Proceedings of 20th International Congress on Acoustics, ICA 2010

23–27 August 2010, Sydney, Australia

Fluctuation strength on the mandolin tremolo with the 1st and 2nd fluctuations

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PACS: 43.75.Cd, 43.75.St

ABSTRACT

A mandolin tremolo is characterized by the average of the plucking rate, as well as the onset and amplitude deviations. Here, the fluctuation of a tremolo elicited with only the average plucking rate is called the "1st fluctuation", and that elicited with both onset and amplitude deviations is called the "2nd fluctuation". Although the fluctuation quantity of the tremolo with only the 1st fluctuation was calculated in our previous studies, that with both the 1st and 2nd fluctuations has not been investigated using the procedure, because the sensation of hearing fluctuation from it has not yet been investigated. Therefore, we propose indexes for calculating the fluctuation quantity of a mandolin tremolo with both the 1st and 2nd fluctuations. To develop the indexes, a procedure for calculating the fluctuation quantity of an imitated tremolo, employed here as stimuli, with both the 1st and 2nd fluctuations is investigated, and the sensation of hearing fluctuation on the tremolo is estimated using the calculated fluctuation quantity. The imitated tremolo is an AM complex tone whose envelope is identical to the tremolo so that it does not give us any musical impression but only the sensation of hearing fluctuation. In the investigation of the procedure, the index for the 1st fluctuation was from the procedure in our previous studies and the indexes for the 2nd fluctuation were calculated on the basis of the differences from a deviation trend curve, obtained by moving average, for a global tendency for each deviation. In addition, an experiment using the magnitude estimation method was conducted to subjectively evaluate the sensation of hearing fluctuation for these sounds. Next, multiple regression analysis was conducted to estimate the sensation of hearing fluctuation, in which evaluation results were used as objective variables and the indexes for 1st and 2nd fluctuations were used as explanatory variables. Finally, we obtained indexes for calculating the fluctuation quantity of a mandolin tremolo with both the 1st and 2nd fluctuations. We found that the procedure using both the 1st and 2nd fluctuations appropriately represents the sensation of hearing fluctuation ($R^2 > 0.75$), which is better than when using only the 1st fluctuation ($R^2 = 0.55$). Thus, we developed indexes for calculating the fluctuation quantity of a mandolin tremolo.

INTRODUCTION

The mandolin is a string instrument played by plucking strings with a pick. It has pairs of unison strings, the four pairs tuned in fifth like a volin. Each string of a pair is tuned at almost the same pitch. There are two common styles of playing the mandolin, “picking” and “tremolo”. “Picking” means plucking the strings to produce a duple tone while playing a musical note, and “tremolo”means repetition of plucking on a pair of strings for a musical note [1]. Attenuating sounds produced by simple plucking quickly decay on its waveform, so a tremolo played on the mandolin is said to be a continuous fluctuating sound with an amplitude envelope in the form of Amplitude-Modulated(AM) sound, especially for being similar to a saw-tooth wave.

AM sounds are known to elicit the sensation of hearing fluctuation. Previous studies have represented the sensation of hearing fluctuation as Fluctuation Strength(FS) by conducting subjective experiments [2, 3]. Another study estimated FS from acoustic signals [4]. Although it has been confirmed that the fluctuation quantity calculated based on the procedure proposed in the first two studies mentioned above [2, 3] and commercial software for evaluating sound quality represents the sensation of hearing fluctuation for AM sounds [4], the fluctuation quantity on the tremolo has not been investigated using those procedures. Moreover, the sensation of hearing fluctuation from a tremolo has not yet been investigated. We investigated the acoustic characteristics of a tremolo with a mandolin played by players. Unlike AM sounds used in the above-mentioned studies [2–4], the modulation period and modulation depth of the tremolo with a mandolin are not constant during the playing of a musical note because of the irregularity in plucking that occurs by the player’s habit or performance level. In other words, tremolo is regarded as AM sounds with an AM amplitude envelope because both onset and amplitude deviations are elicited by the fluctuation elicited by plucking. In this study, we call the fluctuation of the tremolo elicited by only the average of plucking rate, i.e., frequency of amplitude modulation, “1st fluctuation”, and that elicited by both onset and amplitude deviations “2nd fluctuation”. Although the procedure proposed in the above-mentioned studies [2–4] is regarded as based on only the 1st fluctuation, not based on both the 1st and 2nd fluctuations. Also, it is difficult to say that the fluctuation quantity calculated using conventional procedures represents the sensation of hearing fluctuation from the tremolo with both the 1st and the 2nd fluctuations. Therefore, we confirm the contribution of the 2nd fluctuation for FS, by comparing the prediction accuracy for the sensation of hearing fluctuation by the fluctuation quantity calculated using a procedure based on the 1st and 2nd fluctuations to that by the fluctuation quantity calculated using a procedure based on only the 1st fluctuation. We also propose indexes for calculating the fluctuation quantity that represents the sensation of hearing fluctuation from tremolo with both the 1st and 2nd fluctuations.

BACKGROUND AND AIM OF THIS STUDY

Fluctuation Strength

The FS is an evaluation index of the psychological level, proposed by Fastl *et al.*, in relation to the sensations of hearing fluctuation from modulated sounds with a modulation frequency [2, 3]. FS is elicited by modulated sounds with a modulation frequency of up to about 20 Hz. The findings of previous studies were that the FS for an amplitude-modulated pure tone (AM SIN) with a modulation frequency within 4-8 Hz is larger than that outside this range, and the strongest sensation for fluctuation subjectivity is obtained within 4-8 Hz [2, 3]. Another study estimated FS from acoustic signals [4]. They confirmed that the fluctuation quantity calculated by extracting characteristics of the fluctuation from acoustic signals correspond approximately to FS. In the calculation procedure, the fluctuation components that strongly affect the sensation of hearing fluctuation are calculated based on Fastl's study [2, 3]. It has been confirmed that fluctuation quantities calculated using the procedure and commercial software for evaluating sound quality represent the sensation of hearing fluctuation from AM SIN [4]. However, fluctuating sounds played on musical instruments, such as the mandolin or marimba, have not yet been investigated, though fluctuations are thought of as important for understanding the characteristics of musical performance.

Parameters for sensation of hearing fluctuation from tremolo played on the mandolin

The tremolo played on a mandolin can be regarded as an AM sound [1]. However, most mandolin players cannot produce a tremolo with a constant intensity and a constant inter-onset interval, so that it is inevitable to produce fluctuation of the tremolo. Therefore, a tremolo always includes not only the 1st fluctuation but also the 2nd fluctuation. The 1st fluctuation is elicited by only the average plucking rate, so it is assumed that the perception of a tremolo greatly depends on the plucking rate. The 2nd fluctuation is elicited by both onset and amplitude deviations, where the onset deviation means deviation from the ideal onset time, and the amplitude deviation means deviation from the ideal intensity on the onset time. Actual performance sounds without these deviations would be perceived as an mechanical performance, so it is assumed that with such sounds it is hard to mimic a performance by an actual player. Therefore, it is thought that the average plucking rate and onset and amplitude deviations affect perception of a tremolo and that these features are in almost all tremolos in actual performances; therefore, it is necessary to consider these features by analyzing the tremolo played on the mandolin.

Aim of this study

The procedure for calculating the fluctuation quantity for representing the sensation of hearing fluctuation from sounds, such as AM or Frequency-Modulated(FM) sounds with a constant fluctuation rate, in other words, the procedure of calculating the one on fluctuating sounds with only the 1st fluctuation was proposed in previous studies [2–4]. However, it has not been investigated whether the fluctuation quantity calculated represents the sensation of hearing fluctuation from a tremolo with both 1st and 2nd fluctuations.

Therefore, we propose indexes for calculating the fluctuation quantity that represents the sensation of hearing fluctuation from a tremolo with both 1st and 2nd fluctuations, by investigating the sensation of hearing fluctuation affected by the 2nd fluctuation. First, the relation between the fluctuation quantity and the sensation of hearing fluctuation obtained from the evaluation of this sensation using a tremolo is investigated. Second, the fluctuation quantity is calculated based on the 1st and 2nd fluctuations extracted from acoustical signals of the tremolo. Finally, we propose indexes for calculating the fluctuation quantity considering both the 1st and 2nd fluctuations. The performance of the procedure was confirmed by comparing a procedure of calculating the fluctuation quantity by considering only the 1st fluctuation and another procedure by considering both the 1st and 2nd fluctuations. These investigations were conducted using not actual performance sounds but synthesized sounds because it is thought that the 2nd fluctuations of an actual performance by players cannot be controlled for the purpose of synthesizing the stimuli used on the evaluation experiment; therefore it was not appropriate to use in this study. Instead, we synthesized tremolos with various 2nd fluctuations by keeping the trend of 2nd fluctuation on performance sounds performed by musicians. The outline of this study is shown Fig.1.

SYNTHESIS

To develop indexes for calculating the fluctuation quantity that represents the sensation of hearing fluctuation from a tremolo with both the 1st and 2nd fluctuations, an investigation using tremolos with various 2nd fluctuations are required. We synthesized tremolos with various 2nd fluctuations by keeping the trend of 2nd fluctuations on performance sounds by alternately conjoining down-stroke and up-stroke sounds, based on the fact that the tremolo is produced by the repetition of such sounds. When listening to those tremolos, it is possible to perceive the sensation of hearing fluctuation and another impression such as performance proficiency. Because both the sensation of hearing fluctuation and proficiency are subjective, they may affect each other. We need to separate these two subjective evaluations, so we get rid of the timbre from the synthesized tremolo. To synthesize a tremolo without timbre on a mandolin, we used pseudo down-stroke and pseudo up-stroke sounds obtained by interpolating a harmonic sound with envelopes for actual down-stroke and up-stroke sounds played on the mandolin. Although amplitude envelopes for these pseudo sounds are consistent with those for down-stroke and up-stroke sounds, the timbre of the interpolated sound is not consistent with but similar to that of the mandolin. Therefore, only the sensation of hearing fluctuation perceived from the tremolo can be synthesized using these pseudo sounds. Also, the tremolo with both the 1st and 2nd fluctuations can be synthesized by setting onset and amplitude deviations extracted from an actual performance on synthesizing a tremolo.

However, the procedure of synthesizing a tremolo would restrict these deviations of characteristics on synthesized stimuli. In other words, the procedure cannot generate various 2nd fluctuations. We used a feature exaggeration method for scale performance on a piano proposed by Morita *et al*.[5], in which a performance can be suppressed or exaggerated based on the feature of current performance keeping the trend of the performance. We obtained tremolos with various 2nd fluctuations using this feature exaggeration method.

First, onset and amplitude deviations were extracted from an acoustic signal, and these deviations were suppressed or exaggerated based on this feature exaggeration method [5]. Next, these suppressed or exaggerated deviations were set on synthesizing by alternately conjoining pseudo down-stroke and pseudo up-stroke sounds. We call the tremolo synthesized using pseudo down-stroke and pseudo up-stroke sounds "imitated tremolo". The procedure for synthesizing an imitated tremolo is shown in Fig.2.

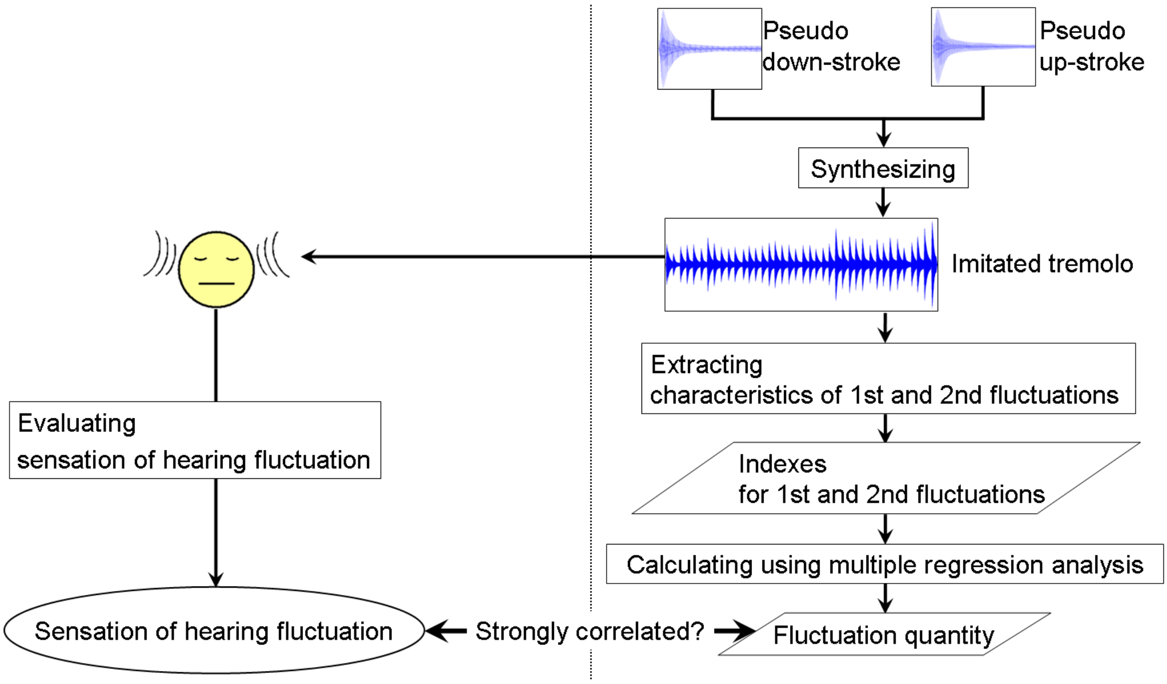


Figure 1: Outline of this study.

Extracting onset and amplitude deviations

Tremolos were recorded using a microphone, and the onset times were estimated from a recorded tremolo. Onset and amplitude deviations were extracted based on the ideal onset time and maximum level on amplitude, respectively.

Recording experiment of tremolo

Outline of experiment: Tremolos performed by an expert were recorded using a microphone in a soundproof room.
Player: A mandolin player with over three years experience.
Task: The player was asked to perform a tremolo at a plucking rate of 8 Hz for five seconds. She was then instructed to play at 120 bpm (a speed corresponding to 8 Hz). The player could hear the clicking sounds from a metronome that matched the tempo with a dynamic earphone placed in her left ear. Hearing the clicking sound in both ears would interfere with playing. The tone height of the tremolo was D4 (about 295 Hz), or the open tone for the third pair of strings. The player was asked to keep the intensity of sound constant and play in "*p* (piano)".
Mandolin: M-150 (Suzuki Violin Co., Ltd.).
Pick: A black 0.635-mm-thick nylon pick (YAMAHA) shaved or thinned to make it easy to use.
Recording equipment: A metronome (DB-90, Roland Co., Ltd.), a dynamic earphone (ME-L91D, SONY Co., Ltd.), a microphone (NT2-A, RODE Microphones) and a recorder (HD-P2, TEAC Co., Ltd.). Sounds were recorded in 16 bits for each sample at a rate of 48 kHz.

Procedure of extracting onset and amplitude deviations

The plucking period was obtained from the plucking rate instructed to the player, and the time when the maximum amplitude level envelope occurred around every period was estimated as the onset time. Next, the differences from the ideal onset and estimated onset times were calculated, so that these deviations were determined as the onset deviations $OD_k (k = 1\text{-}N)$, where k represents the ID of the onset time and N represents total number of plucks. Each OD_k was calculated using the onset time when $k = 1$ as a standard. Also, the deviations from the ideal amplitude on the onset time were extracted from an acoustic signal, so that these deviations were determined as the amplitude deviations AD_k. The outline of onset and amplitude deviations is shown in Fig.3.

Exaggerating onset and amplitude deviations

In this study, the onset and amplitude deviations were suppressed or exaggerated based on the feature exaggeration method for scale performance on a piano [5]. By using this method, it is possible to synthesize an imitated tremolo with various 2nd fluctuations by keeping the trend of the 2nd fluctuations on performance sounds.

In the method, a feature exaggeration maintaining a trend of the original performance was produced by controlling the feature parameters proposed in a previous study [6]. First, the deviation trend curves are calculated for the onset and amplitude deviations, where the moving average was conducted for three points around itself. Next, we suppressed or exaggerated feature parameters with respect to these deviations $p_{i,j} (i = 1\text{-}2, j = 1\text{-}4)$ using obtained deviations and deviation trend curves, the suffix i in $p_{i,j}$ distinguishes OD ($i = 1$) or AD ($i = 2$), and the suffix j in $p_{i,j}$ represents the ID of feature parameters on the onset and amplitude deviations. A detailed explanation of $p_{i,j}$ is described in The details of the method for suppressing or exaggerating are as follows;

$$x'_{i,1} = \hat{x}_i + C_{i,1}(x_i - \hat{x}_i) \tag{1}$$

$$M = \frac{\max(\hat{x}_i) + \min(\hat{x}_i)}{2} \tag{2}$$

$$x'_{i,2} = M + C_{i,2}(\hat{x}_i - M) \tag{3}$$

$$S_{\mathrm{U}}(z) = \frac{(\max(\hat{x}_i) - \min(\hat{x}_i))}{N-1} z + \min(\hat{x}_i) \tag{4}$$

$$S_{\mathrm{L}}(z) = \frac{(\min(\hat{x}_i) - \max(\hat{x}_i))}{N-1} z + \max(\hat{x}_i) \tag{5}$$

$$x'_{i,3} = \begin{cases} S_{\mathrm{L}} + C_{i,3}(\hat{x}_i - S_{\mathrm{L}}) & (\sum|S_{\mathrm{L}} - \hat{x}_i| < \sum|S_{\mathrm{U}} - \hat{x}_i|) \\ S_{\mathrm{U}} + C_{i,3}(\hat{x}_i - S_{\mathrm{U}}) & (\sum|S_{\mathrm{L}} - \hat{x}_i| > \sum|S_{\mathrm{U}} - \hat{x}_i|) \end{cases} \tag{6}$$

$$x'_{i,4} = C_{i,4}\hat{x}_i \tag{7}$$

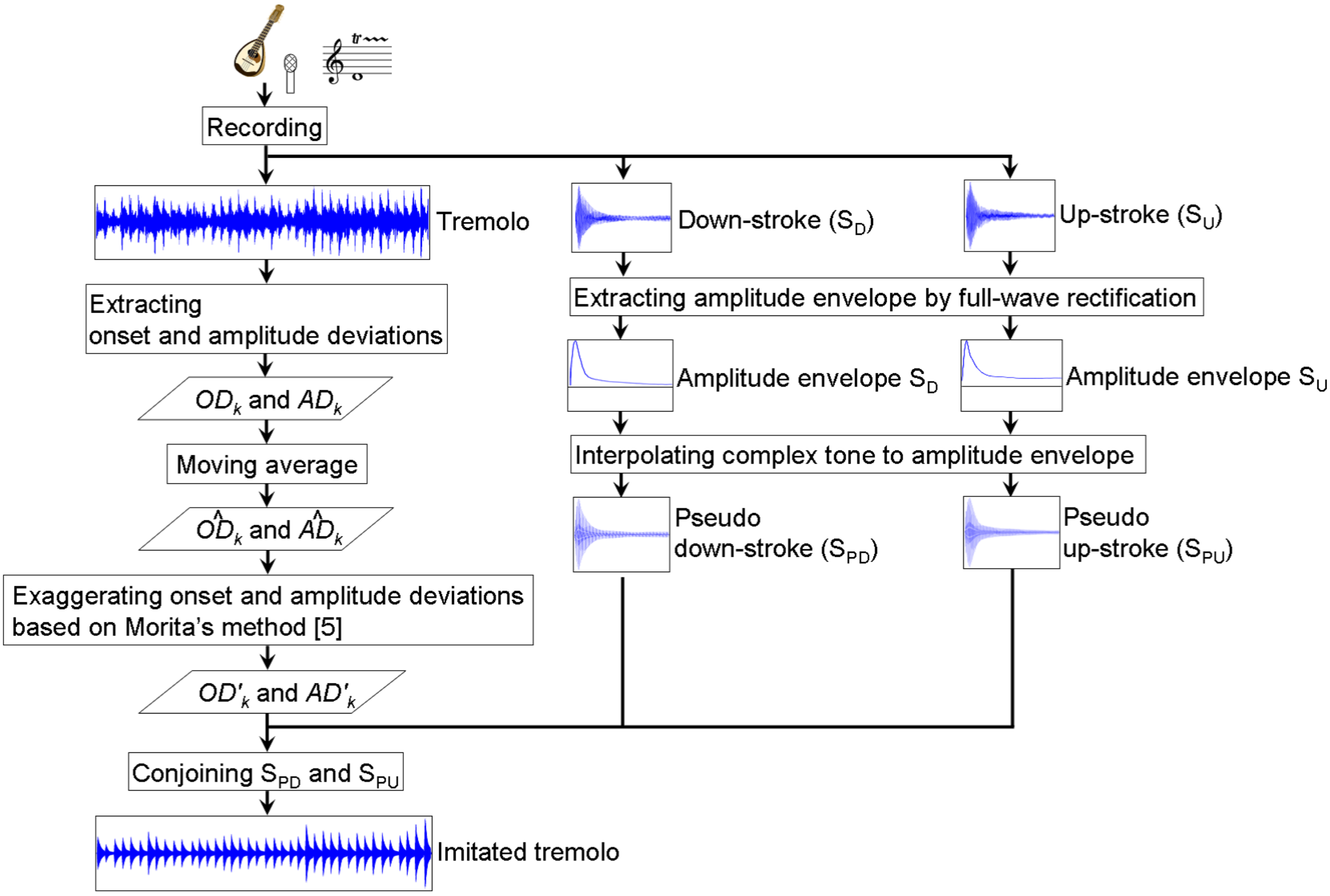
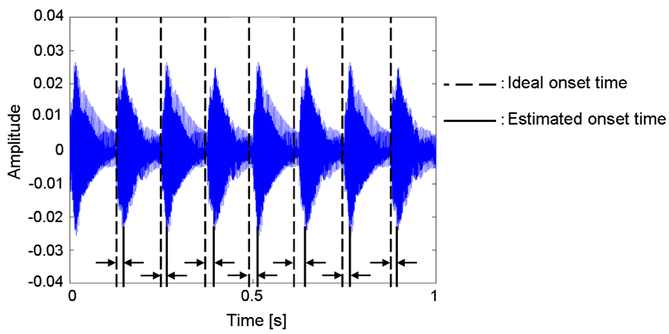
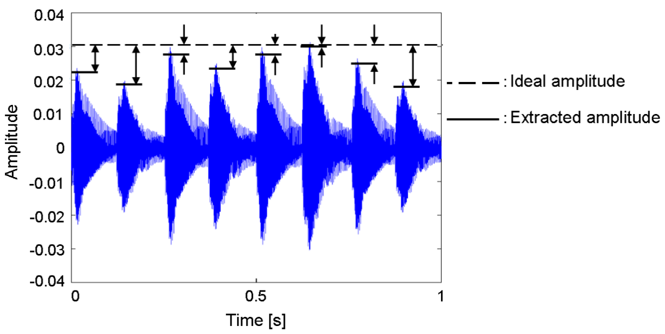


Figure 2: Procedure for synthesizing imitated tremolo.



(a) Onset deviation



(b) Amplitude deviation

Figure 3: Outline of onset and amplitude deviations.

, where x_i represents OD or AD, $\hat{x}_i$ is the parameter of the deviation trend curve, $C_{i,j}$ is the rate for changing $p_{i,j}$, and $x'_{i,j}$ is the suppressed or exaggerated parameter for $p_{i,j}$. $x'_{i,1}$ is obtained by manipulating the difference between the deviation trend curve and the actual performance of each plucking. $x'_{i,2}$ is obtained by the control value of the range, which is calculated in the deviation trend curve. M represents the control value of the range in the deviation trend curve. $x'_{i,3}$ is obtained by manipulating the difference between the deviation trend curve and a standard straight line that connects the maximum and minimum points on the deviation trend curve. A simply increasing straight line is defined as S_U, and a decreasing line is defined as S_L. The straight line, in which the sum of the difference between the deviation trend curve and itself is the minimum, is assumed to be the standard. $x'_{i,4}$ is obtained by manipulating the average of the difference between the deviation trend curve and the ideal performance. The onset deviation on actual performance, the deviation trend curve on the onset deviation, and the example of exaggerated onset deviation using the feature exaggeration method [5] are shown in Fig.4.

EXPERIMENT

Outline of experiment

To investigate the sensation of hearing fluctuation from imitated tremolos with both the 1st and 2nd fluctuations, we conducted an evaluation experiment using the magnitude estimation method with five listeners in a soundproof room.

Listeners: Four of the listeners had experiences in performing musical instrument, and one listener did not have any experience.

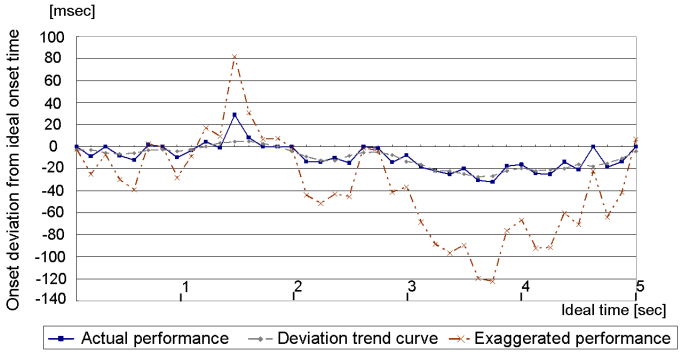


Figure 4: Onset deviation on actual performance, deviation trend curve on onset deviation, and examples of exaggerated onset deviation.

Stimuli: Imitated tremolos with onset and amplitude deviations on each plucking, 25 in total (5 deviation patterns on the onset deviation × 5 deviation patterns on the amplitude deviation). These sounds were synthesized using the method described in chapter , have just the sensation of hearing fluctuation without performance proficiency.
Equipment: An electrostatic earspeaker (SR-303, STAX Ltd.) and an amplifier (SRM-313, STAX Ltd.).
Procedure: Pairs of stimuli were presented to the listeners. The first pair was assigned a number (e.g. 100), representing the magnitude of its fluctuation. The listeners were asked to rate the fluctuation of the second stimulus within each pair and compare it to this assigned number. For example, for a decrease in fluctuation by a factor of two, the listeners had to write down the number 50 onto an answer sheet. A stimulus was chosen as the first stimulus of each pair, and was synthesized with no deviation. The stimuli were presented to the listeners through an earspeaker. Before the experiment, each listener was allowed to adjust the acoustic level of sound to the level that best enabled him or her to listen to the tremolo. The average level was about L_A = 48.0 [dB].

Experimental results

The results of the evaluation experiment are shown in Fig.5. The magnitude of fluctuation for the imitated tremolo in Fig. 5 is the average of all results, represented as percentages. These percentages were obtained by assigning the number 100 to the maximal value of each listener's answer. As can be seen in Fig. 5, we confirmed that the magnitude of fluctuation for the imitated tremolo increased, as the rates for suppressing or exaggerating the onset deviation or the amplitude deviation increased.

ANALYSIS

To develop indexes for calculating the fluctuation quantity of a tremolo with both the 1st and 2nd fluctuations, characteristics of the 1st and 2nd fluctuations were extracted from acoustic signals, and a multiple regression analysis was conducted to estimate the sensation of hearing fluctuation, in which the evaluation results obtained from the experiment was used as an objective variable, and extracted characteristics of the 1st and 2nd fluctuations were used as explanatory variables.

Extracting 1st fluctuation

To obtain the characteristic of the 1st fluctuation, we extracted a fluctuation component. The levels of acoustic power of imitated tremolos were equalized. We performed a Fast Fourier Transform(FFT) for the acoustic signal converted to absolute values. A weighted Band-Pass Filter (BPF) between 1-20 Hz was used to cut signals of other regions of the converted signal, where the weighted BPF was obtained from the results of Fastl's study [2, 3], which was the same as the other study concerning the calculation of the fluctuation quantity [4]. We performed a Inverse Fast Fourier Transform(IFFT) for them obtained by cutting the signals, and the Root Mean Square (RMS) of the obtained waveforms was calculated. We introduce the RMS as the "index for the 1st fluctuation". The procedure of extracting the index for the 1st fluctuation is shown in Fig.6. $S_{l,m}$ represents imitated tremolos, l is the ID of the rate for suppressing or exaggerating OD, and m is the ID of the rate for suppressing or exaggerating AD under $1 \le l \le 5$, and $1 \le m \le 5$.

Extracting 2nd fluctuation

We extracted the characteristics of the 2nd fluctuation based on method of extracting the performance features for scale performance on a piano [6]. First, the moving average was conducted for OD and AD on imitated tremolos, and the deviation trend curves were calculated. Next, the characteristics of the 2nd fluctuation $p_{i,j}(i = 1\text{-}2,\ j = 0\text{-}4)$ were obtained using Eqs. 8-12, introduced as the indexes for the 2nd fluctuation.

$$p_{i,0} = \sqrt{\frac{\sum_{k=1}^{N}(x'_{i,k} - \overline{x'}_{i,k-1})^2}{N-1}} \tag{8}$$

$$p_{i,1} = \sqrt{\sum_{k=1}^{N}(x'_{i,k} - \hat{x'}_{i,k})^2} \tag{9}$$

$$p_{i,2} = \max(\hat{x'}_i) - \min(\hat{x'}_i) \tag{10}$$

$$p_{i,3} = \sqrt{\sum_{k=2}^{N}(\hat{x'}_{i,k} - \hat{x'}_{i,k-1})^2} \tag{11}$$

$$p_{i,4} = \sum_{k=1}^{N}\hat{x'}_{i,k} \tag{12}$$

The suffix j in $p_{i,j}$ distinguishes the standard deviations of each deviation on the imitated tremolos (j = 0), the square root sum of squares(srss) of the deviation from the deviation trend curve to actual performance (j = 1), the range of the deviation trend curve (j = 2), the srss of the difference between successive notes on the deviation trend curve (j = 3), and the sum of the deviation from the ideal performance to the deviation trend curve (j = 4). A semantic explanation of the indexes for the 2nd fluctuation on the onset deviation except for $p_{1,0}$ is shown in Fig.7.

Multiple regression analysis

A multiple regression analysis was conducted to estimate the sensation of hearing fluctuation, in which the evaluation result obtained from the experiment was used as an objective variable and extracted indexes for the 1st and 2nd fluctuations were used as explanatory variables. The coefficient of determination between the evaluation result and estimated score using only the index for the 1st fluctuation and those between the evaluation results and estimated scores using the indexes for the 1st and 2nd fluctuations are shown in Fig.8. The "0" on the abscissa in Fig.8 represents the condition for conducting multiple regression analysis using only the 1st fluctuation, and the "1"-"5" represents the condition for conducting multiple regression analysis using both the 1st and 2nd fluctuations, where "n"(n=1/2/3/4/5) is the average of the coefficients of determination between the evaluation results and estimated scores by using n indexes for both the onset and amplitude deviations. As

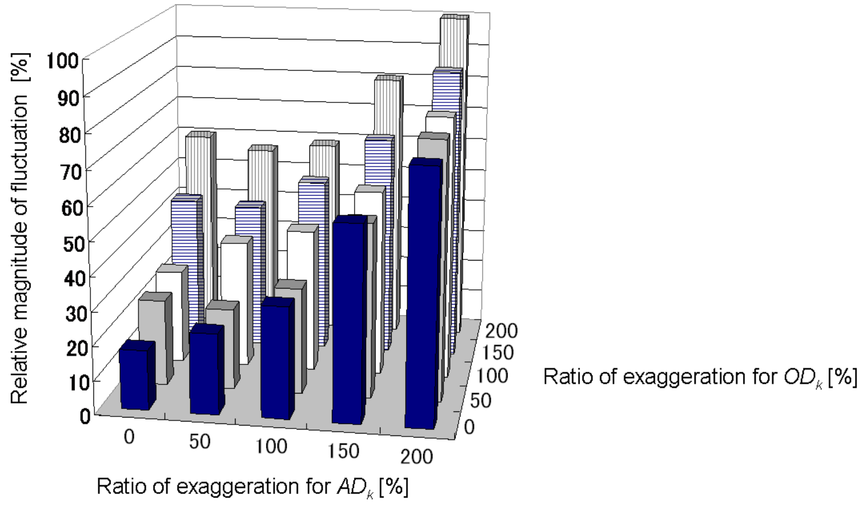


Figure 5: Results of evaluation experiment.

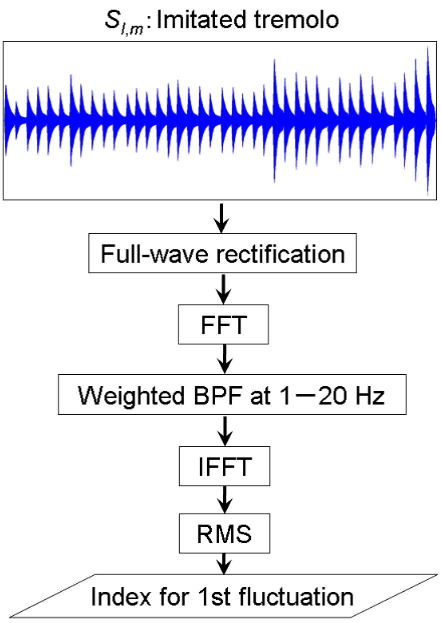


Figure 6: Procedure of extracting index for 1st fluctuation.

can be seen in Fig.8, we confirmed that the coefficients of determination between the evaluation results and obtained scores by using both the index for the 1st fluctuation and indexes for the 2nd fluctuation are higher than the coefficient of determination between the evaluation results and obtained scores by using only the index for the 1st fluctuation.

DISCUSSION

As can be seen in Fig.8, it was thought that the procedure using not only the 1st but also the 2nd fluctuation approximately represents the sensation of hearing fluctuation ($R^2 > 0.75$), which is greater than when using only the 1st fluctuation ($R^2 = 0.55$). Thus, we obtain indexes for calculating the fluctuation quantity that represents the sensation of hearing fluctuation from a tremolo with both the 1st and 2nd fluctuations.

The adjusted coefficients of determination defined to prevent the fault of the coefficients of determination were calculated because generally, the more explanatory variables are added, the higher the coefficient of determination is on the multiple regression analysis. The adjusted coefficients of determination calculated in the same manner as in Fig. 8 are shown in Fig.9. Like Fig.8, the “0” on the abscissa in Fig. 9 represents the condition for conducting multiple regression analysis using only the 1st fluctuation, “n” represents the condition for conducting multiple regression analysis using n indexes for both the onset and amplitude deviations. As can be seen in Fig.9, we confirmed that the adjusted coefficients of determination between the evaluation results and obtained scores by using both the 1st and 2nd fluctuations is higher than those between the evaluation results and obtained scores using only the index for the 1st fluctuation like Fig. 8. We also confirmed that the adjusted coefficients of determination calculated for “1” and “5” are lower than the others. Therefore, we investigated the indexes that contribute to estimating the sensation of hearing fluctuation on $p_{i,j}$. The adjusted coefficients of determination between the evaluation results and both the index for the 1st fluctuation and those of $p_{i,j}$ for i = 1, 2 were calculated. The calculated adjusted coefficients of determination are shown in Fig.10. The abscissa represents each $p_{i,j}$ used on the multiple regression analysis and the ordinate represent adjusted R^2. As can be seen in Fig.10, we confirmed that the adjusted coefficients of determination calculated using only $p_{i,1}$ is somewhat lower than the others. It is thought that the degree of influence on estimating the hearing sensation would be different between $p_{i,1}$ and the others. Discussion on the interaction with each index is expected in the near future.

CONCLUSION

We proposed indexes for calculating the fluctuation quantity that represents the sensation of hearing fluctuation from a tremolo with irregular plucking. Our results show that the procedure using both the 1st and 2nd fluctuations approximately represents the sensation of hearing fluctuation. In future work, we plan to investigate the interaction of each index and estimate the sensation of hearing fluctuation based on other plucking rates.

ACKNOWLEDGEMENTS

This study is partly supported by the High-Tech Research Center Project for Private Universities matching fund subsidy from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Research for Promoting Technological Seeds from the Japan Science and Technology Agency

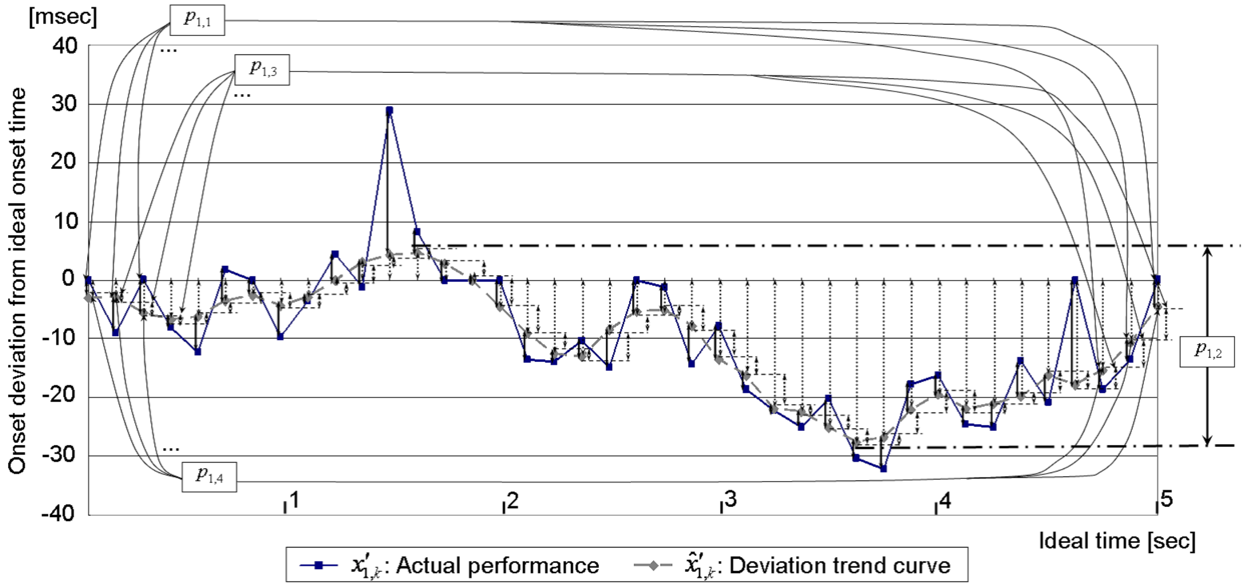


Figure 7: Indexes for 2nd fluctuation on onset deviation except for $p_{1,0}$ ($p_{1,1}$, $p_{1,2}$, $p_{1,3}$ and $p_{1,4}$).

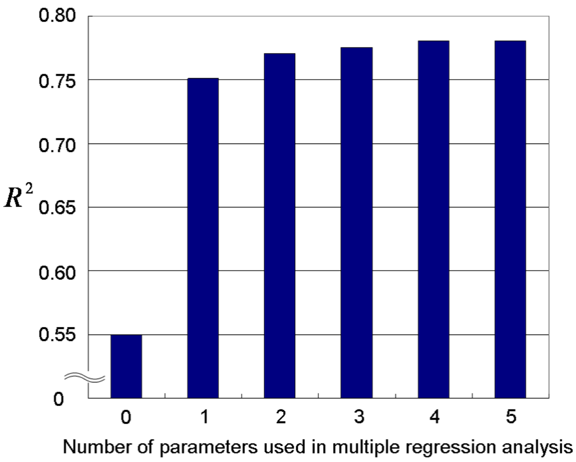


Figure 8: Results of calculating coefficients of determination.

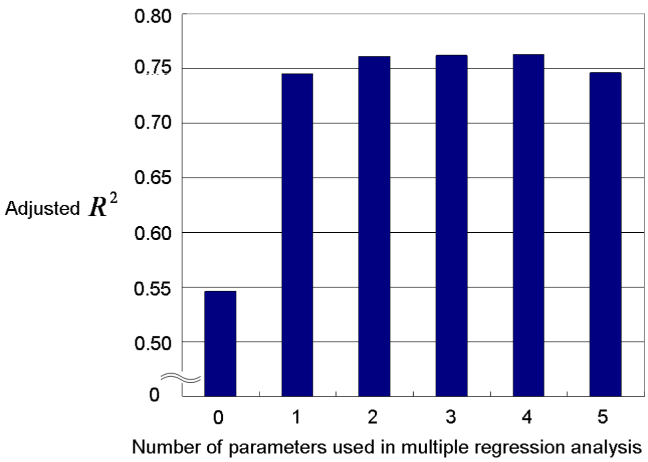


Figure 9: Results of calculating adjusted coefficients of determination.

(JST).

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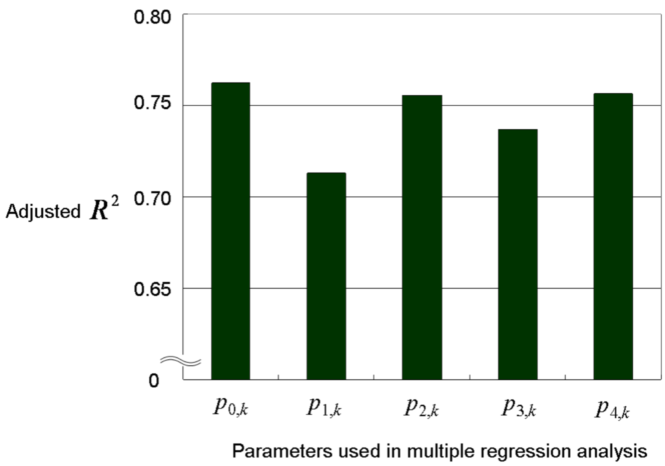

Figure 10: Adjusted coefficients of determination between the evaluation results and both index for 1st fluctuation and those of $p_{i,j}$ for $i = 1, 2$.