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Envelope Effect Study on Collision Vibration Perception through Investigating Just Noticeable Difference of Time Constant

Nan Cao[1], Hikaru Nagano[1], Masashi Konyo[1], Shogo Okamoto[2], and Satoshi Tadokoro[1]

***Abstract*— It is known that human can feel the vibratory envelope on periodic sinusoidal vibrations; however, the role of the envelope on non-periodic transient vibrations is still not clear. This study investigated Just Noticeable Difference (JND) of the time constant in the decaying sinusoidal vibration model, which is one reasonable factor relating to discrimination of tapped materials. The authors conducted psychophysical experiments to evaluate JNDs for two referenced time constants (10.8 and 50 ms) among five frequencies (150, 250, 500, 800 and 1000 Hz). The analysis showed that significant frequency effect on JNDs was only found for the lower JNDs of reference time constant 50 ms. JNDs of the time constant was lower around 250 Hz (150 to 500 Hz, average JND was 12.8%) and was higher at high frequencies (800 to 1000 Hz, average JND was 27.9%). No significant frequency effects were found in the upper JNDs of reference 50 ms (average JND was 23%) and upper JNDs of reference 10.8 ms (average JND was 65%).**

I. Introduction

Human can perceive the frequency of amplitude modulated sinusoidal vibration even when carrier frequency is higher than human perceivable frequency range [1], [2]. This finding can be translated as that human can perceive the envelope of periodic sinusoidal vibrations. In terms of periodic sinusoidal vibrations, the perceptual characteristics on envelope and frequency of vibrations have been investigated by several researchers; however, those characteristics for non-periodic transient vibrations such as collision vibration have not yet been investigated.

An example of non-periodic transient vibration is collision vibration. It occurs when we tap a surface, which waveforms differ based on tapped materials and help us to perceive the different characteristics of the tapped materials. The perceptual characteristics for collision vibrations which contribute a discrimination of tapped materials have been investigated by several researchers in order to virtually represent collision feeling by simulating transient collision vibrations. Okamura et. al [3] parametrically modeled collision vibrations in which the amplitude, the frequency and the time constant (envelope) of vibrations partially reflect materials. They used the model to realize the representation of the differences in collision frequencies by using the frequencies different from measured natural frequencies. These frequencies they used elicited people to distinguish materials [4]. This model combined with kinesthetic force displays has been used to represent hardness sensation greater than the hardness limited in the force devices [5]. These studies are based on the findings that higher frequencies in the model lead to the perception of greater hardness. In a transient collision vibration, the role of frequency has been investigated. However, effects of the envelope as the time constant in the model have not yet been thoroughly investigated.

This study investigated the role of the envelope as the time constant on collision perception through measuring just notification difference (JND) of the time constant. JND is frequently used to evaluate perceptual resolutions for target parameters as several studies found for amplitude (e.g. [6]) and frequency (e.g. [7]) of periodic vibrations. The relationships between hardness perception and mechanical parameters including time constant have been investigated [8], [9]; however, perceptual resolutions for the time constant remain to be investigated.

In order to efficiently generate the collision vibrations caused by tapping, we need to investigate the perceptual resolutions for parameters in rendering models. For example, if we want to generate perceptual different collision vibrations, we can generate the vibrations by using two perceptually different time constants of generated model based on its perceptual resolutions.

We investigated JND of the time constant at several different frequencies. Generally, the most sensitive frequencies for human are in the range 200–300 Hz, so for the time constant, the highest perceptual resolution (lowest JND) range may be also in the range of 200-300 Hz. High frequencies like 1000 Hz are not sensitive for human and their JNDs of the time constant are expected to be high. By investigating JND of time constant, we can find how it will be changed by frequency, for example in which frequency range JND of time constant will be the lowest or highest, whether the JND of time constant was linearly changed by frequency and if not in which frequency range the JND of time constant change most rapidly.

II. Method

In this section, we introduced the subjects, experiment parameters, apparatus, and procedures.

A. Subjects

7 subjects (age from 21 to 28, 6 males, 1 female, all right-handed) took part in the study. All subjects had no motor or sensory limitations by self-report.

B. Experiment Parameters

1) Stimuli: The vibration feedback model developed from the tapping data is the decaying sinusoidal waveform [3]

[1]The authors are with Graduate School of Information Sciences, Tohoku University, Sendai, Japan. cao.nan@rm.is.tohoku.ac.jp
[2]The author is with Graduate School of Engineering, Nagoya University, Nagoya, Japan.

where $Q(t)$ is the vibration produced by the contact, A is an attack amplitude, τ is a time constant and f is a frequency.

$$Q(t) = Ae^{-\frac{t}{\tau}} sin(2\pi f t) \tag{1}$$

Considering an observed amplitude will be changed with the change of time constant, dynamic amplitude was used to keep the maximum value of waveform identical. This process was to remove the perception effects of amplitude.

When $Q'(t_0) = 0$ and $t_0 = tan^{-1}(2\pi f \tau)/2\pi f$, $Q(t_0) = Q_0$ is the maximum value of the waveform. Set the maximum value Q_0 to be a constant value. Finally, the amplitude adapted function of vibration model is

$$P(t) = \frac{Q_0}{e^{-\frac{t_0}{\tau}} sin(2\pi f t_0)} e^{-\frac{t}{\tau}} sin(2\pi f t) \tag{2}$$

In addition, the generated vibration cannot reflect the input vibratory profiles of signals because of physical characteristics of apparatus such as the frequency characteristics of voice coil actuator. Therefore, we preliminary analyzed frequency characteristics of the actuator and then modified input signals using the frequency characteristics to generate desired output. The frequency characteristic of the actuator was measured and its result was shown in the Fig. 1.

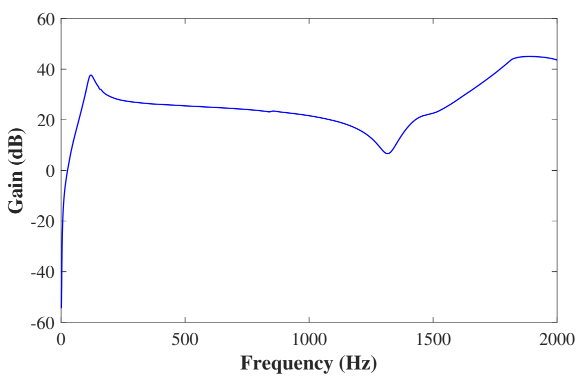

Fig. 1. The frequency characteristic of the vibrator

2) Time Constant: The time constant was measured by the output signal of the piezo sensor rather than the input signal. As shown in the Fig. 2, function $y = A * e^{-\frac{t}{\tau}}$ was found by a least square fit to the positive and negative peaks of the vibration waveform. The maximum absolute value of the waveform was set to be the start point for fitting the function. Fig. 2 shows that time constant τ reflected the envelope shape of the stimuli (fitting the peak values). When τ is bigger, the envelope shape of stimuli is smoother and when τ is smaller, the envelope shape is steeper.

5 times of the input time constant τ_i and output time constant τ_o were measured. The standard error of five times τ_o was calculated. The test time constants were used only when the standard error was less than 5% of the average value. Several input values were tested. Other stimuli with the different time constant were linearly interpolated by these values. The lower boundaries of the time constant at different frequencies were shown in the Table. I.

TABLE I

STABLE RANGE OF TIME CONSTANT

Frequency (Hz)	Lower boundary (ms)
150	10.8
250	5.6
500	5
800	2.4
1000	8

In order to get the JNDs at all test frequencies, a relatively high time constant of 50 ms was used based on the preliminary experiments. A lower reference of time constant was not used in this experiment because some subjects were not able to distinguish the time constant at some frequencies in the test range shown in Table. I. One of the results was shown in the Fig. 3 by using the experimental procedure in this research. While the reference time constant was 30 ms and frequency was 800 Hz, the possible distinguish time constant was not able to get due to the limited low boundary of the time constant 2.4 ms.

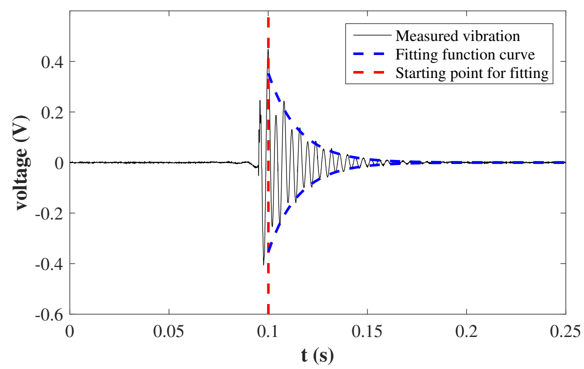

Fig. 2. Time constant measured by piezo signal

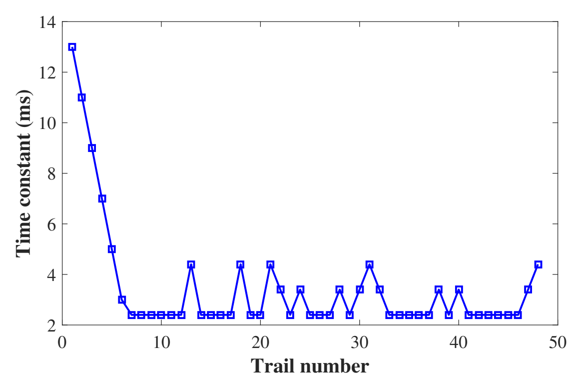

Fig. 3. Distinguished time constant out of test range

3) JND: This psychophysical parameter is defined by Weber's Law as the detectable difference between a reference stimuli and test stimuli. JND of the time constant in this research was calculated as following,

$$JND = \frac{|tc_t - tc_0|}{tc_0} \times 100 \qquad (3)$$

Where the tc_t is the time constant of test stimuli and the tc_0 is the time constant of reference stimuli. Both sides of JNDs were investigated in this research. When the test time constant was lower than the reference time constant, the calculated JND was called lower JND. When the test time constant was higher than the reference time constant, the calculated JND was called upper JND.

C. Apparatus

As shown in Fig. 4, a subject gripped the actuator to perceive collision vibrations to measure gripped normal force.

Collision vibration was apparatus consisted of an actuator (Vp210, ACOUVE LABORATORY, INC., JAPAN), amplifier and the PC. The vibrator was hanging in the air by sewing thread. A force sensing resistor was attached on the center of the actuator to measure the subjects' force gripping on the actuator.

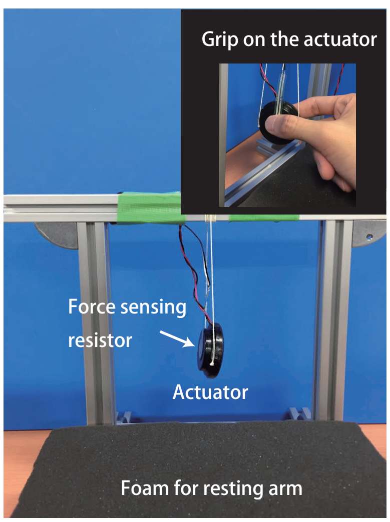

Fig. 4. Experimental apparatus. Actuator was hanging in the air and subject gripped the actuator by thumb and index finger.

Piezoelectric vibration sensor (VS-BV02, NEC TOKIN, JAPAN) was used to measure the vibration of the actuator.

D. Design and Procedure

The subject sat comfortably in front of a PC and gripped the actuator with his or her thumb and index finger. The subject's forearm rested on a big foam. According to the value of force sensing resistor, the subject was instructed to grip the actuator with a constant force (around 0.25 N) by the thumb and index finger of right hand. After subject reached the required force, one short test run was completed by each subject to get familiar with the procedure. The order of the measurement runs was randomized distributed for each subject.

5 test frequencies (150, 250, 500, 800 and 1000 Hz) were used. 250 Hz and 1000 Hz were chosen because in general, the most sensitive frequency is in the range 200 - 300 and the 1000 Hz is the highest frequency in human haptic perceptual range. 500 Hz was also an important frequency and many haptic devices generate the frequency up to 500. 150 (lower than human most sensitive range) and 800 Hz (higher than 500 Hz but may occur in collision vibration by tapping hard materials) were selected to better analyze the frequency effect in the human perceptual frequency range.

JNDs were obtained by an adaptive staircase method with a 1down-1up progression rule combined with a 3 interval forced choice answer paradigm (3IFC) [10]. In this method, JNDs obtained were corresponding to 50 percent point on the psychometric function [10].

On each trial, the subject was presented with 3 stimuli. There was 1.5-sec long interval between each stimulus. One of the stimuli was the test stimuli while the other two were the same reference stimulus. The subject's task was to find out the different one (test stimulus) out of the 3 stimuli by pressing a corresponding key ("1", "2", "3") on the keyboard. Subjects were not instructed about what kind of differences were between the test and reference stimulus. Instead, at the beginning, the initial test stimuli was set easily to be distinguished and subjects were able to find out the differences between the reference and test stimulus by themselves in the first several trails.

Due to the long time experiment (around 2 hours), subjects might lose their concentration some time so they could repeat the same 3 stimulus by pressing the key ("space") but the order of stimulus would be changed by every repeat. The subject was suggested to choose their answer for the first time feeling.

Both sides of JNDs (upper and lower JNDs) were tested for the reference time constant 50 ms. In addition, upper JNDs were tested at the time constant 10.8 ms. For all the tests, the former 6 step sizes were set to be 5 ms (for fast converge) and the following last 12 step sizes were set to be 1 ms (for finer resolution). A test series was terminated after 18 reversals.

Each measurement run lasted about 6 to 10 minutes and subjects had 3 minutes break between 2 runs. The entire experiment took about 2 hours.

III. Results

5 subjects took part in the tests of reference 50 ms and 5 subjects (3 subjects also did tests in reference 50 ms) took part in the tests of reference 10.8 ms. For each subject with each frequency, JND was calculated by the mean of the last 12 reversals of the staircase.

For reference 50 ms of the time constant, the average upper JNDs of all subjects and standard errors were shown in the Fig. 5, while the average of lower JNDs and standard errors were shown in the Fig. 6. For reference 10.8 ms of the time constant, the average of upper JNDs and standard errors were shown in the Fig. 7.

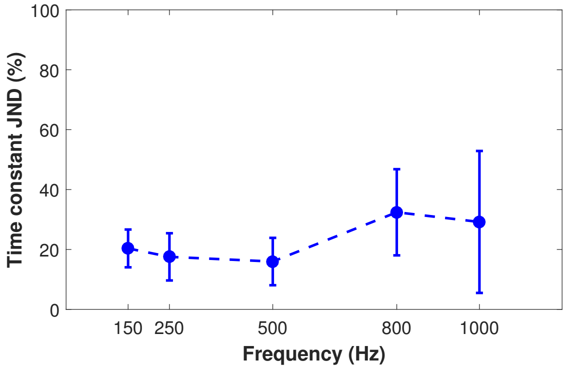

Fig. 5. Reference 50 ms: the average upper JND and standard error of time constant

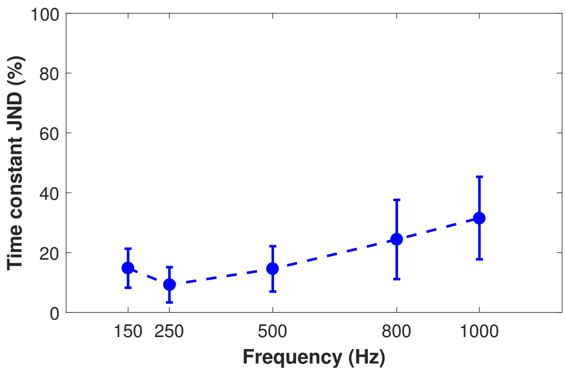

Fig. 6. Reference 50 ms: the average lower JND and standard error of time constant

Two-way ANOVA with frequency and subject as independent variables were calculated separately for upper JNDs of reference 50 ms, lower JNDs of reference 50 ms and upper JNDs of reference 10.8 ms.

For upper JNDs of reference 50 ms, it showed no significant influence of the frequency ($F(4,24) = 1.88, p = 0.1625$) and the subjects ($F(4,24) = 2.59, p = 0.0762$). It meant that the JNDs of time constant were similar among frequencies.

For lower JNDs of reference 50 ms, it showed significant influences of both the frequency ($F(4,24) = 7.85, p = 0.0011$) and the subject ($F(4,24) = 5.85, p = 0.0043$). A multiple comparison test was performed by using the Bonferroni method to investigate which compared frequencies had a significant difference on the JNDs of the time constant. The results were shown in the Table. II. The first two columns of Table. II showed the frequencies that were compared. The third column showed the mean differences between the JNDs of compared frequencies. The fourth columns show the p-values for the compared frequencies. It showed that small p-values occurred in the compared frequencies between 1000 and 150, 1000 and 250, 1000 and 500, 800 and 250 Hz (significantly different).

For upper JNDs of reference 10.8 ms, it showed no significant influences of the frequency ($F(4,24) = 2.26, p = 0.1076$) and significant influence of the subjects ($F(4,24) = 7.1, p = 0.0017$).

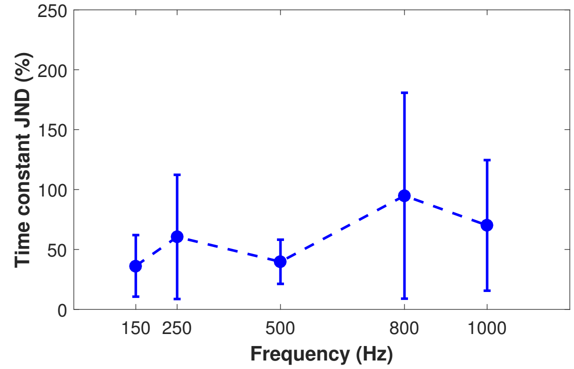

Fig. 7. Reference 10.8 ms: the average upper JND and standard error of time constant

TABLE II
LOWER JND OF REFERENCE 50 MS: THE RESULT OF A MULTIPLE COMPARISON TEST PERFORMED BY USING THE BONFERRONI METHOD

Frequency 1	Frequency 2	Mean difference	P-value
150	250	5.55	1.00
150	500	0.22	1.00
150	800	-9.60	0.49
150	1000	-16.77	0.02
250	500	-5.33	1.00
250	800	-15.15	0.04
250	1000	-22.32	0.00
500	800	-9.82	0.45
500	1000	-16.98	0.02
800	1000	-7.17	1.00

IV. DISCUSSION

Our experiment investigated the JNDs of time constant based on the collision vibration model. To the best of our knowledge, the perceptual resolution of collision vibration parameters has not been investigated. Our research attributes to understand the perceptual resolution of time constant which is a parameter in collision vibration model.

A. Sensitive frequency of time constant

3 kinds JNDs of the time constant (upper JND of reference 50 ms, lower JND of reference 50 ms and upper JND of reference 10.8 ms) were tested in our experiment. The results of two-way ANOVA showed significant differences among frequencies only occurred for lower JND of reference 50 ms.

For lower JNDs of reference 50 ms, Fig. 6 showed that the shape of average JNDs had two parts, 2 slopes occurred at the frequency range (-0.138 %/Hz lower than 250 Hz and 0.085 %/Hz higher than 250 Hz) and lowest JND occurred at 250 Hz. The results of two multiple comparison tests showed that 1000 Hz was significantly different from 150, 250, 500 Hz while 250 Hz was significant from 800. Average JNDs of 800 and 1000 Hz were higher than JNDs of 150, 250, 500Hz. So it may mean the JNDs of the time constant were lower when the frequency was lower than 500 Hz (sensitive, average JND was 12.8%) and the JNDs were higher when the frequency was higher than 800 Hz (not sensitive, average JND was 27.9%).

For upper JNDs of reference 50 ms, Fig. 5 showed that the curve of average upper JNDs had a stage shape and at frequencies 150, 250 and 500 Hz, JNDs were similar (average 17.9%) while at frequencies 800 and 1000 HZ, JNDs were similar (average 30.8%). Average JNDs of 800 and 1000 Hz were also higher than average JNDs of 150, 250, 500Hz. However, the result of two-way ANOVA showed that there was no significant effect of frequency. It may mean that the JNDs of time constant did not have obvious differences in the frequency range. The average JND of all frequencies was 23%.

For upper JNDs of reference 10.8 ms, Fig. 7 showed that the curve of average upper JND also had a stage shape and at frequencies 150, 250 and 500 Hz, JNDs were similar (average 52.8%) while at frequencies 800 and 1000 HZ, JNDS were similar (average 66%). Average JND of 800 and 1000 Hz were also higher than JND of 150, 250, 500Hz. However, the result of two-way ANOVA shows that there was no significant effect of frequency. It may mean that the JNDs of the time constant do not have obvious differences in the frequency range. The average JND of all frequencies was 65%.

In conclusion, the sensitive frequency of time constant was around 250 Hz (150 to 500 Hz, average JND was 12.8%) and it was not sensitive at high frequencies (800 to 1000 Hz, average JND was 27.9%) for the lower JNDs of reference 50 ms. JNDs of the time constant did not have obvious differences in the upper JNDs of reference 50 ms (average JND was 23%) and upper JNDs of reference 10.8 ms (average JND was 65%).

B. Time constant range effects on JNDs

The average upper JNDs of lower reference 10.8 ms were bigger than the JNDs of reference 50 ms and relative higher standard errors occurred. In the research [11], Hatzfled et al. investigated the JND of force near the absolute threshold and every subject was tested by using the individual threshold at frequencies tested in [12]. They found JNDs are much larger than using the reference well above threshold. In our research, we investigated JNDs of the time constant not the force, however, the reference value may also affect the JNDs.

At lower reference 10.8 ms, subjects had significant effects on JNDs of the time constant. The reason of subjects effects on JNDs may be caused by their individual threshold on time constant. In some frequencies, the reference time constant 10.8 ms may be near their threshold, so higher JNDs and big differences between subjects occurred. In this research, we did not investigate the threshold of the time constant because the threshold of the time constant may be quite small. In our tests, the smallest time constant were shown in the Table. I could be easily perceived by subjects. However, the JNDs (perception resolution) of the time constant may be largely affected near the individual threshold.

Before we conducted these experiments, we assumed that frequency would affect the JND of the time constant. Considering the test range of time constant based on JNDs, the time constant range (considering the differences among subjects) was around 50 ms to 80 ms for the upper JNDs of reference 50 ms, 30 ms to 50 ms for the lower JNDs of reference 50 ms, 10.8 ms to 30 ms for the upper JNDs of reference 10.8 ms. With the view of time constant range, the results showed that there were no significant effects (subject and frequency) at test range 50 ms to 80 ms, significant effect (frequency and subject) at the test range 30 ms to 50 ms and significant effects (subject) at the test range 10.8 ms to 30 ms. Therefore, for the high time constant range (e.g. 50 ms to 80 ms), JNDs may be similar in the frequency range. For the low time constant range (e.g. 10 ms to 30 ms), JNDs may be largely affected by the individual threshold. While in the middle range of the time constant (e.g. 30 ms to 50 ms), JNDs of the time constant may be significantly affected by frequency. The perceptual threshold of the time constant and the effect of time constant range on perception resolution need to be investigated in the future.

However, results of the experiment like the different tendency between upper and lower JNDs may be due to the limited subjects' number. Further investigation is needed in the future.

V. Conclusion and further work

In a transient collision vibration, the role of frequency has been investigated. However, effects of the envelope as the time constant in the model have not yet been thoroughly investigated. This study investigated the role of the time constant on collision perception through investigating just notification difference (JND) of the time constant. The upper and lower JNDs of reference time constant 50 ms and upper JNDs of reference time constant 10.8 ms have been tested in the frequencies (150, 250, 500, 800, 1000 Hz). Significant frequency effect on JNDs was found only for the lower JNDs of reference time constant 50 ms. The sensitive frequency of time constant was around 250 Hz (150 to 500 Hz, average JND was 12.8%) and not sensitive at high frequencies (800 to 1000 Hz, average JND was 27.9%) for the lower JNDs of reference 50 ms. JNDs of the time constant did not have significant differences in the upper JNDs of reference 50 ms (average JND was 23%) and upper JNDs of reference 10.8 ms (average JND was 65%). It suggests that perceptual resolution of the time constant may be affected by frequency in some range and relatively stable in some other range. The effect of time constant range on perception resolution need to be investigated in the future.

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