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Perception of longitudinal components in piano string vibrations

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Abstract: This paper investigates the audibility of longitudinal components in piano string vibrations with listening tests. The recorded fortissimo sounds of two grand and one upright pianos have been resynthesized with and without longitudinal components and used in ABX type listening tests. Results suggest that the longitudinal components are audible up to note C_5. However, a second test seeking the importance of the difference shows that the effect of longitudinal components for the range A_3-C_5 is subtle. This means that modeling the phenomenon up to around note A_3 only is acceptable for sound synthesis applications.

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1. Introduction

This paper investigates the perception of longitudinal vibrations in piano strings. In particular, the range of the keyboard in which the longitudinal components are audible are of interest and, if audible, the importance the listeners place on the difference between the tones with and without longitudinal components.

The importance of the longitudinal vibration of piano strings was recognized long ago by piano builders. Conklin[1] demonstrated that the pitch relation of the transverse and longitudinal modes strongly influences the quality of the tone. In addition to the longitudinal modes of the string, Nakamura and Naganuma[2] found a second series of partials in piano sound that later was named "phantom partials" by Conklin. Conklin[3] pointed out that phantom partials are generated by nonlinear mixing and their frequencies are the sum or difference of transverse modal frequencies.

Bank and Sujbert[4] have demonstrated that phantom partials are also generated by the longitudinal motion of the string as a response to the tension variation coming from the transverse string motion. Accordingly, "longitudinal components" refer to both longitudinal modes and phantom partials throughout the paper, and this study seeks the audibility limits of the longitudinal modes and phantom partials together. For a detailed theoretical explanation the reader is referred to the above work[4] or to that of Watzky,[5] who has investigated the longitudinal vibration of strings independently.

While the theory of longitudinal components in piano string vibrations is relatively well understood, little is known of the range of the keyboard in which the effect is audible. This forms the topic of the present paper. First, an ABX listening test[6] was conducted using sound samples with and without longitudinal components, called the "audibility test" later. Then, a second, "preference" test followed, addressing the question in which pitch region the difference is substantial enough to be included in sound synthesis applications.

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2. Preparation of test samples

For both listening tests, pairs of piano samples with and without longitudinal components were generated by processing recorded piano tones. The tones were played at fortissimo levels, since the longitudinal components are more prominent at higher vibration amplitudes due to their nonlinear generation mechanism. The recorded sounds $r[n]$ are separated into three synthetic components: the transverse component $s_{\mathrm{tr}}[n]$, the longitudinal component $s_{\mathrm{ln}}[n]$, and the residual $s_{\mathrm{res}}[n]$. The residual contains the attack transient and the low frequency "knock" of the soundboard. The steps of the analysis–resynthesis procedure are outlined in the following.

(1) Approximate frequencies: The approximate frequencies for the transverse components $f_{\mathrm{tr},k}$ and for the longitudinal components $f_{\mathrm{ln},k}$ are picked semi-automatically from the spectrum of the recorded tones.

(2) Resynthesis of transverse components: Based on the approximate partial frequencies $f_{\mathrm{tr},k}$, the poles of the transverse partial groups are estimated with FZ-ARMA modeling.[7] Using these poles, a parallel set of second-order filters[8] is fitted to the recorded sound, corresponding to modeling the transverse partial groups as a sum of exponentially decaying sinusoids. Finally, the transverse component $s_{\mathrm{tr}}[n]$ is obtained as the impulse response of the parallel second-order filter.

(3) Resynthesis of longitudinal components: For obtaining the longitudinal components, first the resynthesized transverse components are subtracted from the recorded sound $r[n]-s_{\mathrm{tr}}[n]$. Then the same analysis–synthesis scheme is applied as for the transverse components described in (2), using the estimated frequencies of longitudinal components, $f_{\mathrm{ln},k}$. This results in $s_{\mathrm{ln}}[n]$.

(4) Processing of the residual signal: By subtracting both the transverse and longitudinal components from the recorded sound, the residual $s_{\mathrm{res}}[n]=r[n]-s_{\mathrm{tr}}[n]-s_{\mathrm{ln}}[n]$ is obtained containing the attack transient, the low frequency "knock" of the soundboard, and some error components arising from the fact that the transverse and longitudinal components cannot be resynthesized perfectly. In order to avoid the leakage of longitudinal components into the residual, the residual is windowed to 1000 samples above a particular cut-off frequency f_c (four times that of the transverse fundamental), while it is left untouched below to be able to resynthesize the much longer low frequency knock or "thump" of high notes.

(5) Composition of the tone pairs with and without longitudinal components: For the test tones that contain no longitudinal components $y_{\mathrm{noln}}[n]$ the signal consists of the sum of the transverse and residual signals, while for the tones with longitudinal components $y_{\mathrm{ln}}[n]$ all the three signals are added:

$$y_{\mathrm{noln}}[n] = s_{\mathrm{tr}}[n] + s_{\mathrm{res}}[n], \quad (1)$$

$$y_{\mathrm{ln}}[n] = s_{\mathrm{tr}}[n] + s_{\mathrm{ln}}[n] + s_{\mathrm{res}}[n]. \quad (2)$$

3. Subjects and test method

The audibility test was an ABX test,[6] in which X is the unknown reference tone and A and B are the tones without and with the longitudinal components, respectively. After listening to the sounds A, B, and X the subject judges whether the tone X is the same as the tone A or B. In order to be able to concentrate on the pitch region of interest in the final test, a preliminary ABX listening test was conducted for one set of piano sounds. Based on the results of the preliminary test the keyboard region from C_3 to $F_6^{\#}$ (MIDI note numbers 48–78) was chosen for the final test with one note in each half-octave (six semitones) wide region. From the half-octave regions the sound having the largest longitudinal peaks in the spectrum was selected.

Five subjects participated in the preliminary test and two of these subjects took part also in the final test. Altogether eight subjects of age 23–35 years took part in the final test. All subjects had musical training on some musical instrument and previous experience in participating in listening tests. None of them reported a hearing defect. Subjects 5–8 have played the

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piano for 10–15 years, while subjects 1–4 had no or little experience with the instrument. One of the subjects was the author Heidi-Maria Lehtonen (denoted subject 8).

The listening tests were conducted in the listening room of the Department of Signal Processing and Acoustics at Aalto University School of Science and Technology. The tones were played to the subjects using Sennheiser HD 580 headphones. A user interface for playing the sounds was coded with Matlab. Before the test the subjects did a rehearsal test during which they were allowed to familiarize themselves with the user interface, the test tones, and set the volume to a comfortable level. The subjects were allowed to listen to the sounds as many times as they wanted.

The audibility test was divided into three similar parts, but the three parts used tones from different pianos (a Steinway grand, a Yamaha upright, and a Yamaha grand). In each part, six different tones with and without longitudinal components were presented to the subjects. Each tone was judged 16 times and the order of the tones was randomized. The first two parts (Steinway grand and Yamaha upright tones) were completed in one test session and the third part (Yamaha grand tones) was completed in another session on a different day.

In addition to the third part of the ABX audibility test, the subjects took another test during the second session. In this preference test, the subjects were asked whether they find the differences between the tones with and without the longitudinal components substantial enough to be taken into account in a piano synthesizer. This was a "yes" or "no" type of question with a forced answer, that is, there was no "I don't know" option. This test consisted of three parts, and in each part eight tone pairs from one of the three instruments were presented to the subjects. Six of the tone pairs were the same as in the ABX test and two additional tone pairs were tones from the C_1-C_2 range. Note that these very low tones were omitted from the ABX audibility test because all subjects were able to discriminate between the tones with and without the longitudinal components in this pitch range during the preliminary test.

4. Results of the audibility test

The results of the audibility test are displayed in the subtables of Table 1. The first row of each subtable displays the MIDI note number (and note name) of the sound and the cells show in how many percent of the 16 trials the subjects were able to correctly identify whether the tone was with or without longitudinal components. The values with 75% and above (12 or more correct answers of 16 trials) are highlighted, since at this level the authors assume that the listener was able to hear the difference between tones. This limit is customary in 16–trial listening tests[6] and is based on the fact that if the listener is guessing he/she will produce 12 or more correct answers in less than 5% (actually, in 3.84%) of the time.

Note that below 75% no conclusion can be drawn on the audibility of the difference, since in theory it may happen that the listener was able to hear the difference in some of the cases and unable to in others. All what can be said is that the difference is so subtle that the listener cannot hear it for most of the trials. Therefore, it is more precise to say that for less than 75% of correct answers the difference is considered insignificant.

The last row of the subtables shows how many listeners of the eight had more than 75% correct answers, and this is also visualized in Fig. 1(a). The three pianos provide similar results; for all the instruments more than half of the listeners can hear a difference up to note number 60 (note C_4) and then again around note number 72 (note C_5). The reason for the drop in audibility for the notes in between is yet unclear and is left for future research. What can be said in general is that the difference is audible up to note number 72 (note C_5, fundamental frequency $f_0 = 523.3$ Hz), in contrast to the general belief that longitudinal components are audible in the low range of the piano only.

5. Results of the preference test

The results of the preference test are presented in Table 2, in a similar form as for the audibility test. Number "1" indicates that the listener would prefer including the longitudinal components in a piano synthesizer. The one in parentheses "(1)" indicates that the preference is questionable since the listener was not able to hear a significant difference in the audibility test for that tone

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Table 1. Results of the audibility test for the (a) Steinway grand, (b) Yamaha upright, and (c) Yamaha grand pianos. The first row of each table gives the MIDI note numbers and note names of the test tones and the cells show the percentage of correct answers for that particular tone and listener. The last rows show the number of listeners with ≥75% correct answer for each tone.

(a) Steinway grand piano

Subject \ Note	50 (D_3)	57 (A_3)	61 ($C_4^\#$)	69 (A_4)	73 ($C_5^\#$)	78 ($F_5^\#$)
1	**81.25**	**87.5**	56.25	**81.25**	62.5	50
2	62.5	**75**	62.5	43.75	50	25
3	**93.75**	62.5	56.25	37.5	**75**	37.5
4	68.75	**87.5**	43.75	62.5	**100**	68.75
5	**100**	**100**	**75**	**100**	**100**	68.75
6	**81.25**	**100**	68.75	62.5	56.25	56.25
7	**87.5**	**81.25**	56.25	43.75	**100**	50
8	**100**	**93.75**	**81.25**	**87.5**	**93.75**	56.25
Listeners	6	7	2	3	5	0

(b) Yamaha upright piano

Subject \ Note	50 (D_3)	59 (B_3)	62 (D_4)	67 (G_4)	72 (C_5)	78 ($F_5^\#$)
1	62.5	50	**87.5**	56.25	56.25	62.5
2	50	62.5	68.75	56.25	**75**	43.75
3	50	37.5	37.5	25	**81.25**	56.25
4	**100**	**75**	56.25	62.5	56.25	68.75
5	**100**	**100**	43.75	**81.25**	**100**	68.75
6	68.75	**75**	37.5	62.5	**81.25**	43.75
7	68.75	**100**	43.75	56.25	**100**	43.75
8	**100**	62.5	50	50	62.5	50
Listeners	3	4	1	1	5	0

(c) Yamaha grand piano

Subject \ Note	48 (C_3)	55 (G_3)	60 (C_4)	68 ($G_4^\#$)	72 (C_5)	78 ($F_5^\#$)
1	**81.25**	**100**	50	68.75	**75**	62.5
2	68.75	**75**	62.5	43.75	56.25	43.75
3	68.75	31.25	50	43.75	50	50
4	**100**	**87.5**	50	68.75	**87.5**	56.25
5	**100**	**100**	**87.5**	**93.75**	**81.25**	37.5
6	**100**	**100**	56.25	62.5	**75**	43.75
7	**87.5**	**100**	43.75	**75**	**100**	37.5
8	**100**	**100**	**81.25**	**81.25**	25	**75**
Listeners	6	7	2	3	5	1

(less than 75% percent correct answers). The last row of the tables show how many of the eight listeners consider that the difference is significant, with the "(1)"s excluded. This is visualized in Fig. 1(b). The results indicate that it is essential to include longitudinal components for the lowest notes (C_1-C_2 range with note numbers 20–40), while around half of the listeners (and most of the pianists Subj. 5–8) also feel that the longitudinal components are important for the notes around note number 48 (C_3) for the two grand pianos. This trend starts to drop at around note number 57 (A_3), and for the note numbers around 60 (C_4 range) the difference is consid-

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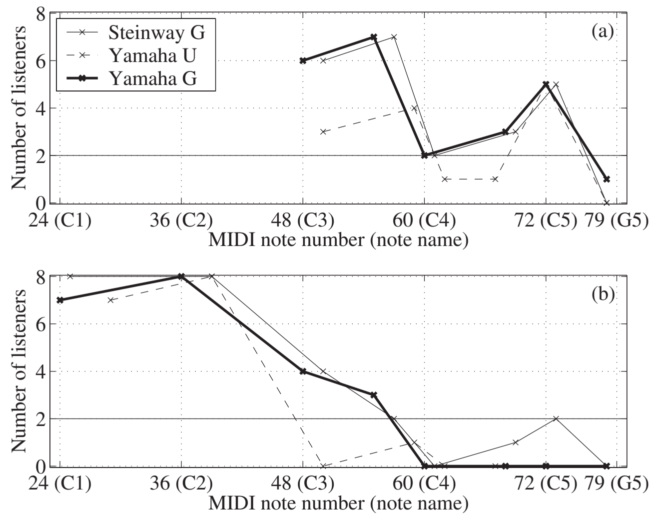

Fig. 1. Results of the (a) audibility and (b) preference tests for the Steinway grand (solid line), Yamaha upright (dashed line), and Yamaha grand (thick solid line) pianos. For the audibility test (a), the number of listeners having ≥75% correct answers is shown, while for the preference test (b) the number of listeners indicating a significant difference between the tones is shown. The horizontal lines display the threshold of audibility/significant difference, which was chosen to be 25% (the effect is considered audible in (a) or significant in (b) if more than one fourth of the listeners give a positive answer).

ered unimportant by the listeners. If the phenomenon is considered important when more than 25% of listeners think so [threshold displayed by a horizontal line in Fig. 1(b)], the longitudinal components should be implemented up to around MIDI note number 57 (note $A_3, f_0=220$ Hz) in piano synthesizers.

6. Listeners' opinion

Besides the tests, the listeners were interviewed about their musical background, previous experience in listening tests, how hard the test was, and, most importantly, how they describe the difference between the tones with and without longitudinal components. The test was easier for low tones and quite hard for the high ones, as the test results also suggest. The tones with longitudinal components are considered more realistic by all listeners and the ones without are often described as more synthetic. According to the subjects, the tones with longitudinal components sound "broader," are more lively, and have a more powerful attack, especially in the low range. Some subjects also indicated that the beginning of the tones with the longitudinal components is "out of tune," harsher, or sound distorted, and the tones without longitudinal components are softer, duller, and even boring. Subjects reported that the difference is subtle for the high notes, in agreement with the results of the tests.

7. Conclusion

This paper has investigated the audibility of longitudinal components in fortissimo piano tones. First, an analysis-synthesis scheme has been developed that allows the resynthesis of recorded piano tones with and without longitudinal components. Test tones were generated for three pianos in the range of $C_3-F_6^{\#}$ with a half-octave resolution. The test tones were used in an ABX type of listening test with 8 listeners and 16 trials for each listener. The results of the audibility test show that the longitudinal components can be heard up to note C_5 ($f_0=523.3$ Hz) by more than half of the listeners. However, a second test asking the importance of these components has revealed that the sonic effect in the middle range of the keyboard is subtle. Thus, for sound synthesis applications, it is suggested that the phenomenon is modeled up to around note A_3 ($f_0=220$ Hz) only.

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Table 2. Results of the preference test for the (a) Steinway grand, (b) Yamaha upright, and (c) Yamaha grand pianos. The first row of each table shows the MIDI note numbers and note names of the test tones, and "1" in the cells means the listener feels that the difference for that tone is significant. The one in parenthesis "(1)" indicates that the preference is questionable since the listener had less than 75% percent correct answers in the audibility test for that tone. The last rows show the number of "1" answers for each tone.

(a) Steinway grand piano

Subject \ Note	25 ($C_1^{\#}$)	39 ($D_2^{\#}$)	50 (D_3)	57 (A_3)	61 ($C_4^{\#}$)	69 (A_4)	73 ($C_5^{\#}$)	78 ($F_5^{\#}$)
1	**1**	**1**	**1**	0	0	0	0	0
2	**1**	**1**	0	0	0	0	0	0
3	**1**	**1**	**1**	0	0	0	0	0
4	**1**	**1**	0	0	0	(1)	**1**	0
5	**1**	**1**	0	0	0	**1**	0	0
6	**1**	**1**	**1**	**1**	0	(1)	0	0
7	**1**	**1**	**1**	0	0	0	**1**	0
8	**1**	**1**	0	**1**	0	0	0	0
Listeners	8	8	4	2	0	1	2	0

(b) Yamaha upright piano

Subject \ Note	29 (F_1)	39 ($D_2^{\#}$)	50 (D_3)	59 (B_3)	62 (D_4)	67 (G_4)	72 (C_5)	78 ($F_5^{\#}$)
1	**1**	**1**	(1)	0	0	0	0	0
2	**1**	**1**	0	0	0	0	0	0
3	0	**1**	0	0	0	0	0	0
4	**1**	**1**	0	0	0	0	0	0
5	**1**	**1**	0	0	0	0	0	0
6	**1**	**1**	0	0	(1)	0	0	0
7	**1**	**1**	(1)	**1**	0	0	0	0
8	**1**	**1**	0	0	0	0	0	0
Listeners	7	8	0	1	0	0	0	0

(c) Yamaha grand piano

Subject \ Note	24 (C_1)	36 (C_2)	48 (C_3)	55 (G_3)	60 (C_4)	68 ($G_4^{\#}$)	72 (C_5)	78 ($F_5^{\#}$)
1	**1**	**1**	0	**1**	0	0	0	0
2	**1**	**1**	(1)	0	0	0	0	0
3	0	**1**	0	0	0	0	0	0
4	**1**	**1**	**1**	0	0	0	0	0
5	**1**	**1**	**1**	0	0	0	0	0
6	**1**	**1**	**1**	**1**	0	0	0	0
7	**1**	**1**	0	0	0	0	0	(1)
8	**1**	**1**	**1**	**1**	0	0	0	0
Listeners	7	8	4	3	0	0	0	0

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