Vibration analysis of a temple bell by Finite Element Method

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ABSTRACT

The relationships between various shapes in a Buddhist temple bell and the corresponding acoustic characteristics are clarified mainly by Finite Element Method (FEM) analysis.

First, it is shown that the cross-sectional shapes of the "Komazume" (lower part that is slightly thicker than the rest of the bell) have high correlations to the vibration modes as well as the vibration positions. As a result, the Komazume has a large influence on the bell's acoustic characteristics. Second, it is shown that the "Doza" (part where the bell is struck), which functions as an formal asymmetrical factor when the bell vibrates, is highly related to beat characteristics.

1. ANALYSIS MODEL

The FEM analysis model of the bell was structured as follows. First, its two dimensional FEM cross sectional shape was made. The full model was configured so that its cross sectional shape was rotated by 360 degrees. The actual bell shape of the Hojobo Temple (in Isehara, Kanagawa Prefecture, Japan) was utilized as the analysis model[1][2].

Figure 1 shows the analysis model. Each element was composed of 20 contact points. The elements of the Komazume and Doza parts were made smaller than the other parts. The number of circumferential divisions was 60, and the upper two small areas were selected as fixed areas, as shown in the figure. The analysis software is Marc K7.3.

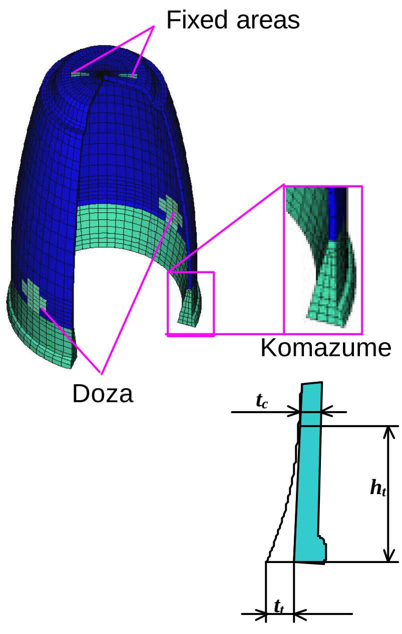


Fig.1 The FEM analysis model of the bell

Table 1 shows the bronze material constants related to the bell.

Table 1 Bronze material constants of bell

Young's Modulus	8.08×10^{10} N/m^2
Poisson's ratio	0.358
Mass density	8.60×10^3 kg/m^3

Table 2 compares the measured and FEM analyzed vibration frequencies of each mode for the Hojobo Temple bell. As shown in the table, the differences between them are around 3-5%. The reason for this can be considered due to the differences in each material constants and in the details of the partial shapes. Such differences, however, are not important in understanding the bell's acoustics.

Table 2 Vibration frequencies

Mode	FEM analyzed	Measured
4-0	143.0	137.8
6-0	319.0	301.8
8-0	395.4	378.6

(Hz)

2. INFLUENCE OF KOMAZUME SHAPE ON BELL SOUND

The influence of the cross-sectional shape of the Komazume on the acoustic characteristics was investigated in detail by FEM analysis. The bottom width of the Komazume t_t (Fig.1) was varied on condition that its cross-sectional area was always kept constant. Table 3 shows pairs of analyzed bottom widths t_t and heights h_t of the Komazume.

Table 3 Analyzed bottom widths and heights of Komazume

width t_t	20	30	40	50	60	71
height h_t	149	98	73	58	48	40

(mm)

Figure 2 shows the relationships between three vibration mode frequencies and the bottom width of the Komazume t_t. From the figure, it can be seen that each vibration mode frequency increases as t_t increases (i.e., as h_t decreases).

Each mode's tendency of increasing, however, has its own characteristics. While the 4-0 mode curve increases linearly with the increase in t_t, the 6-0 mode curve saturates with the increase. The 8-0 mode curve, however, is nearly independent of t_t. The reason for the differences in these tendencies can be explained by considering each mode's vibration position[3].

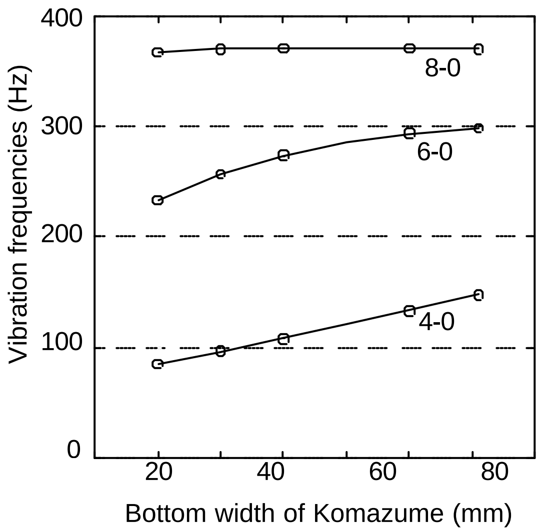


Fig.2 Relationships between three vibration mode frequencies and bottom width of Komazume t_t

Figure 3 shows the relationships between vibration center positions (defined by the height from the bottom of the bell) for the three vibration modes and the bottom width of Komazume t_t.

As shown in the figure, the vibration center positions of the 4-0 mode and 8-0 mode hardly change as t_t values increase, being fixed at the Komazume and at around 500 mm from the bottom of the bell, respectively. Otherwise, only that of 6-0 mode steeply changes as t_t increase. As explained, the 4-0 mode vibration center position is located almost at the Komazume, and so its vibration frequency is directly influenced by changes in the Komazume's shape. As for the 8-0 mode, its vibration center position remains independently distant from the Komazume as t_t increase, and so its vibration frequency is hardly influenced by the increase in t_t. As for the 6-0 mode, its vibration frequency is directly influenced by the increase in t_t when t_t is relatively small because then its vibration center position is located at around the Komazume. However, as the position steeply moves far from the Komazume position when t_t exceed a certain value (around 35 mm), its vibration frequency becomes only slightly influenced by the increase in t_t.

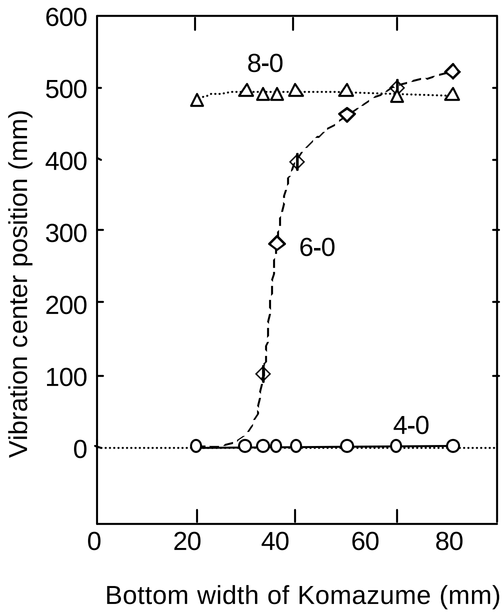


Fig.3 Relationships between vibration center positions for three vibration modes and bottom width of Komazume $\boldsymbol{t_t}$

The reason for the 6-0 mode vibration center position movement can be considered as follows. Since the stiffness of the Komazume becomes too strong for the 6-0 mode to vibrate at the Komazume position for over certain values of t_t, the 6-0 mode vibration center position moves to positions of weaker stiffness. On the other hand, for the 4-0 and 8-0 mode vibration, the Komazume position and the higher position are their proper vibration center positions, respectively, because the stiffness of each position, when the t_t values are those shown in Table 3, fits each vibration.

Figure 4 shows 6-0 mode vibration patterns of several t_t values obtained by FEM simulation. As shown in the figure, the change in vibration center position with the change in the bottom width of the Komazume can be clearly seen.

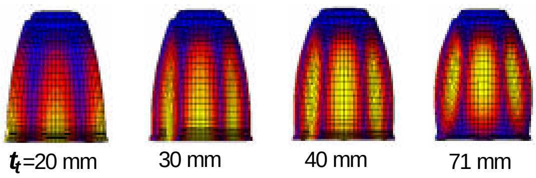


Fig.4 6-0 mode vibration patterns at several $\boldsymbol{t_t}$

Figure 5 shows the relationships between t_t values and the ratios of the 6-0 and 8-0 vibration mode frequencies to that of the 4-0 mode. From these figures, it can be concluded that the "tone" of the bell sound can be controlled by adjusting the Komazume's shape.

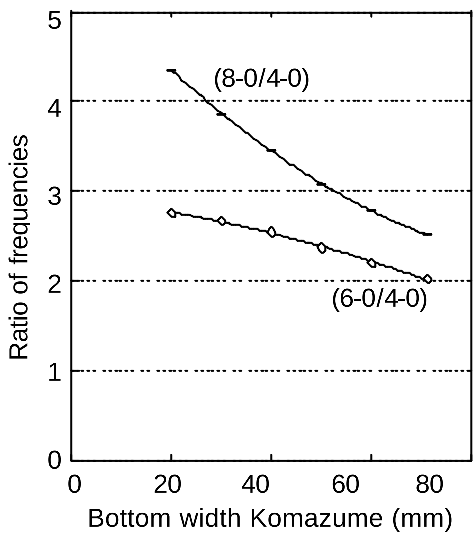


Fig. 5 Relationships between $\boldsymbol{t_t}$ values and ratios of 6-0 and 8-0 vibration mode frequencies to that of the 4-0 mode

To confirm the above assumption, the

influence of the thickness of higher positions of the bell t_c (Fig.1) on each vibration mode frequency was analyzed. The thickness t_c, except at the Komazume, was changed from 8 mm to 32 mm, under the condition that t_t value of the Komazume is fixed to be the value of the Hojobo bell (46.2 mm).

Figure 6 shows the results. As shown in the figure, while the 6-0 and 8-0 vibration mode frequencies change with the increase in t_c, that of the 4-0 mode hardly changes because the main vibration positions remain at around the Komazume. Therefore, the change in thickness t_c can be considered another method of changing the bell tone.

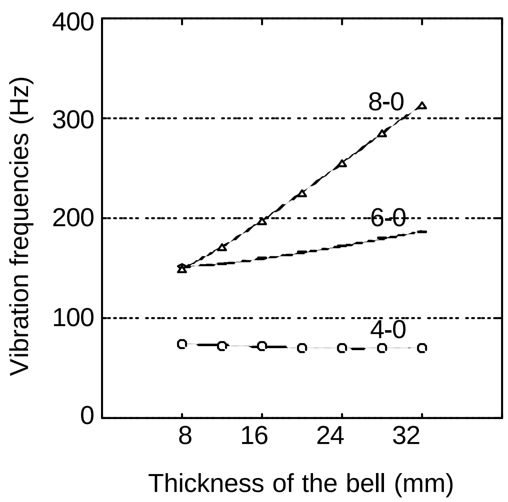
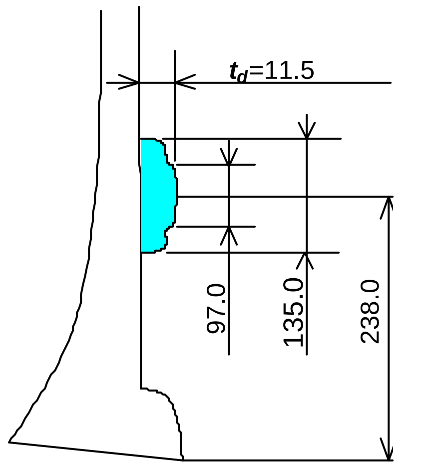


Fig.6 Influence of thickness t_c of higher bell positions on each vibration mode frequency

3. INFLUENCE OF DOZA THICKNESS ON THE BELL BEAT SOUND

Though the beat sound is another important factor for the Bell sound, its origin has not yet been fully clarified. Fundamentally, the beat is considered to generate due to formal or material asymmetrical factors of the bell. Since the Doza, which is the portion where the bell is struck by a pole, can be regarded as one of the main formal asymmetrical factors of the bell, we investigated its influence on the bell beat[4].

Figure 7 shows the sectional shape and dimensions of Hojobo's Doza. Though the real Doza shape is circular, the FEM-simulated shape was configured with quadrilateral factors (See Fig. 1) on condition that the area of each Doza is the same. This is due to the limit of the shape of the minimum finite element for FEM analysis. Although Hojobo's bell has two Dozas placed 180 degrees opposite each other on the circumference, we investigated three cases in which the numbers of Dozas are 1, 2 and 4.



(unit : mm)

Fig. 7 A sectional shape and the dimensions of Hojobo's Doza

Figure 8 shows the relationships between 4-0H and 4-0L vibration mode frequencies and the thickness of Doza t_d, where the number of Dozas are 1, 2 and 4.

Here, 4-0H and 4-0L modes are defined as follows. When a bell has formal asymmetrical factors on its circumference, each vibration mode splits into two modes whose vibration frequencies are slightly different from each other. Here, using 4-0 mode vibration as an example, a little bit higher vibration frequency is defined as the 4-0H mode, as well as the 4-0L mode for a little bit lower frequency. The reason for the split can be explained as follows.

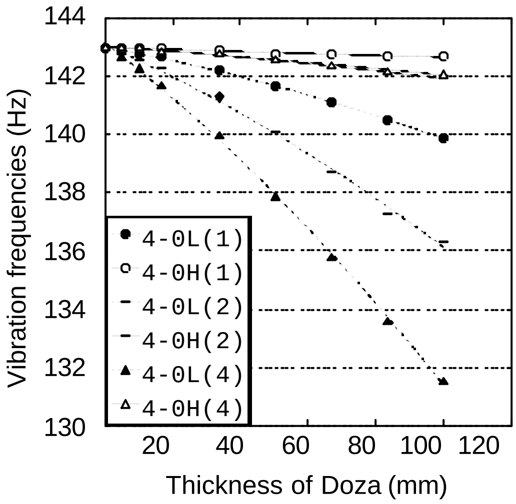


Fig.8 Relationships between 4-0H and 4-0L mode vibration frequencies and the thickness of Doza t_d, where number of Doza's are 1, 2 and 4

Figure 9 shows vibration aspects for both 4-0H and 4-0L modes when the number of Dozas is 1. As shown in the figure, in the case of the 4-0 mode, two vibration modes coexist whose mutual vibration directions differ by 45 degrees of each other. Although for the 4-0L mode, the Doza is located at the position where the vibration amplitude shows maximum value, the Doza is located at the position where vibration scarcely occurs for the 4-0H mode.

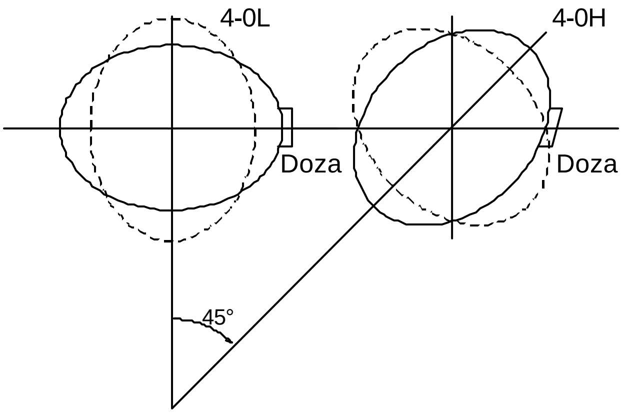


Fig. 9 Vibration aspects for 4-0H and 4-0L modes when number of Dozas is 1

Therefore, since the Doza functions as added mass for 4-0L vibration mode when the bell vibrates, the 4-0L mode's vibration frequency is slightly lower than that of the 4-0H mode, for which the Doza does not function as added mass when the bell vibrates. The beat frequencies can be calculated as the difference between 4-0H and 4-0L vibration mode frequencies. From figure 8, we obtain figure 10 to show the relationships between t_d (11.5 mm for Hojobo's Doza) and the beat frequencies of the bell.

From the figure, it can be seen that in relation to the number of Dozas as well as their thicknesses, the beat frequencies increase almost proportionally. The reasons for these results can also be explained by principles similar to those shown in figure 9. These results show that the beat frequency of bells can be controlled artificially by choosing the proper number as well as thicknesses of Dozas.

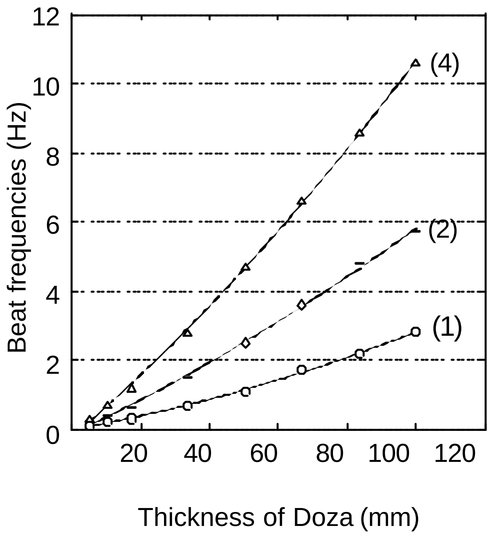


Fig. 10 Relationships between thickness of Doza t_d and bell's beat frequencies, where numbers of Dozas are 1, 2 and 4

Moreover, to confirm the influence of the Doza on bell beat frequency, a miniaturized bell was made of brass material. Its height, inner diameter, and the thickness are 176 mm, 69 mm, and 6 mm, respectively. A 16 mm diameter Doza was attached to this miniaturized bell.

Figure 11 shows an FEM model of the miniaturized bell. As is shown, although the real Doza shape is circular, the FEM simulated shape of this miniaturized bell was also configured with quadrilateral shape on condition that the area of each Doza is the same.

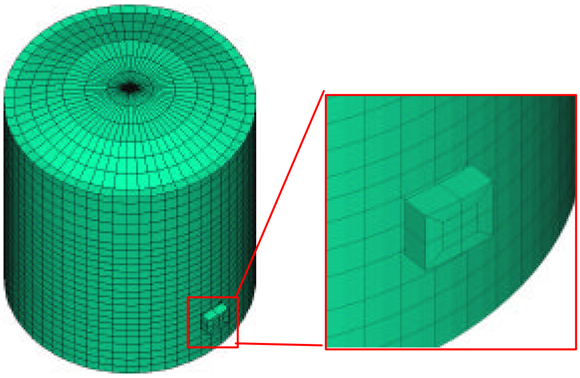


Fig. 11 FEM model of miniaturized bell

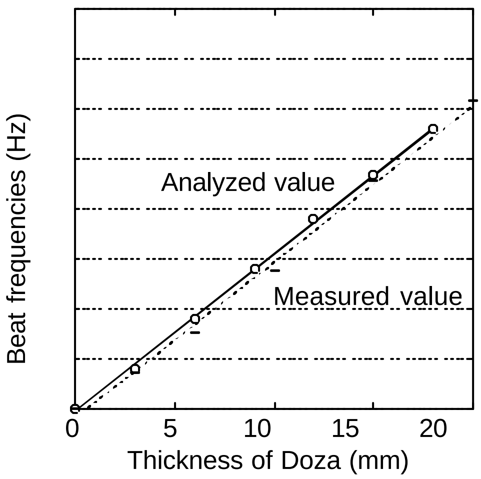


Fig.12 Experimental and simulated results showing the relationships between the thickness of Doza t_d and the beat frequencies of the miniaturized bell

Figure 12 shows experimental and simulated results for the relationships between the thickness of the Doza t_d and the beat frequencies of the miniaturized bell. As shown in the figure, the experimental and simulated results closely coincide with each other, which confirmed the simulation results.

4. CONCLUSIONS

The relationships between various shapes in a Buddhist temple bell and the corresponding acoustic characteristics were clarified mainly by Finite Element Method analysis.

Through the analysis, it was clarified that the cross-sectional shapes of the Komazume had high correlations to each mode vibration frequency according to its particular vibration position. As a result, the Komazume has a major influence on acoustic characteristics.

It was also clarified that both Doza mass and the number of Dozas are highly related to beat characteristics.

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