EFFECT OF THE FLUCTUATIONS OF HARMONICS ON THE SUBJECTIVE QUALITY OF FLUTE TONE

PACS: 43.66.Jh, 43.75.Cd, 43.75.Qr

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ABSTRACT

We studied the relationship between amplitude and frequency fluctuations of harmonics and the perceived quality of flute tones with vibrato. To investigate the effects of minute and irregular fluctuations on timbre, a real flute tone and synthesized flute tones whose relative amplitude levels of harmonics and extent of vibrato were equal to those of the real tone, were used for the subjective experiments. Listener's preference for flute tones was found to be affected by the degree of intensification or attenuation of the frequency and amplitude fluctuations above 13Hz.

INTRODUCTION

Several studies have been conducted on the relationship between the amplitude envelope or spectral envelope of the sounds of musical instrument and their timbre. Relatively slow and regular fluctuation of harmonics (that is, vibrato) has been shown to be one of the factors which affect the perceived naturalness of timbre of musical instruments. However, few studies have been conducted on the relationship between minute and irregular fluctuations of amplitude and frequency (non-vibrato) and the perceived beauty or preference of timbre.

Ando and his colleagues investigated the relationship between the physical properties and their perceived qualities, for sustained flute tones [1], the treble recorder [2] and the syakuhach [3]. The sounds of these musical instruments had no vibrato. The general conclusion that can be drawn from these studies is that not only the amplitude spectrum (which is regarded as the most important factor for timbre of sustained musical tones) but also the frequency and amplitude fluctuations of harmonics play an important role in the quality of air-reed instrument tones. However, previous studies have only dealt with musical tones without vibrato. Therefore, it is not obvious whether the findings obtained from those studies will hold true for flute tones played with vibrato. In addition, the results of informal experiments by Ando indicate that more minute properties of fluctuation waves probably affect the quality of air-reed instrument tones.

Here, we are concerned with flute tones with vibrato, and we focus on the amplitude and frequency fluctuations of their harmonics. The target frequency range of these fluctuations is above the vibrato frequency, because we want to investigate minute and non-periodic fluctuations that a flute tone intrinsically contains. In this paper, we report on our investigation into the relationship between these amplitude and frequency fluctuations of harmonics and the perceived quality of flute tones.

ANALYSIS OF A FLUTE TONE AND ITS FLUCTUATIONS

Sound Material

Flute sounds were recorded on a DAT recorder at a sampling frequency of 48kHz, with a microphone (B&K 4190) positioned 50cm from the mouth hole. The recorded melody was the cadence composed by Donjon from Mozart's "Concert No.2 for Flute and Orchestra in D K.314," played by Prof. Iwasaki of Kurashiki Sakuyo University, Faculty of Music.

The recorded sounds were down-sampled to 22.05kHz before analysis. The sound which was analyzed was the first note of the melody, and its duration was 2.1 seconds. Its fundamental frequency was approximately 900Hz.

Amplitude And Frequency Fluctuation Waves And Their Spectra

Harmonic components were separated by a bandpass filter bank whose bandwidth was the fundamental frequency and whose center frequencies were integer multiples of thefundamental. Frequency and amplitude fluctuation waves of each harmonic were then extracted using analytic signals. The analytic signal is a complex signal in which the real component is the original signal and the imaginary component is its Hilbert transform. The frequency fluctuation wave is obtained by the derivation of the phase of the analytic signal. And the amplitude fluctuation wave is derived from the absolute value of the analytic signal.

Figure 1 shows the frequency fluctuation waveforms of the first to sixth harmonics, relative to the integer multiples of the fundamental frequency. In the figure, the harmonics are sequentially shifted apart by -10%, for clarity. Figure 2 shows amplitude fluctuation waveforms of the first to sixth harmonics, relative to the maximum amplitude level of the sound file format (Microsoft RIFF audio file). Here, the harmonics are sequentially shifted apart by -20dB, for clarity.

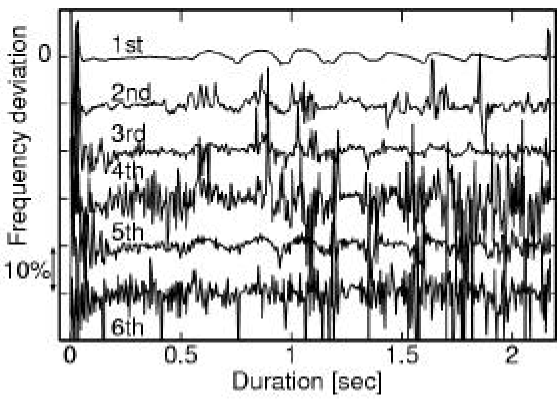

Figure 1: Frequency fluctuation waveforms of the first to sixth harmonics relative to the integer multiples of the fundamental frequency. The harmonics are sequentially shifted apart by -10%, for clarity

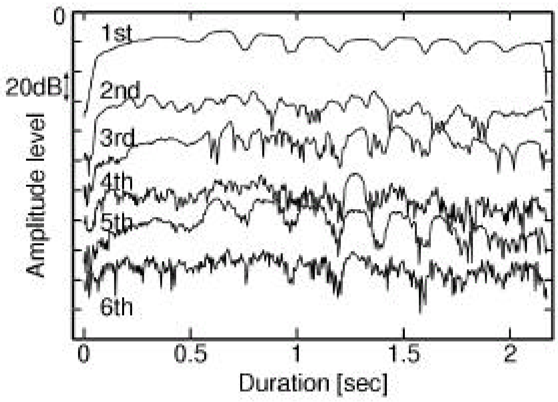

Figure 2: Amplitude fluctuation waveforms of the first to sixth harmonics relative to the maximum amplitude level of the sound file format. The harmonics are sequentially shifted apart by -20dB, for clarity.

In order to investigate characteristics of the fluctuation wave, long-term spectrum analysis [44100-points discrete Fourier transform (DFT) after 44100-points Hanning-windowing] was applied to frequency and amplitude fluctuation waves of each harmonic.

Figure 3 shows the spectra of frequency fluctuation waves extracted from the fundamental and the second harmonic, as an example. All harmonics show frequency vibrato at approximately 5Hz with modulation index of approximately 1%. In the fundamental, strong harmonic components of vibrato are seen in the frequency range below 30Hz. However, in the frequency range 30Hz to 400Hz, only slight fluctuations of approximately 0.01% in modulation index are observed. In the second harmonic, the strong component is only seen at vibrato of 5Hz, and at other frequencies the modulation index remains constant at approximately 0.1%. The spectra of the frequency fluctuations extracted from the harmonics above the second harmonic show the same spectral envelope as the second harmonic. The results of the spectral analysis of the other tones extracted from the recorded melody show almost the same tendency as the first tone.

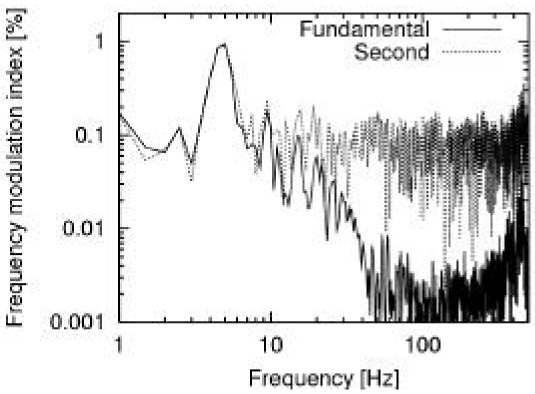

Figure 3: Power spectra of frequency fluctuation extracted from the fundamental and the second harmonic.

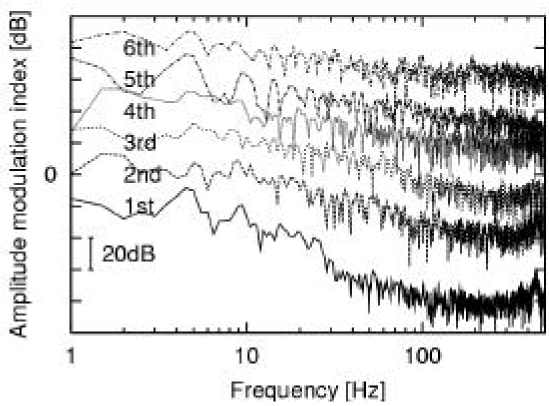

Figure 4: Power spectra of amplitude fluctuation extracted from the fundamental to sixth harmonic. The harmonics are sequentially shifted apart by 20dB, for clarity.

Figure 4 shows power spectra of the amplitude fluctuation waves extracted from the fundamental to the sixth harmonic. Each harmonic shows a constant negative slant in its spectrum. These slants are almost the same as for the results obtained for the other tones from the recorded melody. The slant in the spectrum of the fundamental is -10 to -15dB/octave. The degree of slant gradually decreases with increasing harmonic number, and it becomes -3dB/octave above the 6th harmonic.

EXPERIMENT

A preliminary experiment was conducted to evaluate the perceived quality of synthesized flute tones with intensified or attenuated frequency and amplitude fluctuations of harmonics, with the vibrato fluctuation and the amplitude spectrum held constant. The results showed that the perceptions of timbre differed according to variations in the power of fluctuations. Therefore, we conducted an experiment on subjective evaluation of synthesized flute sounds, which attempted to determine which frequency region of the fluctuations affects the perceived quality of flute tones, by attenuating or intensifying amplitude and frequency fluctuations of each harmonic.

Table 1: Stimuli and their parameter for synthesis in experiment 1.

label	method of synthesis: filter of frequency fluctuation	method of synthesis: filter of amplitude fluctuation
f13a13	low-pass 13Hz	low-pass 13Hz
f94a94	low-pass 94Hz	low-pass 94Hz
s_peak	128points FFT, 64points overlapped (Sinusoidal modeling synthesis)	
f13aw	low-pass 13Hz	—
fwaw	—	—
fwa13	—	low-pass 13Hz
orig	original	
fwah200	—	+6dB high-boost at 200Hz
fwah40	—	+6dB high-boost at 40Hz

Stimuli

Table 1 shows the parameters for synthesis. The meanings of the labels of the different stimuli are as follows. The stimulus orig is the original tone. The stimulus s_peak was synthesized from a time sequence of amplitude and frequency data which were calculated by 3-point interpolation [4] around spectral peaks obtained from 128-point fast Fourier transform (FFT), shifting 64 points each. The letters used in the label of the other stimuli have the following meanings: `f', frequency fluctuation; `a', amplitude fluctuation; `w', wide band; `h', high boost condition. The numbers represent cutoff frequency of the fluctuation filtering. Thus, the stimulus fwa13 was synthesized using the frequency fluctuation waves extracted from the harmonics of the original tone and the amplitude fluctuation waves which were lowpass-filtered at 13Hz. Characteristics of the fluctuation filters are shown in Fig. 5. All filters left the vibrato frequency region unchanged. All stimuli except orig were synthesized up to the 10th harmonic.

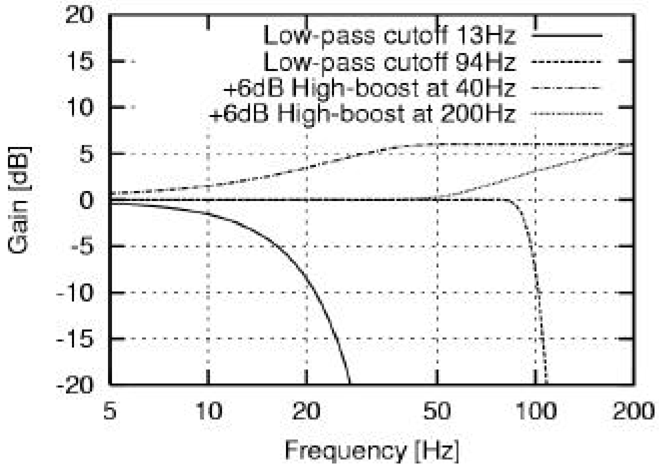

Figure 5: Characteristics of filters.

Average power spectra of the nine stimuli, calculated by half-overlapped 4096-point FFT with Hanning-windowing, are shown in Fig. 6. The apparent noise floor, at a level of -60dB relative to the fundamental, is not background noise. It represents inherent noise that every flute tone has. A subharmonic series of order two which was observed in the original tone and the synthesized tones reflects the first resonance frequency of a flute pipe.

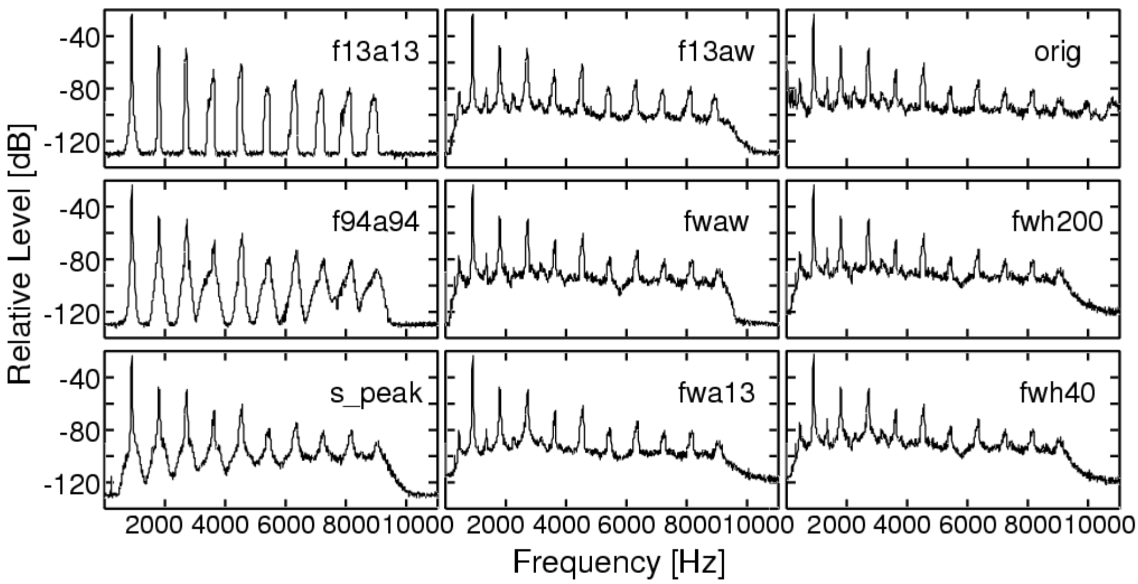

Figure 6: Average power spectra of stimuli.

<u>Experimental Procedure</u>

The experiment consisted of three listening sessions per subject. All possible combinations of nine stimuli shown in Table 1, including reverse order, were presented to each test subject once per session, in random order. The subjects answered the preference of the latter tone compared to the former tone, in five steps, immediately after the pair was played. The total number of the pairs presented in a session is 72. Details of the nine subjects are as follows: Subjects 1 and 5 were two of the present authors; Subjects 2, 3 and 4 were amateur flute players; Subjects 6, 7, 8 and 9 were undergraduate students of the faculty of music, majoring in flute. Stimuli were presented diotically via headphones (Audio-Technica ATH-A5X). Sound pressure levels [measured by artificial ears (B&K 4153 and B&K 4134)] were in the range from 63 to 69dB. The results of each subject's first session were not used for the analysis; this was meant to compensate for results that may have been due to subjects' lack of familiarity with the experimental procedure.

<u>Results</u>

Scheff'e's method for analysis of variance (ANOVA), modified by Ura, was applied to the results of the experiments. Estimated values of preference, with their 95% confidence limits, are shown in Fig. 7.

A cluster analysis was performed on the subjects. The subjects were classified into two groups, one consisting of subjects 4, 5, 7 and 9, and the other consisting of subjects 2, 3, 6 and 8. All Spearman's correlation coefficients obtained within each group of subjects were significant ($p <$

0.05). The former group tended to prefer flute tones with more fluctuation in the harmonics, and the latter group tended to prefer tones with less fluctuation.

Ando and Shima calculated average levels of components of flute tones without vibrato in the frequency range 2kHz to 5kHz excluding 100Hz bandwidth centered around the harmonic frequencies. They assumed that these noise components were not due to inherent fluctuation of the harmonics, but rather to inherent noise. They found that the perceived quality of a real flute tone deteriorated with increases in this noise level.

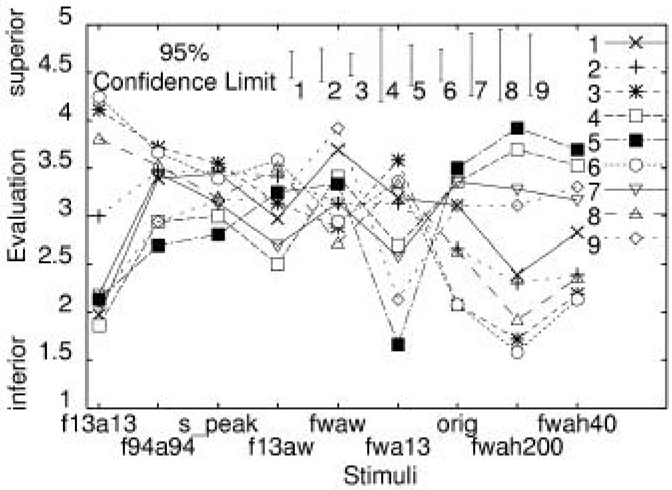

Figure 7: Estimated preferences for flute tones with 95% confidence limit.

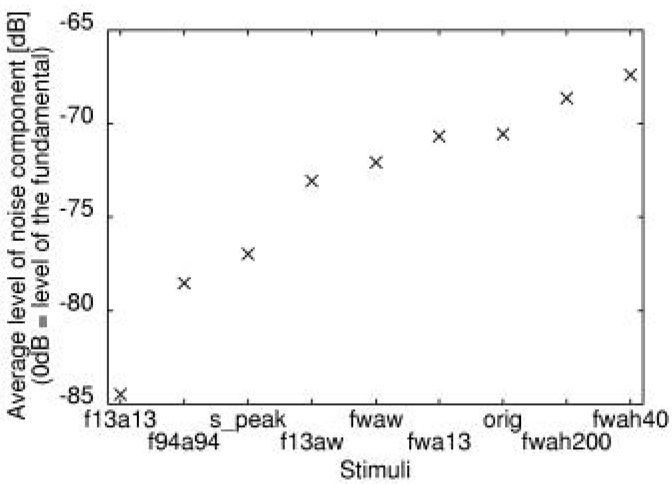

Figure 8: Average noise level.

We also calculated the average noise levels of the stimuli, and investigated the relationship between these noise levels and listener's preference. We observed no periodic amplitude or frequency fluctuations, other than vibrato, in any of the harmonics, so that it is appropriate to consider fluctuation components other than vibrato to be random fluctuations, and these fluctuations generate noise components. In addition, the side band components generated by the frequency vibrato do not effect outside the 200Hz bandwidth centered around the harmonic frequencies. Therefore, we regarded the average level of the components in the frequency range from 1900 to 5300Hz, excluding the 200Hz bandwidth centered around the harmonic frequencies, as the noise level, and calculated this level for each stimulus from the results of the spectral analysis (Fig. 6). Figure 8 shows the average noise levels for all stimuli.

Correlation coefficients between these noise levels and estimated values of preference were calculated for each subject. Negative correlation was significant ($p < 0.05$) for Subjects 3, 6 and 8. According to these results, some of our subjects had a tendency to prefer flute tones with low noise levels, like the amateur subjects who participated in the experiment conducted by Ando and Shima [1]. Figure 7 reveals that all subjects showed significant differences ($p < 0.05$) in preference between f94a94 (in which fluctuations above 94Hz were eliminated) and fwaw (which consisted of the original fluctuations). This result demonstrates that fuctuations above 94Hz affect the perceived quality of flute tone, although the extent of preference for the tones varied by subject. Moreover, eight of our nine subjects showed significant difference in preference between f94a94 and f13a13, and all subjects showed significant difference in preference between fwaw and f13a13 ($p < 0.05$). Therefore, fluctuation components at frequencies from 13 to 94Hz can also affect the perceived quality of flute tones.

DISCUSSION

Relationship Between Subject's Playing Experience And Preferred Amount Of Fluctua tion

In a series of studies by Ando and his colleagues [1,2,3] which dealt with air-reed instruments, professional players were found to prefer those synthesized tones which had moderate degrees of fluctuation, whereas amateur players preferred synthesized tones with lesser degrees of fluctuation.

In the present experiment, four of the nine subjects were undergraduate music students majoring in flute, and they were considered to be more experienced flute players than the other subjects. Two of the four subjects who preferred tones with lesser degrees of fluctuation, such as f13a13, were undergraduates majoring in flute. The other two undergraduates majoring in flute preferred tones with moderate fluctuation, such as fwaw or orig. These results suggest that, among our subjects, the level of flute playing experience did not affect the preferred amount of fluctuation.

The synthesized flute tone with a low degree of fluctuation was f13a13. This tone differs from the synthesized flute tone with no fluctuations, which was the one most preferred in Ando and Shima's experiment [1], in that it contains low-frequency fluctuations (below 13Hz) and vibrato. This difference may be the source of the disagreement seen here between the preferences reported in the present study and the previous study.

The Nature Of The Fluctuations And Spectra Of Synthesized Tones

There were two pairs of stimuli that had nearly equal average noise levels (Fig. 8) but produced noticeably different results for preference (Fig. 7). The first pair was fwa13 and orig, which had average noise levels that differed by only 0.1dB. The other pair was f13aw and fwaw, which had average noise levels that differed by 1.0dB. Six subjects showed significant differences in preference for both pairs ($p < 0.05$).

The noise components with frequencies outside of the 200Hz bandwidth centered around the harmonic frequencies were considered to be the side band components generated by the amplitude fluctuations (above 100Hz) and the frequency fluctuations (excluding the vibrato components) of the harmonics. Although the energy levels of these noise components were nearly the same for all the stimuli in this study, the nature of the fluctuations which generated them differed, as follows: only amplitude fluctuation (f13aw), both amplitude and frequency fluctuations (fwaw, orig), only frequency fluctuation (fwa13). These differences may affect the quality of timbre, regardless of whether the side band components that are generated by the fluctuations have equal levels of power.

CONCLUSION

We studied the relationship between amplitude and frequency fluctuations of harmonics and the perceived quality of flute tones with vibrato. To investigate the effects of minute and irregular fluctuations on timbre, a real flute tone and synthesized flute tones whose relative amplitude levels of harmonics and extent of vibrato were equal to those of the real tone, were used for the subjective experiments. Listener's preference for flute tones was found to be affected by the degree of intensification or attenuation of the frequency and amplitude fluctuations above 13Hz.

ACKNOWLEDGEMENTS

We would like to thank Prof. Iwasaki for recording flute sounds and taking part in the listening experiment.

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