Acoustic Analysis of the Sacred Bell of King Seongdeok and the Utilization of Digital Sound Sources

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Keywords: Sacred Bell of King Seongdeok, Vibrational and acoustic characteristics, Natural frequency, Digital sound source.

Abstract

The Sacred Bell of King Seongdeok, cast in 771, is one of Korea’s most iconic cultural heritage artifacts, renowned for its elegant appearance and magnificent sound. To ensure its preservation, regular striking of the bell was discontinued in 1992. Since then, several scientific investigations have been conducted to accurately assess the bell’s condition and develop effective conservation strategies. The most recent investigation was an acoustic analysis carried out from 2020 to 2022. This study aimed to diagnose potential structural changes in the bell by comparing the results with those from an acoustic investigation conducted two decades earlier. Upon comparison, no changes were observed in the distribution of natural frequencies. Furthermore, there were no differences in beat duration or directionality—factors that are highly sensitive to even subtle structural changes—suggesting that no significant structural alterations have occurred, based on vibration and acoustic measurements. Alongside this diagnostic analysis, sound sources were recorded during the investigation in an effort to capture audio as close as possible to the bell’s original sound. The digitized sound data obtained through this process is now made publicly available in various formats, allowing the general public to listen to and experience the sound of the Sacred Bell.

1. Introduction

The Sacred Bell of King Seongdeok, cast in 771, is a representative bronze bell from the Unified Silla period and is recognized as a national treasure of Korea. Celebrated for its exceptional artistry, advanced casting techniques, and magnificent, beautiful sound, it stands as one of Korea’s most iconic cultural heritage artifacts. Although the bell resounded for over 1,200 years, regular striking was discontinued in 1992 for preservation purposes. Since then, several scientific and acoustic investigations have been conducted to accurately assess the bell’s condition and develop effective conservation strategies. A comprehensive investigation carried out from 1996 to 1997 included an assessment of the bell’s external condition, measurements of its weight and dimensions, analysis of its material composition, and a study of its basic acoustic properties. From 2001 to 2003, more detailed research focused specifically on its vibrational and acoustic characteristics.

The most recent investigation, conducted from 2020 to 2022, was an acoustic study carried out in collaboration with Professor Seokhyeon Kim’s research team from the Department of Mechanical and Mechatronics Engineering at Kangwon National University. In this study, measurements of natural frequencies and beat waveforms recorded two decades earlier were compared to assess potential structural deformation. Alongside this diagnostic analysis, various recording techniques—including the 5.0.4 3D system and 5.0 multi-channel setup—were employed to capture the bell’s sound as faithfully as possible. These sound sources were digitized to create a high-fidelity archive of the bell’s acoustic profile at the time of investigation. The resulting digital data is being utilized in a variety of ways: to support the scientific preservation of the Sacred Bell of King Seongdeok, to reproduce its sound in audible formats, and to provide the general public with immersive opportunities to experience this cultural heritage.

Figure 1. Acoustic investigation of the Bell in 2020.

2. Acoustic Study

In recent years, the growing frequency of natural phenomena in the Gyeongju region—including typhoons, extreme heat, and earthquakes—has raised concerns about the structural safety of the Sacred Bell of King Seongdeok, which is displayed outdoors. To assess the current condition of the bell, various scientific methods were considered, including ultrasonic testing, non-destructive CT scanning, gamma-ray inspection, and acoustic study. Among these, acoustic study was deemed the most viable method, as historical data were available for direct comparison.

Acoustic study is a diagnostic method that compares the acoustic fingerprint—such as natural frequencies and vibration patterns—generated when the bell is struck, against past data to determine whether any significant cracks or defects have developed. The fundamental principle is similar to the acoustic study used in railway maintenance to detect damage to bolts and screws.

If substantial internal corrosion or cracking has occurred, it can result in noticeable changes in the bell’s natural frequencies. For example, in the case of the bronze bell at Sangwonsa Temple,

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-735-2025

which ceased being struck in 1971 due to cracking, the hum tone frequency at the time was 102 Hz, with a beat period of just 0.5 seconds. Following conservation efforts, including welding of the cracked area, the hum tone frequency rose to 105 Hz, and the beat period extended to 4.5 seconds. This demonstrates how internal structural changes can affect frequency data, making such testing a valuable tool for detecting internal defects. The acoustic study of the Sacred Bell of King Seongdeok was conducted over a three-year period from 2020 to 2022 as part of a comprehensive safety evaluation.

2.1 Methodology

Figures 2 and 3 show the configuration of the acoustic study equipment and the 24 measurement points on the Sacred Bell of King Seongdeok. These 24 locations match those used in measurements conducted in the early 2000s. First, the bell was lightly struck at Point 1 (the designated striking point) using a dedicated wooden hammer. To minimize background noise, the sound was measured at a point 30 cm from the bell’s surface and 1 meter above ground level.

Subsequently, a small portable hammer was used to sequentially strike all 24 designated points, during which vibration data were collected. Vibrations were measured at Point 1 using an accelerometer placed 30 cm above the lower rim of the bell, while sound was recorded simultaneously using a microphone. Additional measurements were taken at other locations as needed.

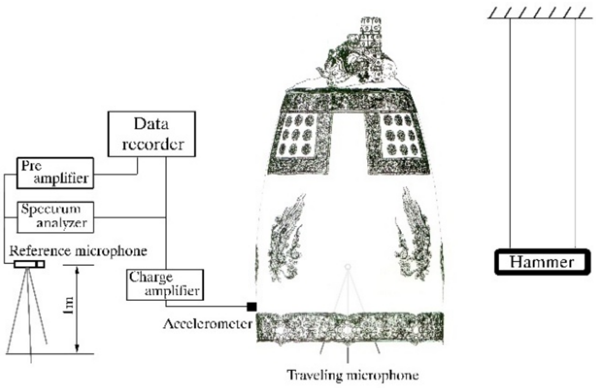


Figure 2. Configuration of the acoustic study equipment

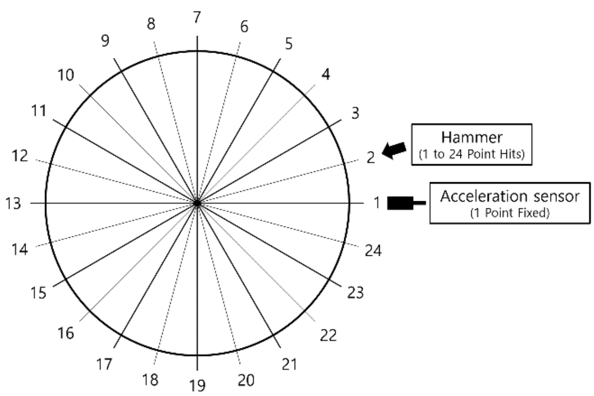


Figure 3. Bell striking points and sensor placement locations

Figure 4. Acoustic analysis of bell striking

3. Results and Analysis of Acoustic Study

3.1 Measurement of Natural Frequencies

Natural frequency is an inherent property of a physical object, and even minor structural changes—such as internal defects—can result in subtle shifts in its frequency distribution. In this study, vibration and acoustic signals were measured using two types of hammers: a dedicated wooden hammer for the designated striking surface, and a smaller portable hammer for sequentially striking 24 points around the lower body of the bell. From these measurements, the natural frequency components within the 1,000 Hz range—those that govern the bell’s vibration and acoustic characteristics—were extracted.

In the impact test on the designated striking point, approximately 50 natural frequency components within the 1,000 Hz range were identified and compared with data recorded in 2003. The results revealed almost no difference between the natural frequencies measured in 2003 and those measured between 2020 and 2022. The first natural frequency, which produces the bell’s hum tone, was approximately 64 Hz, while the second natural frequency, which creates the fundamental tone, was around 168 Hz. Both showed differences within just 0.1% compared to the 2003 data. The 50th natural frequency also showed a very small difference—within 0.1%—compared to the 2003 data. The minute differences are likely attributable to variations in frequency resolution due to measurement conditions or environmental factors at the time of striking. Figure 5, overlaying the frequency measurements from 2003 and 2020–2022, shows that the results are nearly identical—appearing almost as a single curve. This high level of consistency indicates that the acoustic properties of the Sacred Bell have been well preserved over time, without significant change.

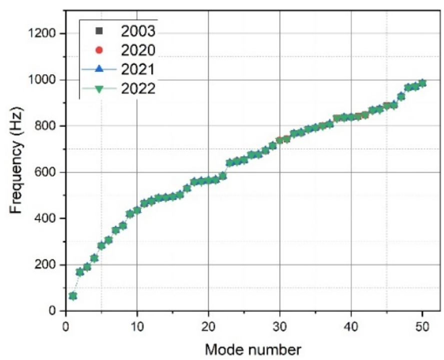


Figure 5. Comparison of Measured Natural Frequency Distributions by Year

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-735-2025

3.2 Natural Frequency Pairs and Beat Duration

Due to the bell's subtle asymmetry, each natural frequency occurs as a pair of closely spaced frequencies. These natural frequency pairs interfere with each other to produce beat phenomena. Because beat duration is highly sensitive to even minute frequency shifts, it serves as a useful indicator for detecting potential structural changes. In this study, the frequency pairs and mode pairs associated with the hum tone and fundamental tone were measured, and their corresponding beat durations were analyzed and compared with previous data.

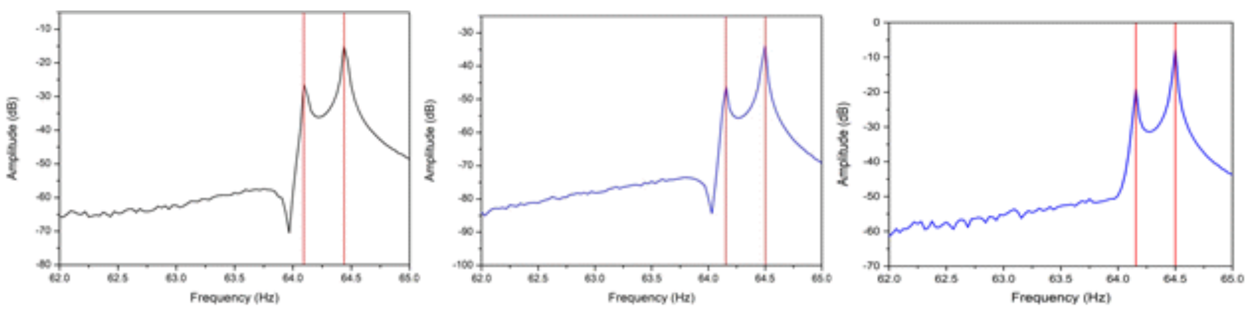
The pair of frequencies associated with the first natural mode produces a "breathing" hum tone, creating a prolonged and resonant auditory effect. Meanwhile, the pair of frequencies associated with the second natural mode generates beat phenomena in the fundamental tone, giving the bell a dynamic and magnificent impact sound. These frequency pairs corresponding to the first and second natural modes are therefore of great acoustic importance. Table 1 compares the frequency pairs of the first and second natural modes. In each pair, the mode with the slightly lower frequency is labeled L, and the one with the higher frequency is labeled H. For the first natural mode, the difference of the frequency pair ranged from 0.32 Hz to 0.37 Hz between 1996 and 2022. In both 2021 and 2022, the difference was measured identically at 0.34 Hz. The beat duration was likewise consistent, measured at 2.94 seconds. For the second natural mode, which contributes to the beating in the fundamental tone, the frequency difference between the pair ranged from 0.10 Hz to 0.13 Hz since 1996. The beat duration measured from the time-domain waveform has remained stable at 9 seconds, both in data recorded two decades ago and in recent measurements. The stability of the beat durations in both the first and second natural modes over the past 20 years indicates that the frequency differences within each pair have remained unchanged. This, in turn, suggests that no significant structural changes have occurred in the bell during that time.

3.3 Beat Map

Beat waveforms of the first and second vibrational tones were measured at 24 circumferential points around the Sacred Bell. Based on these measurements, a beat map was created. This map was used to identify acoustic variations depending on direction along the circumference, to locate positions where distinct beats were most clearly observed, and to determine whether any changes had occurred over time.

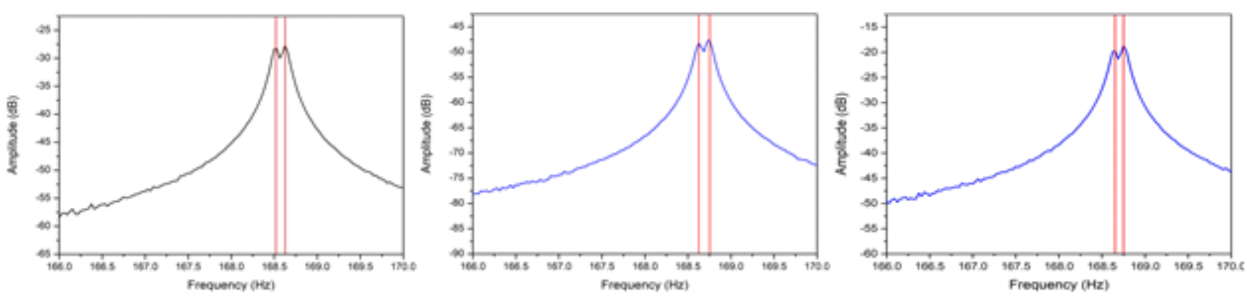
Mode shape	Mode pair	1996	2001	2002	2003	2020	2021	2022
1	**L**	**64.06**	**64.07**	**64.14**	**64.08**	**64.09**	**64.16**	**64.13**
	H	**64.38**	**64.42**	**64.48**	**64.45**	**64.44**	**64.50**	**64.47**
2	**L**	**168.31**	**168.52**	**168.60**	**168.47**	**168.53**	**168.63**	**168.59**
	H	**168.44**	**168.63**	**168.72**	**168.59**	**168.63**	**168.75**	**168.72**

Table 1. Comparison of Paired Natural Frequencies (Hz)



Year 2020 Year 2021 Year 2022

Figure 6. Magnified Spectrum of the First Mode Frequency



Year 2020 Year 2021 Year 2022

Figure 7. Magnified Spectrum of the Second Mode Frequency

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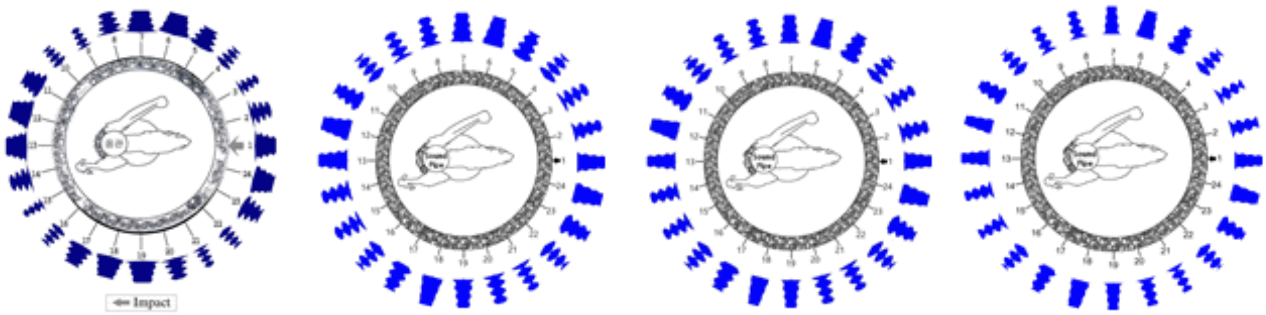
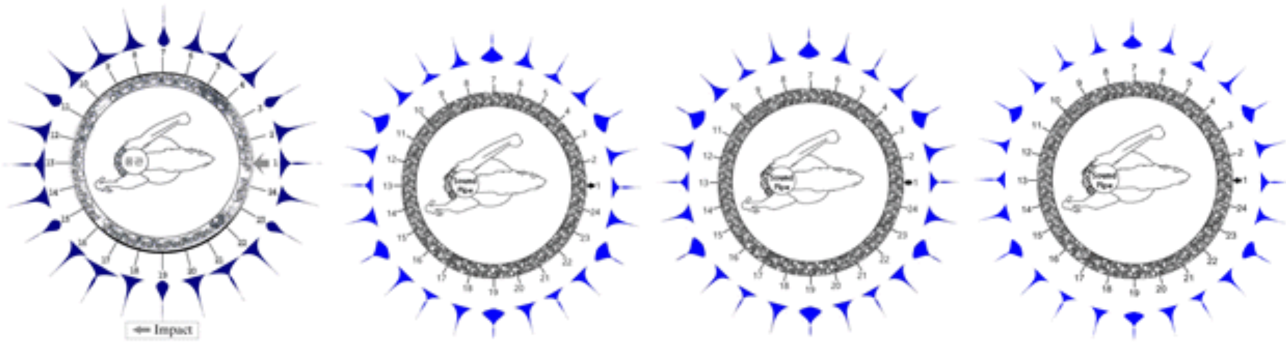


Year 2002 Year 2020 Year 2021 Year 2022

Figure 8. Beat map of the hum tone (first vibrational mode)



Year 2002 Year 2020 Year 2021 Year 2022

Figure 9. Beat pattern map of the fundamental tone

An analysis of the beat map for the first vibrational tone shows that beat of the hum tone is clearly audible at Points 3 and 4, as well as at positions spaced 90 degrees apart from them. In contrast, although the sound was louder at the striking point and its corresponding 90-degree intervals, the beat sound was not clear at those locations. This directional pattern of the beats was found to be identical in both the 2003 and 2022 measurements, indicating that the spatial orientation of the mode pair has remained unchanged.

In the beat map for the second vibrational mode (fundamental tone), a strong and distinct beat is emitted from Point 3, and similarly intense beats are observed at all positions spaced 30 degrees apart from it. This pattern is attributed to the precise symmetrical arrangement of the second mode frequency pair around the designated striking point. The second vibrational tone of the Sacred Bell—measured at approximately 168 Hz—lasts for about 20 seconds after impact and plays a crucial role in producing the bell’s dynamic and magnificent sound. The magnificent sound of 9 seconds seems to fade away, then comes back to life and is heard faintly for about 9 seconds. This perceptual effect is a direct result of the strong beat phenomenon associated with the second fundamental frequency pair. The fact that the directional characteristics of the beats remain unchanged further confirms that no significant structural changes have occurred inside the bell.

3.4 Results of the Acoustic Study

A comprehensive review of the results shows that the natural frequency distribution measured in 2022 exhibited virtually no change when compared to earlier data from 2001–2003 and more recent measurements from 2020–2021. Additionally, there were no observable differences in beat duration or directional characteristics—both of which are highly sensitive to even subtle structural changes. Overall, the vibration and acoustic measurements conducted over the monitoring period suggest that no significant structural changes have occurred in the bell.

4. Recording and Utilization of the Sound of the Sacred Bell of King Seongdeok

The bell sound produced during the acoustic study conducted from 2020 to 2022 was recorded using the 5.0.4 3D sound format, a type of immersive spatial audio. Because the recording was originally captured in the 5.0.4 3D sound format, it can berendered in 3D spatial audio, 2D 5.1 surround sound, and stereo sound formats. Furthermore, the recording was made using the DSD 256fs format, allowing for conversion into a wide range of file types, including DSD, DXD, all WAV formats, all FLAC formats, and MP3. The resulting audio recordings of the Sacred Bell are publicly available on the National Gyeongju Museum’s website, where they are accessible for anyone to use.

The sound of the Sacred Bell of King Seongdeok allows visitors to engage with the artifact in a more immersive and sensory way, extending beyond mere visual appreciation. At the National Gyeongju Museum, speakers have been installed around the bell pavilion to broadcast the bell’s sound every 20 minutes, allowing visitors to not only observe the bell visually but also experience it acoustically. Since 2021, the museum has also introduced a sound experience hall that allows for multisensory interaction with the bell's sound. Under the theme, "A journey to discover the true resonance of the Sacred Bell of King Seongdeok across time and space," the space was designed using a 9.1-channel surround sound system, delivering an immersive 3D audio environment. Through this setup, visitors can both hear and

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physically feel the resonance of the bell, offering a unique, full-bodied sensory experience.

Figure 10. Public access to the sound recordings of the Sacred Bell of King Seongdeok (available on the National Gyeongju Museum website)

Figure 11. Utilization of the Sacred Bell of King Seongdeok’s sound source (Digital Exhibition Hall, National Gyeongju Museum)

Figure 12. The Divine Bell of King Seong-deok on display at the Gyeongju National Museum

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This approach has evolved further to make sound accessible to hearing-impaired audiences. In 2025, the National Museum of Korea introduced a sensory exhibition space titled "Between Spaces (공간-사이)." At the heart of this space lies the sound of the Sacred Bell of King Seongdeok recorded in 2020-2022. The exhibition enables visitors to experience the bell’s signature acoustic feature—beat phenomena, a gentle and sustained fluctuation in loudness—through visual, auditory, and tactile modalities. The bell's most important acoustic features lie in its low-frequency tones at 64 Hz and 168 Hz, and recreating these accurately required a specialized subwoofer system. To deliver the depth of sound, subwoofers were installed in all four corners of the exhibition floor, simulating the beat effect of the 64.18 Hz and 64.52 Hz tones. Listening chairs were also provided, allowing visitors to fully appreciate the soundscape of the bell. Moreover, each chair is equipped with a shaker device that transmits the bell's vibrations to the body, offering a rare and engaging way to physically feel the sound—making the experience inclusive and memorable for all audiences.

Figure 13. Sensory Exhibition Room and Listening Chair at the National Museum of Korea

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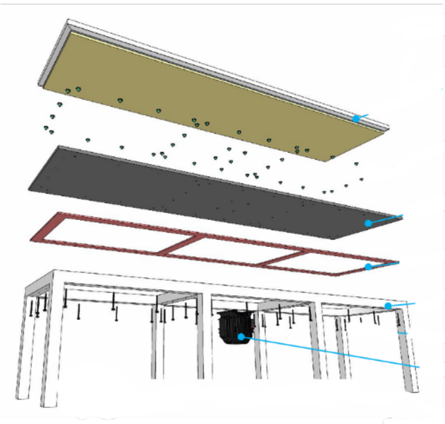

Figure 14. Listening Chair and Structural Diagram

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