Study of Ivory Alternatives for Koto Bridges: Correlation between Sensory Evaluation and Amplitude Modulation of Fundamental Spectrum

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ABSTRACT

The bridges of a koto, a Japanese musical instrument, have traditionally been made of ivory for its superior sound quality and appearance. On the contrary, in the conference of CITES CoP17, 2016, a resolution for the closedown of the domestic market of the ivory was adopted. Therefore, the demand for substitute materials for the ivory is expected to increase in future. Despite this, from the viewpoint of sound quality, the currently available substitute materials used to manufacture koto bridges remain inferior in comparison with ivory. This study investigates the performance of substitute materials by investigating the properties of koto bridges made of metal, resin, and wood. A sensory evaluation of a single tone played by professional and expert koto players was performed for all substitute materials. Additionally, a wavelet analysis of the recorded tone was conducted. The amplitude modulation of the fundamental spectrum level varied in time with respect to each of the chosen materials. The study also includes an investigation of the correlation between sensory evaluation and the recorded amplitude modulation of fundamental spectrum.

Keywords: Wavelet transform, Fast Fourier transform, Sensory evaluation, Harmonic, Fundamental mode, Pearson productmoment correlation coefficient

1. INTRODUCTION

Koto bridge supports strings, thereby transmitting vibrations to the torso (1). In this regard, violin has been extensively studied because it is a typical stringed instrument with a bridge (2–12). However, Koto bridges have been rarely studied because Japanese Koto is an instrument used only in Japan mainly. Koto bridges made of ivory have excellent appearance and timbre (when played); thus, they are in great demand. The Washington Convention was adopted in 1975, and by 1989, the international trade in ivory had virtually ended. A resolution to ban the domestic trade of ivory was adopted at the 2016 Conference of the Parties. However, resin-based materials that are currently used as substitutes for ivory have poor sound quality. Therefore, alternative materials for ivory must be identified.

Physical properties of materials for Koto bridges made of ivory and various other materials were determined using dynamic viscoelasticity measurements and ultrasonic waves. These studies indicated that the physical and mechanical properties of the bridge were closely related to the sound fluctuations. Analysis of single tones revealed that characteristic fluctuations appeared during reverberation and these fluctuations differed depending on the bridge material (13–15). From the above, we deduced that physical and mechanical properties of materials used in Koto bridges affect the sound quality. Therefore, we built bridges using various materials and performed a trial and a sensory evaluation of sound using Koto performers. We also examined the correlation between the analysis results of recorded data and sensory evaluation.

2. QUANTIFICATION OF THE FLUCTUATION COMPONENT OF REVERBERATION

2.1 RMS Value of the AC Component in the Time Waveform of a Spectrum Level in the

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Standard Harmonic Overtone

We recorded the sound played on the Koto and performed wavelet transform. Further, we determined the time variation of the spectral level for each harmonic to analyze the sound differences produced due to different Koto bridge materials. The fluctuation in spectrum level affects the sensory evaluation. Detailed analysis of this fluctuation involved the following steps: 1) conducting a fast Fourier transform of the time waveform of the spectrum level of the standard harmonic overtone, determining the frequency and magnitude of the fluctuation component. 2) by focusing on the point at which the behavior of the time variation of the spectrum level changes with time, applying a filter to the time waveform of the spectrum level for each frequency band and time, and 3) obtaining the effective value of the AC component for each condition.

2.2   Procedure for Obtaining RMS Values

We recorded the sound in a studio using a Sony ICD-SX 2000 audio recorder. A recording device was installed near the hole at the bottom of the Koto. The standard harmonic overtone frequency unified at ~390 Hz.

The recorded sound was 4.5-s long after the first sound level peak. After 4.5 s, the recorded sound was almost inaudible and had attenuated by more than 60 dB from the peak value.

The recorded sound was subjected to time–frequency analysis by wavelet transform using an Ono Sokki Oscope 2 acoustic analysis tool. The Gabor function was used for characterizing the mother wavelet. Figure 1 shows an example of a color map obtained from the analysis. In this figure, the vertical axis represents frequency, the horizontal axis represents time, and the spectral levels are color coded.
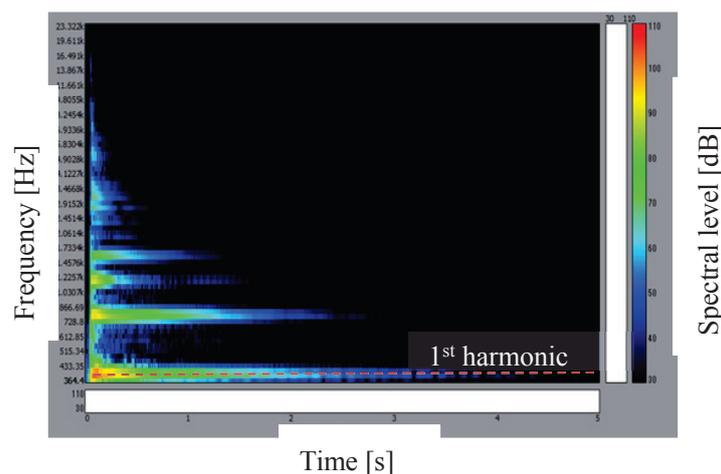

Figure 1– Example of a color map for time–frequency spectral levels
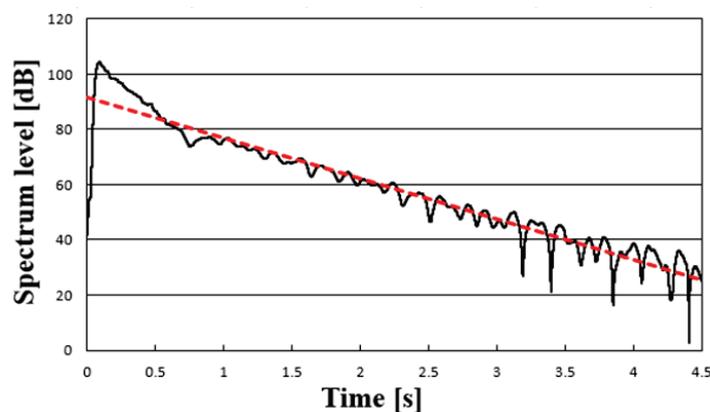

Figure 2 – Time waveform of the spectrum level of the standard harmonic overtone and approximation line

Figure 2 shows an extraction of the temporal change in the spectrum level of the standard harmonic overtone in Fig. 1. For this time waveform, the approximate line obtained using the least squares method at 4.5 s after the peak is also shown. By removing the slope of this approximate line, only the time waveform of the fluctuation component of the spectrum level of the standard harmonic overtone is obtained, as shown in Fig. 3.

Fig. 4 shows the frequency characteristics of the fluctuation components obtained by performing a Fourier transform on the time waveform of Fig. 3. The Fourier-transformed calculation data of Fig. 4 were filtered offline and divided into six frequency bands: 2–6, 6–10, 10–14, 14–18, 18–22, and 22–26 Hz. By performing inverse Fourier transforms on the data for these six frequency bands, the time waveform of the spectrum level (Fig. 5) was determined for each band.
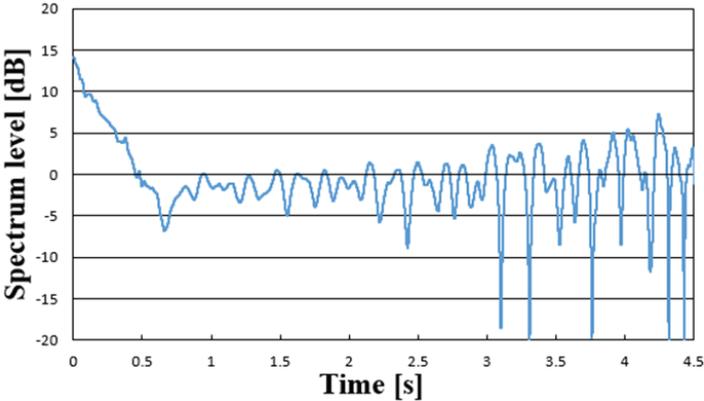
Figure 3 – Time waveform of only the fluctuation component in the time waveform of the spectrum level of the standard harmonic overtone
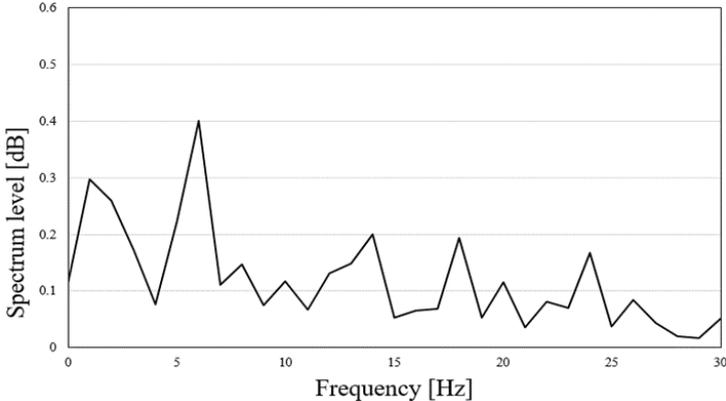
Figure 4 – Frequency characteristic of the fluctuation component in the time waveform of the spectrum level of the standard harmonic overtone
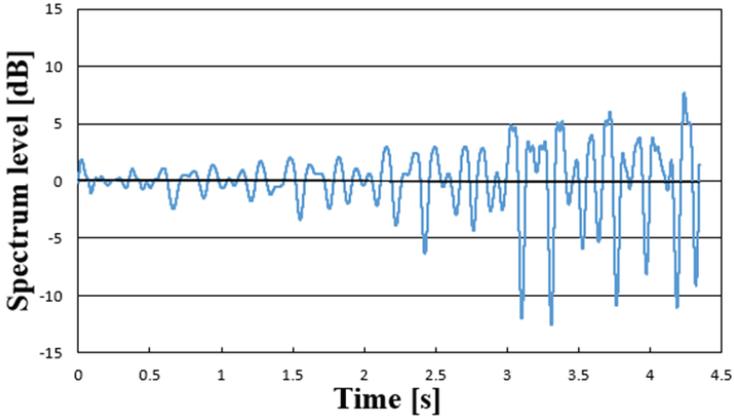
Figure 5 – Time waveform of the spectrum level in a certain frequency band

The time waveforms shown in Fig. 5 were divided into three time zones of 0–1.5, 1.5–3.0, and 3.0–4.5 s. Next, by plotting the RMS values of these time waveforms, as shown in Fig. 6, the RMS values of AC components "for each time zone in each frequency band" were calculated.

The time waveform of the spectrum level at the frequency of the standard harmonic overtone was divided into six frequency bands and three time zones. The RMS values of the AC components for these 18 conditions were then obtained.
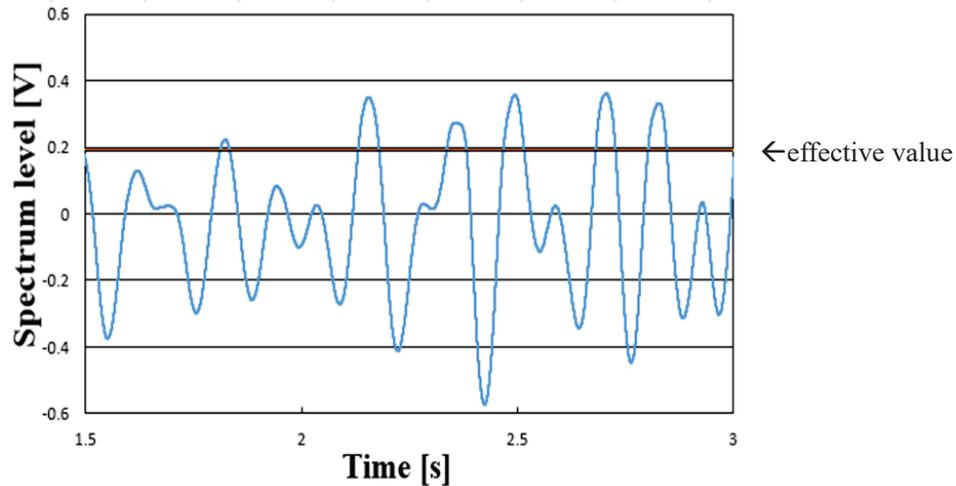

Figure 6 – RMS value of the AC components for each time zone in a certain frequency band

Table 1 – RMS values of the AC components obtained for ivory

	0-1.5 s	1.5-3 s	3-4.5 s
2-6 Hz	0.0968	0.294	0.385
6-10 Hz	0.00238	0.00168	0.00216
10-14 Hz	0.0283	0.105	0.214
14-18 Hz	0.0145	0.0591	0.173
18-22 Hz	0.00238	0.00168	0.00216
22-26 Hz	0.0106	0.0402	0.141

Table 1 shows an example of the RMS values obtained for ivory. Observation of the sound characteristics of a Koto bridge made of ivory using the RMS values of the AC components revealed the following. The RMS values of the AC components in the time zone indicate that the latter half tends to be larger. The RMS values of the AC components in the frequency band indicates that the low-frequency side tends to be larger.

3. CORRELATION BETWEEN SENSORY EVALUATION AND THE RMS VALUES OF THE AC COMPONENTS

We show the correlation coefficient of the RMS values of the AC components and the scores of the sensory evaluation for a total of 73 types of bridges comprising 70 prototype bridges and three commercially available bridges (including ivory).

First, the "RMS values of the AC components" under the 18 conditions identified in the previous chapter were obtained for Koto bridges made of 73 materials.

A sensory evaluation of the sound of a Koto being played was also performed for those bridges. The criteria used in the sensory evaluation are shown in Table 2. The evaluators were five professional or skilled performers.

Table 2 – Evaluation criteria for sensory evaluation

Evaluation	Point	Index
A	4	Equivalent to ivory
A⁻	3.7	
B⁺	3.3	
B	3	Superior to distribution products
B⁻	2.7	
C⁺	2.3	
C	2	Equivalent to distribution products
C⁻	1.7	
—	1	Inferior to distribution products

As an example of high correlation, the condition of a frequency in the 2−6 Hz band and a time of 3.0–4.5 s, the RMS values of the AC component, and the scores of the sensory evaluation for each material were plotted in Fig. 7. Herein, the straight line shows the correlation. The plot with a score of 4.0 is for ivory.
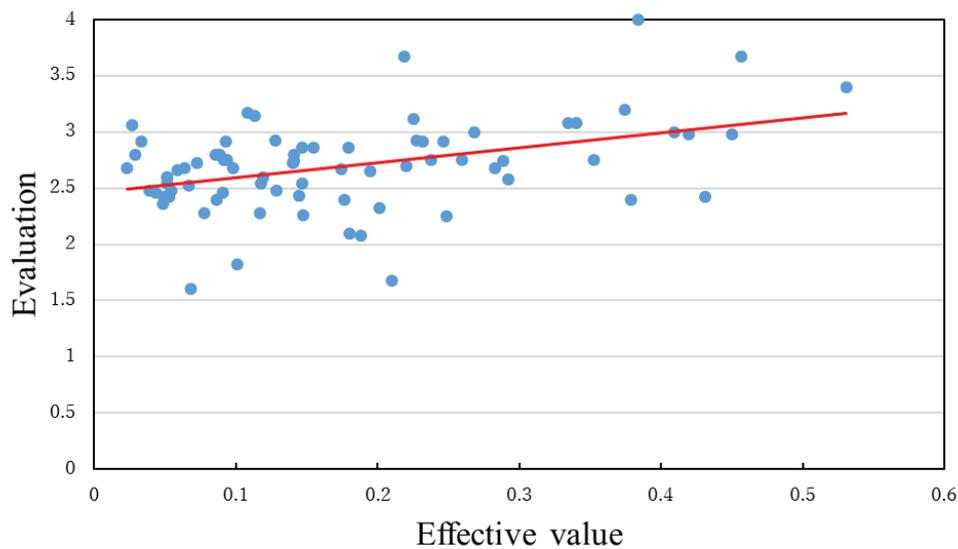

Figure 7 – Plots of the RMS values of the AC components and scores of the sensory evaluation for 73 types of Koto bridges (an example with high correlation).
(Frequency range: 2−6 Hz , Time: 3–4.5 s)

Table 3 shows the coefficients of correlation and P-values for 18 conditions by processes like that in Fig. 7. These coefficients of correlation increase with the passage of time in all frequency bands except 6–10 Hz. In addition, as the P-values decrease with time, the reliability of the correlation is improved. Based on these facts, if the RMS value of the AC component in the second half of the sound is large, it tends to be a "good sound evaluation."

Focusing on the coefficient of correlation in the frequency band in the 3.0–4.5-s zone (Table 3), we can see the coefficient is high at 14–18 Hz and 22–26 Hz. In addition, because the coefficients of correlation exceed 0.4 in any frequency band, there is considerable correlation.

Here, in the example for ivory shown in Table 1, the RMS value of the AC component becomes high as the frequency band becomes low. This tendency is the same in the other materials. Here, we speculate that the score (hearing sense) is affected by audible sound. Therefore, the score may be affected by the frequency band in the 3.0–4.5-s time zone in Table 3 with a high RMS value of the AC component.

Table 3 – Coefficients of correlation between the sensory evaluation and the RMS values of the AC components and P-values

Frequency range [Hz]	Time [s]	0 - 1.5	1.5 - 3.0	3.0 - 4.5
2 - 6	Correlation - coefficient	0.299	0.358	0.417
	P - value	0.00876	0.00148	0.000179
6 - 10	Correlation - coefficient	0.362	0.286	0.409
	P - value	0.00131	0.0122	0.000243
10 - 14	Correlation - coefficient	0.161	0.326	0.420
	P - value	0.166	0.00408	0.000159
14 - 18	Correlation - coefficient	0.205	0.377	0.470
	P - value	0.0750	0.000789	1.85E-05
18 - 22	Correlation - coefficient	0.362	0.286	0.409
	P - value	0.00131	0.0122	0.000243
22 - 26	Correlation - coefficient	0.234	0.351	0.467
	P - value	0.0418	0.00187	2.16E-05

4. RELATION BETWEEN THE RMS VALUES OF THE AC COMPONENTS, SENSORY EVALUATION, AND FREQUENCY BAND

Figure 8 shows a three-dimensional graph of the "RMS values of the AC components," "scores of sensory evaluation," and "frequency band" for the 18 conditions obtained by the procedure shown in Section 2-2. The vertical axis is the RMS value of the AC component, the horizontal axis is the frequency band, and the score is in the depth direction. In addition, the magnitude of the effective value of the AC component is color coded.

From Fig. 8, the higher the score, the higher is the effective value of the AC component. In the low-frequency band, when the RMS value of the AC component is high, the score also tends to be high. In the example of ivory shown in Table 1, the RMS value of the AC component is higher in the low-frequency band. Thus, if a material has a high RMS value of the AC component in the low-frequency band, then the sensory evaluation score may be high. We believe that this is a useful finding in the development of and search for alternative materials to ivory.
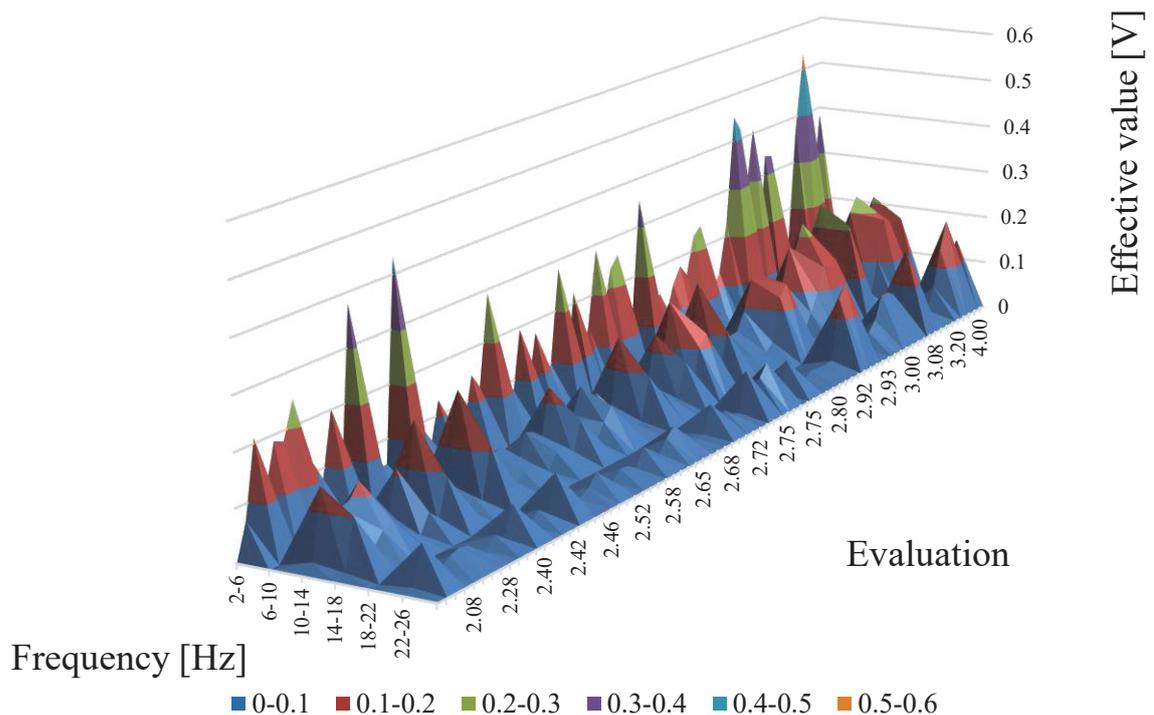
Figure 8 – The RMS value of the AC component, the score, and the frequency band
(Frequency range: 4 Hz step from 2 Hz, Time: 3.0 – 4.5 s)

5. CONCLUSIONS

We extracted the RMS values of the AC components in a time change of the spectrum level of the standard harmonic overtone by analyzing single tones using Koto bridges made of ivory and various other materials. As a result of examining the correlation between those values and the scores of the sensory evaluation, the following conclusions were obtained.

The correlation between the RMS values of the AC components and the scores of the sensory evaluation increased with time. The material for a Koto bridge with a large RMS value of the AC component during the 3–4.5 s time period might have a high sensory evaluation score.

ACKNOWLEDGEMENTS

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