COMPARING ACOUSTIC AND DIGITAL PIANO ACTIONS: DATA ANALYSIS AND KEY INSIGHTS

Michael Fioretti , Giuseppe Bergamino , Leonardo Gabrielli , Gianluca Ciattaglia , Susanna Spinsante

Dept. of Information Engineering
Università Politecnica delle Marche
Ancona, IT
<m.fioretti,g.bergamino>@pm.univpm.it,
<l.gabrielli,g.ciattaglia,s.spinsante>@staff.univpm.it

ABSTRACT

The acoustic piano and its sound production mechanisms have been extensively studied in the field of acoustics. Similarly, digital piano synthesis has been the focus of numerous signal processing research studies. However, the role of the piano action in shaping the dynamics and nuances of piano sound has received less attention, particularly in the context of digital pianos. Digital pianos are well-established commercial instruments that typically use weighted keys with two or three sensors to measure the average key velocity—this being the only input to a sampling synthesis engine. In this study, we investigate whether this simplified measurement method adequately captures the full dynamic behavior of the original piano action. After a brief review of the state of the art, we describe an experimental setup designed to measure physical properties of the keys and hammers of a piano. This setup enables high-precision readings of acceleration, velocity, and position for both the key and hammer across various dynamic levels. Through extensive data analysis, we examine their relationships and identify the optimal key position for velocity measurement. We also analyze a digital piano key to determine where the average key velocity is measured and compare it with our proposed optimal timing. We find that the instantaneous key velocity just before let-off correlates most strongly with hammer impact velocity, indicating a target for improved sensing; however, due to the limitations of discrete velocity sensing this optimization alone may not suffice to replicate the nuanced expressiveness of acoustic piano touch. This study represents the first step in a broader research effort aimed at linking piano touch, dynamics, and sound production.

1. INTRODUCTION

Capturing and reproducing the complex dynamic and the nuances of the acoustic piano with an electronic instrument is a dream that researchers and engineers have been chasing for decades. With the advent of digital signal processing and sampling sound synthesis techniques, digital pianos have become popular both as a learning tool for piano students or as a professional instrument for live stage and studio usage. Later, physical modeling promised new methods to enrich the expressivity of the instrument [1, 2], with a few instrument eventually hitting into the market [3, 4]. In the latest years, neural audio synthesis is becoming interesting [5], even if not yet capable of running in real-time on commercial hardware, and may soon take over other techniques.

While much has been done from a signal processing standpoint, less research has been done on the boundary between the physical interface and the synthesis algorithms.

The action of the acoustic piano, both grand and up-right, have been investigated by several studies. Hayashi et al. [6] analyzed hammer motion prior to string contact, providing insights into achieving stable soft tones in automatic piano systems. Additionally, experimental investigations into the hammer-string interaction have offered detailed observations on force-compression behavior and the effects of hammer shank deflection. Goebl et al. [7, 8] have extensively studied the temporal behavior of grand piano actions under varying touch conditions and dynamic levels. These studies focus on sound pressure level as a function of maximum hammer velocity showing that hammer travel times differ notably between pressed and struck touches, though variations between different pianos were minimal. In one study the authors examined the accuracy of computer-controlled grand pianos in recording and reproducing MIDI performances [9]. Kinoshita et al [10] examined the force characteristics involved in piano key presses, investigating how pianists apply force during keystrokes and how these forces relate to the control of sound production.

Digital pianos, however, employ a different action, somewhat mimicking the weight of a hammer and the let-off mechanism, but these are simplified to various degrees, depending on the level of accuracy desired by the user. Most importantly, these keyboards invariably employ a simple sensing mechanism based on electric contacts to estimate the average key velocity, that is translated to a control value used for the sound synthesis.

Even if the piano action is well described and understood, to the best of our knowledge, no study has addressed how well a digital piano action translates into the physical behavior of the acoustic piano. In this study, we built experimental setups to conduct measurements on an acoustic piano action and on a digital piano action. The acoustical piano has been equipped with two synchronized accelerometers - one affixed to the key and another to the hammer - to capture acceleration data throughout the key travel and to reconstruct velocity and position profiles, allowing us to examine their temporal characteristics.

In the analytical sections, we process the acceleration data collected from both key and hammer motion to reconstruct velocity and position profiles. A structured event-detection methodology is applied to identify main events, including the onset of key press, let-off, and hammer-string contact. We then analyze the relationship between key velocity and hammer impact velocity using linear regression, evaluating different sampling points along the key travel to determine the most reliable predictor of impact velocity. Identifying this moment is essential for refining digital piano keyboard mechanisms, as current models often rely on simplifications that may not accurately capture the complexity of acoustic piano actions.

Similarly, we are interested in observing whether digital piano actions correlate well with the hypothetical velocity a piano hammer would have. The insights from this research could inform the design of more sophisticated control algorithms for digital instruments, improving their realism in expressive performance contexts.

The rest of the paper is organized as follows. In Section 2 we provide a brief description of the acoustic and digital piano action and we explain the aims of the paper. In Section 3 we describe the experimental setup used to collect data and the data analysis methods. Section 4 discusses the results of the data analysis and tries to answer the research questions. Finally, Section 5 summarizes principal findings and pinpoints future advancements.

2. BACKGROUND

2.1. Acoustic Piano Action

Although the mechanics of the acoustic piano action are well known, this paragraph provides a brief introduction. When the piano key is depressed, it acts as a Class 2 lever, with the applied force transmitted through an intermediate mechanism known as the wippen assembly. The wippen consists of several components, including the repetition lever, jack, and backcheck, each serving a critical role in facilitating key return and rapid repetition (*ribattuto*). As the key is pressed, the jack pivots and pushes against the hammer shank, propelling the hammer toward the string. Just before impact, the escapement mechanism disengages the jack from the hammer, allowing it to continue its motion freely, ensuring that the hammer rebounds immediately after striking the string to prevent damping. The hammer's velocity, directly proportional to the applied force on the key, influences the amplitude of string vibration, thereby determining the produced sound's dynamic intensity. Additionally, the backcheck captures the returning hammer, preventing excessive rebound and enabling quick repetition, a crucial feature in advanced piano techniques. The integration of the damper system, which rests on the string until the key is pressed, ensures controlled sustain and articulation while also preventing sympathetic resonance.

2.2. Digital Piano Action

Early analog keyboard instruments employed a single electric contact to start the tone production and a series of resistors to determine the desired pitch using the principle of a voltage divider. These instruments had no velocity sensing, and may possibly exhibit some form of aftertouch dynamics control (one of the earliest being the Synket [11]).

With the advent of microcontrollers and the establishment of the MIDI protocol, a method for keyboard scanning became an industry standard to obtain both the keypress instant and, more importantly, an estimated velocity. This would greatly enhance the expressiveness of the instrument and allow it to emulate other musical instruments more accurately, in conjunction with e.g. multi-layer sampling synthesis engines. This method involves the evaluation of an average key velocity, by scanning two or more electric contacts hidden in the key action. The contacts are normally open and generally consist of a carbon-coated conductive silicone rubber that closes two pads on the PCB when pressed against them. The electric contacts are arranged so that they close sequentially during key fall at specific points of the key travel determined by their arrangements. The interval between the two events is measured precisely to estimate the key velocity or, more often, an adimensional integer in the range [1:127] to provide the key velocity according to the MIDI *Note On* and *Note Off* messages. Keyboards are periodically scanned at a high rate, since the microcontroller must be able to sense all contacts multiple times at the maximum expected velocity.

Figure 2 shows a simplified electric schematic of a two-contact key. Please note that other arrangements exist, depending on the keyboard model or the manufacturer, but they follow similar principles. Also note that some keyboards have three contacts, where the added one is in between the first two, and is particularly meaningful for *ribattutos* in piano playing, which - for the sake of simplicity - are left out of the discussion in this work.

The state of the two contacts C_1, C_2 is determined by reading the voltage V_r by means of a microcontroller. The microcontroller decides which one of the contacts to test by connecting it to the reference voltage V_{ref} (typically ground voltage) by means of either G_1 or G_2 (these are not implemented in a PCB but are part of the microcontroller driving peripheral). With this mechanism, when the key is open, the read voltage is $V_r = V_{dd}$. When the contact C_i is closed, the read voltage is V_{ref} plus the voltage drop across the contact (which has a small resistance) and the diode (which is conducting).

In recent years, commercial digital piano key actions have been designed to more closely resemble the mechanical response of acoustic piano actions. Many high-end digital pianos incorporate graded hammer actions with progressively weighted keys that replicate the resistance and inertia of acoustic counterparts. Additionally, some models feature simulated escapement (let-off) mechanisms, which mimic the subtle notch felt when pressing a grand piano key slowly. These design choices aim to improve the realism of digital piano performance, particularly in capturing the tactile feedback and control that pianists expect from acoustic instruments.

2.3. Goals and Hypotheses

The objectives of the paper are twofold. We first aim to provide accurate measurements of the piano key and hammer motion, which,

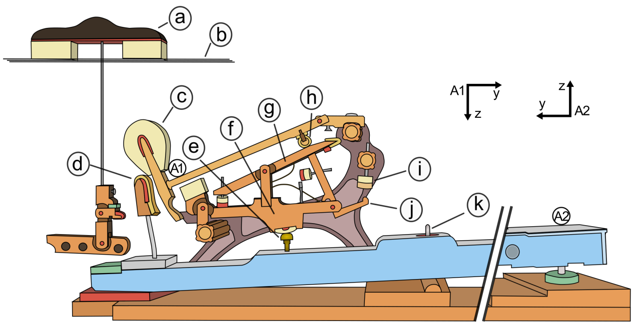

Figure 1: Illustration of an acoustic grand piano action with labeled parts: a) damper; b) strings; c) hammer; d) backcheck; e) capstain; f) wippen; g) repetition lever; h) knuckle; i) let-off button; j) jack; k) key pivot. A1 and A2 mark the positions of the accelerometers used in the experiment with their orientation indicated in the top right part of the figure

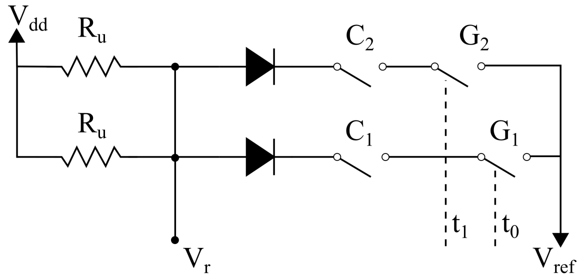

Figure 2: Simplified schematic of a two-contact keyboard key. The state of the contacts C_1, C_2 is determined by reading the voltage V_r by means of a microcontroller.

to the best of our knowledge, are not available in the literature. All data is released in the public at the following URL[1] to foster research in the field.

The second goal of the work is to understand the limitations of existing sensor technologies to identify potential alternatives to refine digital piano touch and realism. Specifically, we try to assess whether the velocity of the key is an accurate estimate of the hammer velocity, and to what extent. The motivation for this research question is that current digital pianos, as discussed above, rely on a (average) measurement of the key velocity.

The implicit assumption under this sensing method is that the key velocity value is all we need for the sound engine to obtain expressiveness. When emulating an acoustic piano string at rest, this assumption is well justified by the fact that the hammer impacts the string after decoupling with the key mechanism, therefore the energy transfer to the string is solely determined by its impact velocity. The same can be applied to other instruments based on a keyboard and a hammer such as the electric piano.

This simplifying assumption, does not necessarily hold for other keyboard instruments. A mechanical action pipe organ, e.g. exhibit slight variations of the attack transients by modulating the velocity at a specific point where the air valve starts to open in response to the key position. Other stringed instruments such as the the clavichord and the Clavinet [12] do not have a hammer, but rather have a tangent which excites the string by getting in contact with it. For the rest of the paper, however, we will deal with the acoustic piano and leave discussions about other keyboard instruments to the future.

The second implicit assumption with the digital piano keyboard action is that the key velocity can be measured accurately by indirect measurement of the time of flight between the closing of two contacts. This method allows to compute only the average of the velocity between these two events. In the paper we try to evaluate how much the velocity fluctuates around the average value during a normal key press, and assess how well this average value correlates to the velocity of the hammer at impact instant.

3. METHODS

3.1. Experimental Setup

The experiment was conducted using a single piano key action model, the type commonly used for training piano technicians. Two accelerometers were mounted on the action: one on the key and

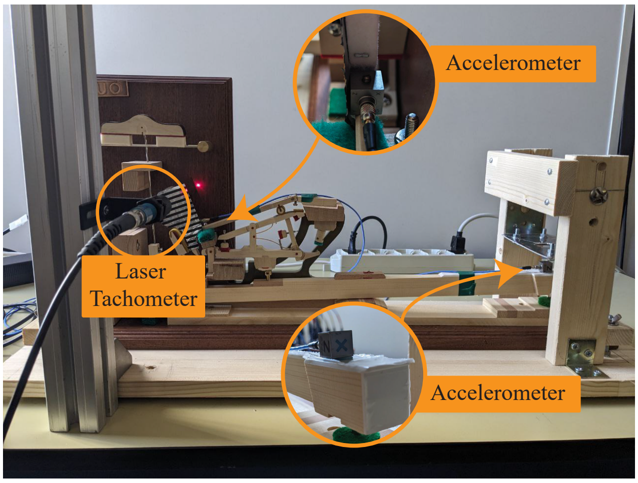

Figure 3: Instrumented single piano key action used for the measurements. The positions of the accelerometers and the laser tachometer are highlighted.

one on the hammer. The accelerometers are both piezoelectric and can measure acceleration along the three axes. The model name is PCB 356A32 [2]. Main features of accelerometers are their weight of 5 g and a sensitivity of 10.2 mV/g. As the sensor attached to the action can influence the results of the experiments, the weight must be considered. On the action, the accelerometers are glued with a specific measurement wax. Such accelerometers are of IEPE (Integrated Electronics Piezo-Electric) technology and require a specific instrument to perform the measurements. The acquisition system used is a Dewesoft Krypton whose inputs have a conditioning stage able to collect the measures. Acceleration values are obtained synchronously as each Krypton input has the same sampling reference. Accelerometers' installation details are reported in Figure 3.

As an additional sensor, a laser tachometer was also installed on the setup. The data collected from the laser tachometer is part of a future work addressing mass-loading effects in the hammer acceleration measures and will not be the object of this work.

The Dewesoft Krypton collects simultaneously the signals coming from the two accelerometers and the laser tachometer. The instrument provides a common sampling time base. A sampling frequency of 20 kHz is used to sample the signals of all the installed sensors.

Before data collection, the action was calibrated to ensure proper mechanical alignment and consistency in movement. The experiment consisted of four separate runs, each performed at a different dynamic level by a professional piano player: piano (*p*), mezzo-piano (*mp*), mezzo-forte (*mf*), and forte (*f*). For each run, 18 key presses were recorded, yielding a total dataset of $N = 72$ individual key presses.

A second setup consisted of a section of a digital keyboard mounted on a wooden frame, which supported a screw positioned above one of its keys. The keyboard was a Fatar TP-100 weighted digital piano keyboard. The key's internal contact system, consisting of three sequentially triggered sensing points, was accessed by soldering wires to the closest available pads on the underlying printed circuit board (PCB). These connections were routed

[1] https://github.com/fiorettimichael/piano-dafx25

[2] ACCELEROMETER, ICP®, TRIAXIAL Model 356A32, `https://www.pcb.com/products?m=356a32`, accessed on: 2025-04-02

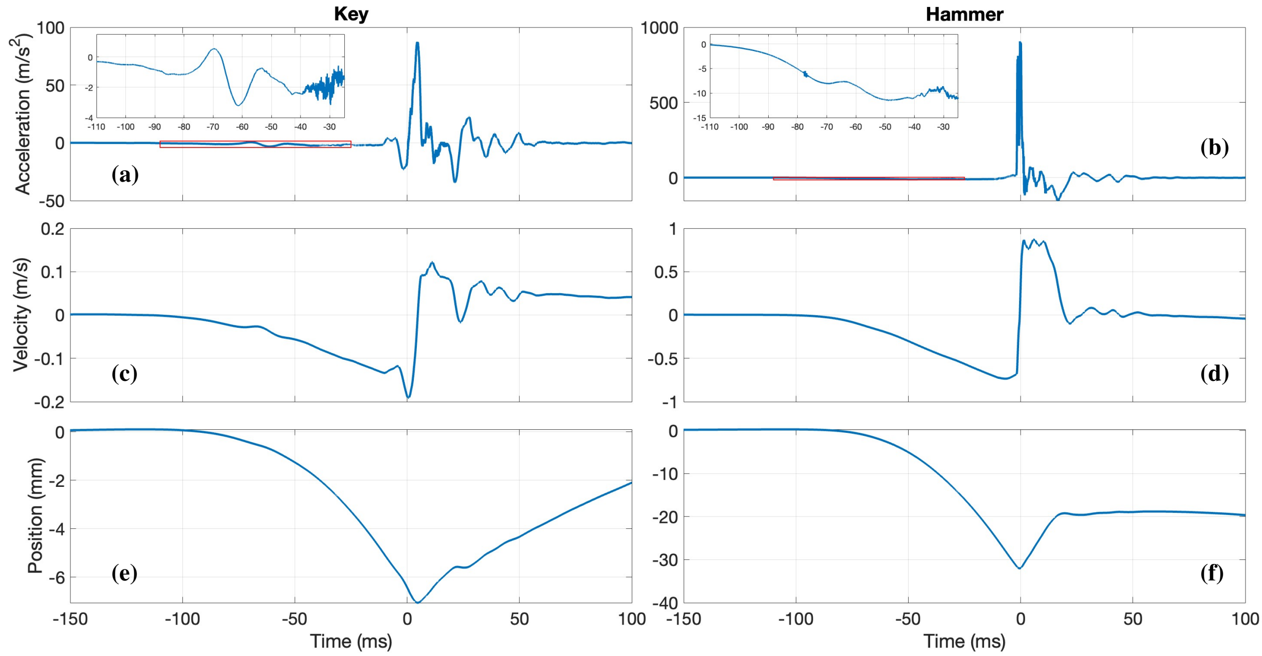

Figure 4: Typical trajectories for a mezzo-forte keystroke along the vertical direction. From top to bottom: acceleration ((a),(b)), velocity ((c),(d)), position ((e),(f)). Data from the key-mounted accelerometer is shown on the left ((a), (c), (e)), and data from the hammer-mounted accelerometer is shown on the right ((b), (d), (f)). For trajectories (a) and (b), the red box delimits the area displayed in the zoomed-in, overlaid plot, showing details in the acceleration trajectories around key-press onset.

to a digital multimeter configured to measure resistance. To determine the key travel distances corresponding to the activation of the key contacts, the screw was gradually adjusted until a measurable resistance was detected at each sensing point and the travel was measured using an electronic caliper.

3.2. Data Processing and Analysis

To obtain velocity and position trajectories, a simple integration was performed on the acceleration data, starting the sum from the key press onset to minimize drift. Position data was similarly calculated starting from the obtained velocities. Typical acceleration, velocity, and position trajectories for a mezzo-forte keystroke are shown in Figure 4.

3.2.1. Event detection

Following this preliminary calculation, a custom script was used to extract primary events in the piano action. The analysis followed a structured event-detection methodology:

- Segmentation of Key Presses: Each run was divided into 18 individual key presses by identifying peaks in the hammer acceleration signal. These peaks were used to establish the striking instant for each press.
- Detection of Key Press Start: The beginning of each key press was determined using a threshold-based method applied to the key acceleration profile, identifying the onset of movement.

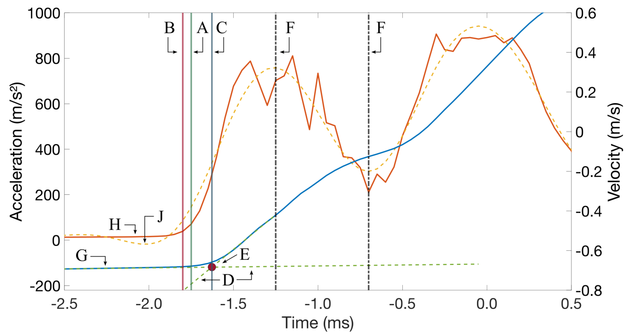

Figure 5: The three estimates for hammer-string contact detection: A) Unfiltered acceleration onset threshold; B) Lowpass filtered acceleration onset threshold ($50\,\mathrm{m/s^2}$); C) Graphically derived onset threshold. Additionally the following curves are shown: D) Construction lines; E) Intercept; F) Local extrema; G) Velocity trajectory; H) Unfiltered acceleration trajectory; J) Lowpass filtered acceleration trajectory

- Let-off Detection: The let-off instant, which marks the release of the jack from the hammer, was identified as the maximum hammer velocity before string contact.
- Hammer-String Contact: To determine the instant of first contact between the hammer and the string, a combined threshold-based and graphical approach was applied as shown in Figure 5. Local maxima and minima in the ham-

mer acceleration profile were examined, working backward from the impact. For the threshold-based method a threshold value of $50\ \frac{\mathrm{m}}{\mathrm{s}^2}$ was used on both the raw and low-passed acceleration signal. For the graphical method, two straight lines were drawn on the velocity trajectory: one was placed tangentially on the instant in which the acceleration trajectory reaches a local maximum, the other intercepts the velocity trajectory at let-off with slope $q = g$ (earth gravitational constant). The intercept point of this two lines provides another measure for time of first contact.

3.2.2. Velocity Data Fitting

Since we are interested in finding the best model to predict hammer impact velocity from key velocity readings, we conducted several analyses to examine the relationship between key velocity and hammer velocity at either the let-off and the impact instants. For these analysis we used the hammer-string contact instant calculated by applying the threshold method on the filtered acceleration trajectory which seemed to give the fastest reacting and therefore more reliable estimate. Linear regression analysis was performed for each case of the four cases, and the corresponding mean squared errors (MSE) were computed. This allows to understand which is the best model to predict the impact hammer velocity by reading the key velocity. Linear regression was conducted in Matlab from all the sampled key strikes with let-off and impact instants extracted as described in Sec. 3.2.1

3.2.3. Best Velocity Sampling Point

To assess the travel point where the velocity best predicts the impact hammer velocity, we conducted a further data analysis including all the key strikes in the dataset. We took a large number of time instants around the let-off up to the hammer impact instant and fitted the velocity of each of these points to the hammer-string contact velocity. To draw the curve in Figure 8 we resample the key velocity trajectories $V_j^{(\mathbf{k})}$, where the superscript **(k)** denotes the key and $j = 1, ..., N$ is the index which keeps track of each keystroke:

$$V_{t,j}^{(\mathbf{k})} \to V_{s,j}^{(\mathbf{k})}. \tag{1}$$

Since the absolute timing of keystrokes across all experiments are non-uniform we also choose s so that let-off and hammer-string contact are fixed points for all experiments. If t_{lo} and t_{hs} are the instants of let-off and hammer-string contact respectively we have that the relations

$$s_j(t_{lo}) = s_{lo} \tag{2}$$

$$s_j(t_{hs}) = s_{hs} \tag{3}$$

and

$$s_{hs} - s_{lo} = d \tag{4}$$

hold true for all $j = 1, ..., N$. This way the length $t_j(s)$ of each sample s_j is fixed for each keystroke j by choosing a constant number of samples d in the interval $[s_{lo}, s_{hs}]$ across all experiments. We chose $d = 50$ and we extended the domain of our plot by adding 75 samples before let-off and 25 samples after hammer-string contact. After this resampling the index s spans from 1 to $M = 150$. For each sample s in the domain we consider the couples $(V_s^{(\mathbf{k})}, V_{t_{hs}}^{(\mathbf{h})})_j$, where the superscript **(h)** denotes the hammer and $V_{t_{hs},j}^{(\mathbf{h})}$ are measured hammer velocities at string contact for each keystroke j. We calculate M linear regressions giving the transformations $V_s^{(\mathbf{k})} \to \hat{V}_s^{(\mathbf{h})}$, where $\hat{V}_s^{(\mathbf{h})}$ are the predicted hammer-string contact velocities through the regression s. If by $\hat{V}_{s,j}^{(\mathbf{h})}$ we mean the value of $\hat{V}_s^{(\mathbf{h})}$ obtained by mapping measured key velocity $V_{s,j}^{(\mathbf{k})}$, the curve ϵ in Figure 8 is given by

$$\epsilon_s = \frac{1}{N} \sum_{j=1}^{N} (V_{t_{hs},j}^{(\mathbf{h})} - \hat{V}_{s,j}^{(\mathbf{h})})^2 \tag{5}$$

for each $s = 1, ..., M$. We finally look for $\bar{s}$ which minimizes ϵ.

For what concerns the digital key, we mapped the percentage of travel of contacts A and C, to the travel of the acoustic piano key and considered the average key velocity measured between these two points on the acoustic piano key. A linear fit was applied, as done previously between the average key velocity measured this way and the impact hammer velocity of the keystroke.

4. RESULTS

Raw accelerometer data for each keystroke has been visually inspected and is available online for further research works. From the raw data we integrated twice to obtain velocity and position of the key and the hammer[1]. Typical trajectories along the vertical axis (Z) are shown in Figure 4. In the rest of the work, the Z and Y are combined to obtain acceleration, velocity and position magnitude. As can be seen from the zoom box in Figure 4(a), the acceleration is not constant during the key fall due to human intervention, varying friction of the action, etc. The impact with the string exhibit a very strong acceleration on the direction opposite to hand motion, as well as vibration due to the impact.

4.1. Key and Hammer Coupling Model

Figure 6 presents four linear fits relating key velocity to hammer velocity at different sampling instants, in accordance to the methods described in Sec. 3.2.2. The subplots compare key velocity at let-off and impact against hammer velocity at let-off and impact. The quality of each fit is evaluated using the mean squared error (MSE), reported above each subplot. The top-left plot shows a strong linear relationship between key velocity at let-off and hammer velocity at let-off, characterized by the lowest MSE among the four fits. On the top-right key velocity at impact with hammer velocity at let-off exhibit a noticeably higher MSE, indicating increased variability in the relationship. The bottom-left plot explores the correlation between key velocity at let-off and hammer velocity at impact, yielding a moderate MSE. On the bottom-right key velocity at impact with hammer velocity at impact present a slightly lower error than the top-right subplot but the MSE remains higher than the let-off-based fits.

These results suggest that key velocity measured at let-off provides a more consistent predictor of hammer velocity than key velocity measured at impact. This observation aligns with the mechanical behavior of the piano action: the hammer's acceleration is largely determined at let-off, while subsequent interactions introduce variability before impact. The differences in MSE values stresses the significance of selecting an appropriate sampling instant for key velocity when modeling the dynamics of the piano action.

To test how accurate this linear model relating let-off key velocity to let-off hammer velocity is, we tried to employ it to estimate the hammer motion from key movement. This approach is particularly useful in applications where direct measurement of hammer

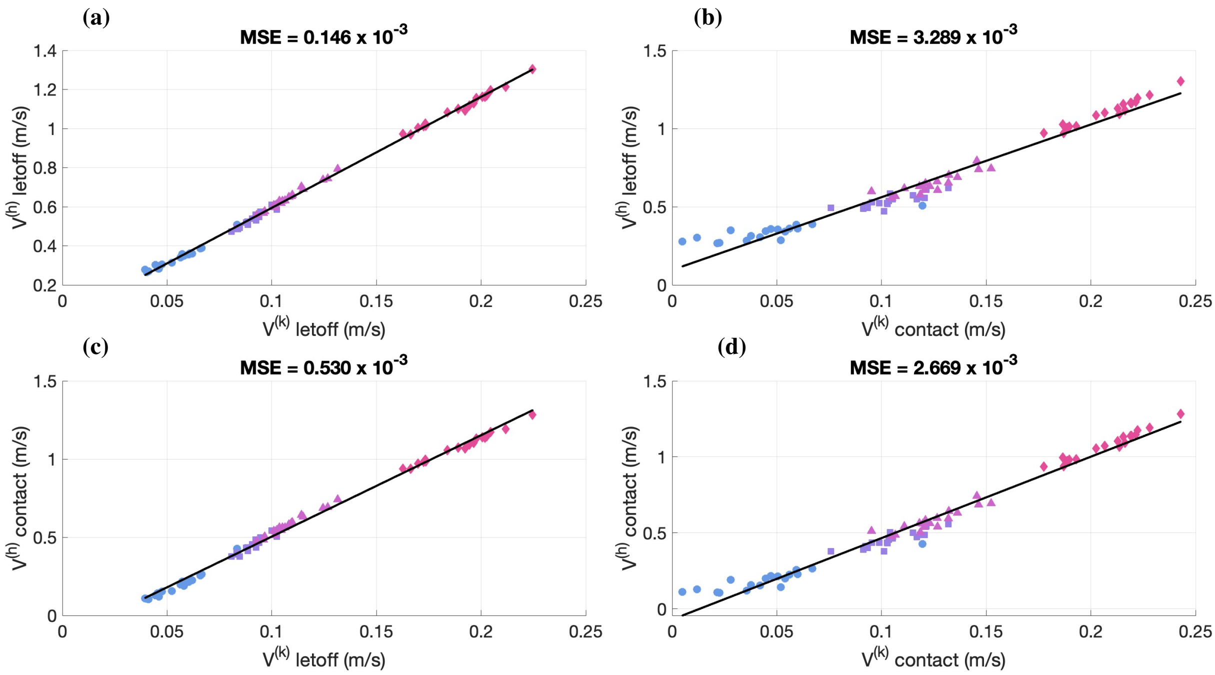

Figure 6: Fitted Hammer Velocities vs Key Velocities with printed MSE. Velocities are sampled at letoff and hammer-string contact. 4 dynamic clusters (one for each run) are shown in different colors and marker styles: circle (p); square (mp); triangle (mf); rhombus (f). In (a) let-off hammer vs. let-ff key velocities, in (b) let-off hammer vs hammer string contact key velocities, in (c) hammer-string contact vs. let-off key velocities, in (d) hammer-string contact vs hammer-string contact key velocities. The fit in subplot (a) shows lowest MSE, comparable with (c), while (b) and (d) display higher MSE by an order of magnitude.

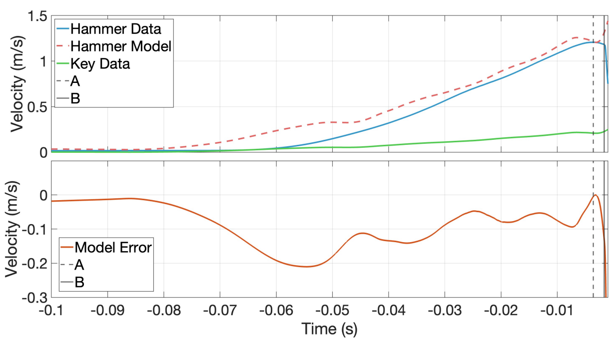

Figure 7: Plotted key and hammer velocity trajectories comparing model and measurement on the top, model error on the bottom. A) letoff; B) hammer-string contact

motion is impractical or where computational efficiency is a priority, such as in digital piano modeling or real-time synthesis of key-hammer dynamics. By using this linear relationship, the full hammer velocity trajectory can be reconstructed from the measured key trajectory, offering a first-order approximation of the action's behavior. Figure 7 compares the measured key velocity trajectory, the predicted hammer velocity trajectory obtained using the lowest MSE fit, and the actual hammer velocity trajectory. While the model effectively captures the general trend of hammer motion, deviations become apparent as the hammer approaches string contact.

The error profile in the lower subplot shows systematic discrepancies, particularly in the later stages of key descent, suggesting that additional mechanical factors influence hammer movement beyond what is accounted for by a simple linear model. This was expected. Indeed, a linear model is too simplistic and would fit only if the hammer and the key were an ideal Class 2 lever.

One likely source of these discrepancies is the effect of jack escapement, which introduces nonlinearities as the hammer is released. Additionally, variations in friction, compression of felt components, and small inconsistencies in key pressing technique may contribute to deviations from the predicted trajectory. These mechanical interactions are not inherently captured by a linear mapping between key and hammer velocity at let-off, leading to an increasing mismatch between the predicted and measured hammer velocities, especially near impact.

4.2. Best Sampling Point

Using the data analysis technique proposed in Sec. 3.2.3, we tried to estimate the time instant (or, the corresponding key travel points) where the fit between the instantaneous velocity and the impact hammer velocity is best.

Figure 8 illustrates the MSE between key velocity at different points of key travel and hammer velocity at impact. A minimum MSE is observed slightly before let-off, indicating that key velocity at this stage provides the best linear fit to the hammer's impact velocity. This result suggests that key velocity at let-off is not necessarily the optimal predictor of hammer impact velocity, despite let-off marking the start of the decoupling of the key movement

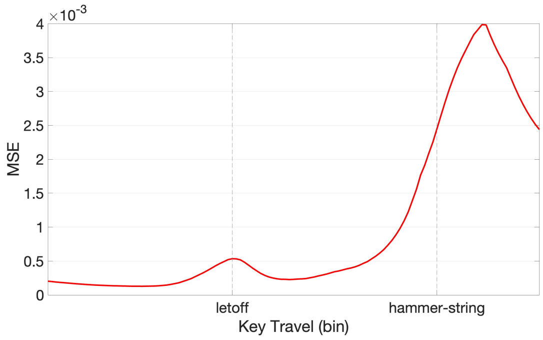

Figure 8: Plotted MSE of linear fits for hammer-string contact velocity against key velocity sampling point according to equation 5. The plot shows that minimum MSE is reached before letoff

from the hammer movement in the action's mechanics. Instead, a slightly earlier point in key travel appears to better capture the relationship between key movement and hammer acceleration through the linear model. This may reflect the cumulative effect of force transmission through the action, where the hammer's velocity begins to stabilize in relation to key input just before let-off occurs. Beyond this minimum, the error remains low until after let-off, where it starts to increase significantly. As the key approaches the bottom of its travel and the hammer nears string contact, the model becomes less effective, likely due to the increasing influence of escapement mechanics, secondary hammer motion after jack release, and other nonlinearities in the key-hammer interaction.

4.3. Digital Piano Key Measurements

To successfully translate the results obtained so far to a digital piano action, we need first to gather information from the latter. The experimental method discussed in Sec. 3.1 allowed to estimate the travel points where the contacts of a digital weighted keyboard are closed. These are shown in Table 1.

Table 1: *Digital contacts and key travel measurements.*

Contact	mm	%
Digital A	5.6	45
Digital B	7.3	58
Digital C	9.1	73
Full travel	12.5	100

The table presents the measured key travel distances at which digital contacts A, B, and C close in a digital piano action, both in absolute terms (millimeters) and as a percentage of full key travel. Contact C is particularly significant, as its closing corresponds to approximately 73% of the total key travel. By scaling the full travel of the digital piano key to that of the instrumented acoustic piano key, we observed that, notably, this phase of key motion coincides with the point where the lowest mean squared error (MSE) is observed in predicting hammer impact velocity, as shown in Figure 9.

However, the velocity on a digital piano is computed as the average between contacts A and C, therefore we decided to perform a linear regression between the average velocity that the tested acoustic piano key would provide, if it would be fitted with a 2-contact measurement method like the one of the TP-100 keyboard described above.

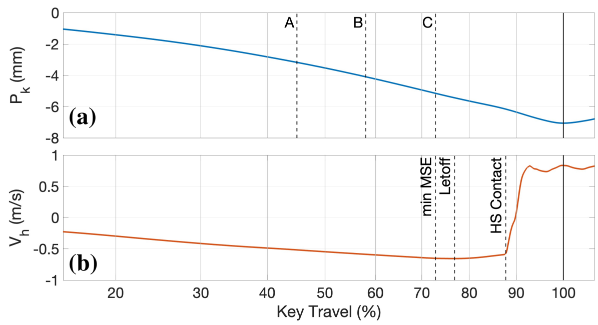

Figure 9: Key position (a) and hammer velocity (b) trajectories as a function of key travel plotted against digital and the sequential closure of the three digital piano contacts at instants A, B and C in (a). In (b) point of lowest MSE in correlating key velocities with hammer velocities at string contact, let-off and hammer-string contact.

In Figure 10 the average key velocity between contacts A and C is compared with the hammer-string contact velocity. The MSE resulting from the linear fit is higher than those in Figures 6 and 8, suggesting that the key average velocity sampled between contact A and C might not be the best candidate for an accurate reproduction of all possible dynamic layers which can be detected in the acoustic action, especially the lowest and highest ones.

On a side note, if, instead of averaging velocity between contact A and C, we consider velocities averaged from 10 % of key travel to contact C, we get a slightly better $MSE = 3.4 \times 10^{-3}$. Moreover the peculiar velocity trajectory of the key at the point of travel in which the jack hits the let-off button (seen Figure 4) could explain why a few points of the plot in Figure 10 exhibit lower key velocity than expected. In any case, averaging the key velocity does not seem to provide as good a fit as the instantaneous velocity sampled at the point identified in Section 4.2.

5. CONCLUSIONS

In this study, the relationship between key motion and hammer velocity in the acoustic piano action was analyzed, with the intent of translating that information to the digital piano action. We describe an experimental setup using high-precision accelerometers to sample both key and hammer acceleration, and we provide a dataset of raw samples, which is open to the public.

Since in digital pianos, the sensing is done by electric contacts placed below the key, we test whether the key motion can effectively predict the hammer motion. By inspecting key and hammer movement using high-precision accelerometers, we observed that the instantaneous key velocity does not perfectly match that of the hammer, as expected, and that some points in the travel are better correlated to the impact hammer velocity, which is the main variable that affects the produced sound when the string is at rest. We show that the best point to sample the instantaneous velocity is just before let-off and this provides the most reliable linear correlation with hammer velocity at impact. A comparative analysis

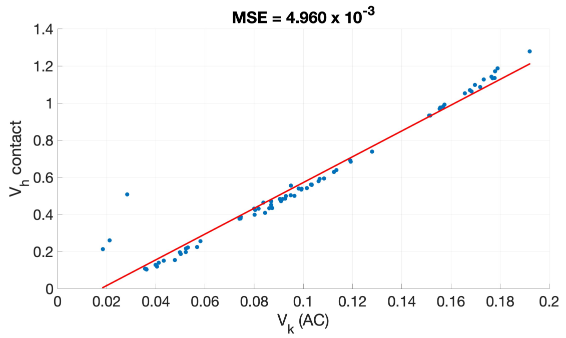

Figure 10: Fitted hammer-string contact velocities using average key velocities sampled between contact A and contact C of our reference digital keyboard

performed on a digital piano key mechanism showed that although the last contact along key travel closely corresponds to the optimal measurement point identified in the acoustic action, the velocity estimation method based on the average velocity between two contacts introduces additional variability, limiting the accuracy with which digital keyboards can replicate the full range of expressive control available in an acoustic piano.

While key velocity sensing using digital switches might provide a solution for dynamical control of sampled or synthesized musical instruments which is both relatively inexpensive and easy to implement, our findings point out that correctly identifying the point along key travel which most reliably correlates with hammer-string velocity may not be sufficient for a realistic piano touch emulation. Moreover, the assumption that key velocity alone is sufficient to characterize the dynamics of key-based actions holds for instruments with a hammer mechanism, such as acoustic and electric pianos, but may not fully capture expressive variations in other keyboard instruments, including the clavichord or mechanical action pipe organs, where the timing and force of key motion can directly influence articulation and tone production.

We suggest that incorporating positional sensors into digital piano actions may offer notable advantages over traditional velocity-based sensing methods. Positional sensors provide continuous, high-resolution data on key movements, enabling a more detailed analysis of the pianist's touch and technique. This enhanced data fidelity allows for a more accurate replication of the nuanced dynamics present in acoustic piano performances. For instance, a study by Oku and Furuya [13] introduced a noncontact, high-precision sensing system capable of recording the vertical positions of piano keys with a temporal resolution of 1 ms and a spatial resolution of 0.01 mm. This system successfully identified distinct characteristics of key motions associated with pianistic virtuosity. Integrating such positional sensing technologies into digital pianos could significantly enhance the expressiveness and responsiveness of these instruments.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge Viscount International SpA for supporting the research.

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