THE PIANO ACTION AS THE PERFORMER'S INTERFACE: TIMING PROPERTIES, DYNAMIC BEHAVIOUR AND THE PERFORMER'S POSSIBILITIES

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ABSTRACT

A concert pianist is able to produce a wide range of imaginable nuances of musical expression by actuating the 88 keys on a piano, none of which travel through a distance greater than one centimeter. In this study, we investigated the temporal behaviour of grand piano actions from different manufacturers using different types of touch ('legato' versus 'staccato'). An experimental setup consisting of accelerometers and a calibrated microphone was used to capture key and hammer movements, as well as the acoustic signal. Five selected keys were played by pianists with the two types of touch. The analysis of the three-channel data was automated by computer software. Discrete measurements (e.g., finger–key, hammer–string, and key bottom contact times, hammer velocity) were extracted for each of the over 4000 recorded tones in order to study several temporal relations. Travel times of the hammer (from finger–key to hammer–string) as a function of hammer velocity varied clearly between the two types of touch, but only slightly between pianos. A travel time versus hammer velocity function found in earlier work [1] derived from a computer-controlled piano was replicated. Key bottom contact times exhibited larger variability between types of touch and pianos. However, no effect of touch type was found in the peak sound level (in dB as a function of hammer velocity).

1. INTRODUCTION

The grand piano action is a highly elaborate and complex mechanical interface, whereby the time and the speed of the hammer hitting the strings is controlled by varying the manner and the force of striking the keys. Its temporal parameters have been studied in detail [2, 3]. However, only exemplary data was reported so far.

The present study aims to collect a large amount of measurement data from different pianos, different types of touch, and different keys, in order to determine benchmark functions for performance research. The measurement setup with accelerometers was the same as used by [4], but the data processing procedure was automated with specially developed computer software in order to obtain a large and reliable data set. With the present setup, various temporal properties (travel time, key bottom time, time of free flight) and acoustic properties (peak sound level, rise time) were determined, only a few of which can be discussed here.

In a performance study on melody lead [1], finger–key onset times were inferred from the hammer–string onset times through an approximation of the travel times of the hammer (from finger–key to hammer–string contact) as a function of hammer velocity. This travel time function was approximated from data of an internal chip of a Bösendorfer SE290 reproducing system. The present study also aims to reconsider that approximation.

2. METHOD

2.1. Material

Three grand pianos by different manufacturers were measured in this study: A **Steinway grand piano,** model C, 225 cm[1], a **Yamaha Disklavier grand piano** DC2IIXG, 173 cm[2], and a **Bösendorfer computer-controlled grand piano** SE290, 290 cm[3]. Immediately before the experiments, all three instruments were tuned, and the piano action and—in the case of the computer-controlled pianos—the reproduction unit serviced.

2.2. Equipment

The tested keys were equipped with two accelerometers: one fastened on the key[4] and one on the bottom side of the hammer shank.[5] Each of the accelerometers was connected with an amplifier[6] with a hardware integrator inside. Thus, their output was velocity in terms of voltage change. A sound level meter (Ono Sokki LA–210) placed above the strings of that particular key (approximately 10 cm distance) picked up the sound. The velocities of the key and the hammer as well as the sound were recorded on a multichannel digital audio tape (DAT) recorder (TEAC RD–200 PCM data recorder) with a sampling rate of 10 kHz (16 bit). The DAT recordings were transferred onto computer hard disk into multichannel WAV files (with a sampling frequency of 16 kHz). Further evaluation of the recorded data was done in Matlab programming environment with routines developed for this purpose (by the first author). The recording sessions were preceded by a calibration

[1] Situated at KTH-TMH in Stockholm (#516000, built in Hamburg, approx. 1992; this particular grand piano was already used in [5]).

[2] Situated at the Dept. of Psychology at Uppsala University (#5516392, built in Japan, approx. 1999; this series issued 1997 by Yamaha).

[3] Situated at the Bösendorfer Company in Vienna (#290–3, built in Vienna in 2000). The *Stahnke Electronics* (SE) system dates back to 1983 [6], but this particular grand piano was built in 2000. The same system used to be installed in an older grand piano (internal number 19–8974, built in 1986), but was put into a newer one for reasons of instrumental quality.

[4] Brüel & Kjær Accelerometer type 4393; 2.4 g; #1190913.

[5] ENDEVCO Accelerometer Model 22; 0.14 g; #20845.

[6] Brüel & Kjær Charge Amplifier Type 2635.

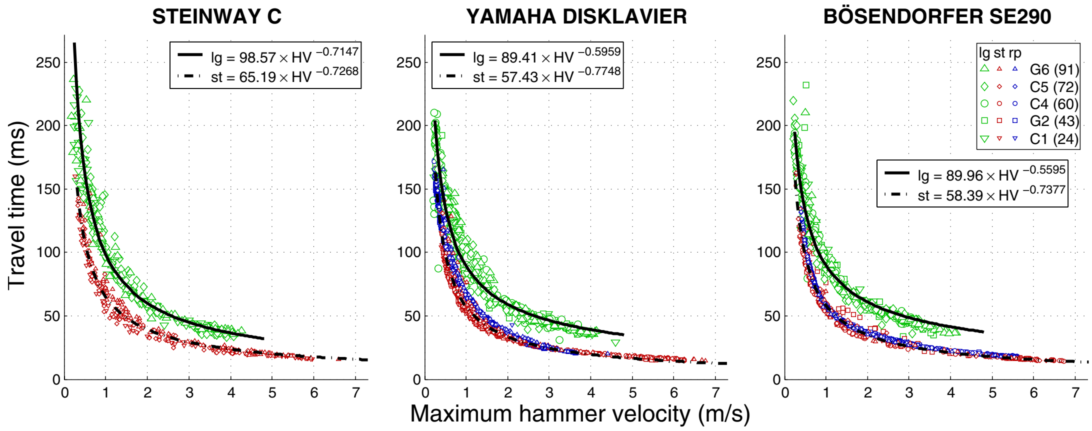

Figure 1: **Travel time** (from finger–key to hammer–string contact) against maximum hammer velocity for the three grand pianos (three panels), different types of touch (*legato*, *staccato*, and reproduction by the piano), and different keys (from C1 to G6, see legend). The two types of touch ('lg'–'st') were approximated by power functions (see legends). The travel time functions by the reproducing devices were similar to those produced by *staccato* touch.

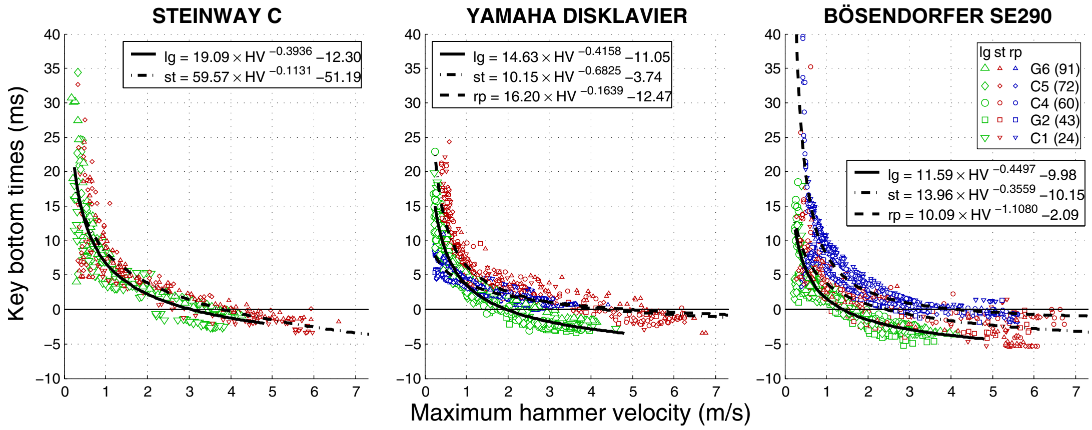

Figure 2: **Key bottom time** relative to hammer–string contact against maximum hammer velocity. Negative key bottom values denote instants *preceding*hammer–string contact. Legends list power curve fits of the data separately for legato ('lg'), staccato ('st'), and reproduction ('rp').

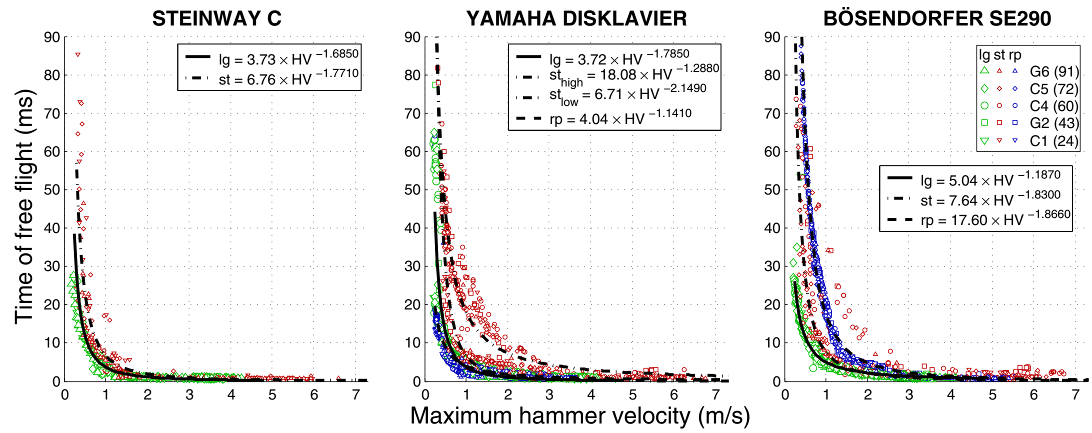

Figure 3: **Time of free flight of the hammer.** Time intervals between the point of maximum hammer velocity and hammer–string contact are plotted against maximum hammer velocity. Power functions were approximated for each type of touch ('lg', 'st', 'rp'). Two functions were fitted for the staccato data of the Yamaha.

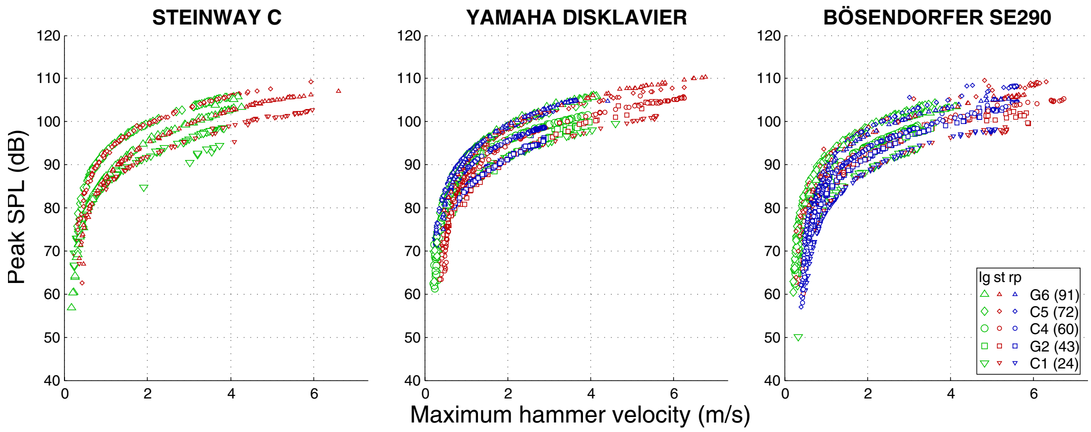

Figure 4: **Peak dB–SPL** values as a function of maximum hammer velocity for the three grand pianos (three panels), different types of touch (*legato*, *staccato*, and reproduction by the piano), and different keys.

procedure which allowed conversion from voltage changes into required units like meters per second or dB–SPL.

2.3. Procedure

Five keys distributed over the whole range of the keyboard were tested: C1 (MIDI note number 24), G2 (43), C4 (60), C5 (72), and G6 (91)[7]. The first two authors served as pianists to perform the recorded test tones. Each key was hit in as many different dynamic levels (hammer velocities) as possible, in two different kinds of touch: once with the finger resting on the surface of the key (*'legato touch'*), once hitting the key from a certain distance above (*'staccato touch'*), striking the key already with a certain speed.

Parallel to the accelerometer setting, the two reproducing pianos recorded these test tones with their internal device on computer hard disk (Bösendorfer) or floppy disk (Disklavier). For each of the five keys, each player played in each type of touch from 30 to 110 individual tones, so that a sufficient amount of data was recorded. Immediately after each recording of a particular key, the recorded file was reproduced by the grand piano, and the accelerometer data was recorded again onto the multi-channel DAT recorder. For the Steinway, 595 individual sound events were recorded, for the Yamaha Disklavier 1992, and for the Bösendorfer 1512 (including the reproduced keystrokes).

2.4. Data analysis

For each keystroke, several instants in time were defined as listed below and obtained automatically from the recorded data with the help of Matlab scripts.

The **hammer–string contact time** was defined as the moment of maximum deceleration (minimum acceleration) of the hammer shank (hammer accelerometer) which corresponded well to the physical onset of the sound, and conceptually with the 'note on' command in the MIDI file. In mathematical terms, the hammer–string contact is the minimum of the first derivative of the measured hammer velocity.

The **finger–key contact time** was defined to be the moment when the key started to move. It was obtained by a simple threshold procedure applied to the key velocity track. In mathematical terms, it was the moment when the (slightly smoothed) key acceleration exceeded a certain threshold which varied relative to the maximum hammer velocity. Finding the correct finger–key point was not difficult for *staccato* tones (they showed typically a very abrupt initial acceleration). However, automatically determining the correct moment for soft legato tones was sometimes more difficult and needed manual correction. When this procedure failed, it failed by several tens of milliseconds—an error easy to discover in explorative data plots.

The **key bottom contact time** was the instant when the downwards travel of the key was stopped by the keybed. This point was defined as the maximum deceleration of the key (MKD). In some keystrokes, the MKD was not the actual keybed contact, but a rebound of the key after the first key bottom contact. For this reason, the time window of searching MKD was restricted to 7 ms before and 50 ms after hammer–string contact. The time window was iteratively modified depending on the maximum hammer velocity until the correct instant was found. MKD as indicator was especially clear and non-ambiguous when the key was depressed in a range of medium intensity.

The **maximum hammer velocity** (in meters per second) was the maximum value in the hammer velocity track before hammer–string contact. An **intensity value** was derived by taking the maximum energy (RMS) of the audio signal immediately after hammer–string contact, using a RMS window of 10 milliseconds. It was calibrated in order to obtain dB–SPL.[8] Data were controlled and inspected for errors with the help of an interactive tool that displayed simultaneously key and hammer velocity and the sound signal for each keystroke.

3. RESULTS & DISCUSSION

Travel times are plotted against the maximum hammer velocity in Figure 1 together with power curve approximations separately for the pianos and type of touch. It can be seen that the travel time functions varied considerably between the types of touch (the difference was of the order of 20 ms in the middle range), but only marginally between pianos. The travel time function of the

[7] Only three keys were tested at the Steinway piano (C1, C5, G6).

[8] B&K Sound Level Calibrator Type 4230; test tone 94 dB, 1 kHz.

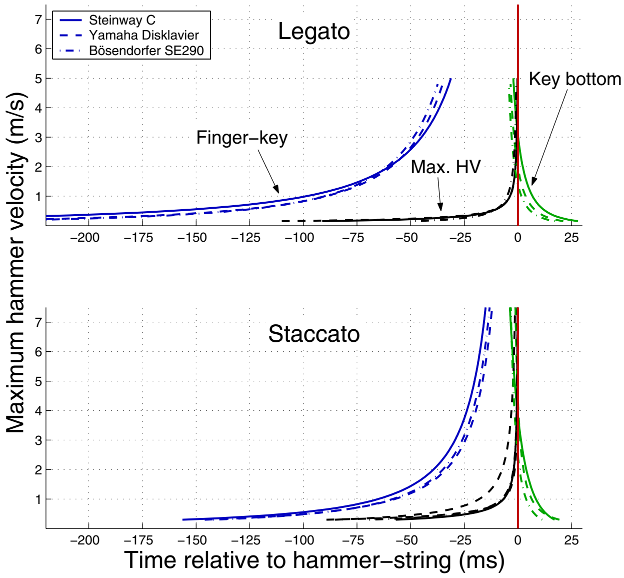

Figure 5: Temporal properties of three grand piano actions. Power curve approximations for the three pianos (line style), the two types of touch (panels), and for finger–key (left), maximum hammer velocity (max. HV, middle), and key bottom times (right).

Bösendorfer replicated the curve used in [1]. Legato keystrokes needed longer time to produce a sound than staccato keystrokes that produced equally fast attacks. Moreover, the softest notes were performed with legato touch, the loudest with staccato. Accelerating the keys in legato manner did not allow to generate hammer velocities far beyond 4 m/s.

Key bottom times are plotted relative to hammer–string contact in Figure 2 (negative values denote key bottom contact *preceding* the hammer–string contact). The data for legato, staccato, and reproduction were approximated by power functions. The data clusters were clearly distinct for the two types of touch on the Yamaha and the Bösendorfer, but almost overlapping on the Steinway.

The instant of the escapement was calculated as the maximum of the hammer velocity. This was a good estimation for strong and medium keystrokes but not for keystrokes when the escapement can occur before the hammer maximum velocity. The time interval between the escapement and the hammer hammer–string contact was calculated (Figure 3). With escapement, the pianist looses control over the tone. The point of maximum hammer velocity coincided well with the escapement point for medium and fast keystrokes, but was earlier for slow keystrokes. The time of free flight was almost zero beyond hammer velocities of 1.5 m/s for the Steinway, and beyond 3 m/s for the Yamaha and the Bösendorfer. On the Yamaha, the staccato data splits into two groups at medium intensities: maximum hammer velocity occurred at two different instants (Figure 3, middle panel).

In Figure 4, peak SPL values are plotted against maximum hammer velocity. The data formed different groups for different tones, but overlapped almost entirely between legato and staccato keystrokes. This indicates that the sound level of the tones does not depend on the way the tone was produced, but exclusively on the hammer velocity.

In Figure 5, all approximations reported above are plotted in a single display. It becomes evident that type of touch affected the shape of the curves more than the instrument.

4. CONCLUSIONS

This contribution provided benchmark data for the temporal properties of different grand pianos under two touch conditions. The temporal properties varied considerably between type of touch, only marginally between pianos, and not at all between the different tested keys. The temporal differences between a *pp* and a *ff* tone can become as large as 200 ms, between types of touch about 20–30 ms. A pianist must not only adapt to the intended dynamic level, but also to the kind of touch in order to control the precise timing of the produced tone.

Generally, a keystroke starts for the pianist kinesthetically with finger–key contact (the acceleration impulse by the finger) and ends at key bottom, but for the audience it starts with the hammer–string contact. Although these three points in time can be apart from each other as far as 200 ms, they might not be perceived as separate events. The intrinsic timing properties of a particular piano might be an important factor pianists have to get acquainted with when they 'warm up' on a yet unknown instrument.

5. ACKNOWLEDGEMENTS

This study was supported by the European Union (Marie Curie Fellowship, HPMT-GH-00-00119-02, the *Sounding Object* project (SOb), IST-2000-25287, *http://www.soundobject.org*, and the MOSART IHP network, HPRN-CT-2000-00115) and the START program from the Austrian Federal Ministry for Education, Science, and Culture (Grant No. Y99–INF) and a visiting grant from the Swedish Institute for the third author. The Austrian Research Institute for Artificial Intelligence acknowledges basic financial support from the Austrian Federal Ministry for Education, Science, and Culture.

6. REFERENCES

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