clamped to the wooden frame of the marimba. This allowed the microphone to be placed very close to the bar of interest (A220) for consistency and accuracy. After achieving this initial setup, the procedure incorporated the sub-experiments of our experimental foci.

Repeatability Procedure

The goal of this sub-experiment was to gauge our experimental uncertainty and to determine whether our trials would be consistent. To obtain this uncertainty, three different marimba mallets struck the A220 bar several times per draw angle for four different draw angles (50, 60, 70 and 80, where 0 degrees is measured at the resting point against the marimba bar). The Musser Red Ball, Balter Red, and Good Vibes Yellow were the mallets that were used. Key peak amplitudes were drawn from the Spectra Plus waveforms for analysis.

Bar Composition Procedure

This sub-experiment involved the use of both the 4 and 4 1/3 octave marimbas. The local percussionists strongly agree that the 4 octave marimba sounds remarkably better than the 4 1/3 octave marimba. The motivation for this section stemmed from the desire to know what is responsible for this difference in tone quality between the two marimba. This experiment explored the quantification of psycho-acoustic responses of various tones. The A220 bar on each of the marimbas was struck with the Balter Red mallet twice for each standard draw angle (50, 60, 70, and 80 degrees).

Resonator Function Procedure

In this sub-experiment we wanted to test the dependence shown in Eq.1 by measuring the even and odd harmonics with and without an active resonator tube. We also wanted to compare measured note decay with and without a resonator to the theoretical curve. Once again, the A220 bar was of interest, and only the 4 1/3 octave marimba was used along with the Balter Red mallets. First, several trials were conducted with the resonator active. For each draw angle (50, 60, 70, and 80 degrees), three strikes were recorded. Following this, the resonator was made inactive by stuffing it with a cotton rag. A corresponding number of trials followed with the inactive resonator. A remarkable difference in tone, timbre, and loudness accompanied this change in the system.

Mallet Harmonic Response Procedure

If a marimbist needs to cut through the massive sound produced by an orchestra in a large-scale concerto, a penetrating mallet is required. These sort of mallet characteristics are the focus of this sub-experiment. We quantified the changes in tone of the instrument by striking the A220 bar with all eight mallets at the draw angles of 50, 70 and 90 degrees. We could immediately distinguish some of the brighter mallets by their increased upper harmonic emphases.

Procedure for Timbral Dependence on Bar Position

Percussionists use a technique of playing on distinct bar locations to change the particular tone color. This motivated the final sub-experiment. The location of the apparatus was paid very close attention in this section. The center of the A220 bar was defined to be the zero point on the bar; the anti-node for the first harmonic exists at this point. Trials were done in which the strike position was moved 2 cm at a time toward the node position of the fundamental (12.5 cm from the center of the bar). We recorded each trial using the Jason White, Musser Red and Balter Red mallets.

Analysis and Results

In almost all trials of every sub-experiment, it was interesting to note that the 4^{th} harmonic (A880) was second in relative amplitude only to the fundamental. This agrees exactly with the theory regarding marimba bar tuning: the first overtone is nominally tuned two octaves above the fundamental.[7] Further, this agrees with information provided by the manufacturer: "each bar is triple-tuned to make the first and second...overtones exactly match to the fundamental."[8] The bars are carved to emphasize the fundamental plus the first distinct overtone two octaves above the fundamental. Given a fundamental of A220, the frequency of $f_4 = 4 \text{ x } f_1 = 880$ Hz. It was gratifying to see this confirmation of theory.

Another interesting phenomenon that was noticed in all trials was the harmonic response immediately after t=0. On a time series, it was noticed that the waveform did not achieve its peak amplitude immediately. This occurred several hundredths of a second after the initial strike at t=0. We hypothesize that this is because immediately after t=0, the vibrating energy is dispersed in the vibrations of the prominent harmonics. After a short time, the upper harmonics die off (see Figure 5) and the energy returns to bring the fundamental to its peak amplitude. Additionally, though we noted a veritable wall of white noise occurring at t=0 across all frequencies (see Figure 5). This would also drain energy from the system. This source of this white noise is suspected to be the mallet's "thwack" – that is, the wood and yarn sound produced by the impact before the bar has actually begun vibrating.

Repeatability Analysis

To the end that this sub-experiment's goal was to characterize an experimental uncertainty, Table 1 shows that an approximate 2% uncertainty carried through all procedures involving the striking apparatus and Spectra Plus. But the fact that this uncertainty is relatively low serves a secondary objective: we could proceed through the rest of our experiments with 98% trust in our equipment and data acquisition methods.

Within these trials, the obtained peak amplitudes were compared across a given data set. Each set of data kept every parameter the same in an attempt to achieve identical waveforms. A standard deviation was taken for each set (according to the usual standard deviation methods[9]), and also expressed in percent error. This yielded an average percent error of 1.48%. To this we added the inherent uncertainty in measuring draw angle with a finitely precise protractor, and the uncertainty in reading peak amplitudes off of a finite pixel screen. With approximation, our experimental uncertainty came to ≈ 2%. This high "confidence factor" was the main gauge of experimental uncertainty and validated our procedures throughout the varying draw angles and mallets; it proves that waveforms remained consistent across all parameter variations.

Bar Composition Analysis

A very revealing waveform (Figure 4) was obtained by keeping all experimental parameters the same and exchanging the 4 octave marimba for the 4 1/3 octave marimba. This direct comparison of each instrument's A220 yielded striking harmonic differences. The waveform of the 4 1/3 octave marimba shows definite deficiencies in the 3rd and 4th harmonic strengths when compared to the 4 octave instrument.

An additionally fascinating phenomenon was noted: the 4 1/3 octave marimba consistently displayed a double peak in the region of 660 Hz, the 3rd harmonic (this is the E one octave and a perfect fifth above the fundamental).[10] We suspect that this double peak – essentially a presence of two conflicting, dissonant tones – was a source of this tonal difference, and is a continuing cause of the 4 1/3 octave marimba's general inferiority. This observation will be further addressed in the resonator function analysis.

From this sub-experiment, we can conclude that the musical adjectives, "warm" and "rich," generally associated with the high quality 4 octave marimba can be scientifically translated in the following way:

- a tone where the fundamental is dominant; also including
- a prominent 4th harmonic, specifically one not preceded by a harmonic gulf; and
- a supporting non-double peaked 3rd harmonic.

Because of these emphasized overtones, the overall sound is more harmonically rich and diverse.

Resonator Function Analysis

An initial goal of this sub-experiment was to compare the decay time relationships to those predicted by theory. It is common practice to express the decay time of a sound as the time that would be required for the sound level to fall 60 dB (even though it fades into background noise before then).[11] The relative peak amplitudes of a tone form this "decay envelope" characteristic of all sounds decaying over time. These peak points were obtained by converting wave file data to a text file of pure numbers. These numbers were then run through a program[12] created in Visual Basic[13] that sorted through the data and determined peaks by comparing the 50 surrounding data points. These data were then cropped to our time interval of interest. The exponential fit appears in Figure 11 while its logarithmically scaled counterpart appears in Figure 12. Figure 11 shows the relative peak amplitudes versus time; this displays a remarkable exponential fit. Figure 12 shows the log amplitude versus the log time and definitely matches the behavior of the theoretical curve (Figure 2). The logarithmic fit of Figure 12 would be nearly flawless if it did not have to account for the background noise which causes the curved grouping of points near the x-axis.

But contrary to what we expected, when comparing the decay times of the tones with and without the resonator we actually found that the tone with an active resonator had a longer decay time. However, Figure 4 gives a reasonable explanation for this. In the region of our primary harmonic interest (200 Hz to 1 kHz), the background noise level was nearly 30 dB higher than that measured past 1.2 kHz. This would provide the background noise level (shown on Figure 2) necessary to obscure the decay time of the tone without the resonator. The specific cause of the background noise is unknown, but it could have been any combination of factors including: a mediocre quality microphone, computer generated noise, and the fan and heating systems of the Fine Arts building.

Figure 6 provides a definitive display of the difference in waveforms when the resonator was active and inactive. This graph accounts for the remarkable difference in tone, timbre, and loudness observed while the data was being taken. Just as theory predicts, the 1st and 3rd harmonics were duly amplified while the 4th remained essentially untouched. Additionally, the lack of a resonator caused a harmonic trough shortly before the un-amplified 4th harmonic. Because the 4th harmonic was un-amplified, we can conclude that the only sound energy a listener hears is that from the bar itself – when a listener hears a 4th harmonic, they are hearing the bar generate the tone unaided.

Also noted in Figure 6 is the aforementioned double peak in the vicinity of the 3rd harmonic (660 Hz). This strange double peak is further clarified in Figure 5, where the two peaks are noted to have different decay times. We propose that their difference in decay times is due to one harmonic having been caused by the bar while the other was caused by the resonator. Were the resonator to be tuned slightly too long, it would resonate a frequency just below the desired 660 Hz. The result would be two dissonant peaks. But by the theory of the bar's longer decay time, its harmonic would eventually supercede the more transient harmonic produced by the resonator. This explains the longer decay time noted for the higher frequency 660 Hz harmonic.

In our attempt to determine if this was the cause of the double we peak, we calculated the theoretical physical length L' for a tube resonating f_l = 220 Hz. Our calculated value for L' = 37.0 ± 0.6 cm. However, our measured value for L' = 37.0 ± 0.1 cm. This leaves the possibility that the resonator is, in fact, tuned correctly. Unfortunately, the precision of our measurements does not allow a conclusive ruling on this phenomenon. It is interesting to note, though, that if the resonator tube had been tuned in conditions other than standard temperature and pressure, it would be out of tune when it reached these conditions of nominal playing. The effective tube length depends on the speed of sound in air which, in turn, is dependent on temperature and pressure. Thus, the double peak could exist simply if the Musser factory were to be hypothetically based in Denver, Colorado, at high elevation, lower pressure, and colder temperatures. Lending more credence to our suspicion of poor resonator tuning is the fact that most marimba manufacturers now incorporate adjustable length resonator tubes. They cite changes in temperature and barometric pressure as reasons for this enhancement.

In our analysis, we found that the 4 octave marimba does not display this double peak; we believe this to be because the resonator tubes of the 4 octave instrument are well tuned. The desired single peak is seen in Figure 7.

Mallet Harmonic Response Analysis

This sub-experiment paid attention to the qualitative ratings that percussionists assign different mallets. A rough spectrum consists of mallets running from "dark" to "bright" tones. The waveforms obtained by testing each of the eight mallets through varying draw angles lend a great deal of insight into exactly what characterizes these adjectives. The 10^{th} harmonic of the fundamental was notably observed in these trials, where the 10^{th} harmonic ($f_{10} \approx 2200$ Hz) functions as the C$\#_7$ four octaves and a major third above the fundamental.[14]

Noting the numbering system of the mallets in Table 2 below, Figure 8 shows the relative strength of the fundamental, 3rd, 4th, and 10th harmonics for each mallet at a draw angle of 90 degrees.

Mallet Name	*Mallet Number*
Jason's White	1
Van Sice	2
Jason's Yellow	3
Balter Red	4
Malletech White	5
Musser Good Vibes	6
Jason's Concerto Blue	7
Musser Red Ball	8

Table 2 – Mallet Number Designation Key for Figure 8

Note that the strength of a harmonic in Figure 8 is characterized by its nearness to the 0 dB level – the more negative the relative peak amplitude, the weaker the harmonic. This graph provides a fascinating display of each mallet's harmonic response characteristics. The Jason's White, Van Sice, and Jason's Yellow mallets have roughly the same harmonic responses, with the upper harmonics evenly spread across the relative amplitudes. Interestingly, the Balter Red mallet completely *d*e-emphasizes the 10th harmonic, one which is generally more prominent at higher striking forces. The Malletech White mallet is unique in that it *only* emphasizes the fundamental; all other harmonics have a uniformly low amplitude. This knowledge could be utilized by percussionists seeking a certain timbre mallet.

Perhaps most "striking" of all is the harmonic response of the Jason's Concerto Blue, mallet number 7. Figure 8 shows the amazing strength of the Jason's Concerto Blue 10th harmonic. This is the aforementioned mallet the author used while preparing a piece where sound projection was a necessity. The piercing, unidentifiable shrillness *was a direct result of this prominent 10th harmonic*. "Brightness" can be characterized by the presence of distinct upper harmonics, as can be seen in Figure 8. Knowing this and the extreme sensitivity of the human ear between 2 kHz and 3 kHz, an upper harmonic between 2 kHz and 3 kHz would prove to be very penetrating to the ear; thus the discomfort experienced.

Another notable conclusion regarding mallet harmonic characterization can be drawn from Figure 9. This figure shows the harmonic response of the Jason's Yellow mallet across three different draw angles. The remarkable element of this response is the difference in slope between the increasing fundamental amplitude and the increasing 10th harmonic amplitude: the 10th harmonic amplitude increases far faster as striking force is increased. This means that playing more loudly does not just uniformly increase amplitudes; in fact, it means that playing more loudly actually emphasizes higher harmonics and leads to a brighter tone. Thus there would be a distinct difference in tone between an amplified marimbist playing softly and a marimbist playing loud enough to equal the electronic amplification. Therefore we can conclude that playing softly generally yields a darker tone while playing loudly generally yields a brighter tone.

Analysis of Timbral Dependence on Bar Position

Much of the motivation for this series of tests came from the desire to recreate the theoretical standing wave patterns shown in Figure 1. Overall, our results completely agreed with the theoretical predictions. This can be observed in Figure 10. This plot shows the relative amplitude of all four harmonics (connected by differing lines) versus the bar position. The zero bar position was calibrated as the center of the bar lengthwise; the center of the bar corresponds to the anti-node of the fundamental. We previously hypothesized that exciting the bar by striking a specific point along its length would emphasize all of the harmonics whose anti-nodes corresponded to the position of mallet impact. Not only did we find this to be true, but excitation of this type emphasized *all* harmonics whose anti-nodes corresponded to the impact point. In Figure 10, one sees that both the 3^{rd} and 4^{th} harmonics (whose anti-nodes are in close proximity after ~ 8cm) are emphasized and even amplified above the fundamental. This gives a unique characterization to the Musser Red Ball Mallet – when played near the node, this mallet sounds extremely bright and thin since the fundamental's amplitude drops so low and the upper harmonics are amplified.

This held true for the other two mallets tested as well: when played near the node of the bar, the listener perceives a "bright" yet muffled, "pingy," and "dead" tone because the amplitude of the fundamental has plummeted. Again, we find evidence to characterize "brightness" as a distinct presence of upper harmonics.

An experimental factor that had to be taken into account was the fact that small deviations in bar position greatly affected the amplitudes of the upper harmonics. We came to this conclusion by the following argument: the location of the anti-node of the fundamental is, effectively quite wide. One can strike as much as 4 cm away from the center while still exciting most of its amplitude (see Figure 10). However, the standing wavelengths of the 3^{rd} and 4^{th} harmonics are much shorter (see Figure 1). Thus their regions of anti-nodes will be all that much narrower, and the upper harmonics will be much more sensitive to deviations in strike position. The "resolution" of the 10^{th} harmonic – the density of its anti-nodes – becomes so high that the width of the mallet's impact area begins to influence the amplitude. At such a high harmonic, it is difficult to pinpoint exactly where an anti-node will occur, especially considering the Jason's White mallet (whose mallet head had a longitudinal diameter of ~ 6 cm).

Extending the Research

This research has proven invaluable to authors' understanding of the acoustical properties of performed music, and the quantifiable adjectives that generally accompany descriptions of this music. These studies have been of even greater asset to the author as a percussionist – the acoustical properties of a mainstream instrument and its mallets will be of great aid in thoroughly understanding the science of this musical passion. The characterizations of tone, timbre, and overall sound quality are powerful tools that musicians can utilize to make more informed and precise musical decisions.

Several sub-experiments yielded unexpected or uncharacterized results that beg further study. As previously described, there exists an end correction in the length of the effective resonator L. This end correction value of $.6R = 1.95 \pm 0.03$ cm nearly coincides with the measured value $h = 2.5 \pm 0.2$ cm of the bottom of the bar above the physical resonator tube; the bar is only ~ 0.55 cm above the end of the effective tube. Whether or not this is merely a coincidence is not known. However, it would be interesting to investigate the relationship between h and the tone produced, specifically in terms of the resonance created and the possible interference caused by the bar being inside the effective length of the tube. Does the distance between the bar and the tube (both laterally and vertically) affect the tone? If the bar is too close to the effective length, does interference occur? If so, what kind of interference is produced?

Figure 12 shows a very clear logarithmic fit of the decay time. By extrapolation, a time constant τ could be calculated to further describe the decay processes.

As noted in the previous resonator function analysis section, a definitive reason for the double peak could not be isolated. However, we hypothesize that it is, in fact, due to a poorly tuned resonator. More precise equipment would allow us to pursue this avenue of study and determine how the measured L compares to the theoretical L.

Finally, Figure 7 shows an interesting phenomenon in its peak: immediately after $t = 0$, a transient double peak is seen which resolves itself into the characteristic single peak at E660 Hz very soon after its appearance. This phenomenon was observed throughout most of the trials involving the 4 octave marimba. We do not know why an initial double peak would resolve into a single peak, but these open questions could certainly fuel further research.

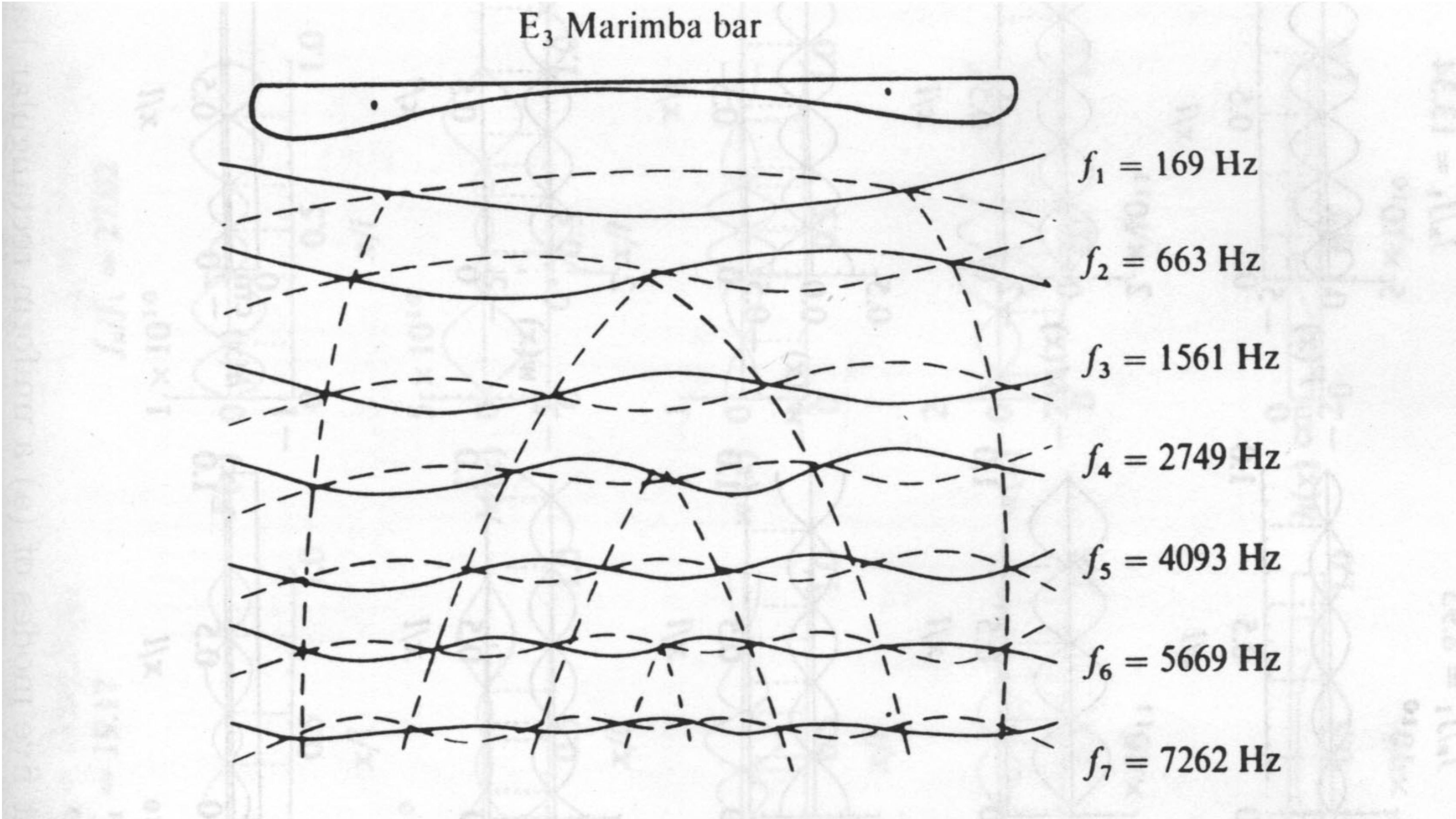

Figure 1 – Scale drawing of a marimba bar tuned to E3 (f = 169 Hz). The dashed lines locate the nodes of the first seven modes of transverse vibration.

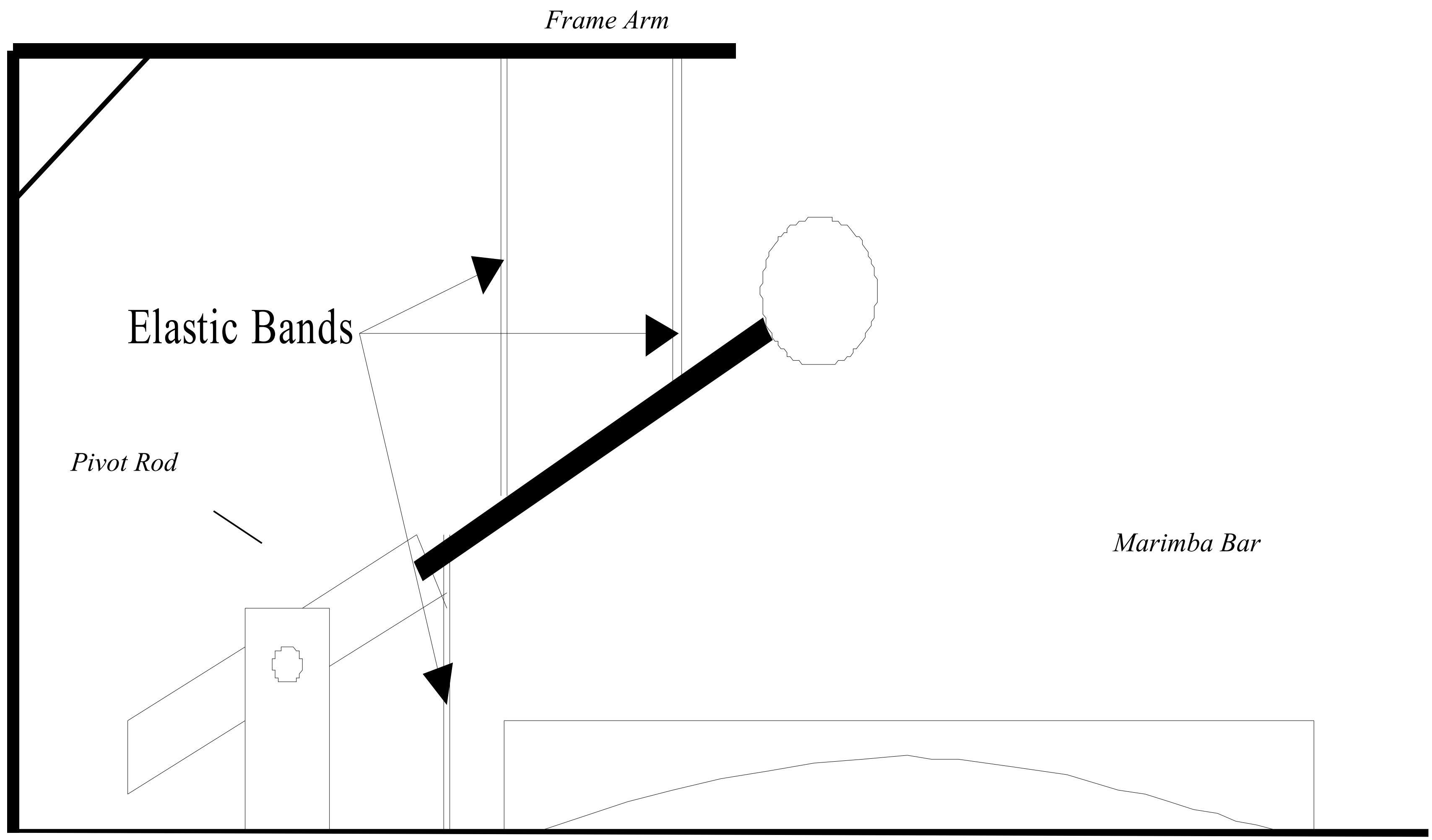

Figure 3 – Striking Apparatus
Apparatus consisting of a wooden base, wooden dowels, a metal pivot rod, eye screws, epoxy, and roller bearings. Standardized rubber bands joined the frame arm to the marimba mallet. Eye screws along the frame arm made it possible to adjust the torque imparted to the mallet shaft. This apparatus was built to facilitate consistent reproduction of a mallet stroke.

Further figures unavailable at this time…

1References

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