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Analysis of the part-pedaling effect in the piano

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Abstract: This letter reports basic acoustic phenomena related to part-pedaling in the piano. With part-pedaling, the piano tone can be divided into three distinct time intervals: initial free vibration, damper-string interaction, and final free vibration. Varying the distance of the damper from the string, the acoustic signal and the damper acceleration were measured for several piano tones. During the damper-string interaction, the piano tone decay is rapid and the timbre of the tone is affected by the nonlinear amplitude limitation of the string motion. During the final free decay, the string continues to vibrate freely with a lower decay rate.

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1. Introduction

The sustain pedal is generally recognized as an essential part of the piano, and it is used to create different artistic expressions in piano performances.[1] Professional pianists apply different pedaling techniques, such as part-pedaling, vibration pedal, and pulsation pedal instead of just depressing and releasing the pedal.[1] Especially part-pedaling is used very often. Part-pedaling in this context means a common use of the sustain pedal where the pedal is not fully depressed, but pressed somewhere between the two extremes. In this letter, the effect of part-pedaling on piano tones is studied through recordings and signal analysis. Interesting questions are how the decay characteristics of the tones vary as a function of the depth of the sustain pedal and how the interaction between the damper and the string affects the sound. Earlier studies[2,3] concentrated on the differences in the two extreme positions: the sustain pedal is not used and it is fully depressed.

Physically informed sound synthesis of musical instruments has gained popularity during the past decades.[4] In order to produce an authentic piano sound with this technique, the underlying acoustical principles of the instrument need to be known. Although the acoustics of the piano are well documented in the literature (see, e.g., the introduction of Ref. 5), the effect of the pedals, and especially the use of different pedaling techniques, has been studied less. Algorithms for producing the full sustain-pedal effect in physics-based piano synthesizers have already been presented.[2,6,7] The fundamental goal of the present study was to obtain information to support the development of a sustain-pedal algorithm for a physics-based piano synthesizer.

Figure 1(b) illustrates how part-pedaling affects the sound waveform of the tone G3. Compared to the tone played without the sustain pedal [Fig. 1(a)], one notices that the decay includes a prolonged, soft tail after the key release, lasting for several seconds. This indicates

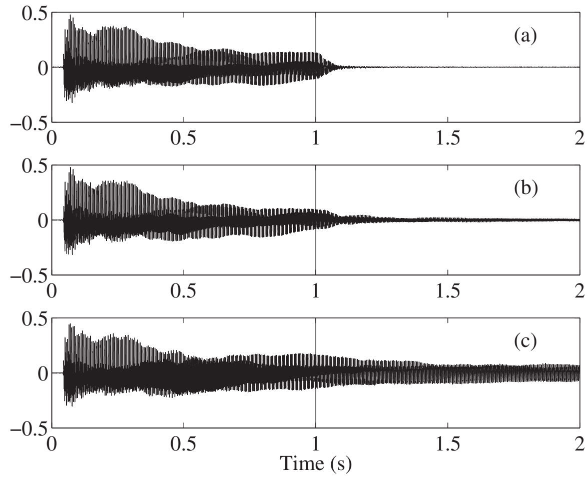

Fig. 1. Sound waveforms of the piano tone G3 (f_0=196.4 Hz) played (a) without the sustain pedal, (b) with part-pedaling, and (c) with full sustain pedal. The curves are aligned at key release (vertical lines), defined as the time instant when the key reached the upper position.

that the damper does not fully attenuate the vibrating string when the key is released. The vertical lines at 1.0 s show the time instant when the key has been fully released. In all three cases the key was released fast by suddenly removing the finger from the key. The example tones are available for listening at the companion web page of this article.[8]

2. Recordings and measurement setup

Six *mezzo forte* tones (C1, A1, G2, G3, D4, and A4) of a Steinway & Sons grand piano (model C, 224 cm) in concert condition were recorded in a rehearsal studio. The tones were selected so that all four damper shapes used in the instrument were represented: C1 was a one-string low bass tone with a ∧ profile damper; A1 was a double-string bass tone with a ∨ profile damper; G2 and G3 were string triplets with double wedges; D4 was a string triplet with a double wedge on the half toward the agraffe and flat cushion toward the bridge; and A4 was a plain string triplet with a flat cushion. The tones were recorded with a Brüel & Kjær model 4003 omnidirectional condenser microphone (powered by a B&K 2812 power supply) positioned about 30 cm above the strings. In order to be able to synchronize the audio signal to the different phases of damper movement, a miniature accelerometer (B&K 4374, mass 0.7 g) was attached on top of the corresponding damper. The tones were played manually. The position of the dampers (height above the strings) was controlled through adjustment of the sustain-pedal rod nut instead of by pressing the sustain pedal with the foot.

Two types of recordings were carried out, both with accurate control of the damper position. First, only the dampers of the selected tones were regulated so that they did not touch the strings when the sustain pedal was not pressed down. This was done by adjusting the position of the damper wire in the damper block. The distance between the selected dampers and the corresponding string groups were then altered in steps by turning the adjustment nut on the sustain-pedal rod. In this way it was possible to control the damper position of the selected notes, while the rest of the strings remained fully damped. Starting from full damping, the distance between the dampers and the strings was increased in steps of 60° until the condition that was considered to correspond to a full sustain pedal was reached. This occurred after about two and three full turns in the treble and bass range, respectively. Each case was repeated three times. In the second recording session the damper regulation was returned to normal, i.e., the turning of the sustain-pedal rod nut made all dampers rise by the same amount. Compared to the previous case, this condition was closer to the normal use of the sustain pedal.

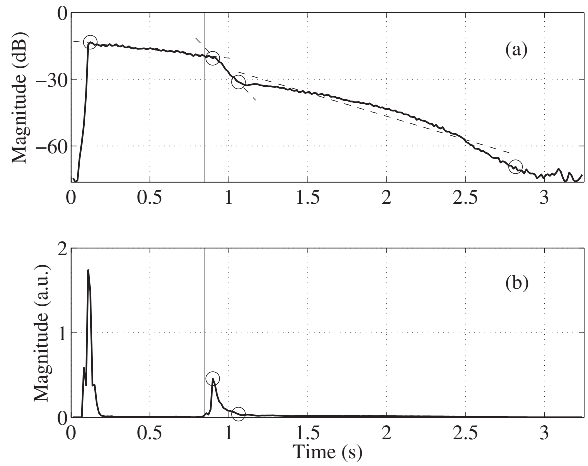

Fig. 2. (a) Log envelope of the microphone signal of the piano tone G3 using part-pedaling (solid line). The damper height adjustment was roughly 0.5 mm above full damping position. The dashed lines, indicating the decay times during initial free vibration, the damper-string interaction, and the final free vibration, were obtained by linear regression. The circles show the start and end points for the interval at which the lines have been fitted. The vertical line shows the approximate time instant when the key was released, determined from the shape of the magnitude of the damper acceleration signal. (b) The magnitude of the corresponding damper acceleration signal. The start and end points for the second time interval have been indicated with circles (see text).

The actual height of the damper was checked with a dial gauge, rigidly mounted on the metal plate inside the piano. In order to minimize the pressing force on the damper during measurements, a piece of copper foil was glued on top of the damper. Measurements were made by observing the electrical contact as the tip of the dial gauge touched the damper. It was found that one full turn corresponded to a 0.45 mm change in damper height. The adjustment step size of 60° corresponded to 0.08 ± 0.01 mm.

3. Analysis of decay characteristics

Decay characteristics were obtained from analysis of tones included in the first recording session, where all but the selected notes were fully damped in order to minimize the amplitude beating caused by sympathetic coupling to other strings. This choice leads to clearer results and reveals adequate information about how the interaction between the damper and the string group affects the decay process for different positions of the damper (corresponding to sustain-pedal depth in normal playing). Following the standard notation, decay time is defined here as the time that it takes for a tone to decay 60 dB.

When part-pedaling is used, the decay process can be divided into three time intervals. This is illustrated for tone G3 in Fig. 2, where panel (a) shows the log envelope of the microphone signal and panel (b) the corresponding envelope of the signal from the accelerometer that was attached to the top of the damper. The vertical line shows the time instant when the key is released, approximated from the shape of the magnitude of the damper acceleration signal. In this case, the damper height adjustment was approximately in the middle of the part-pedaling range, roughly corresponding to 0.5 mm above full damping position.

The first time interval, which is called the initial free vibration, is measured from the maximum of the sound signal log envelope to the second local maximum of the damper acceleration signal, which indicates when the damper stops its downward motion. The second time interval, during which an efficient damper-string interaction takes place, spans from the second local maximum of the damper acceleration signal to the point where the level of the acceleration signal has dropped 90% of the maximum. This level has been determined experimentally from the recorded data by comparing the shapes of the sound signal log envelopes and the magnitude of the damper acceleration signal. For the analyzed tones, this level corresponded well with the end of the second interval in the log envelope of the sound signal. The third time interval, the

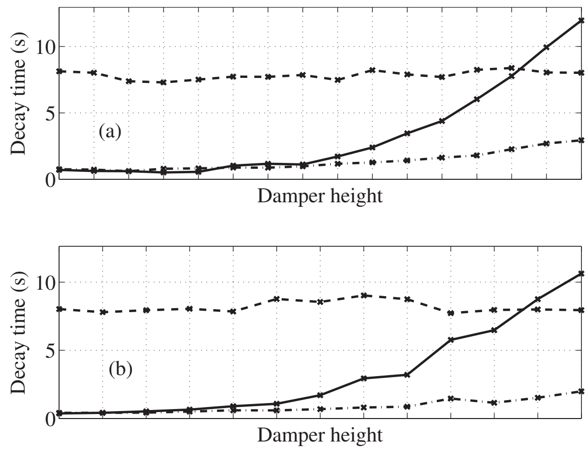

Fig. 3. Decay rates of the three time intervals of the decay (see text) as a function of the damper height adjustment for two piano tones (a) G2 (f_0=98.12 Hz) and (b) G3 (f_0=196.4 Hz): initial free vibration (dashed line), damper-string interaction (dash-dotted line), and final free vibration (solid line). Each adjustment step (grid line) corresponds to 0.08 mm.

final free vibration, is measured from the point where the previous interval ends and the free decay starts. This time interval ends when the log envelope of the microphone signal reaches a level which is 6 dB above the noise floor. The noise floor was measured using the nonlinear least-squares method proposed by Karjalainen *et al.*[9] The three phases of decay could be identified also in part-pedaling tones in the second set of recorded data where all dampers were lifted as the pedal was depressed. Only when the depth of the sustain pedal approaches full pedaling the clear structure of separate phases is lost, in agreement with observations in a previous work.[2]

The decay times for each of the three time intervals were measured using linear regression between the corresponding start and end points. Figure 3 shows the result of the decay time analysis for tones G2 and G3 as a function of damper height adjustment, each step (0.08 mm) indicated by the gridlines and data points. The decay times are averages across three repeated recordings. The three time intervals, the initial free vibration, the damper-string interaction, and the final free vibration are indicated with dashed, dash-dotted, and solid lines, respectively. The part-pedaling effect is seen to set in where the curves for the damper-string interaction and final free vibration start to separate.

As would be expected, the decay time of the initial free vibration remains uninfluenced by the damper adjustments as the damper is lifted to its upper position by the key during this interval. The decay time of the second interval, during which the damper and the string are in efficient contact and rapid damping takes place, increases slightly as a function of the distance between the damper and the string. This is also an expected result.

In addition, it can be seen that the decay time of the final free vibration increases as the distance between the damper and the string increases. A similar result was found also by Brauss.[1] This is expected, since the damper suppresses mainly the vertical polarization of vibration. After the interaction the string continues to vibrate mainly in the horizontal polarization, which is known to have a longer decay time than the vertical polarization.[10] The initial levels for the final free vibration increase 5–10 dB for G2 and G3, respectively, when the depth of the sustain pedal is increased from no pedal to full pedal. It is interesting to note that the typical part-pedaling effect occurs within a very limited range of damper height.

4. Analysis of the nonlinear effects of the damper-string interaction

When the key is released and part-pedaling is used, the damper hits the vibrating string causing a nonlinear limitation of the string amplitude. This is prominent especially in the bass range where the amplitude of the vibration is large. Nonlinear effects are known to transfer energy

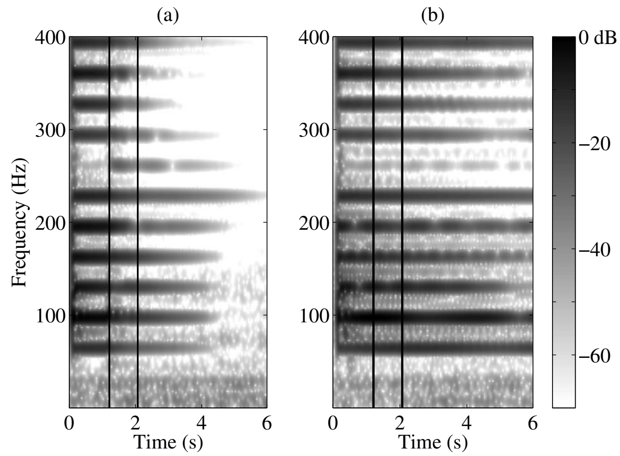

Fig. 4. Spectrograms of the tone C1 (f_0=32.54 Hz) played (a) with part-pedaling and (b) with full pedal. The vertical lines show the duration of the damper-string interaction when part-pedaling is used. The same interval is shown in (b) for reference.

from one mode to another in vibrating strings, for example, through tension modulation.[11] If the string has a nearly-missing mode, i.e., the string is excited close to a node of a string mode, this particular mode can gain energy from lower modes. In this sense, part-pedaling resembles the slapped bass effect,[12] where the frets or the fingerboard limit the amplitude of the string vibration.

This part of the analysis was performed on the second set of recorded tones with the dampers normally adjusted. The nonlinear effect caused by the damper interacting with the vibrating string was studied through spectrograms. Figures 4(a) and 4(b) show the result for the tone C1 when part-pedaling and full pedal, respectively, are used. The vertical lines indicate the duration of the damper-string interaction with part-pedaling determined from the damper acceleration signal, like in Fig. 2. The same interval is shown in Fig. 4(b) for reference. The spectrograms were computed using a Chebyshev window of length 300 ms with 250 ms overlap.

Figure 4(a) shows that the relations between the levels of the partials change during the decay when part-pedaling is used and influence the evolution of the timbre. The fundamental is very weak (not visible in the spectrogram), since it is not radiated efficiently by the soundboard. In addition, the hammer-string contact time is too short in the low bass to excite the lowest mode efficiently, and the striking position is unfavorable. Partials 2–7 are excited, but they decay fast compared to the case when the sustain pedal is fully depressed. Partial 8 is missing in Fig. 4(b) because the striking point is located at 192 mm from the agraffe, corresponding to almost exactly $L/8$, L=1573 mm being the string length. It can be seen in Fig. 4(a), however, that this missing mode gains energy when the damper-string interaction starts in the part-pedaling case. This is caused by the nonlinear limitation of the string amplitude. The tone C1 that is presented in Fig. 4 is available for listening at the companion web page of the article.[8]

For the midrange tones G2 and G3, the effect of energy transfer from lower to higher modes was not easy to observe, simply because there were no nearly-missing partials in the spectra. This is the case for many piano tones as the hammer striking position changes smoothly across the compass, and only for certain tones an efficient cancellation of some partials takes place. The timbre of the tone is still changing during the damper-string interaction, however, since some of the modes are attenuated more efficiently than others. This is explained by the damper position and length: if a particular mode has an antinode at the damper position it will die out quickly. On the other hand, if a mode has a node at the damper position and the length of the damper is short enough, the corresponding partial will keep ringing even if the adjacent partials are decaying fast. This effect can be seen in Fig. 4(a), where the seventh mode is decaying slower compared to the lower modes. The damper covers the range 192–290 mm measured from the agraffe, and the seventh mode has a node at $1573/7=225$ mm, which is close to the middle of the damper. Further, the length of the damper (98 mm) is less than a quarter of the wavelength of the partial 7 (112 mm). For the highest recorded tones D4 and A4, the described behavior was not observed since most of the partials above the partial 4 have an antinode at the damper position. In these tones the fundamental remains prominent after the damper-string interaction. For the examined mid- and high-range tones, it was also typical that the level of the tones decreased notably during the damper-string interaction.

5. Conclusions

This study presents new results on the effect of part-pedaling in the piano. When part-pedaling is used, the decay of piano tones can be divided into three distinct phases: the initial free vibration, the damper-string interaction, and the final free vibration. These three phases have different decay times. When the depth of the sustain pedal is increased from no pedal to full pedal, the decay time of the final free vibration is increased. In the bass range the nonlinear amplitude limitation causes energy transfer from the lower partials to higher partials, which can excite missing modes during the damper-string interaction.

Future work includes further investigation of the properties of the damper-string interaction. The behavior of the dampers affects the piano sound greatly, and especially for low tones the interaction with the string is a complicated process since the string vibrations cause vigorous vibrations in the damper as well.[13] Based on the present study, it can be concluded that a faithful sustain-pedal algorithm design must account for the effect of dampers in part-pedaling.

Acknowledgments

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