Measurement and reproduction accuracy of computer-controlled grand pianos

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The recording and reproducing capabilities of a Yamaha Disklavier grand piano and a Bösendorfer SE290 computer-controlled grand piano were tested, with the goal of examining their reliability for performance research. 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 two types of touch (''*staccato*'' and ''*legato*''). Timing and dynamic differences between the original performance, the corresponding MIDI file recorded by the computer-controlled pianos, and its reproduction were analyzed. The two devices performed quite differently with respect to timing and dynamic accuracy. The Disklavier's onset capturing was slightly more precise (±10 ms) than its reproduction (−20 to +30 ms); the Bösendorfer performed generally better, but its timing accuracy was slightly less precise for recording (−10 to 3 ms) than for reproduction (±2 ms). Both devices exhibited a systematic (linear) error in recording over time. In the dynamic dimension, the Bösendorfer showed higher consistency over the whole dynamic range, while the Disklavier performed well only in a wide middle range. Neither device was able to capture or reproduce different types of touch. © *2003 Acoustical Society of America.*
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I. INTRODUCTION

Current research in expressive music performance mainly deals with piano interpretation because obtaining expressive data from a piano performance is easier than, e.g., from string or wind instruments. Pianists are able to control only a few parameters on their instruments. These are the tone[1] onsets and offsets, the intensity (measured as the final hammer velocity), and the movements of the two pedals.[2] Computer-controlled grand pianos are a practical device to pick up and to measure these expressive parameters and—at the same time—provide a natural and familiar setting for pianists in a recording situation. Two systems are most commonly used in performance research: the Yamaha Disklavier (Behne and Wetekam, 1994; Palmer and Holleran, 1994; Repp, 1995, 1996a, b, c, 1997a; Juslin and Madison, 1999; Bresin and Battel, 2000; Timmers *et al.*, 2000; Riley-Butler, 2001, 2002), and the Bösendorfer SE system (Palmer, 1996; Bresin and Widmer, 2000; Goebl, 2001; Widmer, 2001, 2002, 2003). Some studies made use of various kinds of MIDI keyboards which do not provide a natural playing situation to a classical concert pianist because they have a different tactile and acoustic response (e.g., Palmer, 1989; Repp, 1994).

Both the Disklavier and the SE system are integrated systems (Coenen and Schäfer, 1992), which means that they are permanently built into a modern grand piano. They are based on the same underlying principle. That is, to measure and reproduce movements of the piano action, above all the final speed of the hammer before touching the strings. These devices are not designed for scientific purposes and their precise functionality is unknown or not revealed by the companies. Therefore, exploratory studies on their recording and playback precision are necessary in order to examine the validity of the collected data.

Both devices have sensors at the same places in the piano action (Fig. 1). There is a set of shutters mounted on each of the hammer shanks.[3] This shutter interrupts an infrared light beam at two points just before the hammer hits the strings: the first time approximately 5 mm before hammer–string impact, the second time when the hammer crown just starts to contact the strings. These two points in time yield an estimate of the *final hammer velocity* (FHV). In the case of the Disklavier, no further information about how this data is processed was obtainable. On the Bösendorfer, the time difference between these two trip points is called (by definition) *inverse hammer velocity* (IHV) and is stored as such in the internal file format. Since the counter of this infrared beam is operating at 25.6 kHz, the final hammer velocity (in meters per second) is: FHV=128/IHV (Stahnke, 2000; Goebl, 2001, p. 572). The timing of the trip point closer to the strings is taken as the note onset time which has a resolution of 1.25 ms. It seems that the Disklavier uses the same measuring method for hammer velocity and note onset, but as the company does not distribute any more specific details, this is only speculation. The MIDI files of the Disklavier provided

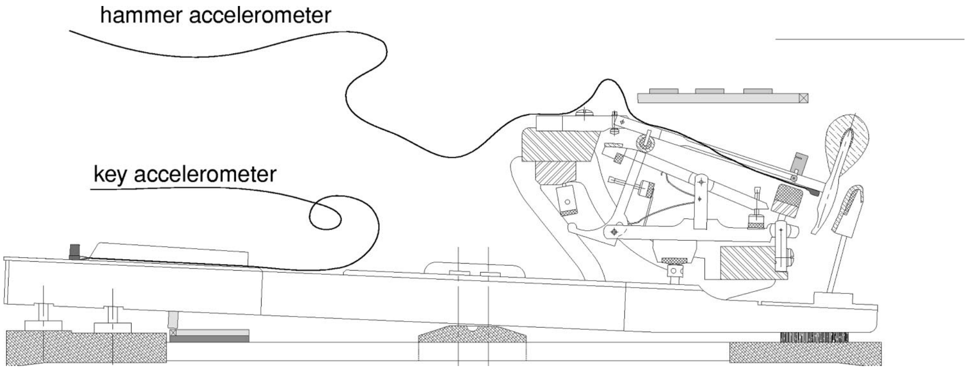

FIG. 1. A Bösendorfer grand piano action with the SE sensors sketched. Additionally, the placement of the two accelerometers are shown. (Figure generated with computer software by the authors. Piano action by Bösendorfer with permission from the company.)

384 MIDI ticks per 512 820 microseconds (as defined in the tempo command in the MIDI file), thus a theoretical timing resolution of 1.34 ms.

A second set of sensors is placed under the keys to measure when the keys are depressed and released. Again, the exact use of this information at the Disklavier cannot be reconstructed, but the Bösendorfer uses this information for releasing the keys correctly (note offsets) and to reproduce silent tones (when the hammer does not reach the strings). The Disklavier used in this study did not reproduce any silent notes at all.

The data picked up by the internal sensors are stored in the Disklavier on an internal floppy drive or externally by using the MIDI out port. The SE system is linked with a special cable plugged into an ISA card of a personal computer running MS DOS. Internal software controls the recording. The information is stored in standard MIDI format on the Disklavier, and in a special file format on the Bösendorfer (each recording comprises a set of three files with the extensions ".kb" for keyboard information, ".lp" for the loud (right) pedal, and ".sp" for the soft (left) pedal). Although the SE file data are encrypted, the content of the files can be listed with the supplied software and used for analysis.

The reproduction is carried out with linear motors (solenoids) placed under the back of each key. The cores of the coils of the Disklavier have a length of approximately 7 cm, whereas those of the SE system are at least double that length or more. Pedal measurement and reproduction is not discussed in the present study.

Only a few studies provide some systematic information about the precise functionality of these devices. Coenen and Schäfer (1992) tested five different reproduction devices (among them a Bösendorfer SE225 and a Yamaha Disklavier grand piano, DG2RE) on various parameters, but their goal was to evaluate their reliability for compositional use; their main focus was therefore on the production mechanism. They determined practical benchmark data like scale speed, note repetition, note density (maximum number of notes which can be played simultaneously), minimum and maximum length of tones, and pedal speed. In their tests, the integrated systems (Disklavier, SE) performed generally more satisfactorily than the systems which are built into an existing piano (Autoklav, Marantz pianocorder). The Bösendorfer, as the most expensive device, had the best results in most of the tasks. Bolzinger (1995) performed some preliminary tests on a Yamaha upright Disklavier (MX-100 A), but his goal was to measure the interdependencies between the pianist's kinematics, performance, and the room acoustics. With his Disklavier, he had the opportunity to play back files and to simultaneously record the movements of the piano with the same device using the MIDI out port. That way, he obtained very easily a production–reproduction matrix of MIDI velocity values, showing a linear reproducing behavior only at MIDI velocity units between approximately 30 and 85 (Bolzinger, 1995, p. 27). On the Disklavier in the present study, this parallel playback and recording was not possible. Maria (1999) developed a complex methodology to perform meticulous tests on a Disklavier (DS6 Pro), but no systematic or quantitative measurements are reported so far.

The focus of this study lies on the recording and reproducing accuracy of two computer-controlled grand pianos with respect to properties of the piano action (hammer–string contact, final hammer velocity), and properties of the sounding piano tone (peak sound-pressure level). In addition to this, we report the correspondence between physical sound properties and their representation as measured by the computer-controlled pianos (MIDI velocity units), in order to provide a benchmark for performance research (see also Palmer and Brown, 1991 and Repp, 1993).

Another issue discussed in the following is the timing behavior of the grand piano action in response to different types of touch and their reproduction by a reproducing piano. Selected keys distributed over the whole range of the keyboard were depressed by pianists with many degrees of force and with two kinds of touch: with the finger resting on the surface of the key (*legato touch*), and with an attack from a certain distance above the keys (*staccato touch*). These different kinds of touch are described in Askenfelt and Jansson (1991).

II. METHOD

A. Material

Two computer-controlled grand pianos were measured in this study.

(i) Yamaha Disklavier grand piano of the Mark II series (DC2IIXG, 173 cm, serial number: 5516392), situated at the Department of Psychology, University of Uppsala, Sweden. The Mark II XG series was issued by Yamaha in 1997 (information by Yamaha Germany, Rellingen, personal communication).

(ii) Bösendorfer computer-controlled grand piano (SE290, internal number 290-3, 290 cm), situated at the Bösendorfer company in Vienna, Austria. The *Stahnke Electronics* (SE) system dates back to 1983 (for more information on its development, see Moog and Rhea, 1990), 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, used, e.g., in Goebl, 2001), but was put into a newer one for reasons of instrumental quality.

Immediately before the experiments, both instruments were tuned, and the piano action and the reproduction unit serviced. In the case of the Disklavier, this procedure was carried out by a specially trained Yamaha piano technician. At the Bösendorfer company, the company's SE technician took care of this work.

B. Equipment

The tested keys were equipped with two accelerometers: one mounted on the key[4] and one on the bottom side of the hammer shank.[5] The accelerometer setting (see Fig. 1) is the same used in Askenfelt and Jansson (1991). 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 next to 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 and a word length of 16 bit. The DAT recordings were transferred onto computer hard disk into multichannel WAV files (with a sampling frequency of 16 kHz).[7] Further evaluation of the recorded data was done in MATLAB programming environment with routines developed for this purpose (by the first author).

C. Calibration

The recordings were preceded by calibration tests in order to be sure about the measured units. The accelerometer amplifiers output ac voltages corresponding to certain measured units (in our case, meters per second) depending on their setting, e.g., 1 V/m/s for the key accelerometer. To calibrate the connection between the TEAC DAT recorder and computer hard disk, different voltages (between -2 and $+2$ V dc) were recorded onto the TEAC recorder and in parallel measured by a volt meter. The recorded dc voltages were transferred to computer hard disk as described above. These values were compared with the values measured by the volt meter. They correlated highly ($R^2=0.9998$), with a factor slightly above 2. The sound recording was calibrated with a 1-kHz test tone produced by a sound-level calibrator.[8]

D. 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). The 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 above (''*staccato touch*''), touching the key already with a certain speed.

Parallel to the accelerometer setting, the grand pianos recorded these test tones with their internal device on computer hard disk (Bösendorfer) or floppy disk (Disklavier). For each of the five keys, both players played in both types of touch 30 to 110 individual tones with interonset time intervals of 1–3 s so that a sufficient amount of data with a large range of different hammer velocities was recorded. Visual feedback of the sound level was provided to the players by the Ono Sokki sound-level meter. Separate MIDI files (or Bösendorfer file triples) were recorded for each key, each type of touch, and for each piano and pianist (5 keys$\times$2 types of touch$\times$2 pianos$\times$2 pianists), containing 964 individual keystrokes for the Yamaha Disklavier and 697 for the Bösendorfer. Immediately after each recording of a particular key and a particular touch by one pianist, the recorded file was reproduced by the grand piano, and the accelerometer data were recorded again onto the multichannel DAT recorder.

This procedure delivered (1) information on timing and dynamics for the *original recording*; (2) the internally stored *MIDI file* of the Disklavier or its correspondent of the SE device; and (3) the precise timing and dynamics for the *reproduction* by the reproducing pianos.

In order to extract discrete data from the hammer and key velocity tracks, several signal processing decisions had to be made.

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

(2) As *hammer velocity*, the maximum hammer velocity (in meters per second) before the hammer–string contact was taken.

(3) An *intensity value* was derived by taking the maximum energy (rms) of the audio signal. The audio channel of each file was calibrated with a 1-kHz pure tone at 94 dB (Brüel & Kjær sound-level calibrator type 4230).

(4) The *MIDI note onset time*, and the *MIDI velocity number* were taken from the MIDI file or the corresponding internal file format of the Bösendorfer.

The onset differences between the original recording and the MIDI file, and those between the original recording and its reproduction were calculated.[9] Since the three measurements (original recording, MIDI file, and reproduction) were not

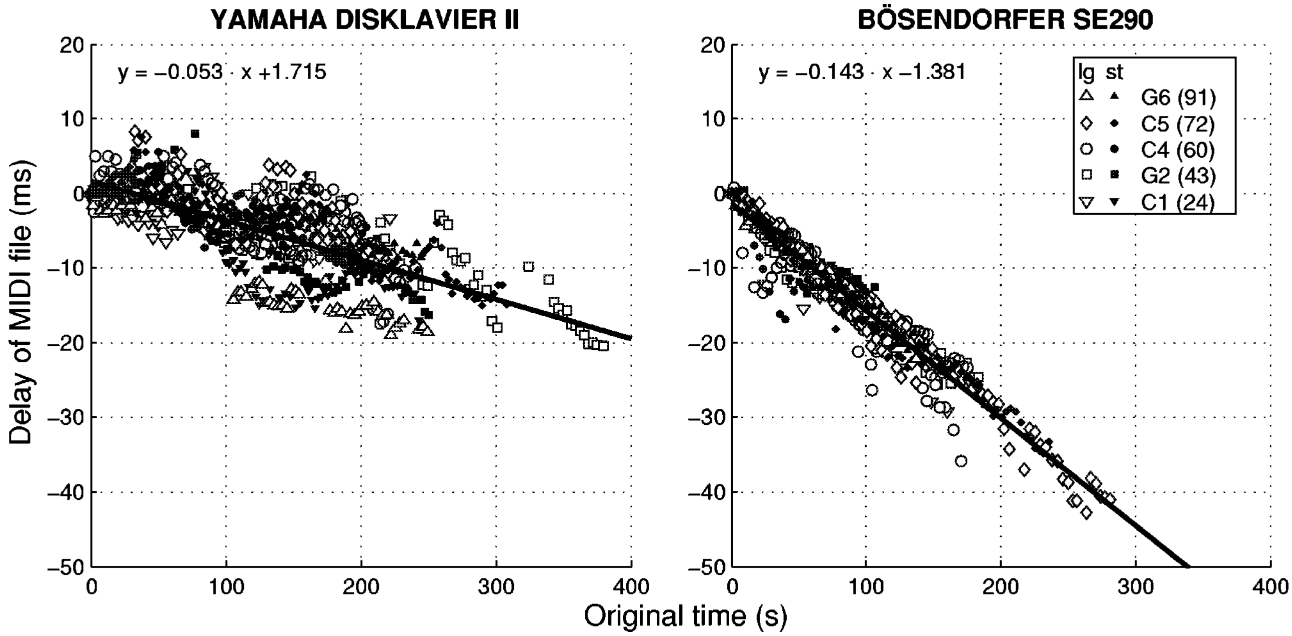

FIG. 2. Timing delays (ms) as a function of recorded time (s) between the original recording and the MIDI file as recorded by the computer-controlled grand pianos for two types of touch: legato ("lg") and staccato ("st"). Negative values indicate that an onset in the MIDI file was earlier than in the original recording. The straight lines are linear fits of the whole data.

synchronized in time by the measurement procedure, their first attacks were defined as being simultaneous. Care was taken that the first tones always were loud attacks in order to minimize synchronization error, since timing error was smaller the faster (the louder) the attack was. If there was a soft attack at the beginning of a trial, the three files were synchronized by the first occurring louder attack (with hammer velocity over 2 m/s or 77 MIDI velocity units).

III. RESULTS AND DISCUSSION

A. Timing accuracy

In Fig. 2, the note onset delays of the MIDI file in comparison to the original recording are plotted against the recorded time separately for the two pianos.[10] It is evident that both MIDI files showed a constantly decreasing delay over time.

This constant timing error in the MIDI file was larger for the SE system than the Disklavier. The origin of this systematic timing error is unknown, but it is likely that the internal counters of the systems (in the case of the SE system, it is a personal computer) did not operate in exactly the desired frequency, probably due to a rounding error.

This time drift over time was small (0.0053% or 0.014%, respectively) and negligible for performance research (tempo changes of that order are far below just-noticeable differences, cf. Friberg and Sundberg, 1995). But, when such a device has to play in time with, i.e., an audio tape, the synchronization error will already be perceivable after some minutes of performing.

To illustrate the recording accuracy without this systematic error, the residual timing error (the differences between the fitted lines and the data) is plotted in Fig. 3 separately for the two pianos against recorded MIDI velocity.[11] In an earlier conference contribution, a different normalization method was applied on the same data of the Disklavier (see Goebl and Bresin, 2001). The variance was larger for the Disklavier than the SE system (Yamaha mean: 1.4 ms, standard deviation (s.d.): 3.8 ms; Bösendorfer mean: 0.2 ms, s.d.: 2.1 ms), but for both pianos, the residual timing error bore a trend with respect to the loudness of the recorded tones. The Disklavier tended to record softer tones later than louder ones; the SE showed the opposite trend, but to a smaller extent and with much less variation (Fig. 3).

The data in Fig. 3 were approximated by polynomial curves; the formulas are printed there. The R^2 values were different for the two pianos. The Disklavier's approximation explained barely 40% of the variance, while at the SE system it was about 70%. The Disklavier's curve fit indicated a larger erroneous trend in recording—in addition to that—it possessed larger variability around that curve.

The timing delays between the original recording and its reproduction are plotted in Fig. 4 separately for the two pianos. The systematic timing error of the recording was not observed, so the display against recorded time (as in Fig. 2) was not required. Evidently, the error in recording was canceled out by the same error in reproduction. The difference between the two systems became most evident in this display. While the reproduced onsets of the Disklavier differed as much as $+20$ and -28 ms (mean: -0.3 ms, s.d.: 5.5 ms) from the actual played onset, the largest timing error of the SE system rarely exceeded ± 3 ms, with a small tendency of soft notes coming up to 5 ms too soon (mean: -0.1 ms, s.d.: 1.3 ms).

Interestingly, the recording accuracy of the SE system was lower than its reproduction accuracy. Obviously, its internal calibration function aimed successfully to absolute precise reproducing capabilities. It could also be that the SE

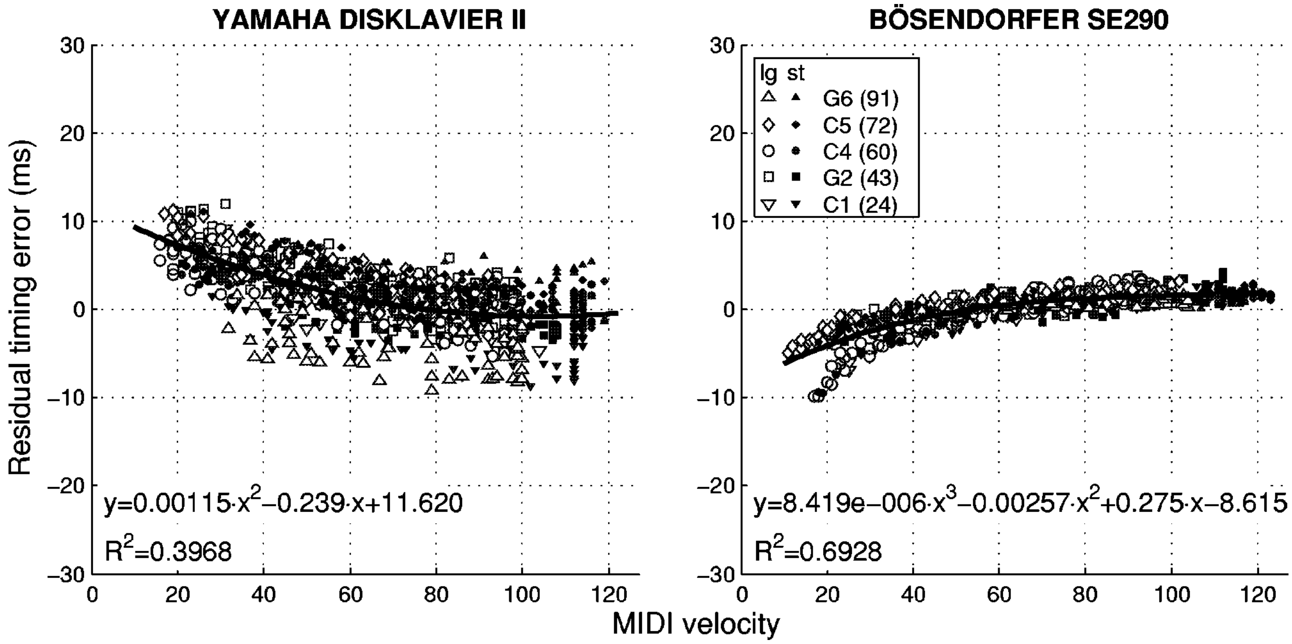

FIG. 3. The residual timing error (ms) between the MIDI file and the original recording as a function of MIDI velocity, as recorded by the computer-controlled pianos. Again, negative values indicate onsets too early in the MIDI data, in comparison to the original file. The trend lines are polynomial functions fitted to the data (as printed in the figures).

takes the first trip point (5 mm before the strings) as being the note onset, but calibrates itself correspondingly to overcome this conceptual mistake. However, this assumption was contradicted by information obtained by the SE's developer, W. Stahnke (Stahnke, 2000; Goebl, 2001).

B. Dynamic accuracy

The second of the investigated parameters is dynamics in terms of the speed of the hammer hitting the strings (m/s) or peak sound-pressure level (dB). We defined the hammer velocity to be the maximum hammer velocity (see above) since it was easy to obtain this value automatically from the recorded hammer track. Usually, this value corresponded very well with the velocity of the hammer when starting to touch the strings (final hammer velocity), but especially for soft notes the maximum hammer speed was larger than the hammer speed at the strings. In this case the time between the escapement (when the hammer loses physical connection to the key, that is, when the jack is catapulted away by the escapement dolly; for more detail see Askenfelt and Jansson, 1990 and Goebl, Bresin, and Galembo, 2003) and hammer–string contact can be as long as 100 ms or more. The actual

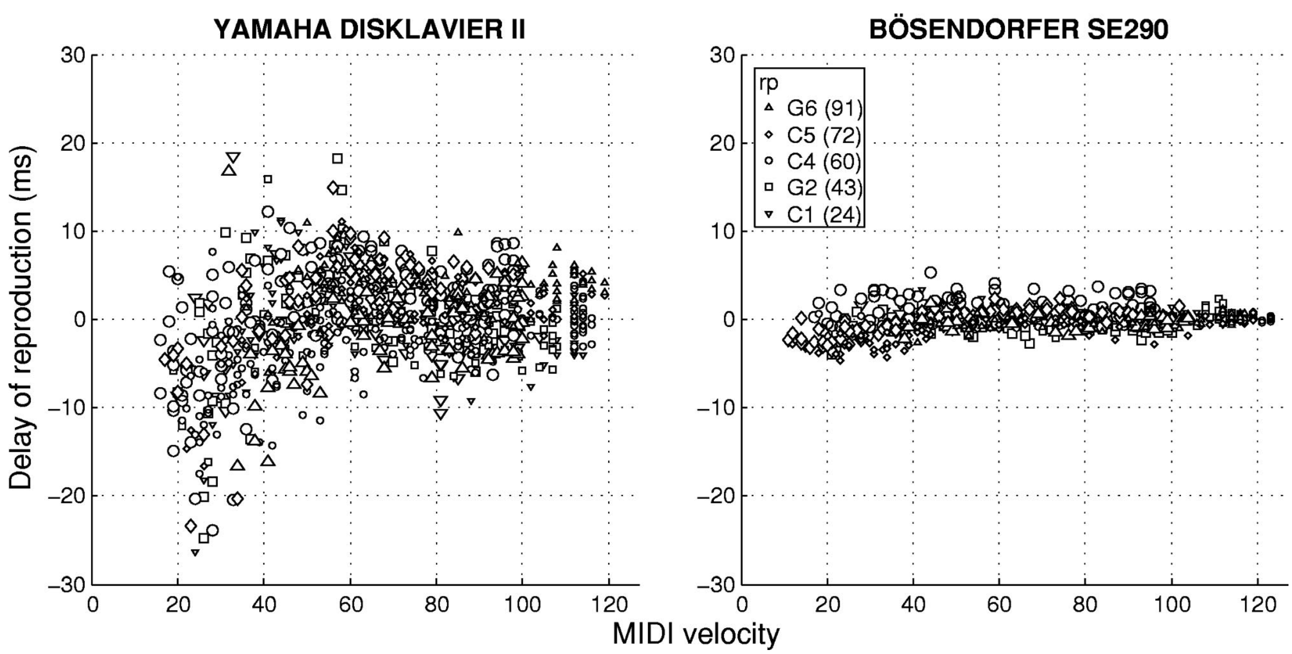

FIG. 4. Timing delays (ms) between the original and its reproduction by the computer-controlled piano. (No systematic trend had to be removed.)

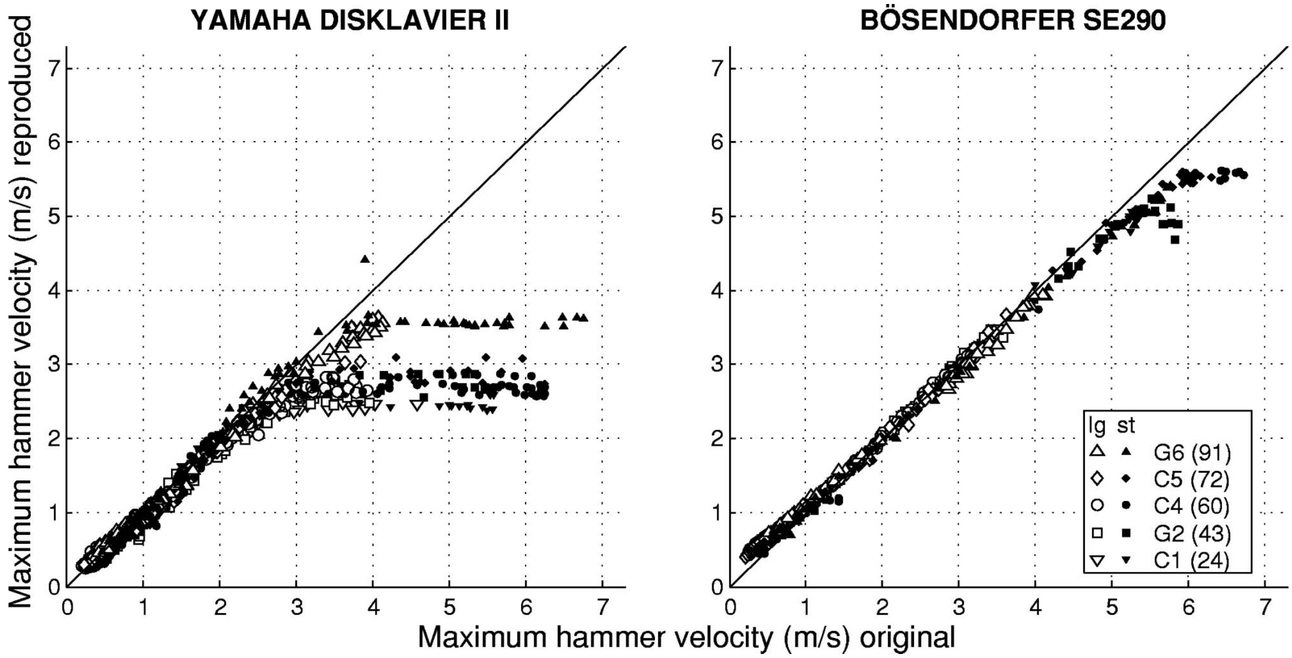

FIG. 5. The maximum hammer velocity (m/s) as played by the pianists (x axes) and reproduced by the computer-controlled pianos (y axes). (The diagonal line indicates ideal reproduction.)

final hammer velocity was hard to determine from the hammer accelerometer measurements, but the computer-controlled devices measured an average velocity of the last 5 mm of the hammer's travel to the strings (approximately the last 10% of that distance).

In Fig. 5, the reproduced maximum hammer velocity is plotted against the original maximum hammer velocity. It becomes evident that the Disklavier's solenoids were not able to reproduce above a certain hammer speed. This varied slightly between keys, e.g., the G6 (with less hammer mass than hammers at a lower pitch) could be accelerated up to 3.5 m/s, whereas a C1 (with a comparatively heavy hammer) only up to 2.4 m/s. On the SE system, this ceiling effect was not so evident, and there was no obvious effect of pitch as for the Disklavier. Especially in very loud staccato tones, the first impact of the finger hitting the key resulted in a very high-peak hammer velocity which decreases significantly until hammer–string contact. The solenoid was not able to reach this high-peak hammer velocity (and is not programed to do so), but it aimed to reproduce the measured final hammer velocity properly (see also Fig. 8). In this light, the maximum hammer velocity did not seem to be an appropriate measure. Instead, the peak sound-pressure level (dB-SPL) was taken (see Fig. 6).

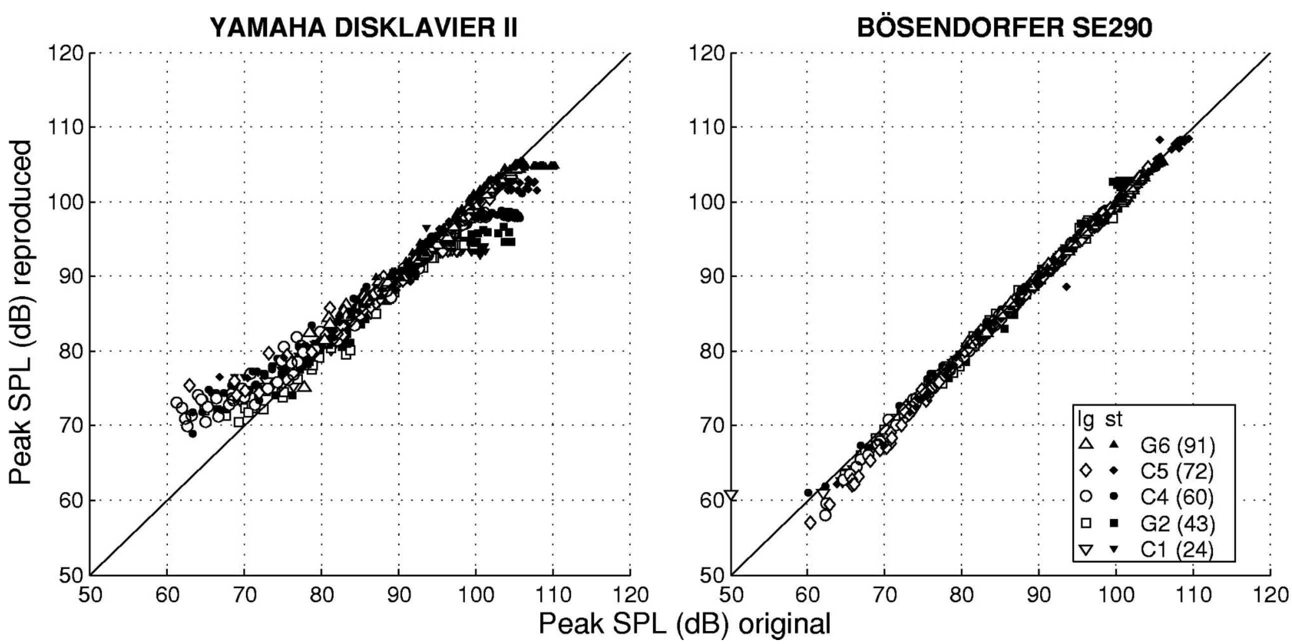

FIG. 6. Peak sound-pressure level (dB) as measured in the tones performed by the pianists (x axes) and reproduced by the computer-controlled pianos (y axes).

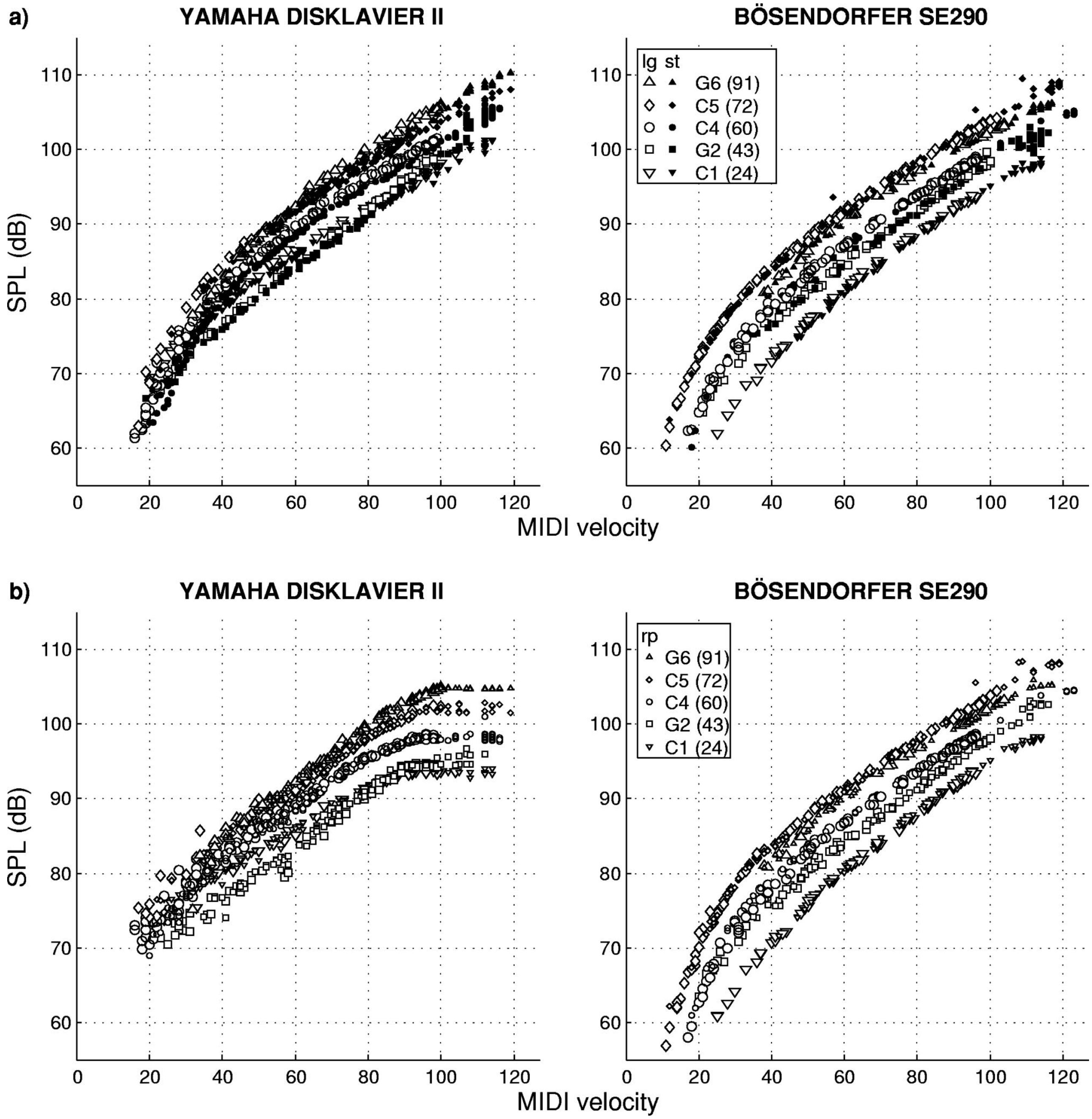

FIG. 7. Peak sound-pressure level (dB) against MIDI velocity as recorded by the computer-controlled pianos. The upper panels show legato touch (''lg''), and staccato touch (''st'') as played by the pianist (a), the lower display the reproduction (''rp'') by the computer-controlled pianos (b).

This display compares acoustic properties of the played tones with their reproduction (peak SPL in dB, Fig. 6). Here, the SE system revealed a much more precise reproducing behavior over the whole dynamic range than the Disklavier. In the latter, the dynamic extremes flattened out, soft tones were played back too loudly, and very loud tones too softly.

In Fig. 7, the relation between MIDI velocity units and peak sound-pressure level is displayed separately for the recording (a) and its reproduction (b). On both instruments, different pitches exhibited a different curve. The higher the pitch, the louder the radiated sound at the same MIDI velocity. The reproduction panel [Fig. 7(b)] reflected the reproducing limitations of the Disklavier already shown in Fig. 6.

C. Two types of touch

Examples of a *legato* keystroke (Disklavier, see Fig. 8) and a *staccato* attack (SE, see Fig. 9) are shown to demonstrate in detail the typical reproducing behavior of the computer-controlled pianos. In these figures, instantaneous key and hammer velocity (first and second row) are plotted above the sound signal (third row). In Fig. 8 on the left side, a *legato* keystroke as played by one of the authors is shown with its smooth acceleration, on the right its reproduction by the Disklavier. The Disklavier hit the key always in a *staccato* manner, with an abrupt acceleration at the beginning of the attack. The parts of the piano action were compressed before their inertia was overcome and the hammer started to

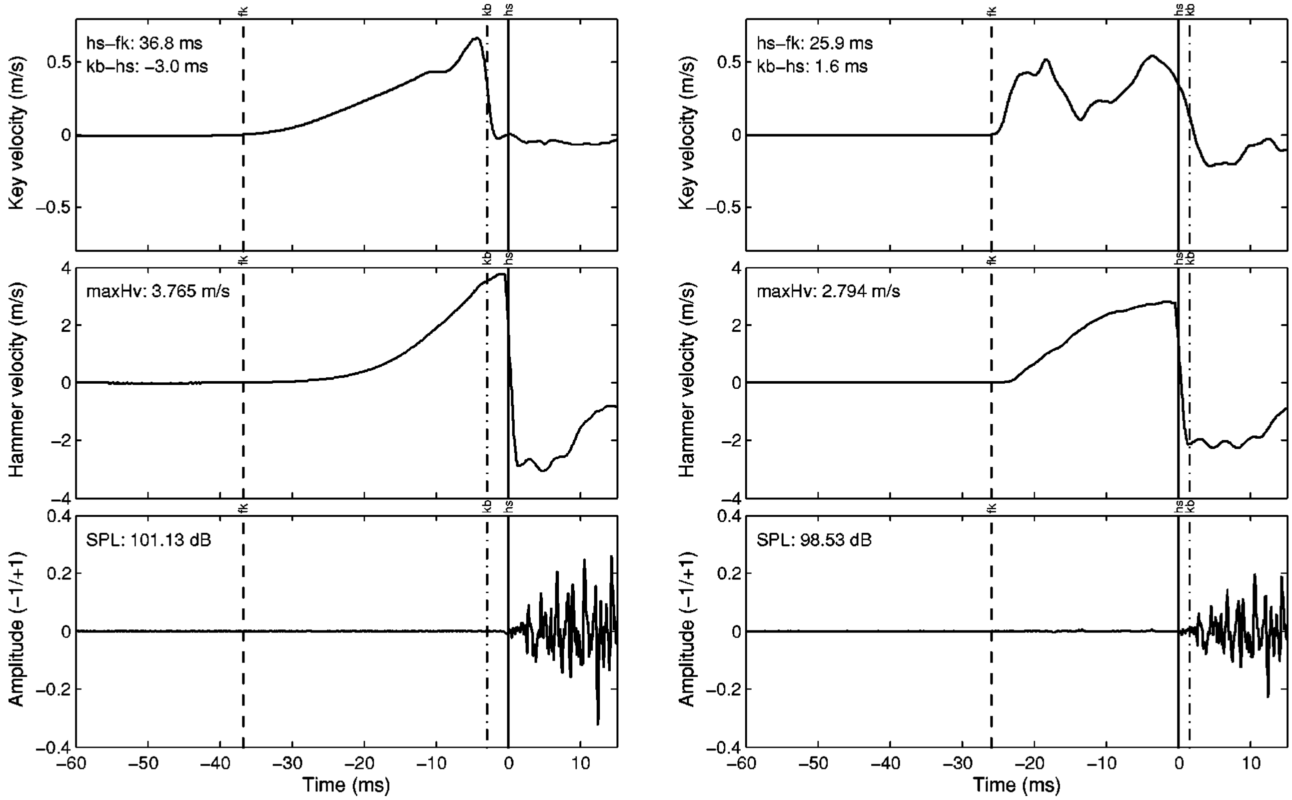

FIG. 8. A *forte* attack (C4, MIDI note number 60) played by one pianist (left panel) "from the key" ("*legato touch*"), and its reproduction by the Yamaha Disklavier (right). The upper panels plot key velocity, the middle hammer velocity, the bottom panels the sound signal. The three lines indicate the finger–key contact (start of the key movement, "fk," left dashed line), the key bottom contact ("kb," dash-dotted line), and the hammer–string contact ("hs," solid line).

move upwards. The solenoid's action resulted in a shorter travel time (the time between finger–key contact ("fk") and hammer–string contact ("hs") was 26 ms instead of 37 ms; see Fig. 8, upper panels). The travel time difference between production and reproduction was even larger at very soft keystrokes. This could be one reason why soft notes appeared earlier in the reproduction by the Disklavier than louder notes.

In this particular keystroke, the difference in peak hammer velocity was clearly audible. When the (final) hammer velocities became similar, the two sounds, independently on how they were produced (*legato*—*staccato*—reproduced) became indistinguishable.[12] We cannot tackle here the controversy as to whether it is only hammer velocity that determines the sound of a single piano tone (White, 1930; Hart, Fuller, and Lusby, 1934; Seashore, 1937) or if there are more influencing factors like various types of noise emerging from the piano action the pianist's interaction with it (Báron and Holló, 1935; Báron, 1958; Podlesak and Lee, 1988; Askenfelt, 1994; Koornhof and van der Walt, 1994).

A very loud staccato attack is plotted in Fig. 9 with the original, human attack on the left, and its reproduction by the Bösendorfer SE on the right. The point of maximum hammer velocity was 5.4 ms before hammer–string contact in the original recording, but only 1.6 ms in the reproduction. Although the reproduced maximum hammer velocity was lower (5.4 m/s instead of 5.8 m/s), the reproduced peak SPL was almost identical with those of the original sound. The human player accelerated the key extremely abruptly so that the hammer reached its highest speed quite some time before hitting the strings and—of course—lost energy at its free flight to the strings. Since the reproducing solenoid cannot accelerate the key in the same abrupt way as the human player, the hammer reached maximum speed later, and—in this example—the machine performed with less energy loss than the human player.

IV. GENERAL DISCUSSION

In this study, we measured the recording and reproducing accuracy of two computer-controlled grand pianos (Yamaha Disklavier, Bösendorfer SE) with an accelerometer setting in order to determine their precision for piano performance research. Both devices showed a systematic timing error over time which was most likely due to a rounding error in the system clock (the internal hardware at the Disklavier, a common personal computer at the SE). This linear error removed, the Bösendorfer had a smaller (residual) timing error than the Disklavier, but both exhibited a certain trend with respect to the loudness of the tones. The Disklavier tended to record soft tones too late, whereas the SE had the tendency to record soft tones too early. But, within these tendencies, the SE was more consistent. At reproduction, the superior performance of the Bösendorfer became more evident: the timing error was smaller than at recording, whereas the Disklavier added some variance in comparison to its recording.

The important point for performance research was the recording accuracy of those systems. Apart from the systematic error that only marginally affected the measured tempo

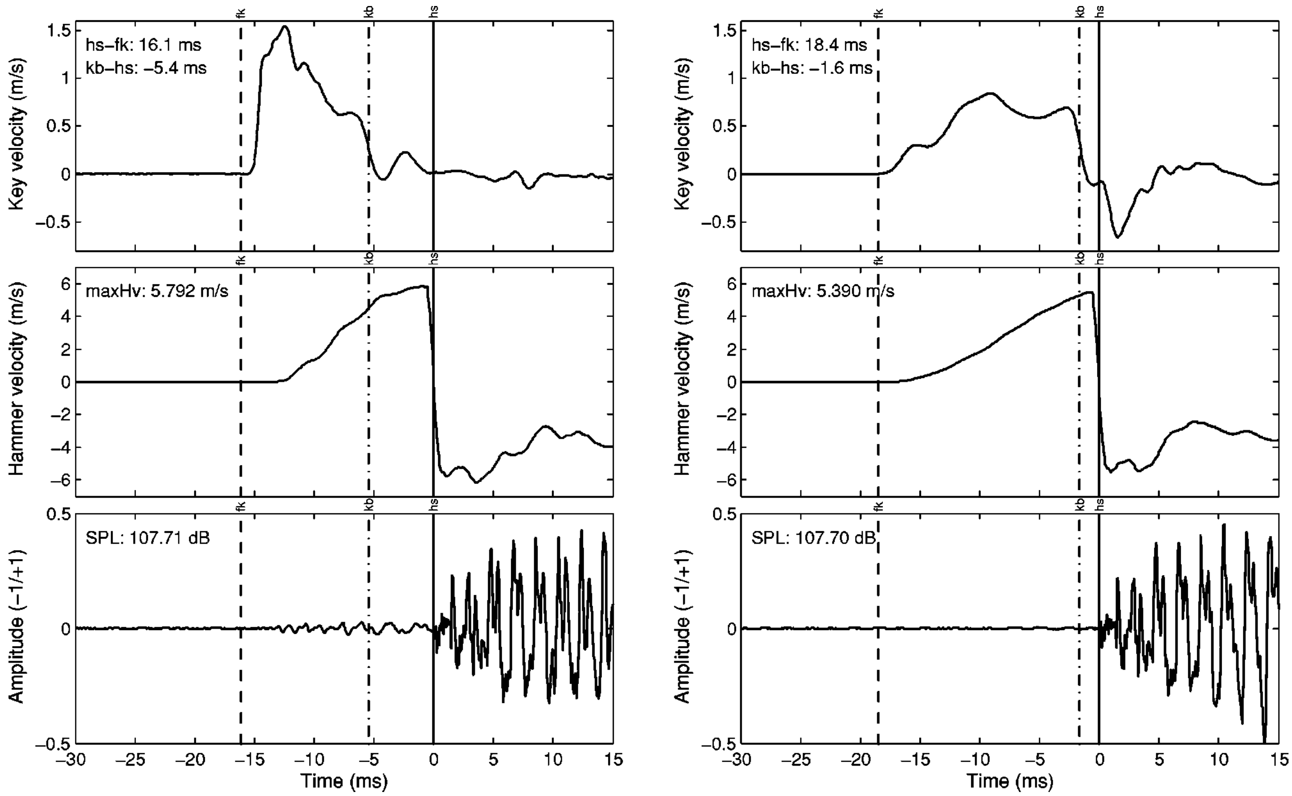

FIG. 9. A *fortissimo* attack (C4, MIDI note number 60) played by one pianist (left panel) from a certain distance above the key (''*staccato touch*''), and its reproduction by the Bösendorfer SE grand piano (right). The upper panels plot key velocity, the middle hammer velocity, the bottom panels the sound signal. The three lines indicate the finger–key contact (start of the key movement, ''fk,'' left dashed line), the key bottom contact (''kb,'' dash-dotted line), and the hammer–string contact (''hs,'' solid line).

value (0.0053% or 0.014%, respectively), the residual timing error (Fig. 3) was considerably large for the Disklavier and smaller for the Bösendorfer. The measurement precision could be improved by subtracting these trends using the polynomial curve approximations as displayed in Fig. 3.

To examine reproducing accuracy in the loudness dimension, we used the maximum hammer velocity and the peak sound-pressure level as measures. Maximum hammer velocity did not correspond to the velocity measures captured by the sensors of the two systems. Considering the peak sound levels of the sounding signal, both devices captured in a similar way, only at reproduction the smaller solenoids of the Disklavier system could not reproduce very loud tones properly. The lower the pitch (and thus the greater the hammer mass), the lower was the maximum sound-pressure level of the Disklavier's reproduction. The reproduction of soft notes was also limited (very soft notes were played back somewhat louder by the Disklavier), because the tested Disklavier prevented very soft tones from being silently reproduced with a minimum velocity matrix, adjustable by the internal control unit. It was also due to this function that the Disklavier was not able to reproduce silent notes, a crucial feature especially for music of the 20th century. The Bösendorfer exhibited linear reproducing behavior over the whole dynamic range (from 60 to 110 dB SPL).

As another, and indeed very important criterion of recording and reproducing capability, we did not investigate the two pedals. (We are talking only of the right and the left pedal of grand pianos, since the middle pedal—the *sostenuto* pedal—only varies the tone length of certain keys depressed during its use, which is recorded and reproduced by simply holding down the corresponding keys at the same time this pedal was depressed.) The use of the right pedal was not investigated extensively up to date (apart from Repp, 1996d, 1997b). We did not have any hypotheses of how pedal recording and reproducing accuracy should be approached. This item remains for future work.

Both the Disklavier and the SE system are based on the same underlying principle: that is, to measure and reproduce movement of the piano action (and the pedals), in particular the final speed of the hammer before touching the strings. This principle is fundamentally different from what a performing artist does when playing expressively. The artist controls finger, hand, and arm movements in order to reproduce a certain mental image of the sound to be produced by continuously listening to the resulting sound and by feeling the hapto-sensory feedback of the keys (Galembo, 1982, 2001). In this way, the performer is able to react to differences in the action, the voicing, the tuning, and the room acoustics, just to mention a few variables that have a certain influence on the radiated sound. On the other hand, a reproducing piano aims to reproduce a certain final hammer velocity independently of whether or not room acoustics, tuning, or voicing changed since the recording. Even if the reproduction takes place on the same piano and immediately after the recording, the tuning might not be the same anymore and the mechanical reproduction, as good as it might be, does not result in an identical sounding performance as the pianist played it before. This obvious limitation of such devices becomes most evident when a file is played from a different piano or in a different room. Especially, if the damping point (the point of the right pedal where it starts to prevent the strings from freely oscillating) is a different one on another piano, tones in the reproduction will be prolonged (too much pedal) or get cut off (too little pedal) incorrectly.

One possible solution to this problem could be a reproducing device with ''ears,'' in other words, the piano should be able to control its acoustical outcome via a feedback loop through a built-in microphone. If put into a different room, the device could check the room acoustics, its pedal settings, and its current tuning and voicing before the playback starts, much the same as a pianist warming up before a concert. Such a system would require a representation of loudness or timbre other than MIDI velocity, indicating at what relative dynamics a certain note was intended to sound in a pianist's performance.

As the present study was planned to investigate the usefulness of the two devices in question for performance research, we have to consider the obtained results in the light of practical applications. Although the Bösendorfer is the older system, it generally performs better. The disadvantage of the Bösendorfer is its price, around double the price of a grand piano of that size. Moreover, the SE system is not produced anymore, and there are only about 35 exemplars sold around the world, and very few in academic institutions (such as *Ohio State University*, or the *Hochschule für Musik* at Karlsruhe, Germany).[13] On the other hand, the Disklavier is a consumer product, the price level generally cheaper than the Bösendorfer (depending on type of system), and therefore more likely to be obtained by an institution.

The Disklavier measured in this study was certainly not the top model of the Yamaha corporation. Since then, Yamaha issued the Mark III series and the high-end series, called ''Pro'' (e.g., the special ''Pro2000 Disklavier''). The latter series uses an extended MIDI format (with a velocity representation using more than 7 bits), and additional measures like key release velocity to reproduce the way the pianist released a particular key. It can be expected that these newer devices perform significantly better than the tested Mark II grand piano. Since these more sophisticated devices were not available for the authors or too far away from the accelerometer equipment, which was too costly to transport, this has to remain a subject for future investigations.

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[1]The onset of a sounding tone is very often called ''note onset,'' because of the MIDI world's terminology. In this paper, the terms ''tone'' and ''note'' are used synonymously, since we are not talking about musical notation.

[2]The middle or *sostenuto* pedal only prolongs certain tones and is not counted as an individual expressive parameter.

[3]On the Disklavier, the hammer shutter is mounted closer to the fixed end of the hammer, whereas the SE has its shutter closer to the hammer (as displayed in Fig. 1).

[4]Brüel & Kjær accelerometer type 4393. Mass without cable: 2.4 g; serial number 1190913.

[5]ENDEVCO accelerometer model 22. Mass without cable: 0.14 g; serial number 20845.

[6]Brüel & Kjær charge amplifier type 2635.

[7]Using an analog connection from the TEAC recorder to a multichannel sound card (Producer: Blue Waves, formerly Longhborough Sound Images; model PC/C32 using its four-channel A/D module) on a PC running Windows 2000 operating system.

[8]Brüel & Kjær sound-level calibrator type 4230, test tone: 94 dB, 1 kHz.

[9]$delay_{\mathrm{MIDI}} = t_{\mathrm{MIDI}} - t_{\mathrm{original}}$; $delay_{\mathrm{repro}} = t_{\mathrm{reproduced}} - t_{\mathrm{original}}$.

[10]There were no systematic differences between the two performing pianists, so the data in this and all subsequent figures were not plotted separately for pianists.

[11]For the SE system, the final hammer velocity needs to be mapped to MIDI velocity values by choosing a velocity map. In the present study, a logarithmic map was always used: $\mathit{MIDI\ velocity} = 52 + 25 \log_2(\mathrm{FHV})$.

[12]As informal listening to the material suggests; systematic listening tests will be performed in future work.

[13]The SE system was recently completely re-engineered and was expected to be available commercially at the Bösendorfer company by mid-2002 (Dain, 2002).

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