Preservation and Visualization of Sound Heritage: Case Study of the Sacred Bell of King Seongdeok

Wan-Ho Cho [1], In-Jee Jung [1], Jung-Han Woo [2], Bong-Ki Kim [2], Jeong-Guon Ih [3]

[1] Division of Physical Metrology, Korea Research Institute of Standards and Science, 34113 Daejeon, Republic of Korea - chowanho@kriss.re.kr; injee@kriss.re.kr
[2] Korea Institute of Machinery and Materials – jhwoo@kimm.re.kr; bkkim@kimm.re.kr
[3] Dept. of Mechanical Engineering, Korea Advanced Institute of Science and Technology – J.G.Ih@kaist.ac.kr

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Abstract

In this study, a sound source modelling method using near-field acoustic holography was proposed as a method to preserve the acoustic radiation characteristics of acoustic heritage, and a series of processes to archive and reproduce the radiation characteristics of the Sacred Bell of King Seongdeok were realized by the proposed approach. The most important essence of an object that produces sound, such as a musical instrument, is the sound itself. Therefore, it is more important to preserve the sound so that future generations can hear it, rather than information such as the appearance, e.g., photo or drawing. However, it cannot be said that all information of sounds is preserved simply by recording well at one point. The sound field radiating from an object also contains spatial radiation characteristics, and it is necessary to preserve information about this. In this study, an actual measurement and reconstruction process based on sound source modeling techniques was proposed to record and reproduce the spatial acoustic radiation characteristics of the Sacred Bell of King Seongdeok. Throughout the process, it was confirmed that the sound field reproduced well represents the unique characteristics of the actual sound heritage and through this, it is expected that a more faithful level of preservation of cultural heritage in the form of intangible sound will be possible.

1. Introduction

The most important essence of an object that produces sound, such as a musical instrument, is the sound itself. Therefore, it is more important to preserve the sound so that future generations can hear it, rather than information such as the appearance, e.g., photo or drawing. However, it cannot be said that all information of sounds is preserved simply by recording well at one point. Even in the case of visual information, it is not possible to preserve whole dimensional information just by taking a picture at one side, and it is necessary to take information in three dimensions and further along time goes by. The sound field radiating from an object also contains spatial radiation characteristics, and it is necessary to preserve information about this.

The Sacred Bell of King Seongdeok has been studied by many researchers due to its historical value and excellence in sound. In the process, research was conducted on the principle of generation of beat, which is said the most important characteristic of the bell (Kim, et al., 1994; Lee et al., 2002; Kim, et al., 2002), and it was also observed that the pattern of beat varies depending on spatial position (Gyeongju National Museum, 2023). For this reason, studies have also been attempted to preserve these variations in spatial characteristics (Cho et al., 2023).

In this study, an actual measurement and reconstruction process based on sound source modeling techniques was proposed to record and reproduce the spatial acoustic radiation characteristics of the Sacred Bell of King Seongdeok.

2. Method

2.1 Basic theory

To preserve the spatial information of the sound field, a modelling method based on acoustic holography was applied for without loos of information. Since the radiation characteristics of a sound source that generates structure-borne sound are determined by the vibration of the sound source, the radiated sound field can be predicted if the structure vibration response can be accurately identified. However, to perfectly predict all structural vibrations, accurate information on the structure and its material properties must be included.

In the case of the Sacred Bell of King Seongdeok, which are large, have complex expressions, and have non-uniform thickness, there are many practical limitations to accurately predicting the vibration response. For this reason, it can be effective to reconstruct the sound source backwards using acoustic information directly connected to actual acoustic radiation, and in this case, it is possible to apply a sound source reconstruction method based on acoustic holography (Williams, 1999).

If the relationship between the sound source and the sound field in space can be derived by solving the wave equation that can express sound transmission, and the sound pressure distribution in a specific measurement plane (hologram plane) can be known through measurement, etc., it is possible to inversely derive the sound source conditions that satisfy the relationship. By applying the estimated sound source conditions, it is possible to predict the sound field at other points where measurements were not made. This series of processes is called acoustic holography, and basically it is possible to predict sound fields in areas farther from the sound source than the measurement surface.

2.2 Equivalent source method

Here, a method based on the equivalent source method (ESM) was applied (Koopmann et al., 1989; Fahnline et al., 1991; Song et al., 1991; Jeon et al., 2005). ESM is one of the representative near-field acoustic holography methods and it is based on the formulation of spherical harmonics.

To describe the sound field radiating from a source at specific position, the spherical coordinate provides a simple description with a finite number of expansion terms. Based on this concept, the radiated sound field from arbitrary sound source can be

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described by the combination of simple sources with specific order of spherical Hankel function with spherical harmonics as follows (Jeon et al., 2005)

$$p_f(\boldsymbol{r}_m;\omega) = \sum_{e=1}^{E}\sum_{j=1}^{J} C_j^e \psi_j(\boldsymbol{r}_{me},\omega)\,, \tag{1}$$

where E is the number of virtual sources, and the subscripts e and m indicate the index of the source and field points, respectively. C_j denotes the source strength, and Ψ_j is considered the spherical radiation function of the corresponding index j (j=1, 2, 3, …, J), and J=$(N+1)^2$, and N is the number of order of the spherical Hankel function. Also, $\boldsymbol{r}_{me}$ means the field points to describe the observation plane to describe the radiation characteristics of equivalent sources.
Equation 1 can be described as following matrix form:

$$\boldsymbol{H}_{source}(\boldsymbol{r}_{me}) = \boldsymbol{\Psi}_1(\boldsymbol{r}_{me})\mathbf{C}_1 + \cdots + \boldsymbol{\Psi}_\mathbf{J}(\boldsymbol{r}_{me})\mathbf{C}_\mathbf{J} = \boldsymbol{\Phi}(\boldsymbol{r}_{me})\cdot\boldsymbol{C} \;, \tag{2}$$

where $\boldsymbol{H}_{source}$ means the sound pressure response. The matrix $\boldsymbol{\Phi}(\boldsymbol{r}_{me})$ can be estimated by the formulation of spherical harmonics. If the sound field information $\boldsymbol{H}_{source}$ is obtained by measurement, the matrix of source characteristics can be obtained by taking the pseudo-inversion of $\boldsymbol{\Phi}(\boldsymbol{r}_{me})$. With this approach, the model of sound source can be established, and the sound field of arbitrary points can be estimated with this model.

3. Measurement

3.1 Measurement setup

Figure 1 shows the Sacred Bell of King Seongdeok and measurement setup for applying the acoustical holography. The height of bell is 3.66 m and the diameter is 2.27 m. The bell hangs in a suspended form on the bell tower, and the lower end of the bell is located about 0.5 m from the floor (Figure 2(.
To enable simultaneous measurement in all directions, 120 channels of microphones were placed surrounding the bell and near-field measurements were conducted. The microphones were placed at equal intervals of 22.5° on each horizontal plane without the hammer position. In the vertical direction, these were placed at 0.5 m intervals. In the case of the top, it was placed 0.5 m inward in the radial direction so that it could be close to the duct structures.

3.2 Result

Figure 3 shows the example of frequency spectrum of measured sound signal and several distinct peaks are observed. Among these main frequency components, when zooming in around 64 Hz, which is known to contribute the most to the beat component, it is observed that two clear peaks exist.
In the previous studies, it has been reported that the strength of beats varies depending on direction (Kim, et al., 1994; Lee et al., 2002; Kim, et al., 2002). These characteristics were also observed in this measurement result as shown in Fig. 4. The cause is due to the level difference in distribution for these two frequency components. Figure 5 shows the sound pressure distribution around the bell for the two frequencies, and it is observed that the ratio between two components are varied from 1.4 to 13. From these results, it is observed that the directions in which the magnitude ratio is small coincides with the direction in which the beat is clearly observed.

Figure 1. Photo of the Sacred Bell of King Seongdeok.

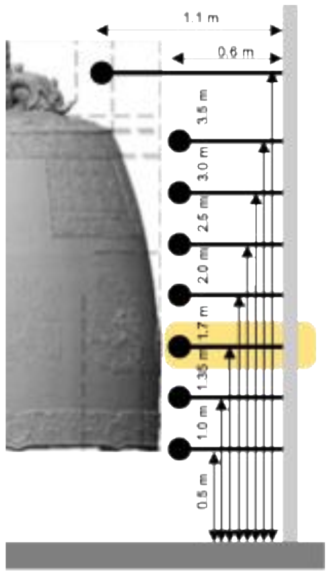

Figure 2. Measurement setup of the single microphone array of vertical line.

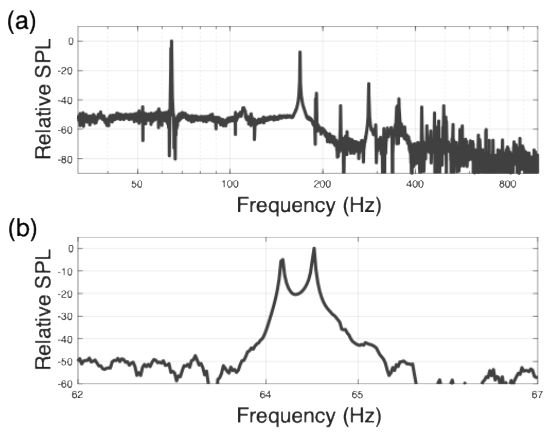

Figure 3. Example of the measured frequency spectrum of ‘Sacred Bell of King Seongdeok’: (a) Overall frequency range, (b) Zoomed spectrum around 64 Hz.

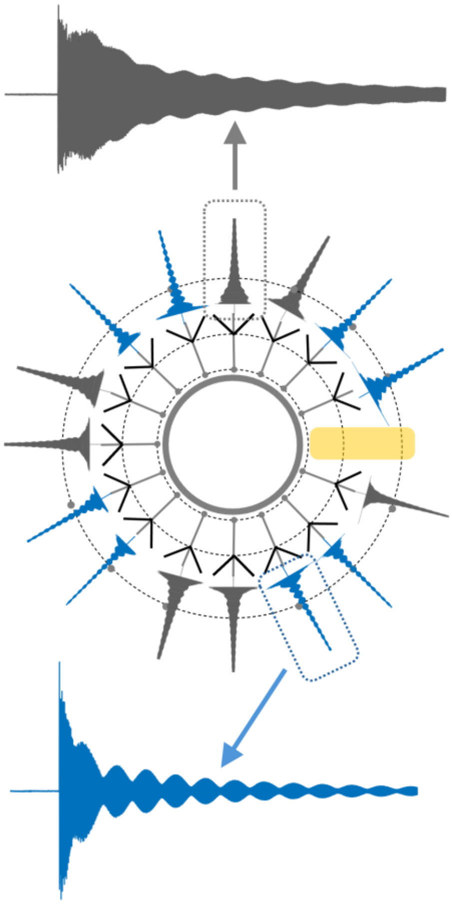

Figure 4. Comparison of the radiated signal on the plane at the height of hammer (blue: strong beat, gray: weak beat).

(a)

(b)

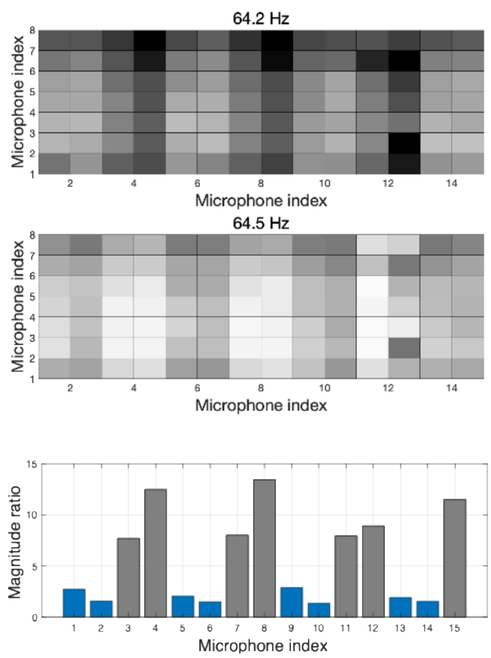

Figure 5. (a) Sound pressure distribution around the bell for 64.2 Hz and 64.5 Hz, (b) magnitude ratio of two frequencies.

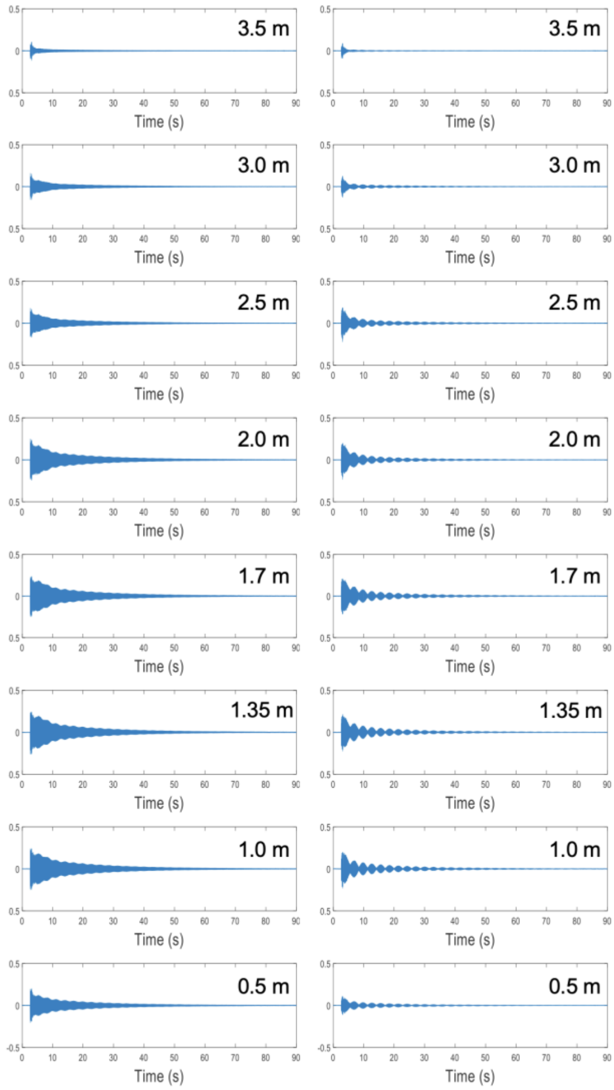

Figure 6. Time domain signal along the vertical direction (Left: 90 ° from hitting position, Right: 135 ° from hitting position).

4. Reconstruction of radiation characteristics

4.1 Visualization of sound field

An example of sound field reconstruction based on measurement results is shown in Figures 4 and 5. Figure 4 shows the reconstructed sound field on the horizontal plane at the height of hitting points and the far-field data farer than the hologram plane can be generated. Figure 5 shows the reconstructed sound field on the cylindrical plane surrounding the bell.

As the results show, it is possible to generate the sound field even in spatial locations where measurements were not conducted, and important features such as beat distribution are well reproduced as shown in Figure 9.

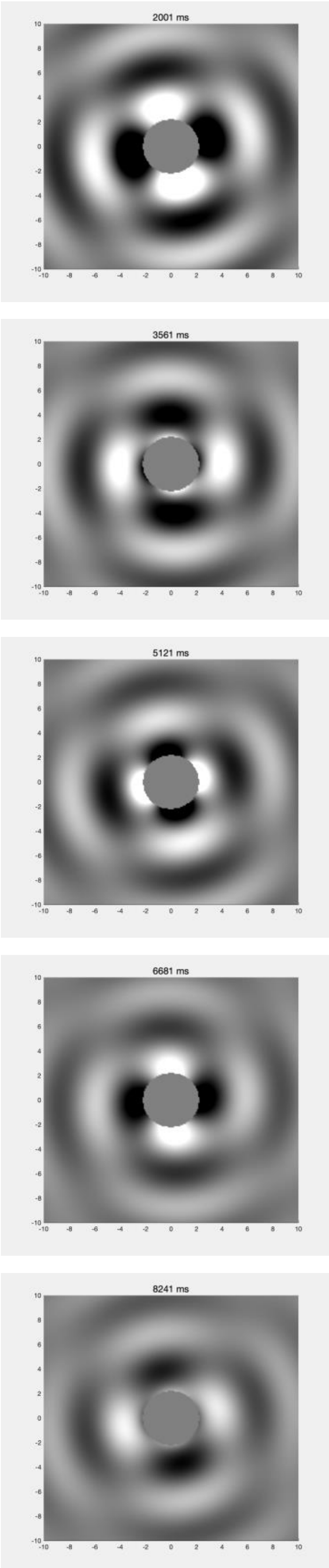

Figure 7. Example of the reconstructed radiated sound on horizontal plane at the height of hammer.

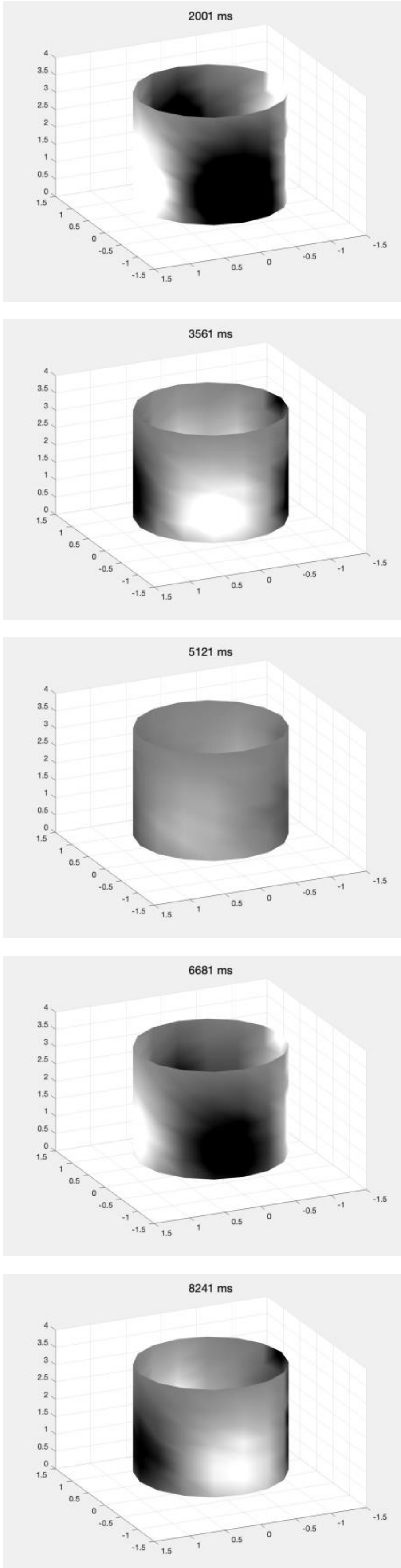

Figure 8. Example of the reconstructed radiated sound on cylindrical plane.

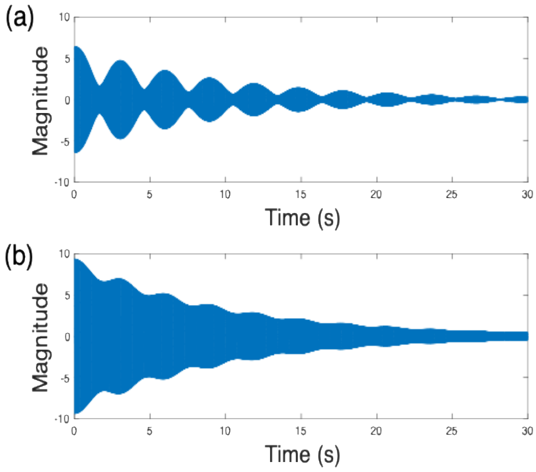

Figure 9: Reconstruction of time domain signal at the height of hitting position and at the direction of: (a) 135 ° from hitting position, (b) 90 ° from hitting position.

4.2 Practical application: exhibition content of museum

The results derived from this study can be used in the development of various audio-visual contents. As an actual example, the sound recordings and reconstructed data were applied to set up a permanent exhibition hall, ‘Room of Senses’ (National Museum of Korea, 2025) in the National Museum of Korea. Figure 10 shows the photo of main hall.
The theme of this exhibition room is ‘Beating: A Multisensory Experience Exhibition on Korean Buddhist Bells’ and is designed to provide a multisensory experience so that you can hear, see, and feel the sound of the Sacred Bell of King Seongdeok. To this end, exhibits that allow users to experience sound and vibration as well as 3D images and models were created based on actual measurement data.
Considering the nature of the museum, the content was created based on actual data to not only provide an artistic and emotional experience, but also to allow users to experience more real information.

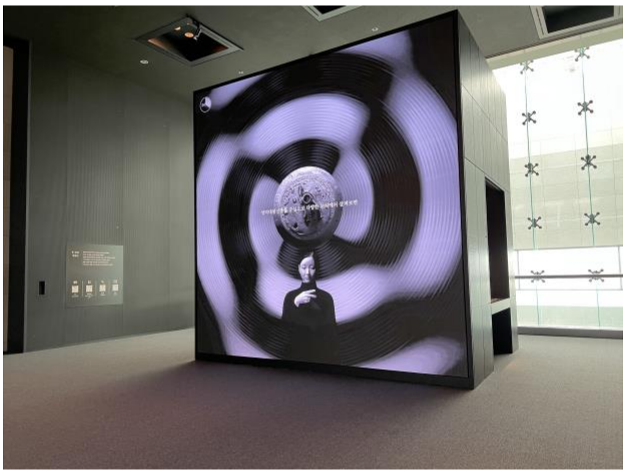

Figure 10: Permanent exhibition hall ‘Room of the Senses’ in the national museum of Korea.

5. Conclusion

In this study, a sound source modelling method using near-field acoustic holography was proposed as a method to preserve the acoustic radiation characteristics of acoustic heritage. The series of processes to archive and reproduce the radiation characteristics of the Sacred Bell of King Seongdeok were realized by the proposed approach. By applying this approach, it is possible to generate the sound field even in spatial locations where measurements were not conducted, and important features such as beat distribution are well reproduced
Throughout the process, it was confirmed that the sound field reproduced well represents the unique characteristics of the actual sound heritage and through this, it is expected that a more faithful level of preservation of cultural heritage in the form of intangible sound will be possible.

Acknowledgements

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References

Cho W.-H., Jung I.-J., Woo J.-H., Kim B.-K., Ih J.-G., 2023: Reconstruction of the spatial radiation characteristics of large Korean bell. Proc. of Forum Acusticum 2023, Torino, Italy.

Cho W.-H., 2015: Reproduction of the radiation pattern from a practical source by an acoustic array and the equivalent source method. Proc. of the Audio Engineering Society Convention, e-Brief 149, April 2015, Berlin, Germany.

Cho W.-H., 2016: Rendering a radiation pattern of an actual sound source by using the equivalent source method with acoustic array. Proc. of Meeting of the Acoustical Society of Japan, March 2016, Tokyo, Japan.

Cho W.-H., 2016: Sound source modelling and synthesis by the equivalent source method for reproducing the spatial radiation characteristics. Proc. of 2016 AES International Conference on Sound Field Control, Guildford, UK, 5-2.

Gyeongju National Museum, 2023: *Investigation on the striking sound of the Sacred Bell of King Seongdeok*, Academic research data collection of Gyeongju National Museum.

Fahnline J., Koopmann G., 1991: A numerical solution for the general radiation problem based on the combined methods of superposition and singular-value decomposition. J. Acoust. Soc. Am., 90, 2808-2819.

Jeon I.-Y., Ih J.-G., 2005: On the holographic reconstruction of vibro-acoustic fields using equivalent sources and inverse boundary element method. J. Acoust. Soc. Am., 118, 3473-3482.

Kim S.-H., Soedel W., Lee J.-M., 1994: Analysis of the beating response of bell type structures. J. Sound Vib., 173, 517-536.

Kim S.-H., Kim J.-H., Jung J.-D., Lee J.-M. 2002: Vibration on sound characteristics of King Song-Dok Bell. Trans. Kor. Soc. Noise Vib. Eng., 7, 534 – 541.

Koopmann G., Song L., Fahnline J., 1989; A method for computing acoustic fields based on the principle of wave superposition. J. Acoust. Soci. Am., 86, 2433-2438.

Lee J.-M., Kim S.-H., Lee S.-H., Jeong J.-D., Choi H.-G., 2002: A Study on the vibration characteristics of a large size Korean Bell. J. Sound and Vib., 257, 779-790.

Song L., Koopmann G., Fahnline J., 1991: Active control of the acoustic radiation of a vibrating structure using a superposition formulation. J. Acoust. Soc. Am., 89, 2786-2792.

Williams E., 1999: *Fourier Acoustics: Sound Radiation and Nearfield Acoustical Holography*. Academic Press, London.

National Museum of Korea, 2025; Room of Senses, https://www.museum.go.kr/ENG/contents/E0201080500.do?showHallId=757&showroomCode=DM0083 (23 June 2025).