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Analytical Study of Acoustic Mechanism of "Suikinkutsu"

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In this report, I describe an experimental analysis of the acoustic mechanism of the suikinkutsu. The sound of the suikinkutsu consists of an original sound generated by water drops striking the surface of the water in the suikinkutsu and a reverberant sound generated by the original sound. The reverberant sound is the sound we hear through the observation holes of the suikinkutsu. The body of the suikinkutsu also has its own natural frequencies and vibrates in synchronism with the natural frequencies of the oscillation modes of air inside it, affecting the tonal quality of the sound emitted from the suikinkutsu. If all of the natural frequencies and time constants of the reverberant sound are optimized, the suikinkutsu can produce a sound of good tonal quality. In this study, we investigate the relationships between the original sound and the reverberant sound emitted from the suikinkutsu. We propose an experimental formula representing the natural frequencies of the suikinkutsu and examine the validity of this formula. [DOI: 10.1143/JJAP.43.6429]

KEYWORDS: suikinkutsu, drop, splash, bubble, underwater sound, proper vibration of suikinkutsu

1. Introduction

The suikinkutsu is said to have originated from the Edo period. Although it became popular in the Meiji period, its popularity waned thereafter. It was around 1980 that people once again began to take interest in the suikinkutsu, and the "Japan Suikinkutsu Forum" was established in January 2001.

A typical suikinkutsu consists of a crock turned upside down and buried in an underground hole storing shallow still water, as shown in Fig. 1. The crock is supported by pieces of stone so that the vibrations of the crock will not be damped by earth. The inverted crock has a through-hole called suimon (meaning water hole) at the top end thereof for allowing water led from a washbasin to drop into the crock like intermittent raindrops. Each water drop results in a sequence of water droplets as it falls. The sequence of droplets generates a sound (hereafter called the original sound) as they hit the surface of the still water. The original sound reverberates and thus can be heard through the suimon. An increasing number of portable suikinkutsus have been produced recently, each having a lid to cover the upper open end of the crock (the crock hereinafter referred to as suikinkutsu body). Such a lid has an extra through-hole in addition to the suimon to emit the reverberant sound. In this study, we focus on such portable suikinkutsus as described above.

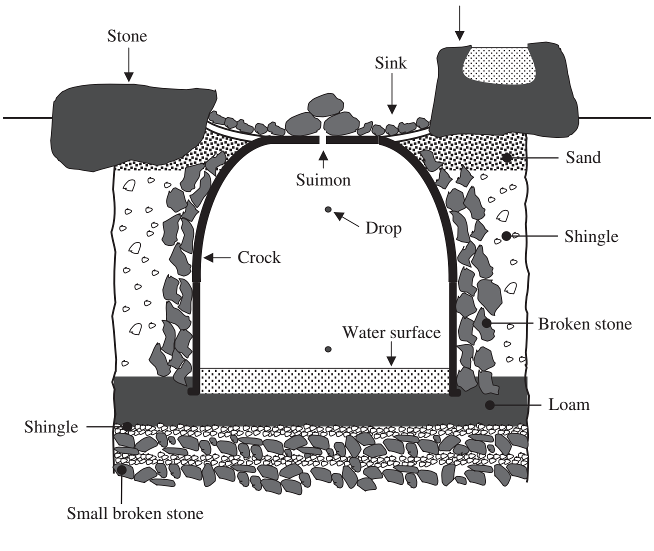


Fig. 1. Traditional suikinkutsu, cited from ref. 1.

A reverberant sound emitted from a suikinkutsu can be a "streaming sound" or a "waterdrop sound". The former sound is created when streaming water flows down from the suimon while the latter sound is created when water drips from the suimon. In the following sections, the latter sound will be discussed.

In a typical suikinkutsu, several droplets originating from a drop fall in sequence at any time. The first droplet of the sequence is the largest. When the first droplet strikes the surface of the water, it causes the struck portion of the surface to become recessed or concaved. Subsequent smaller droplets striking this concaved surface can generate a bubble. When this happens, two types of sound are generated: the first type is a sharp, pulsed sound that arises from the repercussions of the impact of the first large droplet and the subsequent smaller droplets. The second type is a sound that arises from the vibrations of the bubble thus generated. The characteristics of the original sound are determined mainly by the second type of sound.

A typical suikinkutsu has a barrel shape and exhibits very complex frequency profiles associated with the natural modes of air in the cavity (referred to as modes of the cavity) inside the body and of the elastic body itself. It is found in the present analysis that some of the natural modes of the elastic body resonate with the natural modes of the cavity, and that this resonance is an important factor that determines the tonal quality of the reverberant sound emitted from the suikinkutsu.

The art of the suikinkutsu is currently based on suikinkutsu manufacturers' experience accumulated through many years of practice producing different types of suikinkutsu. Thus, further study of the suikinkutsu is inevitable to manufacture a good suikinkutsu in a systematic way. By "good suikinkutsu", we mean one that many suikinkutsu listeners think it emits a soothing reverberant sound. It can be said that a good suikinkutsu is one that generates a sound having appropriate loudness, sufficient duration, and well-balanced harmonics. This definition of a good suikinkutsu is somewhat similar to the standard of a good musical instrument.

A reverberant sound generated by the original sound in the suikinkutsu mainly consists of tones higher than those of the original sound. A good reverberant sound of the suikinkutsu has the following characteristics.

(1) One component having a frequency of approximately 1 kHz (referred to as low-frequency component) and a multiplicity of high-frequency components well balanced in intensity
(2) Sufficiently high sound pressures
(3) Sufficient reverberation time

It is difficult to generate such a low-frequency component.

Thus far, very few acoustic analyses of the suikinkutsu have been carried out, aside from the pioneering work of Kishitsuka,[2] who fabricated a generally cylindrical prototype suikinkutsu and examined its natural frequencies. He calculated and measured the natural frequencies of the cavity inside the prototype suikinkutsu and found that the calculated natural frequencies are in good agreement with the measured natural frequencies. Tomita *et al.* studied the original sound generated by the bubble generated by a droplet.[3] They found that the original sound has a frequency above a few kHz.

Conventional studies of the sound generated by a water drop are mainly concerned with the sound of a single raindrop striking the surface of the water.[4–7] A sound generated under such conditions has frequencies not less than a few kHz.

A number of questions still remain to be answered. For example, under what conditions does a drop generate a good original sound? Is the barrel shape appropriate for the suikinkutsu to generate a good sound? What is the relationship between the natural elastic frequencies of the body of the suikinkutsu and the tonal quality of the reverberant sound of the suikinkutsu?

Considering the fact that the properties of the original sound of the suikinkutsu are determined by the number, size and speed of the droplets falling onto the surface of the water, we conducted a series of experiments to determine the optimum conditions for generating an original sound having a low frequency and a high sound pressure. We analyzed the relationships among the original sound, the reverberant sound, and the elastic modes of the suikinkutsu body, because it is thought that the natural frequencies of the reverberant sound are strongly determined by the natural frequencies of both the cavity inside the suikinkutsu and the body of the suikinkutsu.

2. Experiments

To generate a good suikinkutsu sound (i.e., of good tonal quality), the original sound must have a low frequency and a high sound pressure, which can be generated only by a large bubble formed by a large droplet.[7] Such a large droplet develops from a large drop formed on a clean, wide and preferably flat undersurface.[8] With all this in mind, we studied the mechanism in which the original sound is formed in the geometry shown in Fig. 2. A watch glass was placed above a water tank, and then water was directed into it. As a means of forming a large water drop, we used a watch glass (30 cm in radius of curvature and 2 mm in thickness) having at the center thereof a small water hole 1.5 mm in diameter. This watch glass had a preferred curvature for effectively directing water near the water hole and yet had a substantially flat undersurface over the size of the drop formed. The water in the watch glass flowed into the water hole, spread onto its undersurface around the water hole and then grew to a large drop before it fell and broke into separate droplets.

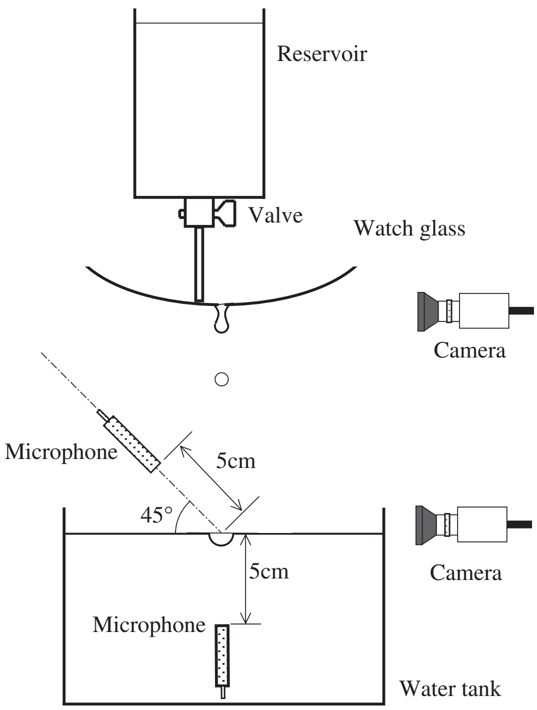


Fig. 2. Apparatus for producing drops that fall from a watch glass and for measuring the original sound generated by the drops. The drop period of the falling drops was controlled with the aid of a reservoir, a valve and a capillary tube. Two microphones were positioned to measure the sound in air and water.

Water droplets fell onto the surface of the water in the tank. A high-speed camera was set up to film the droplets striking the surface of the water and the bubbles generated. The original sound was detected using two microphones, with one microphone positioned 5 cm away from the surface of the water and at 45° deg to the point where droplets strike the water, and the other one 5 cm below the water surface.

The tonal quality of the original sound was determined by the size and speed of the droplets striking the surface of the water. To determine how the tonal quality of the original sound depends on the time interval of drops (this interval will be called the drop period) and the speed of droplets, drop period and the height of the watch glass relative to the surface of the water (this height will be called the drop distance) were changed.

The suikinkutsu used in the experiment, called the "Hana Suikinkutsu", is shown in Fig. 3. It is a vase-type suikinkutsu, with a pan set on it to enclose the body. The thickness of the walls of the body and the pan of this suikinkutsu is approximately 0.6 cm. The pan has a water hole at the center and an observation hole by the side of the water hole. The height of the body of the suikinkutsu is 46 cm and its largest diameter is 36 cm. The height from the surface of the water to the bottom of the top pan (i.e., length of the air column) is

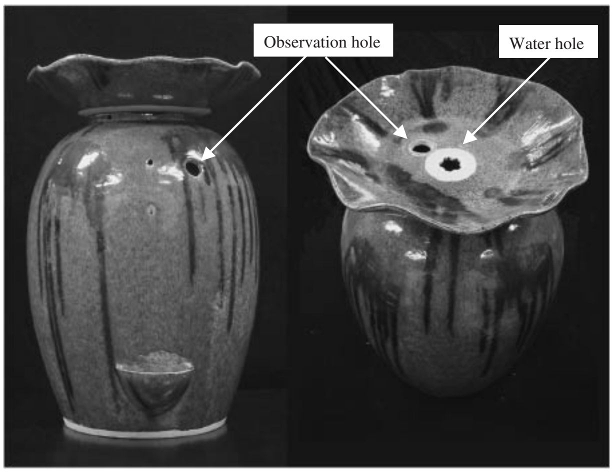


Fig. 3. Portable suikinkutsu, called "Hana Suikinkutsu". The thicknesses of the pan and the wall of the suikinkutsu body are about 0.6 cm. The pan is 5 cm in height and 36 cm in diameter. The outer diameter of the base section of the suikinkutsu body is 25 cm. The height of the drainage hole is 10 cm from the bottom and the outer diameter of the body at that height is 30 cm. The largest outer diameter of the suikinkutsu body is 36 cm at a height of 30 cm from the base. The suikinkutsu body is 46 cm high, and its outer diameter is 17 cm at this height.

36 cm. A drainage hole is provided on the sidewall of the suikinkutsu body so that the suikinkutsu can be filled with water up to this hole. Another observation hole is provided on the sidewall of the suikinkutsu 38 cm from its bottom. The different aspects of the frequency profile of the reverberant sound emitted from this observation hole was measured in the geometry shown in Fig. 4.

The natural frequencies of the body of the Hana Suikinkutsu were determined by striking the body by hand and measuring the frequencies using an acceleration pickup. The natural frequencies of the sound emitted from the suikinkutsu induced by the speaker sound in a certain frequency band were also measured with a speaker set close to the water hole. The natural frequencies of the sounds emitted from the suikinkutsu were measured after the speaker was turned off. Furthermore, to examine the modes of the cavity, the natural frequencies of the reverberant sound were measured for different heights of the pan relative to the water level in the suikinkutsu.

2.1 Sound generated by suikinkutsu

We placed a watch glass on the pan of Hana Suikinkutsu and ran water into it. If the water was allowed to drop from the water hole of the watch glass at fixed time intervals (drop period) of 6 s, we heard a very clear reverberant sound from the suikinkutsu when the height (drop distance) of the watch glass is 36.5 cm above the water in the suikinkutsu body.

In this section, we discuss the original sound formed in the geometry shown in Fig. 2. We also discuss the reverberant sound emitted from the suikinkutsu as an echo of the original sound inside the suikinkutsu with the watch glass set on the pan.

Figure 5(b) shows the droplets observed when the drop period was set to 6 s. In this case, each drop split into a leading or dominant droplet and 4 to 6 subsequent smaller droplets. The average diameter of the dominant droplet was 0.75 cm. The average diameter of the first subsequent droplet was 0.33 cm, that of the second was 0.26 cm, while the diameters of the remaining subsequent droplets were in the range from 0.1 to 0.2 cm.

Figure 6(a) shows a sequence of photographs showing droplets falling from the watch glass and striking the surface of the water in the tank in Fig. 2 when the drop period was 6 s and the drop distance was 36.5 cm. The figure shows a falling dominant droplet (Shot A); the surface of the water struck by the dominant droplet (Shot B); the concave surface of the water formed by the dominant droplet (Shot C); the

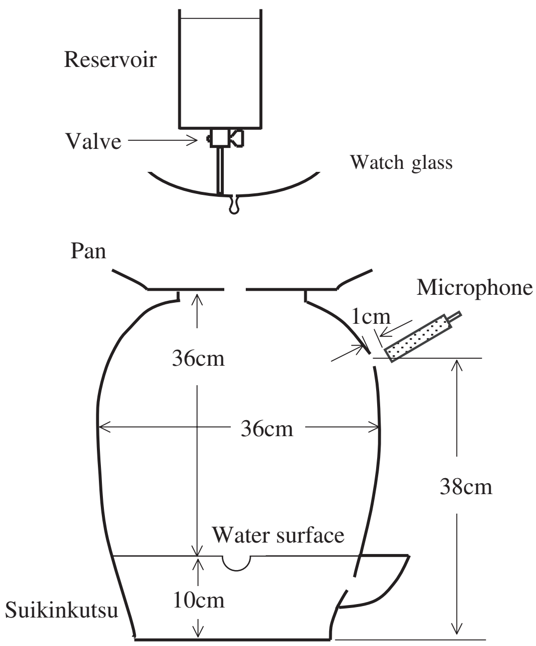
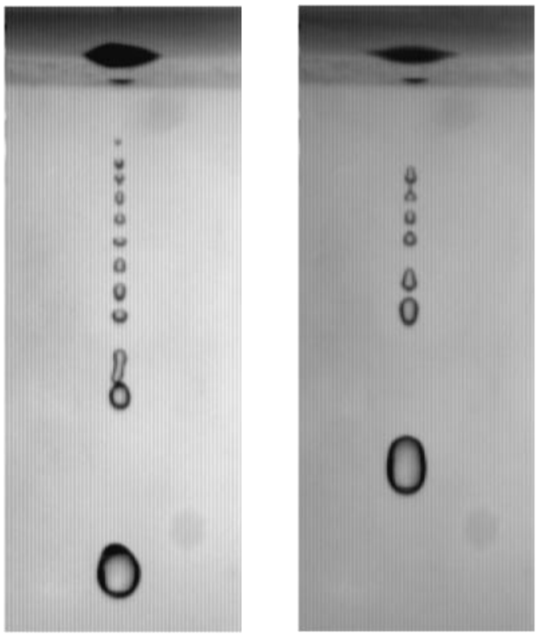
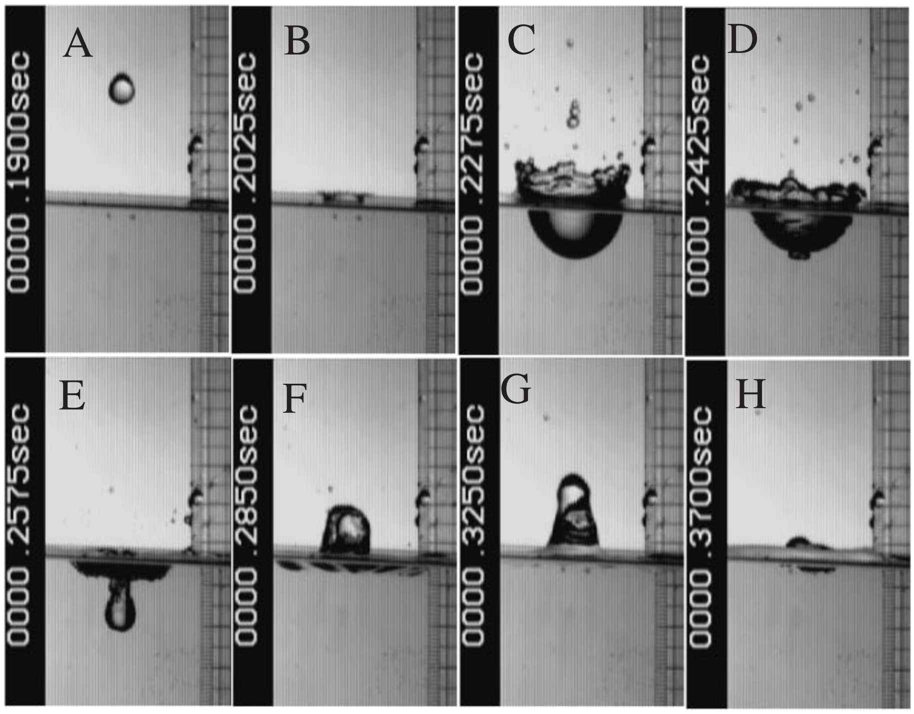


Fig. 4. Apparatus for measuring reverberant sound emitted from suikinkutsu.

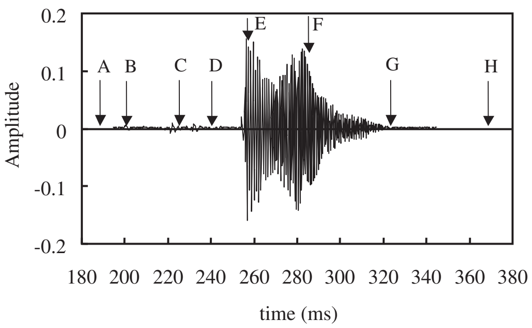


(a) 1 s (b) 6 s

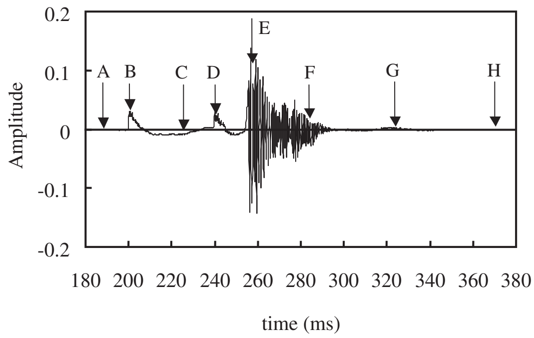
Fig. 5. Comparison of droplets dropping from undersurface of watch glass observed when drop periods of fall were 1 s and 6 s, respectively.



(a)Droplets and a bubble.



(b) Sound measured in air



(c) Sound measured underwater

Fig. 6. (a) Droplets striking surface of water and bubble formed by droplets. The drop period was 6 s and the drop distance was 36.5 cm. The frequency of the sounds generated by droplets striking the surface of the water was measured. Amplitudes of sound measured by (b) a microphone set 5 cm from and at 45° to the water surface of water, and (c) microphone set in the water at a depth of 5 cm.

first and second subsequent droplets striking the concave surface formed by the dominant droplet (Shot D); a bubble formed by the subsequent droplets (Short E); a column of water formed by the repercussion of the dominant droplet, absorbing the bubble (Shorts F and G); and the resultant bubble floating on the water (Short H). The other subsequent droplets have such small volumes that they fail to generate other bubbles. In the example shown herein, the crown-shaped cavity had a diameter of approximately 3.8 cm and a depth of 3.0 cm.

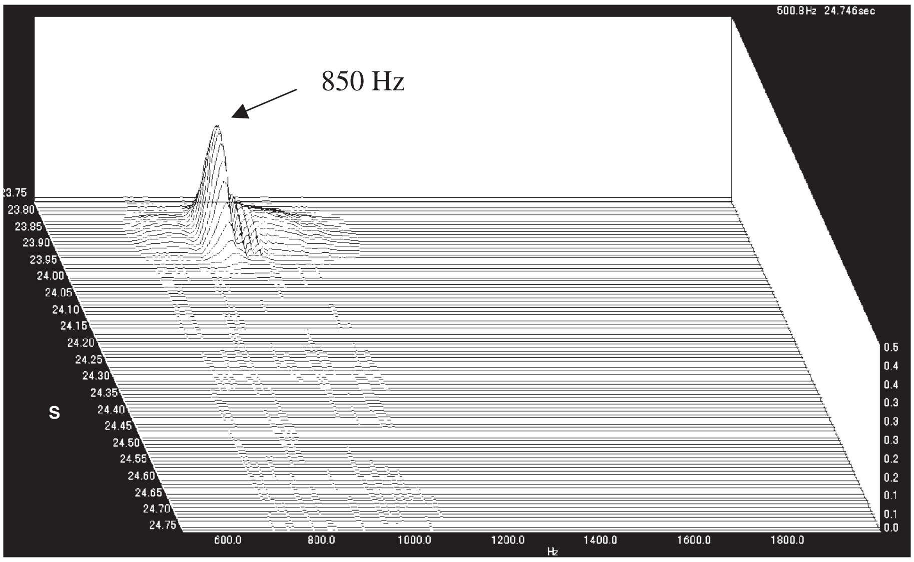
Figures 6(b) and 6(c) respectively show the amplitudes of the sound generated by the droplet striking the surface of the water. The symbol A–H in these figures indicate the respective times of shots shown in Fig. 6(a). As is shown in Figs. 6(b) and 6(c), the generation of the bubble (E) accompanies the generation of the original sound. The measured frequency of the original sound was about 850 Hz. The diameter of the bubble was about 0.75 to 0.80 cm, as shown in Fig. 6(a). Figure 6(c) further shows the sharp, pulsed sounds generated by the dominant droplet (B) and the first subsequent droplet (D).

Minnaert obtained a formula for the resonance frequency of a bubble,[9)]

$$f = \frac{1}{\pi d}\sqrt{\frac{3\gamma p}{\rho}} \tag{1}$$

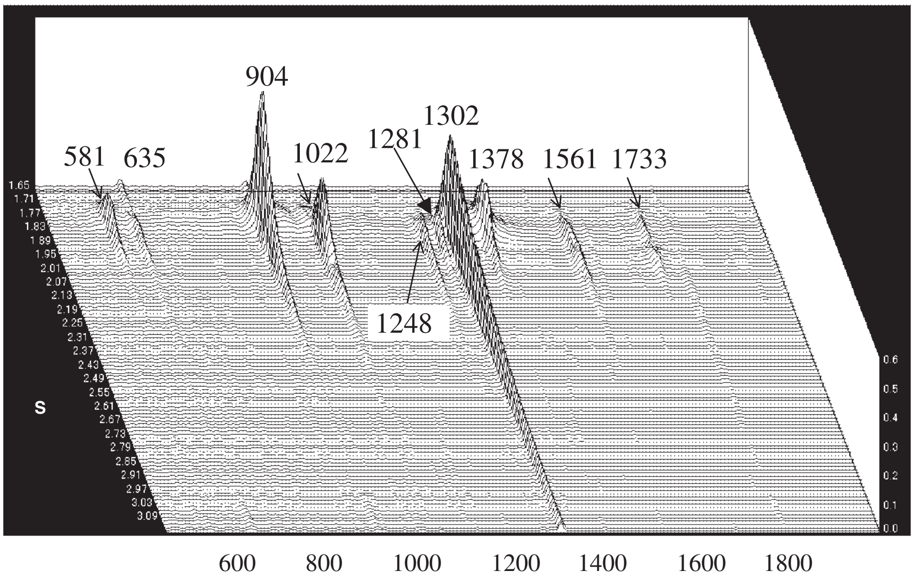
Here, d is the bubble diameter, γ is the specific-heat ratio of air in the bubble, ρ is the water density, and p is the ambient pressure. In the example shown herein, $d = 0.77$ cm, $\gamma = 1.4$, $\rho = 1.0\,\mathrm{g/cm^3}$, $p = 1.0 \times 10^6\,\mathrm{dyn/cm^2}$, for which the resonance frequency calculated by formula (1) is 848 Hz, which is very close to the measured frequency of about 850 Hz of the main original sound.

Figure 7(a) shows the profile of the original sound generated by the bubble in the water tank, and shows that the frequency of the original sound is 850 Hz and has a duration of approximately 0.1 s. Figure 7(b) shows that the profile of the reverberant sound emitted by the suikinkutsu,



Frequency (Hz)

(a) Original sound



Frequency (Hz)

(b) Reverberant sound

Fig. 7. Original sound and reverberant sound emitted by Hana Suikinkutsu as observed for drop period set to 6 s and drop distance to 36.5 cm. (a) Power spectral density of original sound generated by drops that struck surface of water in tank. (b) For reverberant sound emitted by the suikinkutsu. The power spectral density of the sound observed through the observation hole on the side face of the suikinkutsu was measured.

from which one sees that the duration of the reverberant sound is about 1.0 s.

The measurements of these profiles of Figs. 7(a) and 7(b) were carried out under the same conditions, that is, the drop distance was 36.5 cm and the drop period was 6 s. Since the original sound is generated under the same conditions in the tank and suikinkutsu, it is clear that the reverberant sound is generated by the original sound of about 850 Hz. The major frequencies of the reverberant sound were 904, 1022, 1302 and 1378 Hz. The minor frequencies were 581, 635, 1248, 1281, 1561 and 1733 Hz. It should be noted that no peak was detected in the frequency range from 635 to 904 Hz in the reverberant sound. More particularly, the frequency of the original sound is not the same as the frequency of the reverberant sound. It should also be noted that the major reverberant sound frequencies are higher than the frequency of the original sound. The reverberant sound generated by Hana Suikinkutsu as shown in Fig. 7(b) will be called the "naive sound".

Table I lists the 10 modes of the naive sound shown in Fig. 7(b), characterized by wavelength λ, frequency f, and time constant τ (defined to be the period of time that the

Table I. Frequency components (modes) of naive sound emitted by Hana Suikinkutsu (f: frequency, λ: wavelength, and τ: time constant). Intensities of modes are classified into strong ◎, medium ○ and weak △.

Mode No.	f (Hz)	λ (cm)	τ (s)	Intensity
1	581	59.04	0.22	△
2	635	54.02	0.40	△
3	904	37.94	0.29	◎
5	1022	33.56	0.25	○
7	1248	27.48	0.36	△
8	1281	26.78	0.30	△
9	1302	26.34	1.10	◎
10	1378	24.89	0.10	○
12	1561	21.97	0.18	△
13	1733	19.79	0.10	△

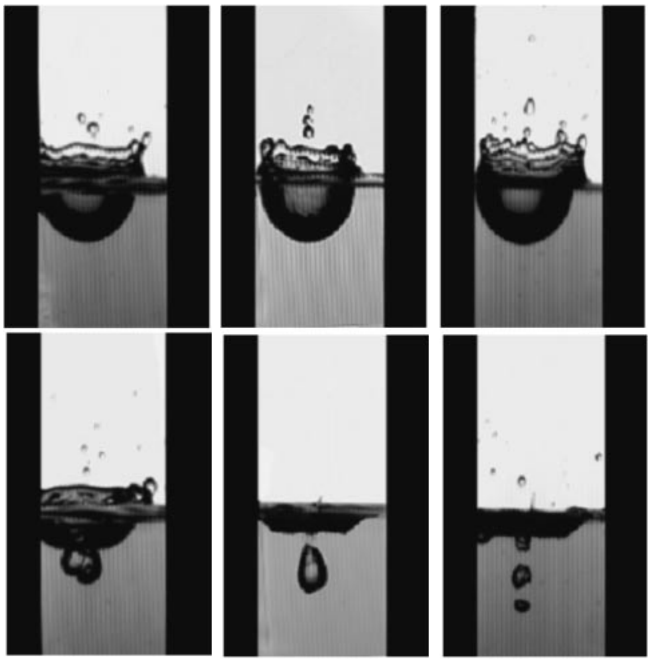
intensity of the sound attenuates by a factor of 1/e). The speed of sound is 343 m/s. The intensity (or sound pressure) of each mode calculated based on the power spectral density of the sound is shown in the column labeled "Intensity". The symbols ◎, ○ and △ respectively represent strong, medium and weak intensities.

2.2 *Drop period*

Figures 5(a) and 5(b) show drops falling from the watch glass at a very short time intervals (drop period of 1 s) and at long time intervals (drop period of 6 s), respectively. In the former case, the number of subsequent droplets falling at one time ranges from 7 to 11 and the first and/or second subsequent droplets exhibited extreme vibrations while falling in air. Whereas in the latter case, the number ranges from 4 to 6 and the first and second subsequent droplets fell gradually. A short drop period implies a large flux of water flowing into the small hole in the watch glass and, as a result, the total volume and the number of droplets associated with one drop increase.[10]

Figure 8(a) shows the shape of the bubble generated by a drop falling from the watch glass at a height of 40 cm with a very short drop period (1 s); Fig. 8(b) shows the shape of the bubble for the height of 40 cm with a long drop period (6 s). When the drop period is short (1 s), the first and/or second subsequent droplets acquire extreme vibrations, as shown in Fig. 5(a). They strike the surface of the water at different points, generating separate small bubbles, as shown in Fig. 8(a). In contrast, when the drop period is long (6 s), the first and second subsequent droplets generate a large bubble, as shown in Fig. 8(b).

Figure 9(a) shows the average frequencies of the original sound and the frequency variations (the length of the vertical line corresponds to twofold the standard deviation) for different drop periods with the drop distance from the watch glass to the surface of the water in the tank set to 36.5 cm. For a short drop period, the average frequency was 1300 Hz; for a long drop period, it was 850 Hz. One sees that the frequency of the original sound markedly changes when the drop period is between 1.5 and 2.0 s. Moreover, if the drop period is shorter than 2.0 s, the frequency variation increases, implying that the original sound tends to incorporate more



(a) 1 s, 40 cm (b) 6 s, 40 cm (c) 6s, 50 cm

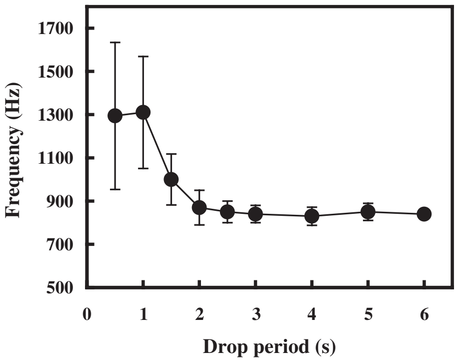
Fig. 8. Shapes of bubbles observed for different combinations of drop period and: drop distance; (a) 1 s and 40 cm, (b) 6 s and 40 cm, and (c) 6 s and 50 cm.

than one frequency components. This may be due to the fact that the first and second subsequent droplets generate many small bubbles as shown in Fig. 8(a).

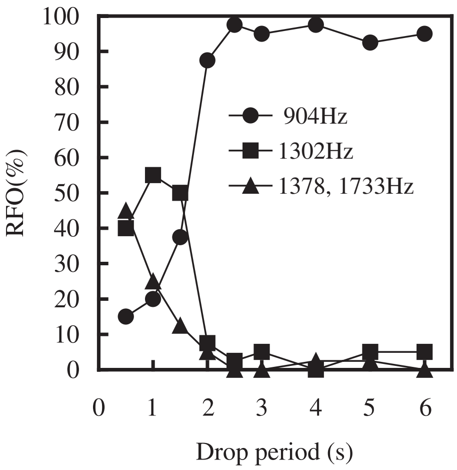
Thus, both the average frequency and the frequency variation of the original sound are large when the drop period is less than 2.0 s. On the other hand, when the drop period is long (6 s), the first and second subsequent droplets generate a large bubble as shown in Fig. 8(b) and, as a result, the average frequency and the frequency variations of the original sound are small.

Figure 9(b) shows the likelihood or relative frequency of occurrence (RFO) of the major frequency components in the reverberant sound as a function of drop period, with the watch glass set on the pan of the suikinkutsu (drop distance being 36.5 cm). In determining the relative frequency, measurements were repeated several times for each drop period. The frequency of occurrence of a respective component was counted every time that the component appeared to be the most intense component (i.e., having the highest sound pressure) in each measurement. The frequency of occurrence of the respective components was normalized by dividing the frequencies of occurrence by the total number of measurements performed to obtain RFO. The frequencies of the major components were 904, 1302, 1378 and 1733 Hz. It is seen in Fig. 9(b) that the RFO changes greatly with drop period in the range from 1.5 to 2.0 s. When the drop period is short, the frequencies of the components exhibiting significant RFO are 1302, 1378 or 1733 Hz, while it is mainly the 904 Hz component that most frequently exhibits the highest sound pressure when the drop period exceeds 2 s.

Note that the frequency of the original sound increases when the drop period decreases and that the original sound



(a) Original sound



(b)Reverberant sound

Fig. 9. (a) Measured frequency of original sound generated by drops that struck surface of water in tank and (b) relative frequency of occurrence (RFO) of frequency components of reverberant sound emitted by Hana Suikinkutsu when drop distance was fixed to 36.5 cm but drop period was varied.

tends to incorporate different frequency components, and that the average frequency and the frequency variation of the original sound are small if the drop period is long. Therefore, when the drop period is longer than 2 s and the drop distance is 36.5 cm, a stable original sound having a frequency of about 850 Hz results, and this original sound in turn generates a reverberant sound that has a dominant mode below 1 kHz.

2.3 *Drop distance*

We have seen in section 2.2 that droplets falling from a height of 40 cm with a drop period of 6 s form a single large bubble in the water, as shown in Fig. 8(b). Figure 8(c) shows the shape of the bubble generated by droplets falling with the same drop period of 6 s but falling from a height of 50 cm. It is seen from this figure that when the drop distance is 50 cm, the first and second subsequent droplets strike the same point on the water surface with a greater speed, which generate a long, slender and large bubble. However, the bubble will instantly break up into two or three smaller bubbles each having a high frequency according to eq. (1). When the drop distance is 70 cm, the bubbles generate a high-frequency band, as shown in Fig. 10. On the other hand, if the drop distance is less than 40 cm and the drop period is 6 s, the first and second subsequent droplets will strike the water surface

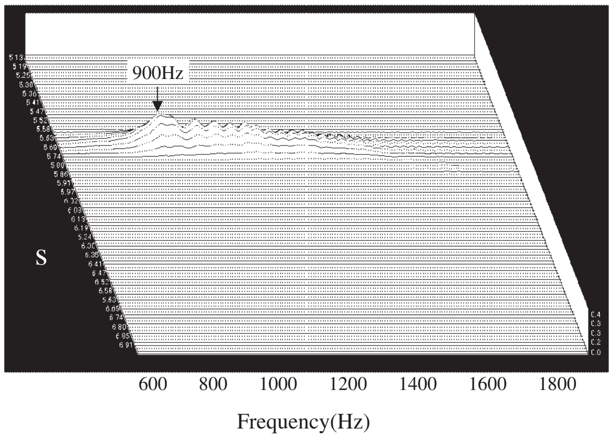
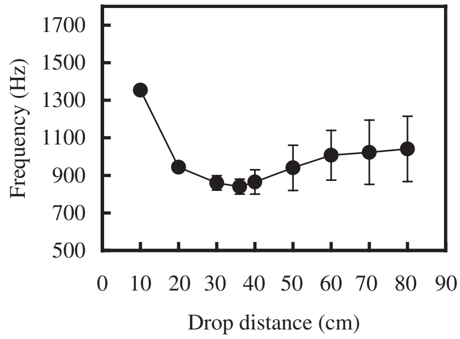
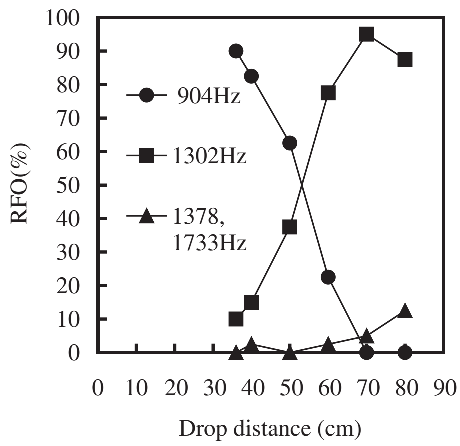


Fig. 10. Measured power spectral density of original sound when drop period was 6 s and the drop distance was 70 cm.



(a) Original sound



(b)Reverberant sound

Fig. 11. (a) Measured frequencies of original sound generated by drops that struck the surface of water in tank and (b) relative frequency of occurrence (RFO) of frequency components of reverberant sound emitted by Hana Suikinkutsu when drop period was fixed to 6 s and drop distance was varied.

with a small speed and, as a result, generate a smaller bubble that has a high frequency.

Figure 11(a) shows the average frequency and frequency variation of the original sound when the drop period is 6 s when drop distance is varied in the range from 10 to 80 cm. The average frequency decreases as drop distance increases from 10 to 36 cm. However, it increases with drop distance when the drop distance exceeds 36 cm. That is, the average frequency becomes minimum (about 850 Hz) at a drop distance of 36 cm. On the other hand, the frequency variation increases with drop distance. These results can be interpreted as follows. The speed of the droplets striking the water surface increases with drop distance up to 36 cm and, as a result, the volume of the bubble increases. The droplets will create a single bubble. On the other hand, as the drop distance exceeds 36 cm, the droplets create a multiplicity of smaller bubbles, as shown in Fig. 8(c), thereby resulting in many higher frequency sounds.

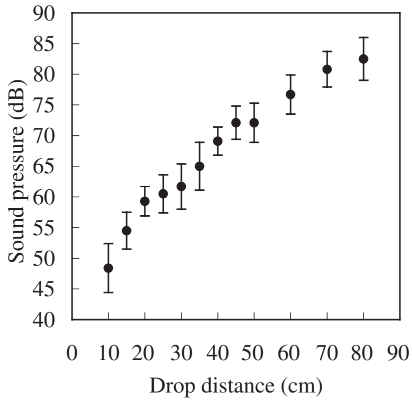
Figure 11(b) shows the RFO of the major frequency components (or modes) in the reverberant sound as a function of drop distance in the range from 36.5 to 80 cm at intervals of 10 cm in the arrangement shown in Fig. 4, with the drop period being 6 s. In determining the relative frequencies, measurements were repeated several times for each of drop distance. Frequency of occurrence of a respective component was counted every time that the component appeared to be the most intense (i.e., the mode having the highest sound pressure) in each measurement. The frequency of occurrence of the respective component was normalized by dividing the frequency of occurrence by the total number of measurements made. The frequencies of the major components were 904, 1302, 1378 and 1733 Hz. It is seen from Fig. 11(b) that when the drop distance is increased from 36.5 cm, the RFO of the 904 Hz sound decreases, while the RFO's of the other sounds increase.

It is also noted that when the drop distance is increased from 36.5 cm, the average frequency of the original sound increase from about 850 Hz as shown in Fig. 11(a) and that the RFO of the 904 Hz sound decreases accordingly, while the RFO's of the other components increase, as shown in Fig. 11(b). When the drop distance is decreased from 36.5 cm, the frequency of the original sound increases from 850 Hz shown in Fig. 11(a). Thus, it is thought that when the drop distance is decreased from 36.5 cm, the RFO of the 904 Hz sound decreases, while the RFO's of other components increase. Therefore, a stable original sound having a frequency of about 850 Hz and a reverberant sound having frequencies lower than 1 kHz can be generated when the drop distance is about 36 cm.

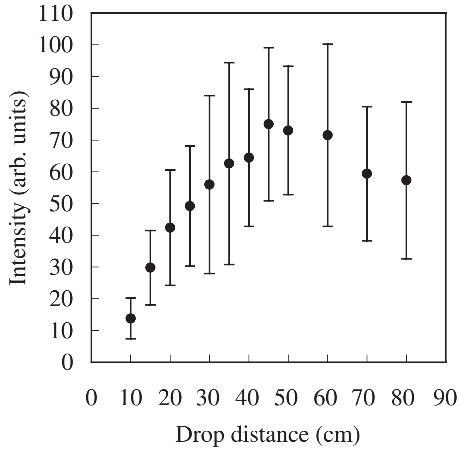
The power spectral density and average sound pressure of the original sound were measured using a frequency analyzer and a noise meter, respectively, as shown in Fig. 2. The drop period was fixed to 6 s and the drop distance was varied from 10 to 80 cm. Figure 12(a) shows the average sound pressure and its variations for each drop distance. Figure 12(b) shows the relative intensity of a maximum peak of the power spectral density and its variations as a function of drop distance. The relative intensity is plotted in arb. units.

As shown in Fig. 12(a), the average sound pressure of the original sound increases monotonically with drop distance. On the other hand, the relative power spectral density of the original sound increases with drop distance at a drop distance between 10 cm and 50 cm, while it decreases slightly when the drop distance exceeds 50 cm, as shown in Fig. 12(b). These show that the original sound contains many high-frequency components when the drop distance is larger than 50 cm, as shown in Fig. 10.

Thus we are led to the conclusion that a low-frequency original sound of about 1 kHz and an intense reverberant sound will be obtained under the optimum conditions in which the drop distance is between 30 and 40 cm and the drop period is longer than 2 s.



(a) Sound pressure measured by noise meter



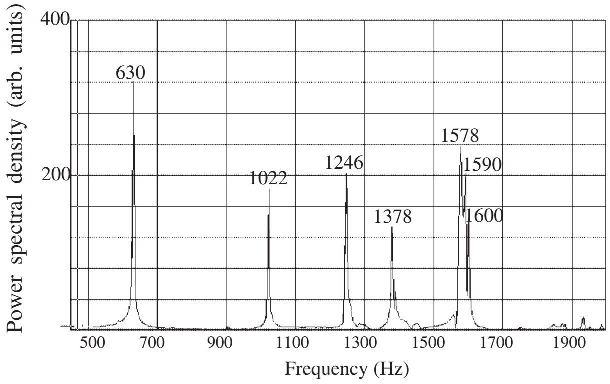
(b) Maximum power spectral density

Fig. 12. (a) Measured sound pressures and (b) measured maximum power spectral densities of original sound when drop period was fixed to 6 s and drop distance was varied.

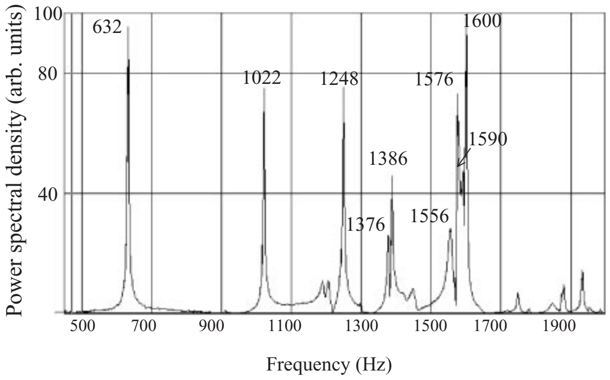
2.4 *Elastic vibration of the suikinkutsu*

We measured the power spectral densities of the sound emitted by the suikinkutsu in two stages. In the first stage, we placed the pan on the suikinkutsu and altered the level of the water to adjust the height of the air column (cavity in the body) to 36 cm. The suikinkutsu body was struck by hand at the point of its maximum diameter (about 30 cm from the bottom), and the frequency profile of the sounds emitted from the observation hole of the suikinkutsu was measured. In the second stage, the pan was removed and the suikinkutsu body was again struck by hand. Figures 13(a) and 13(b) show the power spectral densities measured in this experiment.

It is found that the frequency components of the sound observed with the pan set on the top of the body is almost the same as that of the sound observed with the pan removed. A closer examination reveals that the power of the sound is larger when the pan is in position than when the pan is removed, and that the peak of the spectrum measured with the pan in position shifts slightly to smaller frequencies (by a few Hertz) in the entire frequency range except from 1578 to 1600 Hz than when the pan is removed.

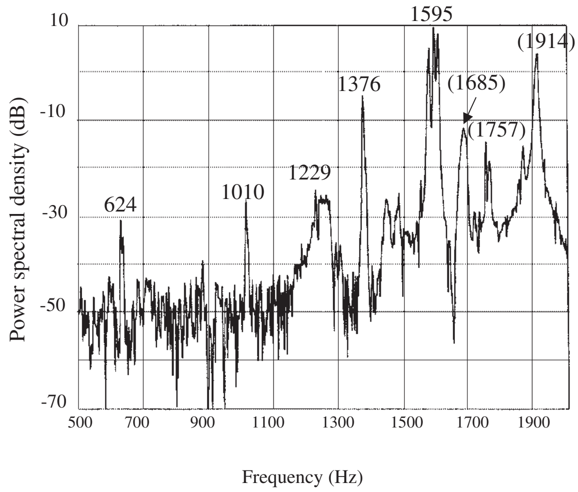


(a) Pan installed

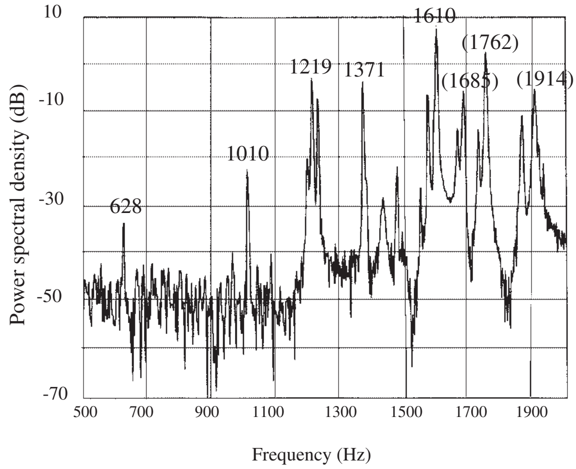


(b) Pan removed

Fig. 13. Power spectral density of sound emitted from Hana Suikinkutsu when struck by hand on body at point where body has maximum outer diameter, with pan (a) set on top of the suikinkutsu and (b) removed. The length of the air column was set to 36 cm.



(a) Pan installed



(b) Pan removed

Fig. 14. Measured power spectral density of elastic vibrations of Hana Suikinkutsu body struck with hammer at pont of its maximum outer diameter, when length of air column was set to 36 cm, with pan (a) set on top of the suikinkutsu and (b) removed.

With the pan set on the top of the suikinkutsu, four major natural frequencies of the suikinkutsu body were observed, namely, 630, 1022, 1246 and 1378 Hz, along with a strong band in the range from 1578 to 1600 Hz. These frequencies are nearly identical to the major frequencies of the naive sound emitted by the suikinkutsu as shown in Fig. 7(b), which appear at 635, 1022, 1248, and 1378 Hz. A strong band in the range from 1578 to 1600 Hz is not observed in Fig. 7(b). 1246 Hz is about twice the value of 630 Hz. The peaks at 581, 904, 1281, 1302, 1561 and 1733 Hz in Fig. 7(b) are not observed in the sounds emitted by the suikinkutsu.

To clarify the relationship between the sound generated by the suikinkutsu body struck by hand and the normal mode of the suikinkutsu body itself, we utilized an acceleration pickup that is adopted to detect the vibrations of an object itself and has a hammer for striking the object to set the object in vibration. In the experiments, the suikinkutsu body was struck with a hammer at the same position as it was struck by hand with and without the pan on the suikinkutsu body. When the pan was set, the level of the water was altered to adjust the height of the air column to 36 cm.

Figures 14(a) and 14(b) respectively show the frequency profiles of the suikinkutsu body measured with the acceleration pickup. It is understood from these figures that the frequencies of the normal modes with the pan set on the top are substantially the same as those of the sounds observed without the pan. The major natural frequencies of vibration are 624, 1010, 1229, 1376, 1595, 1685, 1757 and 1914 Hz. Of these, the lower five major natural frequencies are very close to 630, 1022, 1248, 1378, and a frequency band ranging from 1578 to 1600 Hz of the sounds generated by striking the suikinkutsu body by hand, as shown in Fig. 13(a), but the remaining three higher frequencies are not. Furthermore, the intensities of the modes shown in Fig. 13(a) are nearly the same, while the intensity of the modes shown in Fig. 14(a) increases with frequency.

Of the frequencies of the sound in Fig. 13(a), 635, 1022, 1248 and 1378 Hz have corresponding counterparts in Fig. 7(b). These four frequencies are the natural frequencies of the cavity associated with the natural vibrations of the suikinkutsu body, and substantially exhibit the same frequencies with and without the pan. Thus they are transverse modes of the cavity.

To understand the mechanism of the reflection and absorption of the sound echoing in the cavity by the suikinkutsu body, the frequency measurement of the suikinkutsu sound was repeated with the suikinkutsu body wrapped with clay to a thickness of 2 cm. Figure 15 shows the results of the measurements, which compares with

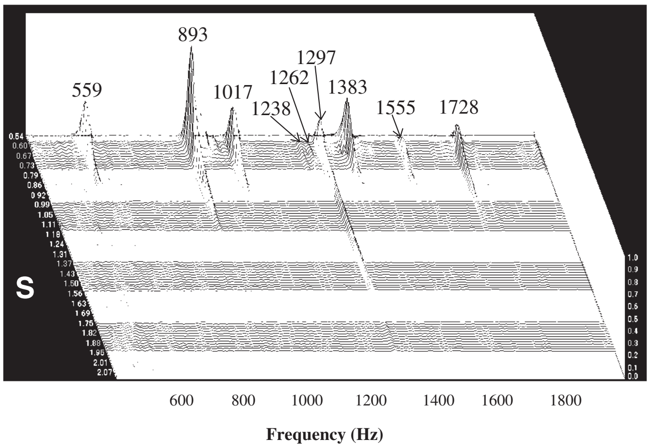


Fig. 15. Measured power spectral density of reverberant sound emitted by Hana Suikinkutsu wrapped with clay, observed through observation hole on side of the suikinkutsu.

Fig. 7(b) showing the results for the suikinkutsu body not wrapped with clay. The frequencies in Fig. 7(b) include 581, 635, 904, 1022, 1248, 1281, 1302, 1378, 1561 and 1733 Hz. On the other hand, the frequencies in Fig. 15 includes 559, 893, 1017, 1238, 1262, 1297, 1383, 1555 and 1728 Hz.

It is seen from the Fig. 15 that the frequencies of the sounds have slightly lower frequencies than the corresponding frequencies in Fig. 7(b). This difference is attributed to the difference in mass density per unit area between the bare wall and the clay-wrapped wall of the suikinkutsu. The latter wall has a mass density larger than the former wall and hence a reduced natural frequency. The modes of 635 and 1378 Hz are not shown in Fig. 15 due to the fact that these modes resonated with the body and hence were absorbed by dissipative clay. The large peak at 1302 Hz in Fig. 7(b) appears small (1297 Hz) in Fig. 15. This is probably because the 1297 Hz mode is a transverse mode of the air column in interaction with the body having dissipative clay on it. Fig. 15 shows that the reverberant sound has weak transverse modes and a single strong mode at 893 Hz. Thus, the suikinkutsu body preferably absorbs little transverse modes of the air column.

Thus, these experiments show that the sounds emitted by the suikinkutsu body struck by hand originate from the normal modes of the suikinkutsu body. In other words, these modes arise from the vibration of the air column in the cavity in resonance with the suikinkutsu body, thereby sustaining its transverse vibration modes. Thus, the traditional means of striking the suikinkutsu body by hand is a simple and practical method to "sense and assess" the reverberant sound.

2.5 *Vibration modes induced by speaker sound*

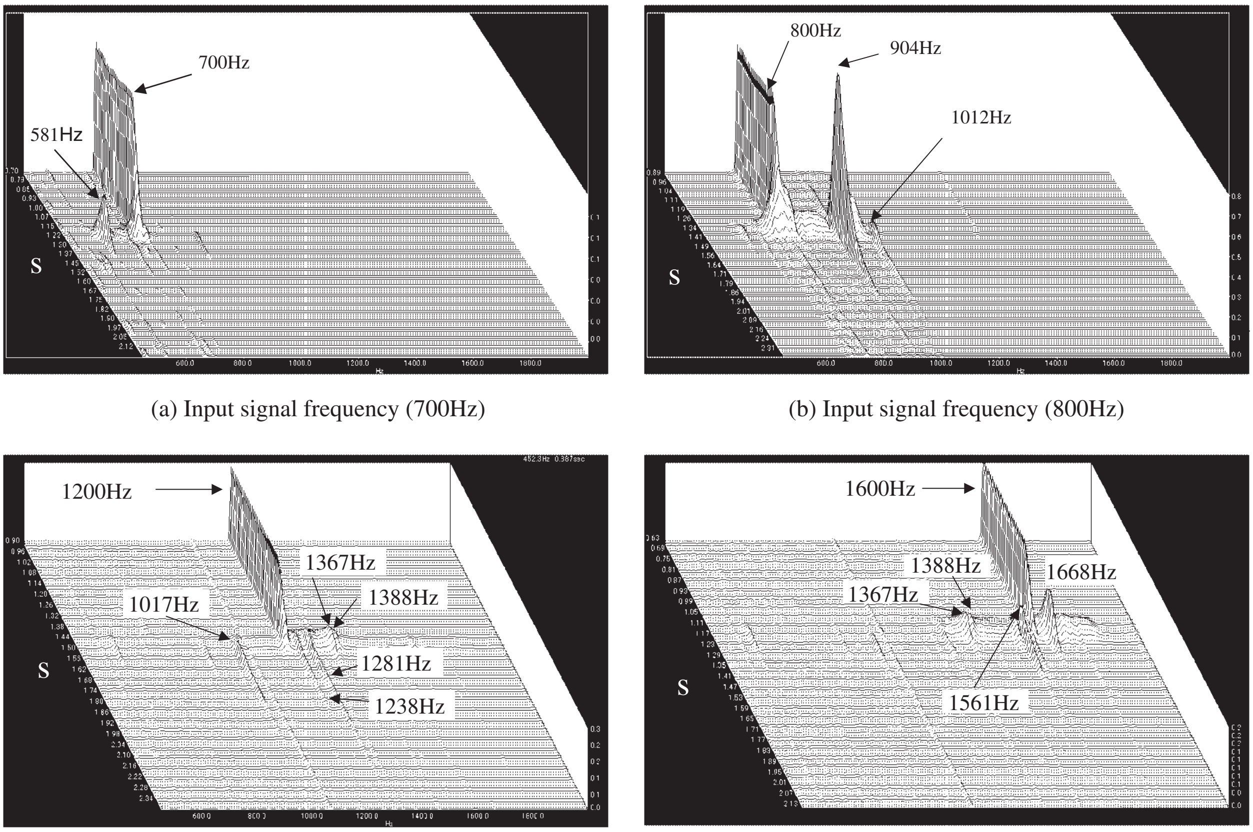
A test was conducted to observe possible resonance between a sound from a speaker and the reverberant sound with the height of the cavity (length of the air column) set to 36 cm and the speaker set directly above the water hole in the pan. This speaker was adapted to produce a sound having a frequency in the range from 500 Hz to 1700 Hz at intervals of 100 Hz. The intensity profiles of the sound emitted by the suikinkutsu were measured through the observation hole on the sidewall of the suikinkutsu with the speaker turned on or off. However, only four of them are shown in Figs. 16(a)–16(d), where Fig. 16(a) shows the profile for 700 Hz, Fig. 16(b) for 800 Hz, Fig. 16(c) for 1200 Hz, and Fig. 16(d) for 1600 Hz.

It is seen from these figures that the 581 Hz sound was emitted from the suikinkutsu immediately after the 700 Hz speaker sound was input, 904 and 1012 Hz sounds after the 800 Hz speaker sound, 1017, 1238, 1281, 1367 and 1388 Hz sounds after the 1200 Hz speaker sound, and 1367, 1388, 1561 and 1668 Hz sounds after the 1600 Hz speaker sound.

One may compare the sounds induced by the speaker (referred to as speaker-induced sounds) with the naive sound in Fig. 7(b). The frequencies in Fig. 7(b) include 581, 635, 904, 1022, 1248, 1281, 1302, 1378, 1561 and 1733 Hz. On the other hand, the speaker-induced sounds include 581, 904, 1012, 1017, 1238, 1281, 1367, 1388, 1561 and 1668 Hz. The speaker-induced sounds, however, lack the 635, 1302 and 1733 Hz modes, and have an additional frequency of 1668 Hz. Moreover, in the vicinity of each missing frequency mode, alternative modes appear. For example, the 1022 Hz mode is replaced by the pair of 1012 and 1017 Hz modes; the 1248 Hz mode is replaced by the 1238 Hz mode; and the 1378 Hz mode is replaced by the pair of 1367 and 1388 Hz modes. Since the speaker is more likely to induce longitudinal modes because of the position of the speaker, the missing frequencies, 635, 1302 and 1733 Hz are thought to be of transverse modes. The disappearance and appearance of modes having similar frequencies may be attributed to the coexistence of longitudinal and transverse modes in the narrow-frequency band.

2.6 *Length of air column and wavelength*

The level of water in the suikinkutsu was varied to change the height L of the pan relative to the surface of water in the range from 24 cm to 36 cm at intervals of 2 cm. The magnitude of L equals the length of the air column in the cavity. In addition, the watch glass was moved vertically above the pan to adjust the drop distance to 36.5 cm. It was observed that the water spread over an area on the under surface of the watch glass and then dropped onto the surface of water through the water hole with a drop period of 6 s. The frequency of the original sound produced by the bubble is about 850 Hz. The wavelengths λ (or equivalently frequencies) of the reverberant sounds emitted from Hana Suikinkutsu were determined for the respective lengths of the air column L when the speed of sound was 343 m/s. The results are shown in Fig. 17, from which it is seen that the resultant sound contains three types of mode whose wavelengths depend on L. This feature of the modes will be referred to as the L dependence of wavelength. From this L dependence, these modes can be classified into three types: Type A, modes having wavelengths that increase linearly with the L of the air column modes (marked by a light square and numbered 1); Type B, modes having wavelength independent of L (marked by dark circles and numbered 2, 13 and 14); and Type C, modes having a wavelength that is partly proportional to the L of the air column (marked by light triangles and numbered 3, 6 and 11). It will be understood that modes of Types A and B are longitudinal and transverse modes, respectively, since only longitudinal modes can change their wavelength linearly with L and only



(a) Input signal frequency (700Hz) (b) Input signal frequency (800Hz)

(c) Input signal frequency (1200Hz) (d) Input signal frequency (1600Hz)

Fig. 16. Change in frequency profiles of sound emitted by Hana Suikinkutsu with time, measured while turning speaker on or off set directly above water hole of the suikinkutsu when frequencies of the input signal were (a) 700 Hz, (b) 800 Hz, (c) 1200 Hz, and (d) 1600 Hz.

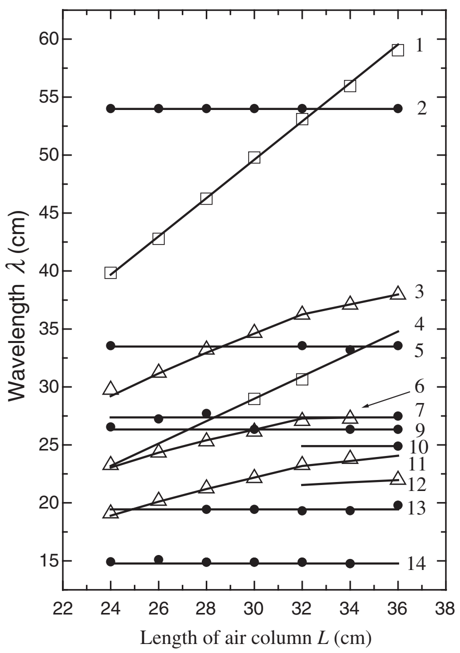


Fig. 17. Measured wavelengths of sounds emitted by Hana Suikinkutsu with drop period set to 6 s, drop distance set to 36.5 cm, and length of air column to between 24 and 36 cm.

Table II. Frequencies and intensities of modes of the naive sound (Naive); hand-struck Suikinkutsu sound (Hand); speaker-induced sound (Speaker), and types of modes appearing in Fig. 17 (Type). Intensities are classified into strong (◎), medium (○), weak (△), and zero (×). Types of modes induced: "Longi" (longitudinal mode), "Trans" (transverse mode), "Mixed" (longitudinal mode mixed with transverse mode).

Mode No.	Naive	Hand	Speaker	Type
1	581△	×	581○	Longi
2	635△	630◎	×	Trans
3	904◎	×	904◎	Mixed
4	×	×	1012○	Longi
5	1022○	1022○	×	Trans
6	×	×	1238△	Mixed
7	1248△	1246○	×	Trans
8	1281△	×	1281△	—
9	1302◎	×	×	Trans
10	1378○	1378○	×	—
11	×	×	1388○	Mixed
12	1561△	×	1561△	—
13	1733△	×	×	Trans
14	×	×	×	Trans

transverse modes have wavelength not affected by the length of the air column. Type C modes may be called mixed modes since they partly exhibit longitudinal and transverse modes. Modes 5, 7 and 9 seem to be transverse modes. Mode 4 seems to be a longitudinal mode. Modes 10 and 12 were measured only at $L = 36$ cm so that their types cannot be discerned from these measurements.

Table II summarizes that the intensity dependences of the frequencies of the modes involved in naive sound (naive), sound emitted by hand-struck Suikinkustu body (hand), speaker-induced sound (speaker), and the types of modes shown in Fig. 17 (rightmost column). The symbols ◎, ○, △, and × respectively represent strong, medium, weak, and zero intensities. "Longi" stands for the longitudinal mode, "Mixed" stands for the longitudinal mode mixed with the transverse mode, "Trans" stands for the transverse mode.

Measurement of the hand-struck and speaker-induced sounds were made for the same air column of 36 cm as in the case of the naive sound, so that the modes of hand-struck and speaker-induced sounds can be compared with the naive-sound modes numbered 1, 2, 3, 5, 7, 8, 9, 10, 12 and 13.

It is noted that the hand-struck sound exhibit substantially the same frequency modes with and without the pan, which implies that these frequencies modes (modes 2, 5, 7 and 10) are transverse modes. Therefore, those modes that appear in either the naive or speaker-induced sound but do not appear in the hand-struck sound (1, 3, 8, 9, 12 and 13 marked ×) are attributed to either the longitudinal modes of the cavity or the transverse modes of the cavity that do not resonate with any of the vibration modes of the suikinkutsu body.

Since the speaker is arranged to transmit sound in the longitudinal direction, the speaker is more likely to induce a longitudinal sound. Therefore, modes 2, 5, 7, 9, 10 and 13 missing in the speaker column (marked ×) can be attributed to the transverse modes. On the other hand, modes 1, 3, 8 and 12 are associated (in one way or the other) with the longitudinal modes of the cavity, in that they do not appear in the speaker column. Of these modes, 1 and 3 respectively belong to Types A (longitudinal mode) and C (mixed mode) in accordance with the classification of the modes shown in Fig. 17.

It should be noted that the mode analysis given above is in good harmony with the classification of modes based on the data in Fig. 17. Thus, one may conclude the following: modes 1 and 4 are longitudinal modes; modes 2, 5, 7, 9, 10, 13 and 14 are transverse modes; modes 3, 6 and 11 are partly longitudinal modes (i.e. mixed modes). However, modes 8 and 12 cannot be determined definitely on the same basis as that for other modes. They can be either longitudinal or mixed modes. The determination of the type of these modes will be further discussed in the next section.

3. Natural Frequency Mode of Suikinkutsu

Hereafter, we will discuss a formula for calculating the frequency of the vibration mode of the cavity of the suikinkutsu, based on an interpolation of two formulas applicable to a cylindrical cavity and to a spherical cavity. The cavity of Hana Suikinkutsu has a circular transverse cross section, which is maximum in the middle of the cavity and decreases toward the upper section of the cavity, as shown in Fig. 3. The upper section of the cavity is covered with a pan having a flat undersurface and a spherically curved wall. The bottom boundary of the cavity is the surface of water.

For an enclosed cylindrical cavity, the natural frequency f_{NMS} of the cavity can be calculated using[11]

$$f_{NMS} = \frac{C}{2\pi}\sqrt{\left(\frac{\mu_{NM}}{R}\right)^2 + \left(\frac{S\pi}{L}\right)^2}, \tag{2}$$

Table III. Turning points of cylindrical Bessel function of order N.

μ_{NM}	$M = 0$	1	2	3	4
$N = 0$	0.000	3.832	7.016	10.17	13.32
1	1.872	5.332	8.536	11.71	14.86
2	3.132	6.707	9.970	13.17	16.35
3	4.339	8.018	11.35	14.59	17.79

where R and L are the radius and height (longitudinal length) of the cylindrical cavity, respectively, C is the speed of sound, S is a zero or positive integer and μ_{NM} is the M-th solution that renders the first derivative of an N-th order cylindrical Bessel function to vanish. The μ_{NM} values are shown in Table III.

For a hemispherical space, the natural frequency f_{NS} can be expressed by eq. (3) with L being the radius of the spherical space.[11]

$$f_{NS} = \frac{C}{2\pi}\left(\frac{\xi_{NS}}{L}\right) \tag{3}$$

Here, ξ_{NS} is the S-th solution that causes the first derivative of an N-th order spherical Bessel function to vanish. Imposing a boundary condition that the normal component of the fluid particle velocity of air is zero on the surface of the water, the lowest order N possible must be zero. Four major values of ξ_{0S} are shown in Table IV.

In actuality, however, the cavity of Hana Suikinkutsu has a hemispherical space on top and a flat surface of the water at the bottom. Thus, the equation describing the natural frequency of the suikinkutsu cavity can be approximated by an interpolating eqs. (2) and (3). We therefore propose the following interpolation formula for the frequency f_{NMS} of the cavity in the actual suikinkutsu.

$$f_{NMS} = \frac{C}{2\pi}\sqrt{\left(\frac{\mu_{NM}}{R}\right)^2 + \left(\frac{\xi_S}{L}\right)^2} \tag{4}$$

Here, ξ_S is an empirical longitudinal mode factor introduced to interpolate eqs. (2) and (3), and hence is in the range

$$S\pi < \xi_S < \xi_{0S}. \tag{5}$$

The inner radius R of Hana Suikinkutsu changes with the height of body from the bottom. R is taken as the radius of the cavity at the midpoint of the axis of the cavity. Table V lists values of R in association with seven lengths L of the cavity. Considering the shape of the suikinkutsu, the radius of the cavity establishing transverse modes therein can be estimated to be in the range from 16.0 to 17.3 cm, based on

Table IV. Turning points of spherical Bessel function of order 0.

ξ_{NS}	$S = 0$	1	2	3
$N = 0$	0.000	4.493	7.725	10.904

Table V. Length L and radius R of air column.

L (cm)	24.0	26.0	28.0	30.0	32.0	34.0	36.0
R (cm)	16.0	16.5	16.8	17	17.3	16.8	16.5

the data listed in Table V.

For each mode that can be predicted from Table II, we insert the measured frequency of the mode along with L and R of the air column, transverse mode factor μ_{NM}, and longitudinal mode factor ξ_S on the left-hand and right-hand sides of eq. (4). If eq. (4) holds, we can say that the mode associated with the mode factor μ_{NM} and ξ_S exists. An approach to determine a specific mode that satisfies eq. (4) will now be shown below by way of example.

For transverse modes, $\xi_{NS} = 0$, the measured frequency of a candidate mode and the μ_{NM} selected from Table III are inserted in eq. (4) to determine the value of R. If R is found in the narrow range from 16.0 to 17.3 cm, then it implies that a transverse mode exists, which is associated with the transverse mode factor μ_{NM} and R is the radius of the resonating air column.

For longitudinal modes, $\mu_{NM} = 0$, the measured frequency of a candidate mode is inserted in eq. (4) along with the value of L to determine ξ_S. If ξ_S is in the range of inequality (5), then it is equal to the magnitude of the longitudinal mode factor ξ_S.

For mixed modes selected from Fig. 17, at least two sets of a measured frequency of the mode, possible R and L selected from Table IV, and a possible μ_{NM} are inserted in eq. (4) to determine ξ_S. If ξ_S is bound, then μ_{NM} and ξ_S constitute a unique set of transverse and longitudinal mode factors.

In this way, except for Mode 12, μ_{NM}, ξ_S, and R are uniquely determined for the respective modes as shown in Table VI. Based on these values, the frequency of each mode is calculated as a function of L using eq. (4) and plotted by solid curves in Fig. 17. It is seen that the plots are in very good agreement with the plot of the measured frequencies.

For Mode 12, eq. (4) enables the determination of two different sets of (μ_{NM}, ξ_S): one for the longitudinal mode (0, 10.29) and another for the mixed mode (4.339, 4.30). However, since only one measured frequency is available for Mode 12, it is not possible to conclude that it is a mixed mode. The solid line and the mode factor for Mode 12 are shown in Fig. 17 and Table VI, respectively, only for the mixed mode. Mode 8 also has only one measured frequency. However, it is found in the above calculation that this is the only possible longitudinal mode. To simplify Fig. 17, neither measured frequency data nor the solid curve for Mode 8 is shown.

It is very important to note that eq. (4) can be applied to all of the measured data, irrespective of whether data belongs to a longitudinal mode, a transverse mode, or a mixed mode. Thus the proposed interpolation formula can fully describe the acoustic modes of the air column in the cavity of the suikinkutsu. Note that the formula can basically determine the pertinent transverse or longitudinal mode from one measured data. Also it can determine the pertinent mixed mode from two measured data.

Table VI. Longitudinal and transverse mode factors and radius used in eq. (4) for 14 modes, along with mode type.

Mode No.	μ_{NM}	ξ_S	R (cm)	Mode
1	0	3.80	0	Longi
2	1.872	0	16.09	Trans
3	1.872	4.33	—	Mixed
4	0	6.50	0	Longi
5	3.132	0	16.70	Trans
6	3.132	4.49	—	Mixed
7	3.832	0	16.70	Trans
8	1.872	7.38	—	Mixed
9	3.832	0	16.07	Trans
10	4.339	0	17.20	Trans
11	3.132	6.45	—	Mixed
12	4.339	4.03	—	Mixed
13	5.332	0	16.50	Trans
14	7.016	0	16.50	Trans

4. Conclusion

The suikinkutsu sound consists of an original sound generated by free-falling droplets striking the surface of the water in the suikinkutsu and a reverberant sound generated by the original sound. The original sound was regenerated using a watch glass and a water tank in the geometry shown in Fig. 2. The original sound was detected with a microphone.

(1) When a drop falls from the watch glass, it splits into a sequence of droplets before they strike the surface of the water in the tank. The original sound consists of pulse-shaped sounds generated by the dominant and subsequent droplets striking the surface and the sound induced by the bubble that is generated by the first and second subsequent droplets striking the concave surface, which is formed by the dominant droplets. It is thought that the pulse-shaped sounds can easily propagate in water and stimulate the natural elastic modes of the suikinkutsu body, whose modes in turn activate the corresponding (i.e., resonating) natural modes of air in the cavity, thereby creating reverberant sound. On the other hand, the sound generated by the bubble stimulates air in the cavity and also generates a reverberant sound, which will produce resonance in the suikinkutsu body. We are presently concerned, however, mainly with the latter sound since it is thought that the latter sound is conventionally utilized as the reverberant sound of the suikinkutsu.

(2) A suikinkutsu capable of generating favorable sound, or sound of good tonal quality, must have an intense, low-frequency and reproducible original sound generated by a large bubble oscillating with a large amplitude. More particularly, there are three criteria for a suikinkutsu of good tonal quality.

a) A large bubble can be formed by a large drop falling from a clean, wide, level undersurface, such as the undersurface of a watch glass. If the first and second subsequent droplets are small, the drop distance must be larger for the large bubble. When the drop distance is increased, the subsequent droplets can generate a large bubble, which, however, is very likely to instantly break up into two or three smaller bubbles.
b) The drop period must be larger than 2.0 s. This ensures the realization and reproduction of the low-frequency original sound. If the drop period is short, the first and second subsequent droplets mostly generate two small bubbles, instead of a single large bubble.

c) The drop distance must be in the range from 30 to 40 cm for three reasons: First, the frequency of the original sound becomes minimum for a drop distance of about 36 cm. Second, the intensity of the dominant original sound becomes maximum at a drop distance of about 50 cm. Third, the reproducibility of the original sound decreases at a drop distance above 40 cm.

If these criteria are satisfied, the frequency of the original sound will be about 850 Hz. The original sound of Hana Suikinkutsu is obtained by setting the drop distance to 36.5 cm. It should be understood that in actuality many suikinkutsus are manufactured to have a drop distance larger than 40 cm, probably based on the manufacturers' experience that a large drop distance will ensure the formation of a bubble of adequate size even after the drop-forming undersurface gets stained in the course of use for months. For a drop distance above 40 cm, however, the reproducibility of the original sound decreases It should be also understood that the drop distance is made much larger than 40 cm in order to generate an intense pulsed original sound if the pulse-shaped original sound is used as the source of the reverberant sound.

(3) The sounds emitted by the suikinkutsu were examined with special intensity interest in the mechanism of how the natural elastic modes of the suikinkutsu body and the natural modes of air in the cavity can be formed and can interact with each other. To elucidate the elastic modes of the suikinkutsu body, we observed the vibration of the body using an acceleration pickup. The changes in the vibration mode of the suikinkutsu were observed by wrapping the suikinkutsu with clay. To check the possible resonance of the suikinkutsu body with air in the cavity, we observed the sound generated by the suikinkutsu struck by hand. A speaker sound was input to the air column in the cavity from the water hole to observe how the sound is transferred to the air column. Furthermore, to examine the modes of the cavity, the natural frequency of the reverberant sound was measured for different heights of the pan relative to the water level in the suikinkutsu.

(4) Our results are as follows: Hana Suikinkutsu, which has a typical movable suikinkutsu configuration, includes a vase-shaped body similarly to other common suikinkutsus. The natural frequencies of the sound emitted by Hana Suikinkutsu can be calculated using eq. (4). This equation was obtained by interpolating a well-known formula describing the natural frequencies of a cylindrical cavity and a semispherical cavity. The upper section of the cavity consists of a flat end and a partially spherical wall. Possible longitudinal modes are determined by the configuration of the cavity. The inner radius of the suikinkutsu body at the midpoint thereof is taken as the radius of the air column. The wavelengths calculated using eq. (4) are in good agreement with the measured values, as shown in Fig. 17.

(5) The natural frequencies of the dominant sounds emitted by Hana Suikinkutsu are 904, 1022, 1302, and 1378 Hz. The duration of the dominant sounds is about 1 s, that is about 10 times as long as the duration of the original sound. The frequencies of the original sound are not found in this frequency domain. 904 Hz is the natural frequency of the mixed mode of the cavity. This mode has an extremely high sound pressure and a time constant of 0.29 s. 1302 Hz is the natural frequency of the typical transverse mode of the cavity. This mode also has an exceedingly high sound pressure and an exceedingly large time constant of 1.10 s. This frequency is important for the tonal quality of the suikinkutsu. 1022 Hz is the natural frequency of the transverse mode of the cavity, which happens to be close to that of the natural elastic frequencies of the suikinkutsu body. It seems, therefore, that the transverse mode of the cavity is in resonance with that of the suikinkutsu body. The mode has a high sound pressure and a time constant of 0.25 s. 1378 Hz is the natural frequency of another transverse mode of the cavity, similar to the transverse mode of 1022 Hz, and the sound at this frequency has a high sound pressure. In fact, the natural frequency of the mode is very close to that of the suikinkutsu body. However, this mode has a time constant of 0.1 s, which is much shorter than that of the 1022 Hz mode. This implies that this transverse mode is not in appreciable resonance with the suikinkutsu body as much as the 1022 Hz mode.

(6) In this study, we have shown that intimate interference or resonance exists between the natural transverse modes of the cavity and the elastic vibration mode of the suikinkutsu body. Thus, we have verified the usefulness of the well-known means of assessing the tonal quality of the suikinkutsu by striking it by hand and hearing the sound emitted therefrom. In other words, the tonal quality of the suikinkutsu may be estimated by striking its body by hand.

The suikinkutsu is normally buried underground and loosely surrounded by broken pieces of rock as shown in Fig. 1. The suikinkutsu preferably have a hard thin wall made of porcelain so that the suikinkutsu will not appreciably absorb the vibration modes of the air column and maintain the elastic vibration of the body well.

It should be understood that the frequency profile of the suikinkutsu sound as observed through a suimon or an observation hole is not necessarily the same as the frequency profile of the natural vibration modes in the cavity of the suikinkutsu body, since the intensity and frequency distributions of the sound in the cavity vary from one position to another, so that the tone of the suikinkutsu sound greatly depends on the position of the observation hole.

There has been a trend in the art favoring suikinkutsus that produce a sound having a frequency as low as 1 kHz and have good reproducibility of sound. Thus our examination was carried out focussing on such suikinkutsus. However, some people might prefer suikinkutsus that irregularly produce a diversified "waterdrop sound" or "streaming sound". Therefore, we do not mean that this study is exhaustive. We hope that further physical analyses of suikinkutsu carried out to facilitate improvements of the suikinkutsu, along with continuing experience of suikinkutsu manufactures.

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