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WHAT DO BELLS MADE FROM LUNAR REGOLITHS SOUND LIKE?

Ana M. Barbancho[1*] **Isabel Barbancho**[1] **Lorenzo J. Tardón**[1] **Carlos Traginer**[2]

[1] ATIC Research Group, ITIS Software, ETSI Telecomunicación,
University of Málaga, 29071 Málaga, Spain
[2] Traginer Music Research LAB, Zaragoza, Spain

ABSTRACT

Building permanent bases for human life on both the moon and Mars is one of the greatest challenges facing humanity. All civilisations, from the most ancient to the present, have had their own music. This music has been conditioned, among other factors, by the material means that were naturally available. Moreover, the initial musical instruments of all civilisations have been percussion instruments. Therefore, if in the future humans are to inhabit the moon or Mars, they must be able to make musical instruments with the materials available in their environment. This article presents the design and the acoustic characterisation of bells made from lunar regolith. This will make it possible to analyse the ability to create music with the materials available on the moon and thus to improve the adaptation of humans.

Keywords: *bell, moon sound, lunar regolith, acoustic characterization*

1. INTRODUCTION

The origins of music are closely intertwined with the origins of humanity [1]. Both archaeological excavations and cave paintings depict music in its simplest forms—percussion and wind instruments. Music has always played a vital role in human communication, from warning of dangers to expressing emotions and serving as a form of entertainment.

**Corresponding author*: abp@uma.es.

Among all percussion instruments, bells have been present in every civilization, and they continue to be studied and constructed today, both as instruments for classical orchestras, church carillons, and as auditory signaling elements on ships, among other uses [2], [3].

Therefore, in a future—whether near or distant—where humanity may establish colonies on other planets or even in other galaxies [4], [5], music must remain an essential part of human life. Moreover, humans will need to build musical instruments using the materials available in the places where they live.

This article presents the design and acoustic characterization of bells made from lunar regolith. This will enable an analysis of the potential to create music using materials found on the Moon, thereby improving human adaptation to extraterrestrial environments.

The article is structured as follows. Chapter 2 presents the design of the bells. Chapter 3 details the data acquisition system used for capturing the sounds of the bells. Chapter 4 describes the bell sound database that has been created. Chapters 5 and 6 present the tools used for characterizing the bell sounds and the results obtained from their analysis, respectively. Finally, Chapter 7 provides the conclusions drawn from this study.

2. BELLS DESIGNS

The design of bells has been a task to which considerable time and effort have been devoted over the centuries across numerous civilizations. Through the analysis of bells and percussion instruments from various cultures, such as Japanese wind bells, Tibetan singing bowls, Japanese-style dopamine bells, the town hall bell of Brihuega (Guadalajara, Spain), wind chimes, and others, it was concluded that a cylindrical geometry provides an effective foundation for bell design. Moreover, considering the nature of the materials to be used, as described in subsection 2.1, the size should be kept compact. Figure 1 presents the dimensioned plans of the bells that were designed and manufactured.

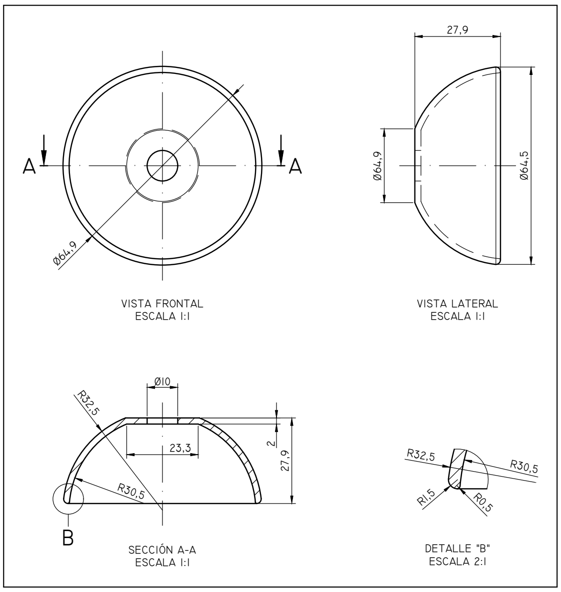


Figure 1: Plan, profile and elevation with dimensions of bells to be measured.

2.1 Bell manufacturing materials

In the present study, the acoustics of bells made from three different materials, each with two casting times, have been measured, resulting in a total of six bells to be measured and characterized. Figure 2 shows the six bells to be acoustically characterized, labeled with their respective material and casting time.

The three materials used are as follows:

- Porcelain (POR-03C-AT): A ceramic made from varying proportions of clay, kaolin, feldspar, and quartz. It is a material with good plasticity, being a casting porcelain suitable for general use [6].
- LHS-1: The Lunar Highlands Simulant (LHS-1) is a high-fidelity, mineral-based simulant designed to represent a generic or average highland location on the Moon. The highlands are considered the "lighter" regions of the Moon's surface, primarily composed of plagioclase, often referred to as Anorthosite. This simulant is not made from a single terrestrial lithology, but accurately replicates the texture of lunar regolith by combining both mineral and rock fragments in precise proportions based on the Apollo mission regolith samples [7].
- LMS-1: Lunar Mare Simulant (LMS-1) simulates the lunar mare regions, which are the darker portions of the Moon's surface. LMS-1 is a high-fidelity, mineral-based analog commonly used for educational and research purposes. This formula was designed based on data from the Apollo Lunar Soil samples [7].

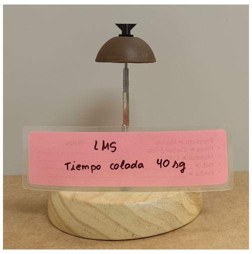
It is noteworthy that due to the fragility and handling difficulties of the materials used, especially the porcelain, the 8-minute porcelain bell presents a small crack on its edge, which could lead to changes in its acoustics.

(a) Porcelain 6 min.

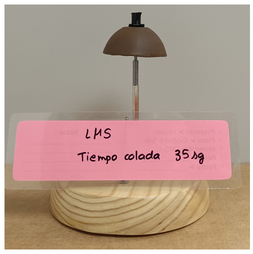
(b) Porcelain 8 min.

(c) LHS-1 40 sec.

(d) LHS-1 35 sec.



(e) LMS-1 40 sec.



(f) LMS-1 35 sg.

Figure 2: Bells to be acoustically characterised labelled with material and casting time (a) Porcelain and casting time 6 min. (b) Porcelain and casting time 8 min. (c) LHS-1 and casting time 40 sec. (d) LHS-1 and casting time 35 sec. (e) LMS-1 and casting time 40 sec. (f) LMS-1 and casting time 35 sg.

2.2 Bell holders and mallets

In addition to the three types of manufacturing materials, three mallets made of different materials were used: wood, metal with a wooden head, and metal. These were used to assess how the type of mallet affects the sound produced by the bells. Figure 3 shows the three mallets used for the acoustic characterization.

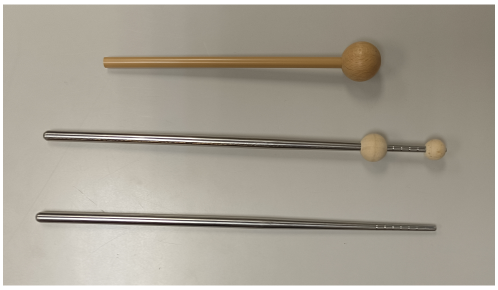
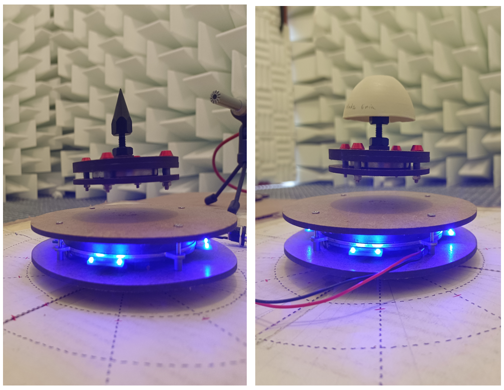


Figure 3: Mallets used for acoustic characterisation, from top to bottom: wooden mallet, metal mallet with shaped head and metal mallet.

Furthermore, to analyze the effect of the bell support, two types of supports were used: a fixed-base support (Fig. 2) and a support using a magnetic levitator (Fig. 4).



(a) Empty (b) With a bell

Figure 4: Magnetic levitator holder. (a) Empty. (b) With 6 min porcelain casting bell.

3. ACOUSTIC DATA ACQUISITION SYSTEM

In order to perform the acoustic characterization of the bells, it is essential to obtain sound recordings that are as pure and clear as possible, minimizing any external noise and interference from the recording environment. To achieve this, the recordings were made in the anechoic chamber at the E.T.S.I. de Telecomunicación, University of Málaga [8]. Figure 5 shows an image of the anechoic chamber at the E.T.S.I. de Telecomunicación, University of Málaga.

The anechoic chamber at the E.T.S.I. de Telecomunicación is specifically designed to eliminate acoustic wave reflections. Both the floor and the interior walls are lined with pyramidal wedges made of sound-absorbing materials, which further enhance the dispersion of any sound that is not absorbed. Additionally, the chamber is fully isolated from external noise sources.

For the recordings, two Behringer ECM8000 microphones [9] were employed. These are ultra-linear condenser microphones with a flat frequency response ranging from 20 Hz to 20 kHz, offering high sound resolution and an omnidirectional pickup pattern, making them ideal for precise acoustic measurements.

The bells were positioned in the center of the anechoic chamber, with the microphones placed at 90° and 180° relative to the striking point, as shown in Figure 6.

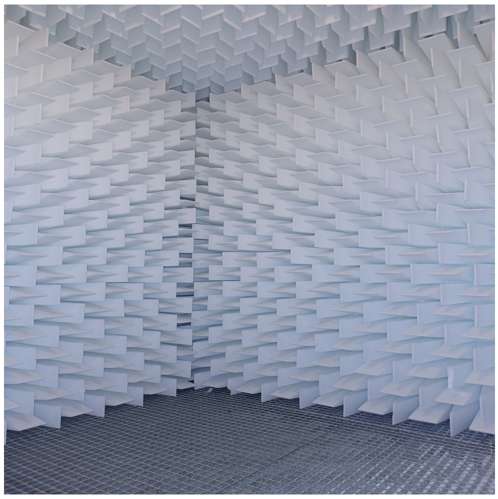


Figure 5: Anechoic chamber of the E.T.S.I. de Telecomunicacion of the University of Malaga [8].

To carry out the recordings, the output signal from the microphones was connected to the Roland QUAD-CAPTURE sound card [10], which allows for the recording of two independent audio channels. The sound card was configured to record at a resolution of 24 bits and a sampling rate of 44.1 kHz.

Regarding the software used, Audacity [11], a free

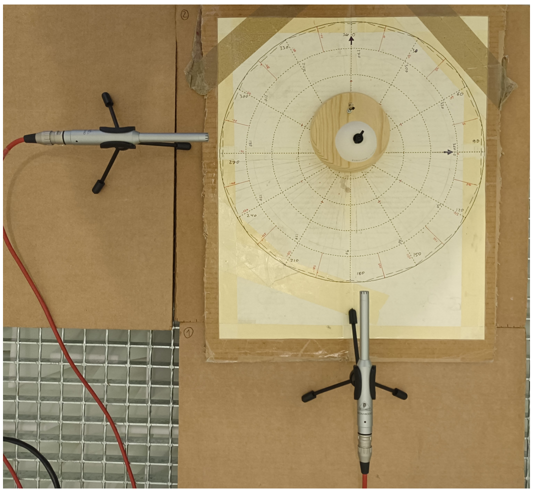


Figure 6: Positioning of the measuring microphones [9] in relation to the bells.

software application for recording and editing audio, was employed for the audio recording. For the analysis and characterization of the recordings, Matlab [12] was utilized due to its computational power and the existing libraries for audio signal processing.

4. DATABASE OF BELLS MADE WITH LUNAR REGOLITH AND PORCELAIN

This study has resulted in a database of bell sounds made from lunar regolith and porcelain. Each of the six bells (Fig. 2) was recorded with both types of supports, fixed and magnetic levitator, using the three types of mallets (Fig. 3), striking the bell twice—once on the lower half and once on the upper half—with two microphones positioned at 90° and 180° relative to the striking point (Fig. 6). This process has generated a database of 144 *.wav files, sampled at 24 bits and 44.1 kHz.

5. TIME AND FREQUENCY TOOLS FOR THE CHARACTERIZATION OF BELL SOUNDS

In this section, the time and frequency tools employed to characterize the bells sounds are described.

5.1 Time domain characterization

The study of the sounds produced by the bells in the time domain aims to determine if there are notable differences in the duration, amplitude, and waveform of the signals between the different bells, so that the influence of the material can be assessed.

A classic parameter for studying the signal in the time domain is the envelope. For this study, the classic envelope model for isolated musical sounds proposed by Jensen [13] will be used. To obtain the envelope, a 5th-order Butterworth filter with a cutoff frequency of 11 Hz was applied. The result was then normalized to a maximum value of 1. The attack time (T_a) is defined as the time between the first sample that exceeds 10% of the maximum value and the first sample that reaches 85% of the maximum amplitude. The release time (T_r) is calculated as the time between the last sample at 70% of the maximum amplitude and the last sample that exceeds 10%. The time between T_a and T_r is called the sustain time (T_s). It is expected that, depending on the material the bell is made from, and under equal excitation conditions, these times will differ.

5.2 Frequency Domain Characterization

To characterize the bell sounds in the frequency domain, both the FFT and the spectrogram will be used. In both cases, the frequency axis will be expressed in MIDI number (eq. 1).

$$MIDI = 69 + 12log_2(f/440) \qquad (1)$$

The FFT calculation will be performed using the entire sound length of each recording. For the calculation of the spectrogram, a window size of 1024 will be used, with an overlap of 512, a Hamming window, and a DFT length of 4096. To determine the fundamental frequency, the algorithm proposed by Yin [14] will be employed. Additionally, for the characterization of the harmonic part of the signal relative to the residual, the model presented in [15] will be used.

6. RESULTS

This section characterizes the different bells and analyzes the influence of the supports, mallets used, and striking point, based on the time and frequency characteristics presented in section 5.

6.1 Analysis of the Envelope, Attack Time, and Decay Time

To perform the analysis of the envelope along with its attack and decay times, the first step was to evaluate whether there were significant differences between using recordings made with the microphones at 90° or 180°. As shown in Fig. 9, the envelopes are similar. Therefore, this section will focus on the recordings made with the microphone positioned at 90°.

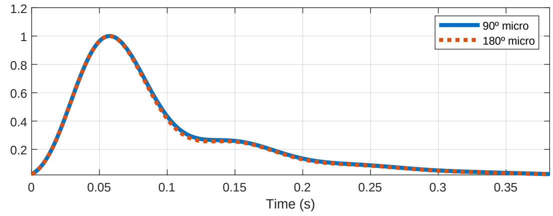


Figure 7: Envelope LHS-35s bell, wooden mallet, low impact and fixed support, for 90º and 180º microphone.

The attack and decay times were calculated as the average of the attack and decay times computed for each bell, with both types of supports, three types of mallets, and two striking positions (12 recordings in total per bell). It is noteworthy that the support and the method of excitation of the bell do not have a significant influence on the attack and decay times.

Table 1: Comparison of bells according to their time attack (T_a) and time release (T_r) (ms) and fundamental frequency ($F0$) in MIDI number and the distance from the fundamental to the first overtone (ΔF) also in MIDI.

Bell type	T_a	T_r	$F0$	ΔF
LHS-35s	31.5 ms	139.2 ms	108	14.80
LHS-40s	31.3 ms	179.0 ms	107	16.02
LMS-35s	30.7 ms	93.9 ms	108	14.18
LMS-40s	31.1 ms	113.9 ms	107	14.64
Por-6min	30.3 ms	81.7 ms	96	19.25
Por-8min	31.6 ms	134.6 ms	101	16.03

Table 1 shows the average attack and release times for each type of bell. The following observations can be made from this table:

- The attack and release times are similar across all bells, showing no significant differences according to the material type.
- The attack times are much shorter than the release times, which aligns with the typical characteristics of small-sized percussion instruments, such as the bells being characterized [16].

Regarding the shape of the envelope, when analyzing all the recordings based on the type of support, mallet, and striking position, it was observed that there are differences depending on whether a fixed support or a levitator support is used (Fig. 8). It was found that the levitator support, which allows the bell to move from its position, causes the envelope to decay uniformly. However, the fixed support, which provides rigid attachment at the top, results in some cases where the envelope does not decay uniformly.

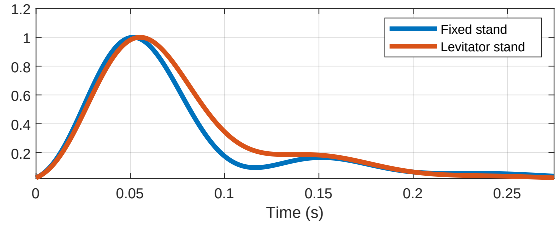


Figure 8: Comparison of envelope between fixed and levitator stand for LMS-40s bell, high stroke with wooden mallet.

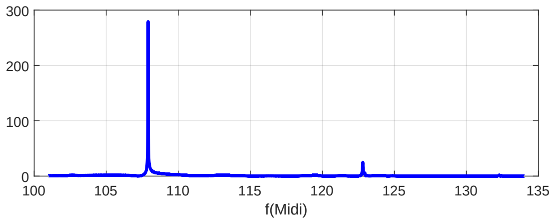
6.2 Analysis of the fundamental frequency

One of the most interesting parameters to study is the fundamental frequency of each bell, as well as the number of overtones they exhibit and the intervals between them.

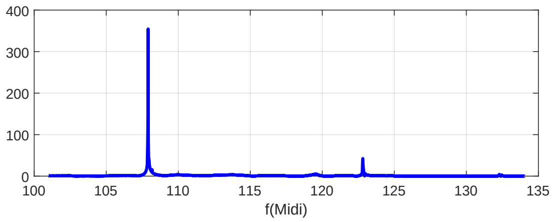
First, it was evaluated whether there were any differences in the frequency analysis when using recordings made with microphones placed at 90º or 18º0 degrees. It was observed that the microphone placement had no significant effect on the analysis, as shown in Fig. **??**. Therefore, it was decided to use the recordings from the microphone placed at 90º degrees.

The fundamental frequency was calculated as the average of the fundamental frequencies calculated for each bell, with both types of supports, the three types of mallets, and the two striking positions (12 recordings in total per bell). It is worth noting that the support type and the excitation method of the sound in the bell do not have a significant influence on the fundamental frequency. Similarly, the difference between the fundamental frequency and the first overtone was also calculated.

Table 1 shows the fundamental frequency of each bell in MIDI number, as well as the distance between the fundamental frequency and the first overtone, in MIDI number. The following observations can be made from this table:



(a) 90º microphone

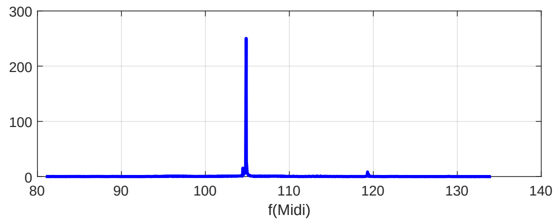


(b) 180º microphone

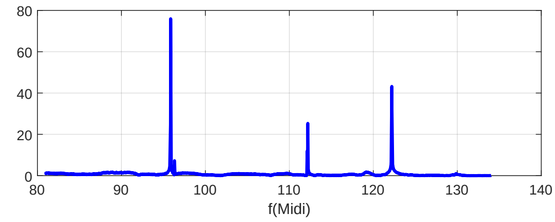
Figure 9: Spectrum of LMS-35s bell, mixed mallet, low stroke, fixed stand for (a) 90º and (b) 180º microphone.

- The fundamental frequencies of the bells made from lunar regolith (LHS and LMS) are higher than those of the porcelain bell.
- The fundamental frequencies of the bells made from lunar regolith are identical for the same pouring time, with those of shorter pouring times being higher. However, for the porcelain bell, the one with the longer pouring time exhibits a higher fundamental frequency.
- The distance between the fundamental frequency and the first overtone is significantly greater for the porcelain bells than for the lunar regolith bells. The harmonic distances in the lunar regolith bells are quite similar, except for the LHS bell with a pouring time of 40s, which shows a greater distance.
- None of the bells exhibit harmonic frequencies, as the distance between the fundamental frequency and the first overtone is not an integer multiple of the fundamental frequency (in Hertz).
- The fundamental frequencies are relatively high, given the small size of the bells.

Another parameter that has been analyzed is the number of overtones present in the recorded sounds of the bells. Upon analyzing all the recorded sounds of the bells, it was observed that the bells made from porcelain exhibit three peaks in the spectrum (fundamental frequency and two overtones), whereas the bells made from lunar regolith only show two peaks (fundamental frequency and one overtone). Clearly, porcelain behaves differently from lunar regolith in this regard. Fig. 10 shows an example of the spectrum of a lunar regolith bell and a porcelain bell, highlighting the difference in the number of overtones. To conduct a more in-depth study of the overtones produced by each material, it would be necessary to manufacture larger bells, as the ones available, having such high fundamental frequencies, result in any additional overtones falling outside the range of human hearing.



(a) LHS-40s bell



(b) Porcelain 6 min bell

Figure 10: Spectrum for (a) LHS-40s bell and (b) porcelain 6 min bell, mixed mallet, low stroke and fixed stand.

6.3 Influence of the type of support and striking location

As outlined in section 2.2, two distinct types of supports were used, fixed and magnetic levitation, to characterize the bell sounds. The magnetic levitation support, being a magnetic system, attracted the metal mallet, which led to the recordings being made with lower-force strikes and very light impacts.

The comparative acoustic evaluation of the recordings made with the fixed support versus the levitation support reveals that the recordings with the fixed support exhibit higher volume and richer tonal quality. This can be attributed to two factors: firstly, with the levitation system, the force applied had to be reduced to prevent excessive movement of the bell, which could cause the levitation point to be lost and the bell to fall. Secondly, because the bell was levitating, some of the mallet's energy was dissipated in moving the bell and its support off its axis, which does not contribute to sound production.

This evaluation is evident in the calculation of harmonic energy relative to residual energy from the recordings of all the bells, considering the initial 20% of the total sound duration (from the attack time to the onset of the sustain phase). Table 2 displays the mean harmonic energy relative to residual energy for the six bells, across the three mallet types. It is clear that the higher striking point of the bell generates less harmonic richness than the lower striking point, and that the fixed support also contributes to a richer tonal output, as confirmed by the sound evaluation.

Table 2: Harmonic energy with respect to the residual for comparison of bells according to striking location and the type of support (Striking location-type of support): High-Levitator (H-L), High-Fixed (H-F), Low-Levitator (L-Lev) ando Low-Fixed (L-F).

Bell type	H-Lev	H-F	L-Lev	L-F
LHS-35s	1.37	1.81	1.97	2.52
LHS-40s	0.87	2.97	0.60	2.85
LMS-35s	1.60	2.91	1.10	5.12
LMS-40s	0.28	1.30	0.93	1.78
Por-6min	0.27	0.34	0.67	0.42
Por-8min	0.92	3.22	1.61	1.36

6.4 Influence of the type of mallet

As shown in Fig. 3, three different types of mallets were used. The choice of mallet type has been sonically proven to have an impact on the sound. In general, the sounds produced with the wooden mallet were louder and more resonant than those with the mixed mallet, while the metal mallet yielded the most limited volume and sonority. Clearly, more than the material, the larger striking surface of the mallet excites more movement in the bells (note that the wooden mallet has the largest surface, while the metal tip has the smallest).

In Table 3, the average harmonic energy relative to the residual energy is shown (considering the initial 20% of the total sound duration, which includes the attack time and the start of the sustain time) for the six bells, across both supports, both striking positions, and all three types of mallets (wooden, metal, and mixed). It is evident that the wooden mallet produces the greatest sound output of the three, followed by the mixed mallet.

Table 3: Harmonic energy with respect to the residual for comparison of bells according to evaluate the influence of the type of mallet.

Bell type	Wood	Metal	Mixed
LHS-35s	2.98	0.85	1.83
LHS-40s	4.47	0.55	3.68
LMS-35s	3.74	0.84	3.76
LMS-40s	1.79	0.83	0.68
Por-6min	0.76	0.49	0.41
Por-8min	1.40	1.46	2.52

7. CONCLUSIONS

This paper presents a study of the sound produced by bells made from lunar regolith. For this purpose, recordings were made of six different bells: four made from two types of lunar regolith (LHS and LMS), and two made from porcelain. The goal was to assess the differences between bells made from Earth materials. Additionally, three types of mallets and two support types—fixed and levitation—were employed.

The key conclusions drawn from this study are as follows:

- The sound of the bells made from lunar regolith shows strong similarities both among them and with the porcelain bells. Thus, it is possible to obtain instruments with similar tonal qualities even when using different starting materials.
- Due to their small size, the attack and decay times are relatively short. However, this is consistent with all percussion instruments of similar dimensions.
- Similarly, the fundamental frequencies are relatively high (ranging from 96 to 108 in MIDI number), as expected for small bells.
- The envelopes of the bells are similar across all samples, with the type of support having the greatest influence on their shape. The levitation support, by allowing free movement in all directions, results in smoother envelopes. This behavior could be representative of how such instruments would function

in environments with lower gravity than Earth's.

- The harmonic content of bells made from lunar regolith exhibits fewer overtones compared to porcelain bells. This indicates that the ability of lunar material to vibrate is slightly inferior.
- The study of support type and strike point revealed that striking the bell at a higher point produces fewer harmonic overtones than striking it lower. Furthermore, a fixed support produces a richer sound.
- The influence of mallet type showed that the wooden mallet generates the highest sound production, followed by the mixed mallet. It is evident that the size of the striking surface is the most significant factor influencing the sound, as the wooden mallet has the largest striking surface.

Given that the bells manufactured are very small and thus produce very high fundamental frequencies with short sound durations, it would be beneficial to have larger bells to continue advancing in the acoustic characterization of different materials.

In conclusion, this study demonstrates that it is possible to manufacture musical instruments similar to those used on Earth using materials from other celestial bodies. Thus, this research represents a significant step forward in the possibilities of supporting human life on other parts of the universe.

8. ACKNOWLEDGMENTS

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