# Control of Human Generating Force by Use of Acoustic Information — Utilization of Onomatopoeic Utterance*

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We have performed basic experiments for the purpose of applying onomatopoeia to engineering problems. In these experiments, test subjects were made to perform lifting actions while listening to onomatopoeic utterances. We thereby demonstrated that there is a relationship between the onomatopoeic utterances and the lifting forces exerted by the test subjects. We examined how the lifting forces are related to the envelope of onomatopoeic utterances. Furthermore, we investigated how the lifting force is affected depending on whether or not emotion is expressed when uttering the onomatopoeia.

***Key Words*:** Sound, Human Engineering, Onomatopoeia, Onomatopoeic Utterance, Human Sensitivity, Lifting Action, Sound Waveform, Emotion in Utterance, HAM (Human Adaptive Mechatronics)

## 1. Introduction

Humans tend to associate human actions with onomatopoeia, and are able to imagine the actions that the onomatopoeia correspond to. In this study, by focusing on the fact that onomatopoeia is closely related to human senses and sensitivity, we have attempted to use onomatopoeia in an engineering context.

Onomatopoeia is used to express human senses and body rhythms, allowing senses and feelings to be conveyed in a spontaneous manner[(1),(2)]. In other words, onomatopoeia is word that concisely express human senses, feelings or actions through the filter of human sensitivity.

We turned our attention to these characteristics of onomatopoeia, and we investigated the issues involved in engineering applications of onomatopoeia, especially in relation to the proficiency of operations by humans in HAM (human adaptive mechatronics).

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It was shown that when humans are presented with onomatopoeia as they perform an action, it improves their control and memorization of this action. If young children are given the task of moving a stick while saying the word *gyū*, then their memory of this action is improved[(3)]. As trainers gain more experience in the rehabilitation of handicapped children, it can be shown that they make more use of onomatopoeia[(4),(5)]. Research results such as these suggest that onomatopoeia is easily understood intuitively and through the senses, and that actions presented together with such words are easier to remember.

In this study, as described below, we made people perform lifting actions while listening to onomatopoeic utterances. As the onomatopoeia stimulus, we used the Japanese word *gū*. This word was chosen based on data from the abovementioned study by Tohya[(3)-(5)], where it was found to be the word used voluntarily most often by trainers in order to control their trainee's actions.

## 2. The Relationship between Onomatopoeia and HAM

Consider a situation where a person is walking. Imagine that this person is in a lively energetic mood (Fig. 1 (a)). When we see people walking in this fashion, we say that they are walking "briskly" (in Japanese, "*suta-suta*"). On the other hand, when the person is feeling down as shown in Fig. 1 (b), we say that they are "trudging" along (in Japanese, "*tobo-tobo*"). Words such as "*suta-suta*" and "*tobo-tobo*" are a type of onomatopoeia[(6),(7)].

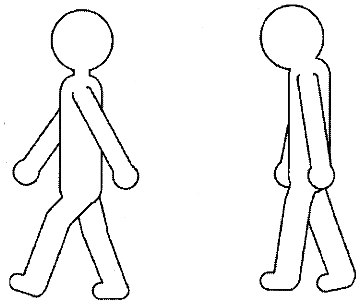



Fig. 1 Walking motion: (a) walking "briskly" (in Japanese, "*suta-suta*"); (b) "trudging" along (in Japanese, "*tobo-tobo*")

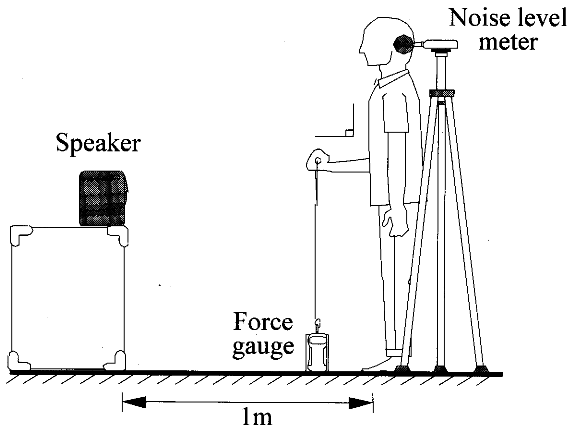



Fig. 2 Lifting action experiment

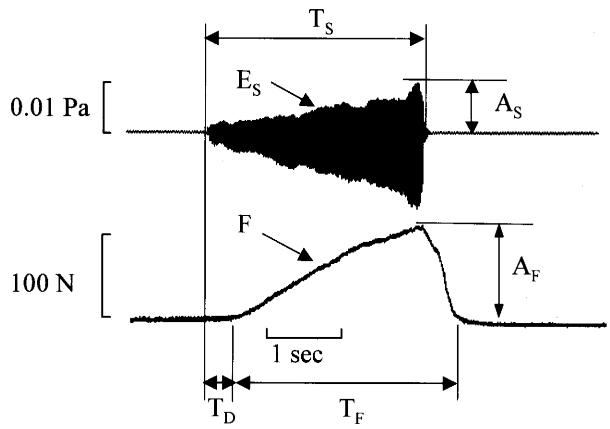



Fig. 3 Sound (onomatopoeic utterance) and lifting force

In general, when we want to precisely express how someone is walking, it is necessary to use numerous physical quantities such as the walking speed, stride length, arm swing and body posture. But if someone uses these precise physical quantities to describe a walking style to us, we find it impossible to visualize what this walking style actually looks like. Conversely, when a walking style is described using onomatopoeia such as "*suta-suta*" and "*tobo-tobo*", it is much easier to paint a mental picture of the walking style.

Thus, when conveying information to other people, there is sometimes little to be gained by providing precise or objective data. In fact there is hardly any point in providing inexperienced laymen with precise physical quantities. From the layman's perspective it is better to use onomatopoeia, which allows states and conditions to be guessed at and visualized more easily, albeit in more general terms.

HAM is the study of mechatronics adapted to human manipulatory skills. There is a need for mechatronic equipment suited to each level of proficiency from beginners to experts.

In this study, we aim to use the abovementioned onomatopoeia to help unskilled laymen acquire skills more quickly.

## 3. Lifting Action Experiments

To measure the forces exerted by people when performing lifting actions, we prepared the simple test apparatus as shown in Fig. 2. A heavy immovable steel member was placed on the floor, and a force gauge was attached to it. A steel wire was extended from the force gauge and a handle for gripping with the hands was attached to the end of this steel wire. The height of the handle above the floor was adjusted so that the test subjects' arms were bent at about 90° when holding the handle.

The onomatopoeia *gū* was spoken and the voice was captured on a personal computer. This signal was amplified with an amplifier and output from a speaker.

The test subjects were asked to lift up the handle while listening to the onomatopoeic utterance *gū*. The sound and the lifting force measured by the force gauge were recorded simultaneously. The magnitude of the sound was also measured with a noise level meter situated near the test subject's ear (at a distance of 50 cm from the ear so as not to obstruct the lifting movement). Note that the noise magnitude mentioned here means the peak value of the noise level displayed while the sound *gū* is being emitted from the speaker.

Figure 3 shows an example of the results of measuring the sound and lifting force. It can be seen that there is a slight time delay (denoted by $T_D$ in the figure) between the subject hearing the *gū* sound and the start of the lifting action. The lifting force then becomes gradually larger, and the lifting action ends shortly after the *gū* sound finishes.

When examining the relationship between the sound and the lifting force, the following items are worthy of study:

- The relationship between the duration of the emitted sound and the duration of the lifting action ($T_S$ and $T_F$)
- The relationship between the magnitude of the sound and the magnitude of the lifting force ($A_S$ and $A_F$)
- The relationship between the sound pressure wave-

form (envelope) and the lifting force ($E_S$ and $F$)

- The relationship between "emotion" in onomatopoeic utterance and the magnitude of the lifting force

Note that although the magnitude of the sound is shown intuitively in the figure as the value of $A_S$ (Pa), it should be stressed that the sound magnitudes described below are expressed as noise levels (dB(A)) as mentioned above.

## 4. Basic Lifting Force Characteristics

We investigated the interesting study items mentioned above. The test subjects consisted of five students in their 20 s. Due to space limitations, the experimental results discussed below are for one of the students, but similar trends were also exhibited in the results obtained with the other student. The test subjects were given no prior instructions other than asking them to perform lifting actions together with the sounds.

### 4.1 Relationship between sound generation time and lifting action time

Waveforms were prepared in which the duration of the *gū* sound was varied between 0.5, 1, 1.5, 2 and 3 seconds. These waveforms were prepared by applying fade-out processing to a long pre-recorded *gū* waveform in order to adjust the sound generation time.

In the tests, the test subjects were made to listen ten times to each of the five different sound samples in random order. In other words, the test subjects were exposed to 50 random sounds of different length. A one-minute interval was left between the completion of one lifting action and the commencement of the next lifting action. Also, taking the tiredness of the test subjects into consideration, a ten minute break was provided in the middle of each sequence. Even though the sound durations were varied, their magnitude (noise level) was kept constant at 60 dB(A) throughout these tests.

The experimental results are shown in Fig. 4. The horizontal axis shows the sound generation time $T_S$, and the vertical axis shows the lifting action time $T_F$. The lifting time results are represented by showing the average values (shown as black diamond symbols) and standard deviations (shown as vertical bars).

As this figure shows, the duration of the lifting action was longer than the duration of the sound, regardless of the sound length. This behavior means that there is a difference between the time interval from the start of the sound to the start of the human action and the time interval from the end of the sound to the end of the human action. This time difference is thought to originate from inertia in the human auditory-motion system.

On the other hand, with regard to the variation of the lifting action duration, these results show that the duration of the lifting actions corresponds very closely to the length of the sound, even though the test subjects were subjected to sounds with randomly varied lengths.

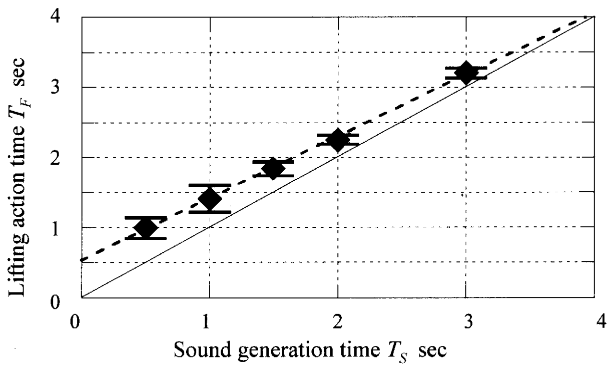



Fig. 4 Relationship between sound generation time and lifting action time

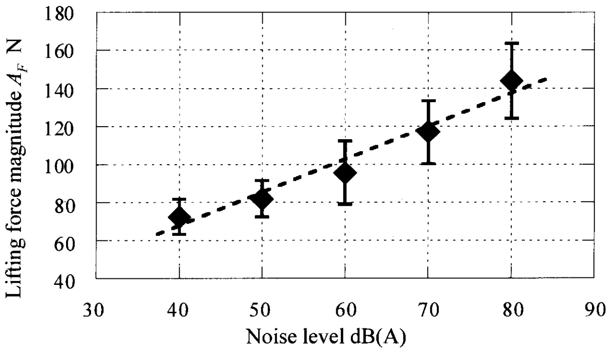



Fig. 5 Relationship between sound magnitude and lifting force magnitude

### 4.2 Relationship between sound magnitude and lifting force magnitude

With the duration of the *gū* sound fixed at 1 second, we performed tests while varying the magnitude of this sound. For this purpose we prepared five different sounds with magnitudes of 40, 50, 60, 70 and 80 dB(A). As before, ten each of the 5 different sound magnitudes were presented randomly.

The test results are shown in Fig. 5. The horizontal axis shows the noise level, and the vertical axis shows the lifting force $A_F$. As this figure shows, the lifting force becomes larger as the magnitude of the sound increases. However, the variation of the lifting force is relatively large.

## 5. Relationship between the Sound Waveform Envelope and the Lifting Force

### 5.1 Comparison of waveforms

Based on the finding that the lifting force increases corresponding to increases in the magnitude of the sound, one might expect the magnitude of the lifting force to follow the temporal variation of sound pressure within the sound in cases where the sound pressure is not constant. We therefore prepared sound waveforms with different envelopes, i.e., sounds with sound pressures that varied as a function of time. Specifically, we prepared four different versions of the sound *gū* with different envelopes. The

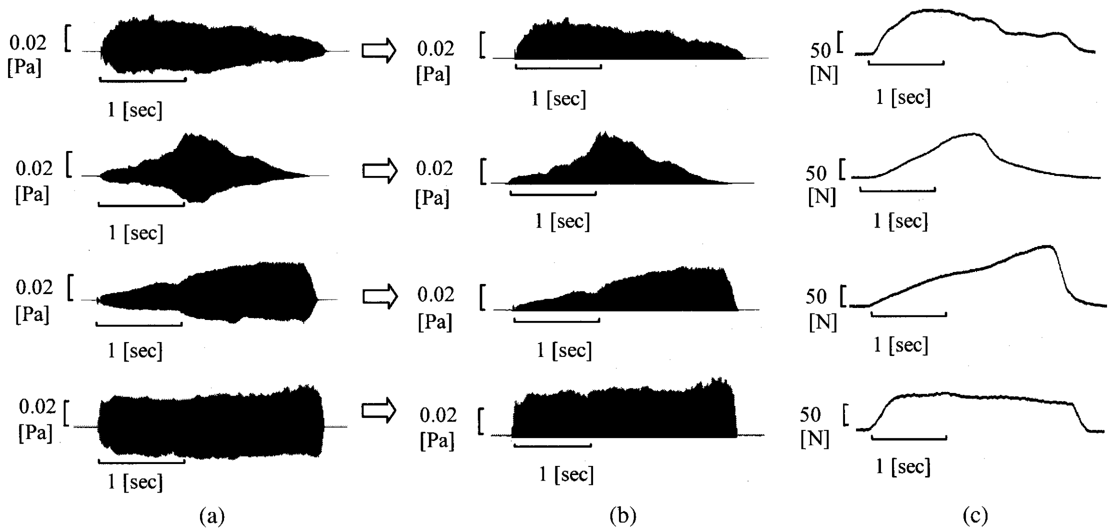



Fig. 6 Sounds and lifting forces: (a) sound waveforms; (b) sound waveforms after magnitude detection; (c) force waveforms

waveforms of these four sounds are shown in Fig. 6 (left column). The first waveform has an envelope in which the sound pressure rises sharply to begin with and tapers off gradually thereafter, the second has an envelope in which the sound pressure gradually rises and falls to form a peak in the middle, the third has an envelope in which the sound pressure increases gradually with time, and the forth has an envelope of rectangular. Each of these sounds has a duration of 2.5 seconds, and a sound pressure of 60 dB(A).

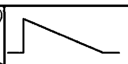
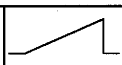
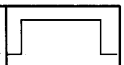
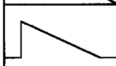
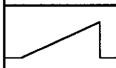
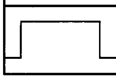
We performed tests during which the test subjects were made to listen to these four sounds 10 times in random order. The results are shown in Fig. 6. The left column in this figure shows the temporal variation of the sound pressure as discussed above. The column on the right shows the waveform of the lifting force. The central column shows the envelope of the sound waveform obtained by magnitude detection of the original signal. These envelopes were obtained in order to facilitate comparison between the sound waveforms and lifting force waveforms.

As the figure shows, the envelope of the detected sound waveform bears a close resemblance to the waveform of the lifting force. In other words, when the sound pressure varies from one moment to the next, it can be understood that the lifting force increases and decreases according to the magnitude of the sound pressure.

### 5.2 Evaluation of similarity of waveforms by contribution rates

We numerically evaluated the similarity between the two sets of waveforms by determining their contribution rates. To do this, we first determined the envelope $E_S(t)$ of the detected waveform (see the top row of Table 1). The contribution rate was then determined from the waveform $E_S(t)$ and the force waveform $F(t)$ by using the following formula:

Table 1 R-squared ($T_S = 2.5$ sec)

| $F(t)$ \ $E_S(t)$ |  |  |  |  |
|---|---|---|---|---|
|  | 0.81 ±0.05 | 0.44 ±0.16 | 0.03 ±0.03 | 0.16 ±0.09 |
|  | 0.57 ±0.11 | 0.81 ±0.07 | 0.02 ±0.02 | 0.14 ±0.04 |
|  | 0.10 ±0.05 | 0.13 ±0.06 | 0.90 ±0.07 | 0.64 ±0.09 |
|  | 0.65 ±0.13 | 0.35 ±0.09 | 0.29 ±0.16 | 0.65 ±0.10 |

$$r^2 = \frac{S_{xy}^2}{S_{xx}S_{yy}} \tag{1}$$

where

$$S_{xy} = \frac{1}{E_{S\max}F_{\max}} \times \sum_i \left[\left(E_S(t_i) - \overline{E_S(t_i)}\right)\left(F(t_i+T_D) - \overline{F(t_i+T_D)}\right)\right]$$

$$S_{xx} = \frac{1}{E_{S\max}^2}\sum_i \left(E_S(t_i) - \overline{E_S(t_i)}\right)^2$$

$$S_{yy} = \frac{1}{F_{\max}^2}\sum_i \left(F(t_i+T_D) - \overline{F(t_i+T_D)}\right)^2$$

In this formula, $T_D$ is the delay time of the force with respect to the sound, as shown in Fig. 3. Also, $E_{S\max}$ and $F_{\max}$ are the peak values of $E_S(t)$ and $F(t)$ respectively.

The magnitudes of the contribution rates are shown in Table 1. $E_S(t)$ represents the envelope waveform of the detected sound, and $F(t)$ represents the force waveform. The numbers in this table indicate the contribution rates. Note that in this experiment, the lifting force was measured 10 times for each sound waveform, so the table shows the average contribution rates and their standard deviations. The values of the diagonal terms in this table indicate the contribution rates of the sounds heard by the test subjects and

Table 2 R-squared ($T_S = 0.5$ sec)

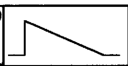
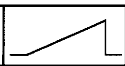
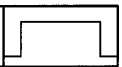
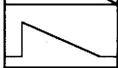
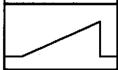
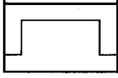
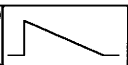
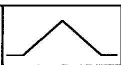
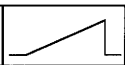
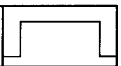
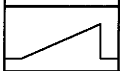
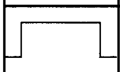
| $E_S(t)$ \ $F(t)$ |  |  |  |  |
|---|---|---|---|---|
|  | 0.20 ±0.18 | 0.68 ±0.29 | 0.35 ±0.25 | 0.48 ±0.22 |
|  | 0.06 ±0.06 | 0.47 ±0.26 | 0.70 ±0.14 | 0.41 ±0.15 |
|  | 0.14 ±0.18 | 0.32 ±0.30 | 0.51 ±0.32 | 0.33 ±0.29 |
|  | 0.15 ±0.11 | 0.21 ±0.18 | 0.50 ±0.13 | 0.19 ±0.14 |

Table 3 R-squared ($T_S = 8.0$ sec)

| $E_S(t)$ \ $F(t)$ |  |  |  |  |
|---|---|---|---|---|
|  | 0.95 ±0.01 | 0.04 ±0.02 | 0.10 ±0.01 | 0.46 ±0.13 |
|  | 0.08 ±0.03 | 0.82 ±0.04 | 0.00 ±0.00 | 0.06 ±0.02 |
|  | 0.09 ±0.04 | 0.03 ±0.02 | 0.90 ±0.05 | 0.25 ±0.09 |
|  | 0.30 ±0.10 | 0.30 ±0.05 | 0.24 ±0.08 | 0.26 ±0.09 |

the forces measured at these times. The other values indicate the contribution rates of each sound with the forces exerted when the test subjects were made to listed to a different sound.

The diagonal terms in this table all have large values. Conversely, the non-diagonal terms have small values. This means that the envelope of the sound waveform played to the test subjects closely resembles the waveform of the force measured at this time. In other words, our experimental results show that it is possible to control the time-varying magnitude of the lifting force by adjusting the time-varying magnitude of the sound.

### 5.3 The effects of sound generation time

We investigated how the abovementioned contribution rates are affected when the sound generation time is varied. The results are shown in Tables 2 and 3. Compared with Table 1 above (where the sound duration was 2.5 seconds), the contribution rates are lower overall in Table 2 (where the sound duration was 0.5 seconds). Furthermore, the results did not exhibit the abovementioned characteristic of having large diagonal terms. We think this is because the sound duration was so short that the test subjects were unable to perform lifting actions that follow the characteristics of the sound.

On the other hand, in Table 3 (where the sound duration was 8 seconds) the diagonal terms have large contribution rates and exhibit similar behavior to Table 1 (sound duration 2.5 seconds). However, when the sound envelope had a rectangular waveform, the contribution rate was found to decrease. On examining the lifting force waveform (not illustrated) in cases where the sound envelope was rectangular, we found that the lifting force tended to decrease with time. This is thought to be what caused the contribution rates to decrease.

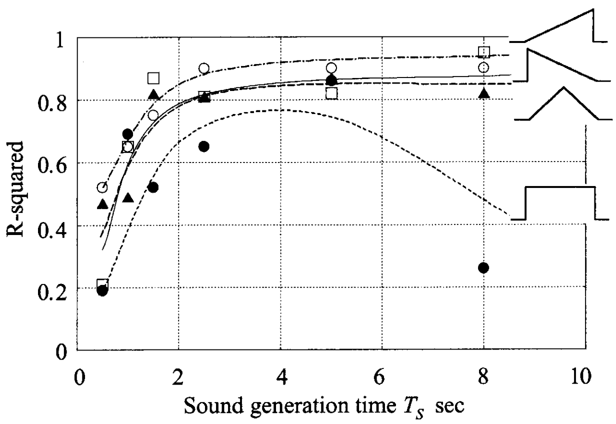



Fig. 7 Influence of sound generation time on lifting force

Figure 7 shows the results of collating the magnitudes of the diagonal terms in the contribution rates for each sound waveform. As these figures show, with a short sound duration it is harder for the lifting force to follow any of the sound envelope waveforms. As the sound duration increases to approximately 2 seconds or more, the lifting force follows the sound envelope waveform. But when the sound envelope waveform is rectangular as mentioned above, we observed behavior whereby — conversely — it becomes difficult to maintain a constant lifting force if the sound duration is too long.

## 6. Investigation of the Significance of Using Onomatopoeia as a Control Sound

Onomatopoeia can be uttered with emotion or without emotion. It can thus be conjectured that the emotions conveyed to humans when they listen to these utterances differ according to whether or not emotion is expressed. This characteristic of onomatopoeia cannot be obtained with other types of sound such as simple tones or white noise.

We therefore decided to investigate how the lifting force is affected by the presence or absence of emotion in the expression of onomatopoeia. Here, utterances that express emotion are referred to as “emotive” and utterances that do not express emotion are referred to as “unemotive”.

### 6.1 The relationship between emotion in onomatopoeic utterances and the lifting force magnitude

For the onomatopoeia *gū* we prepared emotive and unemotive sounds. We also prepared 880 Hz simple tone and white noise samples with the same envelopes and durations as these samples. The length of these sounds was fixed at 2.5 seconds, and the waveform envelopes were all

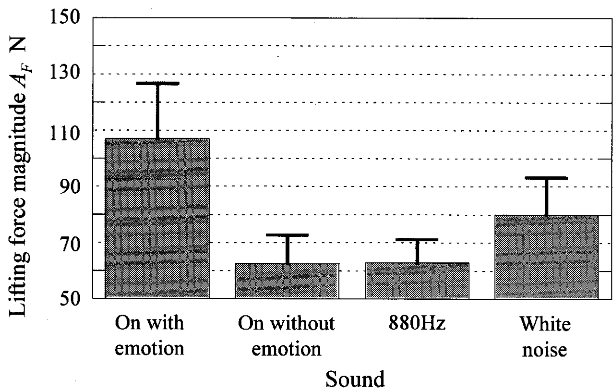



Fig. 8 Difference in lifting force between emotive and unemotive utterances (On: Onomatopoeia)

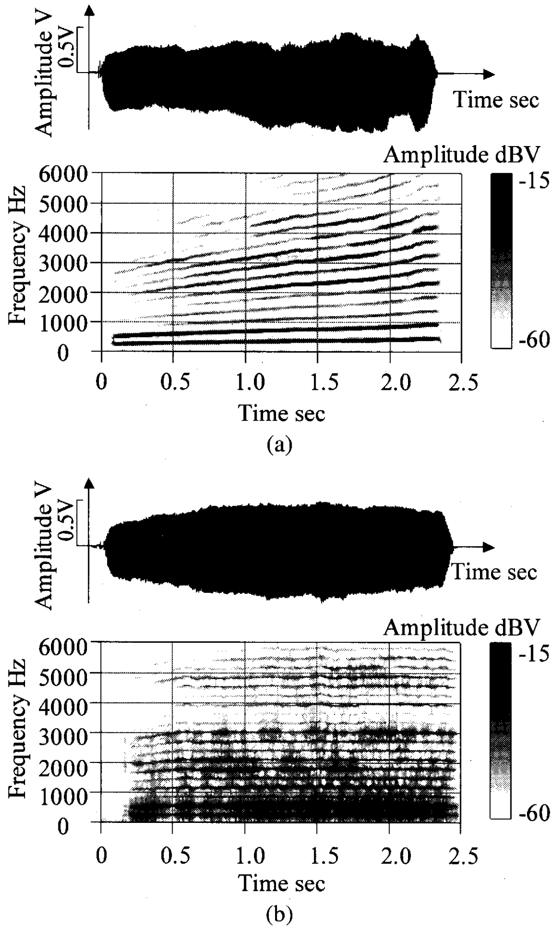



Fig. 9 Frequency-time characteristics of onomatopoeic utterances: (a) with emotion; (b) without emotion

rectangular.

With the magnitude (noise level) of the sounds fixed at 60 dB(A), we performed tests in which the four sounds were played 10 times each, making a total of 40 sounds which were played to the test subjects in random order while performing lifting actions. The test results are shown in Fig. 8. From left to right, this figure shows the results for emotive onomatopoeia, unemotive onomatopoeia, 880 Hz simple tones, and white noise. In the results for the onomatopoeia *gū*, we found a large difference in lifting force between the emotive and unemotive utterances. The lifting force obtained with the unemotive onomatopoeia was about the same as the lifting force obtained with the 880 Hz simple tone. With white noise, the lifting force was slightly larger than with the 880 Hz simple tone or unemotive onomatopoeia, but still small compared with the emotive onomatopoeia.

These results showed that the magnitude of the lifting force depends on whether the onomatopoeic utterance is emotive or not. Or to put it another way, our results suggest that the lifting forces exerted by humans can be widely controlled by means of onomatopoeic utterances.

### 6.2 Frequency characteristics of onomatopoeic utterances and magnitude of lifting forces

We determined the temporal transitions in the frequency characteristics of the onomatopoeic utterance *gū*. The results are shown in Fig. 9, where the horizontal and vertical axes represent time and frequency respectively. Darker shading represents a larger sound.

As the figure shows, both the emotive and unemotive versions of the onomatopoeia *gū* are dominated by the fundamental frequency and formant frequencies of the vowel *ū*. However, there are clear differences in the temporal transitions of the base frequencies and formant frequencies of the emotive and unemotive utterances. In the emotive onomatopoeia, the frequency components can be seen to form a clear and continuous striated pattern which shows that the fundamental frequency and first formant frequency of the vowel *ū* increase continuously with time. Closer examination reveals that the higher frequency components appear more clearly as time passes. In other words, as time passes, the frequency of the utterance increases and a gradually increasing proportion of higher frequency components is included in the utterance. On the other hand, in the unemotive utterance there are a clear fundamental frequency component and first formant frequency component but these frequencies do not change with time, indicating a monotonic sound.

Since these temporal frequency transitions seem to have a large effect on the lifting force, we performed the following test. First of all we basically used the same two versions (emotive and unemotive) of the onomatopoeia *gū* as before. In addition to these sounds, we also prepared sounds by subjecting the emotive sound to low-pass filtering with cut-off frequencies of 2 kHz, 1 kHz and 500 Hz. These five sounds were presented to the test subjects 10 times each in random order (total 50 times) as they performed lifting actions. As before, the magnitude of each sound was fixed at 60 dB(A).

The test results are shown in Fig. 10. From left to right, this figure shows the results for emotive onomatopoeia, 2 kHz low-pass filtered sound, 1 kHz low-pass

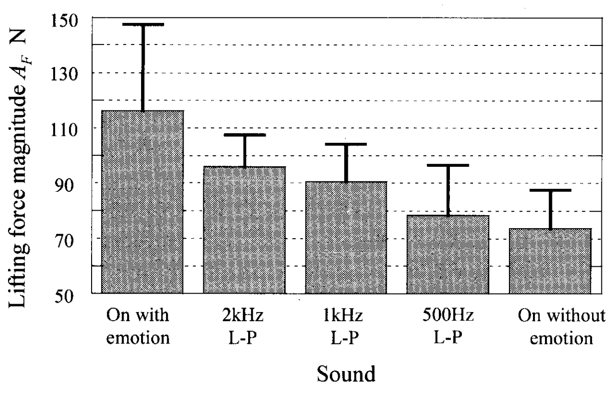



Fig. 10 Influence of low-pass filtering with various cut-off frequencies on emotive utterance (On: Onomatopoeia)

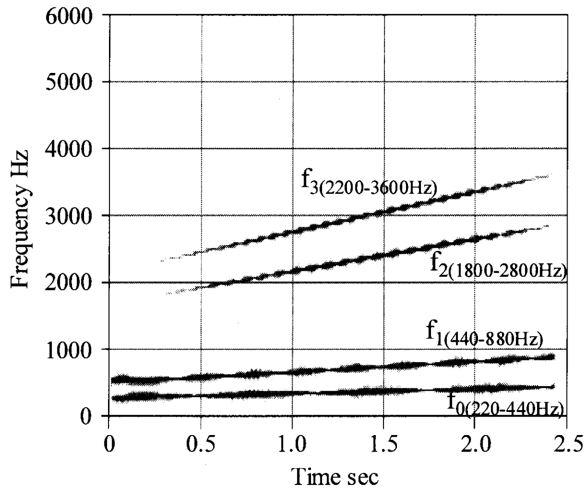



Fig. 11 Frequency-time characteristics of swept-up sounds

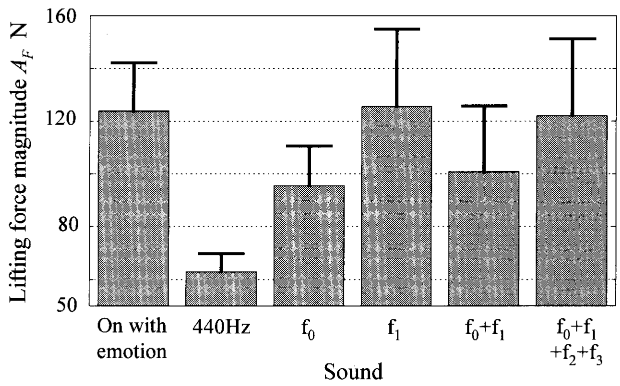



Fig. 12 Control of lifting forces by artificial swept-up sounds (On: Onomatopoeia)

filtered sound, 500 Hz low-pass filtered sound, and unemotive onomatopoeia. The magnitude of the lifting force decreases from left to right across the figure. This means that the lifting forces were largest with the emotive onomatopoeia, and gradually decreased with the 2 kHz, 1 kHz and 500 Hz low-pass filtered sounds, followed by the unemotive sound where the lifting force was even smaller. The effect of applying low-pass filtering to the emotive onomatopoeia is to cut out the high frequency components. The frequency characteristics of the 2 kHz low-pass filtered onomatopoeia are very similar to those of the unfiltered sound. On the other hand, in the frequency characteristics of the 500 Hz filtered sound, the only prominent component is the fundamental frequency of the vowel $\bar{u}$. As the low-pass filtering cut-off frequency decreases from 2 kHz to 1 kHz and 500 Hz, the expression of emotion in the sound becomes perceptually smaller. In other words, it can be said that the magnitude of the lifting force depends not only on the emotiveness of the onomatopoeic utterance, but also on the temporal transitions of the frequency components in the onomatopoeic sound. When the test subjects were asked to express their opinions after this test, it was found that the emotive onomatopoeic sound was perceived as being “stronger”.

## 7. Experiment with a Sinusoidal Sweep Sound

We performed the following experiment to investigate whether the lifting force magnitude is affected by these temporal transitions of frequency.

We prepared 4 sinusoidal sounds in which the frequency increased with time. The frequency-time characteristics of these 4 sounds are shown in Fig. 11. Here, these sounds are referred to as $f_0$, $f_1$, $f_2$ and $f_3$, and the frequency sweep ranges of these sounds are as shown in the figure. For each sound, the frequency sweep duration was set to 2.5 seconds. Lifting action tests were performed in which the test subjects were exposed 10 times in random order to these sounds or combinations thereof, and to “emotive” onomatopoeia and a pure 440 Hz tone. The magnitude of each sound was fixed at 60 dB(A) in the same way as before. Also, each of the sounds $f_0$, $f_1$, $f_2$ and $f_3$ was selected to match the fundamental and formant frequencies clearly observed in emotive onomatopoeic utterances.

The experimental results are shown in Fig. 12. From left to right, this figure shows the results for emotive onomatopoeia, pure 440 Hz tone, the $f_0$ sound, the $f_1$ sound, the $f_0+f_1$ sound, and the $f_0+f_1+f_2+f_3$ sound. As you can see, the results obtained with the emotive onomatopoeia, the $f_1$ sound and the $f_0+f_1+f_2+f_3$ sound are almost identical. This means that it is possible to control lifting forces with artificial sounds as well as with onomatopoeia sounds. It should be noted that the other test subjects were also found to have exerted larger lifting forces with these sinusoidal sweep sounds than with the 440 Hz sound.

## 8. Conclusions

By exposing human subjects to onomatopoeia, we have experimentally investigated the relationship between the sound of the onomatopoeia and the lifting actions performed by the test subjects. Our findings are as follows:

(1) The length of the sound and the lifting action du-

ration are more or less proportional to each other.

(2) The lifting force increases as the magnitude of the sound increases.

(3) The envelopes of the sound waveform and lifting force have similar shapes.

(4) One factor that controls the magnitude of the lifting force is whether or not emotion is present in the onomatopoeic utterance.

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