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A Multi-Instrument, Force-Feedback Keyboard

When playing a musical instrument, a player perceives not only the sound generated, but also the *haptic interaction,* arising during the contact between player and instrument. Such haptic interaction, based on the sense of touch, involves several senses in the player: tactile, kinesthetic (i.e., mediated by end organs located in muscles, tendons, and joints and stimulated by bodily movements and tensions), proprioceptive (i.e., of, relating to, or being stimuli arising within the organism), etc. By its nature, the haptic interaction is bidirectional, and this is exploited by musical instrument players, who can better correlate their actions on the instrument to the sound generated. For instance, by paying attention to the interaction force between key and finger, arising during the descent of the key, pianists can detect the re-triggering of the escapement mechanisms and, in turn, can adjust the key motion to obtain the fastest repetition of the note.

Roughly speaking, haptic information allows the player to perceive the "state" of the mechanism being manipulated through the key. By using this knowledge about the state of the mechanism and correlating it with the sound generated, the player learns a strategy to obtain desired tones. This tight correspondence between acoustic response and touch response, however, is lost in many electronic instruments (e.g., in standard commercial synthesizers), in which sound generation is related only to the key attack velocity and pressure. In this type of synthetic instrument, the touch feedback is independent of the instrument being simulated. For instance, the interaction with different instruments like harpsichord, piano, or pipe organ gives the same haptic information to the player. This constitutes a significant limitation for the musician, who loses expressive control of the instrument and, in turn, of the generated sound.

This consideration led to several research activities, aimed at the realization of an active keyboard, in which actuators connected to the keys are driven in such a way that the haptic interaction experienced is the same as if the player were interacting with the keyboard of the real instrument being emulated by the synthesizer (Baker 1988; Cadoz, Lisowski, and Florens 1990; Gillespie 1992; Gillespie and Cutkosky 1992; Cadoz, Luciani, and Florens 1993; Gillespie 1994). Such haptic displays are usually referred to as "virtual mechanisms," because they are designed for the reproduction of the touch feedback that a user would experience when interacting with an actual multi-body mechanism. A very simple example of virtual mechanism is the "virtual spring" shown in Figure 1.

Figure 1a shows the actual mechanism, realized by a spring, anchored to a wall on one side and to a plate on the other. Pushing the plate, a force proportional to the displacement x is perceived. In Figure 1b, the virtual mechanism is shown. Here, the spring has been replaced by a linear motor. By sensing the position of the plate and driving the motor with a current proportional to such displacement, the force perceived by the user is again proportional to the displacement, as if the user were pushing the system with the real spring. Following the same principle, a damping mechanism can be simulated by generating a force proportional to the velocity of the plate, while an inertial term can be added by sending to the motor a current proportional to plate acceleration.

This very simple example can be extended to multi-body mechanisms, composed of several parts, which interact with one another in terms of impacts, constraints, etc. In such a case, the motion of each part of the virtual mechanism must be calculated by a dynamic simulator, which incorporates all the characteristics of the real mechanism and computes the interaction forces among the parts. It is worth noting that, at times, an overly detailed

Figure 1. Virtual spring.
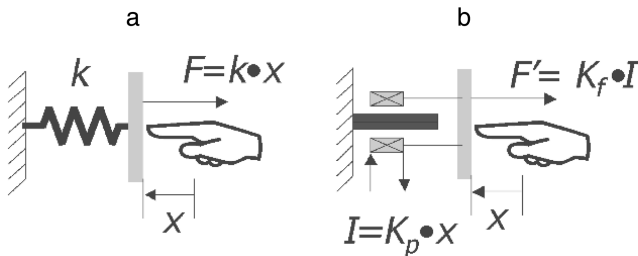
description of the real mechanism leads to a bulky dynamic simulator, not suitable for real-time implementation, as is required in haptic interaction. Moreover, it is usually difficult to tune the parameters of the dynamic simulator, especially when the mechanism to be simulated contains several nonlinear components, such as nonlinear dampers or constraints.

Among all the possible keyboard-operated instruments, the grand piano has by far the most complicated mechanism (Topper and Wills 1987). The grand piano action, in fact, is composed of dozens of components and this, as we mentioned, has impeded the realization of a real-time dynamic simulator for it. A remarkable work by Gillespie and Cutkosky (1992) shows how it is possible to implement a very detailed model of the piano action and tune it by matching simulation and experimental results, the latter obtained by accurately measuring all dynamic and kinematic variables on an actual piano mechanism. However, the obtained model, even if it results in good agreement with experimental data, can run only offline. Given these considerations, several researchers have focused their work on the reproduction of only one or a few specific behaviors of the mechanism. For instance, Baker (1988) proposes the simulation of user-programmable inertial and viscous characteristics to adapt the keyboard to the player's taste.

Gillespie (1992, 1994), on the other hand, has studied the modeling of a simplified piano action, composed of only two bodies: the key and the hammer. Even with this very simple model, it is possible to reproduce part of the hammer motion, composed of three different phases: contact with the key, fly, and return on the key. This model,

however, does not take into account the impact of the hammer with the string and the effect of escapement, even if such characteristics are very useful in regaining the previously mentioned correspondence between acoustic response and haptic interaction.

This article presents the preliminary results obtained by the MIKEY (Multi-Instrument active KEYboard) project. The project is aimed at the realization of a multi-instrument active keyboard with realistic touch feedback. In particular, the instruments to be emulated are the grand piano, the harpsichord, and the Hammond organ. Given the previous consideration, it is clear that some tradeoff between model accuracy and real-time operability had to be made at the beginning of the project, especially for the grand piano. The research presented here started from the work of Gillespie and has been improved by adding some additional features, namely the hammer-string impact, various state-dependent hammer-key impacts, and the escapement effect. Also, to improve the quality of the haptic feedback, a direct-drive, low-friction motor has been used. Finally, particular attention has been paid to the cost of the overall system, by using inexpensive devices for sensing, actuation, and real-time computation.

After introducing the models used in the dynamic simulator, the article describes the experimental setup realized. The experimental results obtained are then reported and compared with those obtained with a standard piano keyboard. Comments on the results presented conclude the article.

Modeling the Mechanisms

The realization of a realistic haptic interaction with an active keyboard requires an accurate model of the mechanism to be emulated. In this section, three different mechanisms emulated by the MIKEY system are described, pointing out the simplification operated on the complete model to achieve a dynamic simulation that runs in real time. The three models considered are the grand piano, the harpsichord, and the Hammond organ.

Figure 2. Grand piano action.
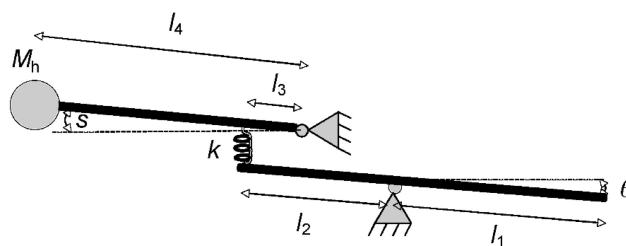

Figure 3. Simplified model of the piano action.
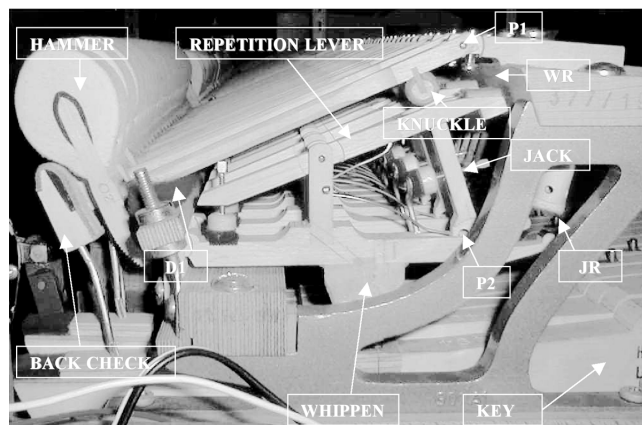
Grand Piano Action

A typical grand piano action is shown in Figure 2. As previously mentioned, this is a mechanism composed of several parts, with characteristics that are not always easily described with simple models. This is the case, for instance, with the "soft" parts, like felts, exhibiting non-linear stiffness and high values of internal friction (i.e., energy dissipation). The parts composing the mechanism are briefly described here (referring to Figure 2). The hammer is free to rotate around the pivot P1 and rests on a soft damper D1. When the key is pressed, the whippen goes up and the jack stays in its position, thanks to the action of a spring. At the same time, the hammer swings up, pushed by the jack and the repetition lever, both in contact with the rubber-covered knuckle. When the key is pressed further, the repetition lever is stopped against the regulator WR, and only the jack remains in contact with the hammer. Finally, the jack is stopped by the regulator JR at one end and starts to rotate clockwise around the pivot P2, losing contact with the hammer.

If the key descent is fast enough, the hammer reaches the string (which is not shown in Figure 2, but which lies horizontally above the action). The impact with the string has quite complicated dynamics, but they can be summarized as a finite-time impact with a loss of energy. Literature in this field says that the impact time is roughly one eighth of the period of the note's waveform, and about 20

percent of the hammer energy is lost during impact (Fletcher and Rossing 1991). The hammer, then, bounces back, and it may impact different parts of the action, according to the key position. If the key is still completely lowered, the hammer tail impacts the back-check and dissipates all its energy, without touching the whippen. (No haptic feedback is generated by this impact.) Should the key be raised a little (enough to have the jack back in its position and ready for repetition), the hammer hits the whippen, and, according to the mutual velocity, may or may not bounce back toward the string. The haptic feedback perceived by the player in this phase is similar to that experienced when a ball hits a pad, rebounds, and hits the pad again. Owing to the dissipation of energy occurring during the impact, only one rebound usually occurs. Finally, should the key be in its rest position, the hammer hits both the whippen and a rest felt D1. The hammer rebounds and, because this lowers the downward force acting on the whippen, the latter moves upward, so a little downward motion of the key can be observed at the front of the key (nearest the player).

This qualitative description of the piano action behavior has an analytical counterpart. So far, Gillespie and Cutkosky (1992) have developed the most accurate dynamic model of the piano action. However, owing to limitations in computational power, the equations of their model could be integrated only off-line. Real time experiments performed by Gillespie (1994) were based on a simplified model of the piano key, composed of the key and the hammer. The simplified model, reported in Figure 3, considers a hammer swinging around a pivot and interacting with the key through a spring-like contact.

The simplified model is fully described by the

contact stiffness k, the lengths l_1 and l_2, the hammer mass M_h and inertia $I_h = M_h l_4^2$, the length l_4, and the distance between hammer pivot and contact point l_3. As a further simplification, all rotational motions are approximated as linear; as a result, the force exchanged between key and hammer is

$$f_{hk} = k(l_2\theta - l_3 s), \qquad (1)$$

where s and θ represent the hammer and key angular position, respectively.

It is worth noting that Equation 1 considers a spring with negligible length, and it is applicable only when the spring results to be compressed, i.e., when

$$(l_2\theta - l_3 s) > 0. \qquad (2)$$

When Equation 2 is not satisfied, this means that the hammer is in free fall, i.e., its motion is driven only by gravity.

The dynamic simulator of the simplified model, then, accounts for two sub-models, corresponding to the conditions of contact and no-contact between the hammer and the key, respectively. Its behavior can be properly represented by a hybrid dynamic system (Brockett 1993), describing the hammer motion with a continuous time differential equation, in which one term (the spring force) depends on a switching function that indicates the occurrence of contact between hammer and key.

Given these considerations, hammer motion is described by the following equations:

$$I_h\ddot{\theta}(t) = h(s,\theta)(kl_3(l_2\theta(t) - l_3 s(t))) - M_h l_4 g$$

$$h(s,\theta) = \begin{cases} 1 & if \ (l_2\theta(t) - l_3 s(t)) \geq 0 \\ 0 & if \ (l_2\theta(t) - l_3 s(t)) < 0 \end{cases}, \qquad (3)$$

where g represents the gravity acceleration and the second equation is simply the Heaviside function of the spring compression, thus representing the switch between contact and no-contact conditions.

As for the haptic feedback, the force to be generated by an actuator replacing the hammer in the mechanism of Figure 2 should be equal to Equation 4, which is a modified version of Equation 1:

$$f_{haptic} = h(s,\theta)(k(l_2\theta - l_3 s)) \qquad (4)$$

It is worth noting that this model includes neither the escapement nor the hammer-string impact modeling. Also, no friction or damping is considered in the model, resulting in an overestimated hammer speed and non-dissipative impacts between hammer and key. Indeed, both dynamic simulation (i.e., the computation of the motion of each part of the mechanism) and haptic feedback cannot be accurately reproduced with such a simplified model. On the other hand, even if it can be expected that the present limitations in computational power will be partially removed by technological improvements, the high cost of the devices needed for the real-time computation is still a major impediment to the realization of a commercial product in which all the characteristics of the piano action are incorporated in a real-time dynamic simulator.

Given the above considerations, it is clear that some trade-offs are necessary in the design of a low-cost active keyboard with realistic haptic feedback. In the MIKEY project, we wanted to have a system in which the angular position and the velocity of the hammer could be accurately computed to provide an input to a sound synthesizer. In addition, we wanted to have the most important haptic effects to be reproduced at the player's hand, namely the escapement, the hammer rebounds on the key, the key weight, and the variable inertia of the system (the latter two both changing when the hammer is not in contact with the whippen or the repetition lever is engaged).

The solution adopted to satisfy both requirements is twofold. First, the dynamic simulator for the hammer motion described herein has been enriched, by modeling the dissipative impacts of the hammer with the string or the whippen and by setting l_3 as a control variable, whose value depends on the state of the repetition mechanism. Second, the haptic feedback is generated by adding the interaction force computed by using the improved dynamic model (i.e., not accounting for impacts) to a set of position-dependent events, like impacts and escapement.

In particular, the dynamic simulator computes the angular position of the hammer according to the following modified version of Equation 3:

$$I_h\ddot{\theta}(t) = h(s,\theta)l_3\left((kl_2s(t) - l_3\theta(t)) + B_k\frac{d}{dt}(l_2s(t) - l_3\theta(t))\right)$$

$$-B_\theta\dot{\theta}(t) - M_hl_4g$$

$$h(s,\theta) = \begin{cases} 1 & if \ (l_2s(t) - l_3\theta(t)) \geq 0 \\ 0 & if \ (l_2s(t) - l_3\theta(t)) < 0 \end{cases}, \quad (5)$$

$$l_3 = \begin{cases} l_{3long} & if \ rep = 0 \\ l_{3short} & if \ rep = 1 \end{cases}$$

where B_θ represents the friction of the hammer joint, and the dissipation of energy in the impact between key and hammer has been modeled like viscous friction B_k. The flag rep represents the state of the repetition mechanism, set to 1 when the repetition lever is engaged. Clearly, should the repetition lever be engaged, this results in a varied ratio between key and hammer speed, to be considered by the dynamic simulator and to be haptically reproduced. This is accounted for in the simulator (Equation 5) by changing the length l_3, depending on the repetition lever state, the latter determined by the position of the key.

This model, though containing more details of the actual mechanisms than does that of Equation 3, does not take into account some very important facts of the grand piano action. The first one is the impact between hammer and string. For this reason, during the free fly phase, the dynamic simulator (Equation 5) evaluates the occurrence of hammer–string impact. If such impact occurs, the angular velocity of the simulated hammer is set so that it bounces back with 90 percent of the velocity it had before the impact. (This corresponds to an energy loss of about 20 percent.) The impact duration, as mentioned before, is about one eighth of the note period in the actual piano, but it has been set to zero in the dynamic simulator to simplify the implementation, because this choice has no consequences on the perceived force.

Another aspect not considered by Equation 5 is that, as mentioned before, when the hammer flies back to the whippen, it may or may not impact on it, depending on the position of the key. This has been considered in the dynamic simulator, which

"stops" the simulated hammer in correspondence to a simulated back-check if the key is fully pressed.

Regarding the haptic feedback, a preliminary consideration should be made on the reproduction of the inertial terms and key weight. In the MIKEY project, to have a keyboard with limited size, the whippen is removed, and only the key is left. The force generated by the motor is applied on the back of the key, i.e., where the whippen interacts with the key in the actual mechanism, as will be shown in the next section. Because the whippen is always in contact with the key in the actual mechanism, this means that part of the force to be generated by the motor should be used to emulate the weight and the inertia of the whippen. An alternative solution that leads to smaller actuators is to replace the whippen with some properly placed weights, as will be shown later.

Regarding the haptic reproduction of the interaction between the key and whippen with the hammer, it is worth noting that Equation 5 represents a rather simplified model of the actual mechanism, leading to the following haptic force:

$$f_{haptic2} = h(s,\theta)\left(k(l_2s(t) - l_3\theta(t)) + B_k\frac{d}{dt}(l_2s(t) - l_3\theta(t))\right). \quad (6)$$

Equation (6), however, does not take into account all the nonlinear terms in friction, arising during impacts, nor does it take into account the effects of the repetition lever engagement, which is perceived as a force that increases while the jack is sliding under the soft surface of the knuckle, and then rapidly decreases as the key is further pressed.

All the above considerations can be summarized by the following equation, representing the force to be applied at the key rear end, in order to have the correct haptic feedback:

$$f_h(t) = f_{haptic2}(t) + G + X(t) + I_x\ddot{\theta}(t), \quad (7)$$

where G represents a user-selectable simulated gravity effect (i.e., a user can program each key to have different weights), and X accounts for extra terms like the escapement or impacts. As for the term I_x, this represents an additional inertial term, which can be used to reproduce the haptic perception of keys with different inertia.
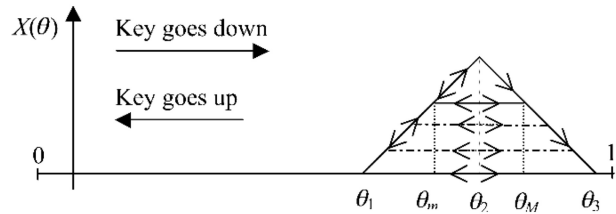
Figure 4. Simplified model of escapement showing force v. position.

Figure 5. Management of inversions during the escapement phase.
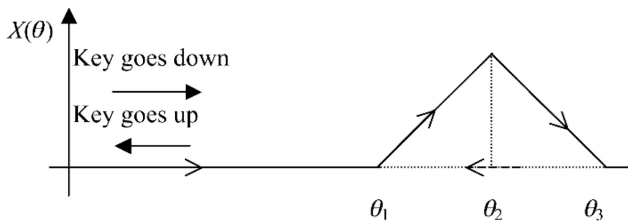
As for the extra terms *X*, we first consider the different types of hammer–key impacts and the corresponding haptic effects. When the key is completely pressed, the hammer head is stopped by the back check, and no haptic feedback must be generated. If the key is completely up, the impact is between the hammer link and the rest damper. This is a dissipative event, in which the energy remaining after the impact is a small part of the original one. Also, to avoid multiple rebounds, when the hammer velocity goes below a certain threshold, its value is set to zero after the impact. When the key is in any other position, the hammer-key impact occurs at the contact point, which can be modeled as a spring-damper element, with a highly nonlinear damping ratio and stiffness. To avoid complex modeling, the force impulse to be haptically reproduced is computed by considering the impact as a partially dissipative event, in which the intensity of the force impulse depends on the relative velocity between hammer and key, and the energy of the hammer (i.e., its speed) after the impact is a fraction of that before the impact. Of course, amplitude and duration of the force pulse depend on the relative speed of hammer and key. In MIKEY, to simplify the system, the duration has been estimated experimentally, and the amplitude is determined on the basis of the observed reduction in absolute speed after the impact in the actual keyboard.

Finally, *X* contains a term depending on the key position θ, which accounts for the escapement. This is essentially a nonlinear spring that intervenes when the key reaches the position corresponding to the contact of the whippen with the regulator. After the contact, the player perceives an increased resistance of the key, which suddenly drops when the
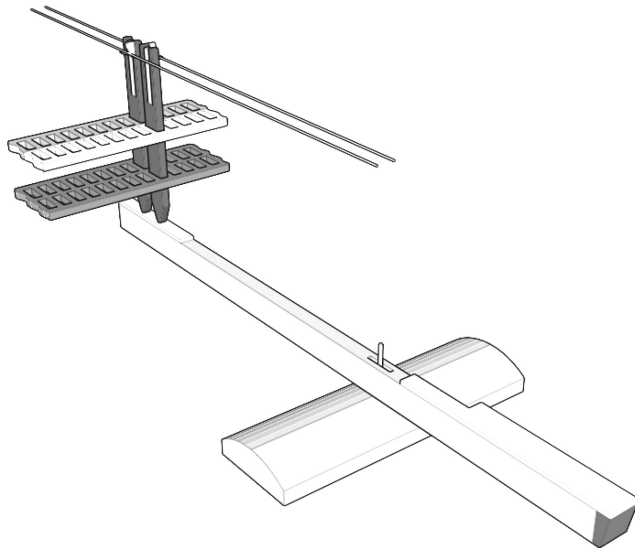
second regulator forces the jack to slide under the knuckle. A simplified model of this sequence has been incorporated in the escapement model used in MIKEY system and it is shown in Figure 4.

When the key reaches the position θ_1, the force applied by the actuator linearly increases until it reaches θ_2. At this point, the force linearly decreases, until it reaches zero in θ_3. On the way back to the origin, the force is held at zero, because the jack reload is an event that does not generate haptic feedback. A problem arises when the key goes up (i.e., it inverts its motion) during escapement. A solution proposed here is to consider the trajectories shown in Figure 5.

If the inversion occurs between θ_1 and θ_2, the force goes down with the position. Once the escapement peak is passed, if an inversion in motion occurs (e.g., at the point θ_M in Figure 5), the force is kept constant, at the value it had at moment of inversion, until the key gets to the position θ_m in which the force of the positive slope is equal. Then, should the position decrease further, the force decreases with it. If during the motion from θ_M to θ_m another inversion occurs, the force is kept constant until the key position gets again to θ_M. With this simple model, the force perceived during escapement first increases and then rapidly decreases, as if a trigger were pushed. Furthermore, the sliding of the jack under the knuckle during re-loading of the escapement is modeled as a constant force, which allows handling, in a simple way, the possible inversion of motion in this phase.

The simple model of the escapement is of course linked to the dynamic simulator, which is informed of the state of the jack and, in turn, may alter the value of the mechanical advantage between key and

Figure 6. Double-plectrum harpsichord mechanism.

Figure 7. Harpsichord jack: (a) key going down; (b) return to rest position.
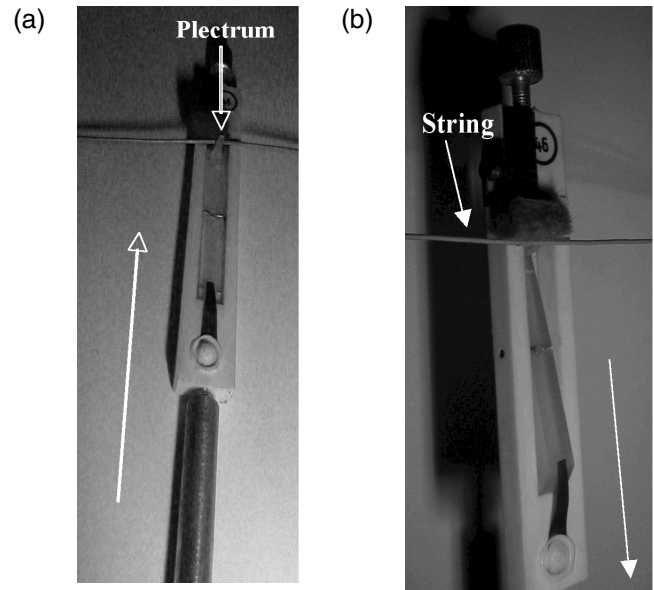
(a) Plectrum (b) String

hammer motion accordingly. Experimental results reported in the next section and informal tests with performers confirm that a quite realistic haptic feedback is obtained by adding the various contributions described in Equation 7.

Harpsichord

Many harpsichords have two strings for each key, with a row of jacks for each set of strings. (A harpsichord mechanism with two jacks is shown in Figure 6.) Stops, or registers, allow the player to move unwanted sets of jacks slightly out of reach of the strings, thus making possible different volumes and combinations of tone colors. One set of strings may sound an octave above normal pitch (Humphries 2002).

In Figure 7a, a jack is shown, with the string between a damper and the plectrum. When the key goes down, the string is pushed against the elastic plectrum, and the force perceived increases as the key goes down until the plectrum plucks the string. After this event, the force approaches a very low value. Then, the key is raised and the plectrum easily slides aside, under the action of the string (see Figure 7b), so that the mechanism is ready to pluck the string again.

The haptic feedback for harpsichords is very similar to the escapement in the grand piano action, with a position-dependent force that increases as the key is pressed until a threshold position, corresponding to the string's plucking. If the key is pressed further, the force rapidly decreases. This behavior is similar to that of the escapement in the grand piano, so it has been emulated by using the function reported in Figure 5. Of course, actual thresholds and forces have been tuned experimentally on an actual harpsichord. As for such multi-string systems, their haptic feedback has been obtained by simply putting together several plectrum simulations, each of them with different (possibly non-overlapping) thresholds, as shown in Figure 8.

In addition to the position-dependent force, a viscous term can be added to the motor command to simulate the friction of the real key, resulting in the following commanded force:

$$f_{harp}(t) = B\dot{\theta}(t) + X(\theta(t)). \qquad (8)$$

It is worth noting that the harpsichord exhibits a smaller key inertia relative to that of the grand piano. Such a difference can be totally handled by the actuators, or it can be obtained by properly placing (and removing) additional weights on the keys, ac-

44

Computer Music Journal

Figure 8. Multi-plectrum harpsichord, force to be generated versus position.

Figure 9. Hammond organ.
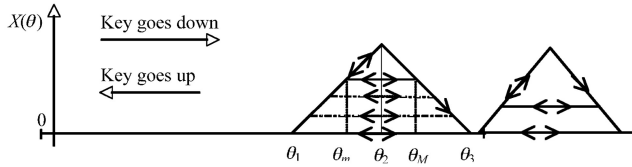
cording to the instrument to be emulated. Of course, the use of additional weights reduces the flexibility of the system but greatly reduces its cost, because the force to be generated by the motor (and thus its size and cost) does not include the inertial term, which can be quite high when playing a fortissimo note on the grand piano.

Hammond Organ

The last keyboard-operated instrument considered in the MIKEY project is the Hammond organ, shown in Figure 9. This instrument was conceived with the goal of giving the player the same haptic feedback as in electrically controlled pipe organs. In such instruments, electrically actuated pneumatic valves are turned on by a small switch placed under each key. The perceived force is the same as if a spring were placed under the key, with a very small inertia and weight for the key itself. This means that the force to be generated by the actuator in the virtual keyboard must be proportional to key position. Should the key in the virtual keyboard have a higher weight and inertia than the desired one, the motor must apply a force to emulate a negative inertial term and weight. This solution, however, may lead to unstable behavior, so it is preferable to have removable weights mounted on each key.

Given these considerations, the force to be generated by the motor in the most general case (i.e., without removable weights) should be expressed as

$$f_{hammond}(t) = k\theta(t) + B\dot{\theta}(t) - \Delta G - \Delta J\dot{\theta}(t), \qquad (9)$$

where ΔG and ΔJ account for the reduction of perceived weight and inertia, respectively. As in the harpsichord, the viscous term B is added, in order to take account of friction that is usually present in the real keyboard.

Experimental Setup

An important issue in designing a realistic simulator is to tune its parameters, in order to closely emulate the behavior of the actual system. For this reason, the first part of the experimental activity has been devoted to the collection of data from a real grand piano keyboard to be used in model tuning.

Key position is measured with a simple reflective linear position sensor, placed under the front part of the key (i.e., near the player). Hammer position is sensed by placing an infrared LED on the hammer stem, with its light beam pointing to a 37-mm position-sensitive detector (PSD) from Hamamatsu Photonics, which in turn produces an analog signal proportional to the hammer position (see Figure 10).

The force exerted on the key is measured by using a piezo-resistive sensor placed on the front part of the key, as shown in Figure 11. Additionally, a simple detector for determining when the hammer is no longer in contact with the whippen has been realized by covering both the hammer and the whippen with a thin layer of conducting material, thus realizing an electrical switch that opens when the hammer leaves the whippen.

Using this modified keyboard, it is possible to estimate several parameters, such as the hammer inertia and the energy loss occurring in the impacts against the whippen and the rest felt. As an example, Figure 12 reports the recorded hammer posi-

Figure 10. Hammer position sensing.

Figure 11. Force sensor.

Figure 12. Hammer rebounds on the whippen.

Figure 11

Figure 12

tion, released from the position at which it impacts on the string. From the observed decay of the amplitude and the oscillation period, the equivalent stiffness and damping ratio can be easily obtained. Furthermore, the same keyboard has been used in validating the simulator by comparing the simulated hammer trajectory with the actual one, under the action of the same input (as will be described later).

The second part of the experimental activity uses a different keyboard, the active one, shown in Figure 13. It represents only a small section of a complete piano keyboard, and only three keys are connected to rotational voice coils motors through rigid links and low friction ball bearings, as shown in detail in Figure 14. The motors, which have been removed from standard hard disk drives (U4-class disks, made by Seagate), have a very low friction and inertia, so that the force applied to the key can be considered directly proportional to the current applied to the motor, thus avoiding the use of expensive force sensors. The torque constant is about
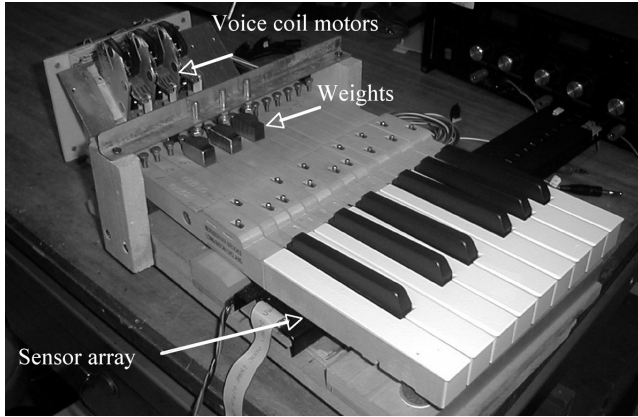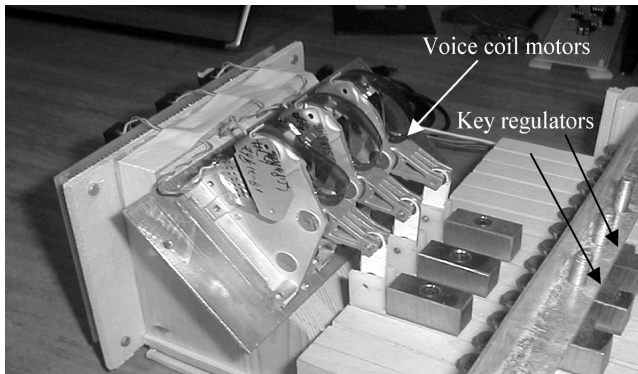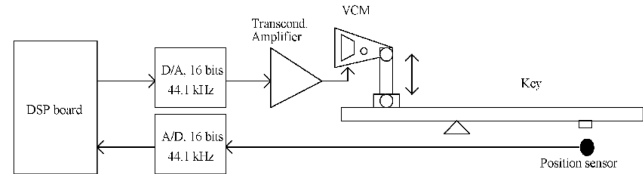
Figure 13. MIKEY key-
board.

Figure 14. Detail of the
MIKEY keyboard.

Figure 15. Block diagram
of the key-control unit.

Figure 13

Figure 14

acceleration, position data are filtered through multi-sample differentiators (Bibbero 1977). The force to be generated by the motor is computed in real time by the DSP and sent to a 16-bit, 44.1-kHz D/A converter. Its output constitutes the input of a linear trans-conductance amplifier (i.e., an amplifier that generates an output current that is proportional to the voltage applied at its input), realized with a high-power operational amplifier and capable of forcing a current up to 2 A into the voice coil motor, with a bandwidth of 40 kHz.

Note that in Figure 14, some weights have been added to the original key structure. Their masses and positions have been chosen to get the same inertia and weight of the key as with the whippen. This solution is required to limit the request of force to be generated by the motor. For instance, it is useless and power-consuming to use the motor to generate the gravitational effect originally due to the whippen, since this constant term can be easily replaced by a properly placed weight. Finally, in Figure 13, key regulators are shown. They have been added to provide a mechanical stop to the key that otherwise could pop off the keyboard in case of fortissimo action, since the "natural" stop, provided by the whippen, has been removed.

It is worth noting that the system consists of low-cost and readily available components. In particular, the voice-coil motor has been obtained from a hard disk drive and can be produced at very low cost (about US$ 2 per motor). The A/D-D/A converters have been realized with a low-cost single chip codec, usually adopted in PC sound boards (about $1 per key). The transconductance amplifier is also derived from hard-disk current drivers (SV123 by STMicroelectronics, $1 per channel). Finally, the DSP used is an outdated device, easily replaceable with present microcontrollers (typically ranging around $4 per chip). As a result, the overall cost for the hardware of each key is below $10.

0.007 Nm/A, and the generated torque can be considered proportional to the applied current, up to the frequency of the first mechanical resonant mode of the voice coil motor (VCM), around 3 kHz. The rated current is around 500 mA, and the peak current is 2 A (which is allowed for less than 100 msec). Key position is measured by using a low-cost reflective sensor, placed under the front of the key. Its output is roughly linear, and its range is normalized between 0 and 1 by an automated tuning procedure.

According to the block diagram of Figure 15, each sensor's output is sampled by a 16-bit, 44.1-kHz A/D converter, which sends the digital data to a digital signal processor (DSP) board built around a Motorola 56000 series chip. To obtain key velocity and

Experimental Results

An active keyboard is designed to generate a haptic feedback as close as possible to that of a real keyboard. In addition, when the piano action is emulated, the dynamic simulator should compute the hammer position accurately to give meaningful information to the sound synthesizer.

The first type of experiment is usually carried out with a group of expert performers, but this has not been done in the MIKEY project, because the first tests with performers were quite biased by the fact that no sound was generated when acting on the key, so the correlation between haptic perception and generated sound was lost. For this reason, the experimental results for the grand piano and the harpsichord first show the force commands generated by the dynamic simulator, pointing out the events that have haptic relevance. For the grand piano, we then show the agreement between actual and simulated hammer motion under the same key motion. No experimental results are presented for the Hammond organ, as the haptic force is trivially obtained by generating a force proportional to key position.

Grand Piano

The force generated by the motor is the sum of several components that in turn depend on the state of the key, its escapement, etc., as stated by Equation 7. Figure 16 shows the profile of the force generated by the motor when the key is completely down and the hammer bounces back from the string. At time t_1, the key descent starts, and the force generated is relative to the viscous term. After awhile, the escapement phase starts, the force rises, and then goes rapidly to zero at t_2, when the key stops. The key remains down until t_3, when it is released by the player. When going up, the key is under the action of a viscous force. When it reaches its final rest position, the hammer rebounds on the rest felt at t_4, and a small key rebound is observed.

A typical experiment to perceive the haptic feedback owing to the rebound of the hammer on the key involves pushing the key down to a middle position (before the escapement region) by placing a
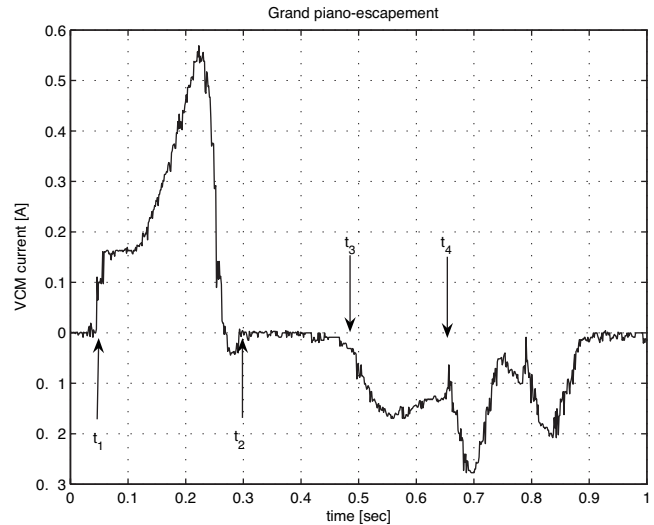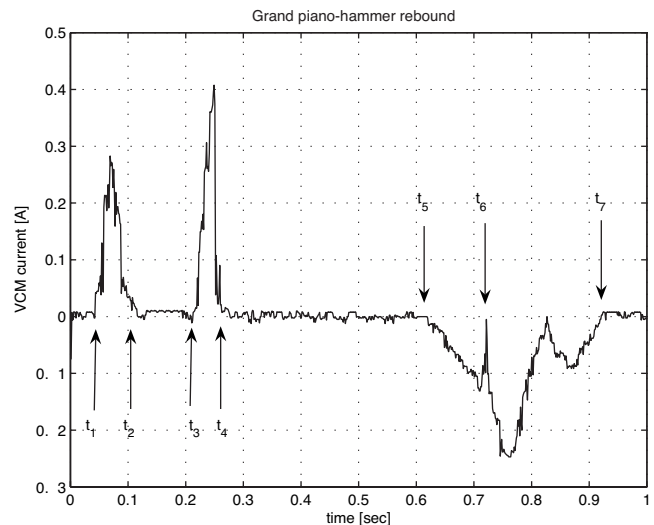

Figure 16

Figure 17

constraint under the key itself. In this case, the effect of the hammer impact is to pull up the key. This can be observed in Figure 17, where the force generated in the above-mentioned conditions is reported. From t_1 to t_2, the key goes from the rest position to the constraint. The corresponding force is caused by inertial and viscous effects. Meanwhile, the dynamic simulator computes the hammer posi-

Figure 18. Position response of the hammer motion.

Virtual hammer position

Virtual key position

Actual hammer position

Actual key position
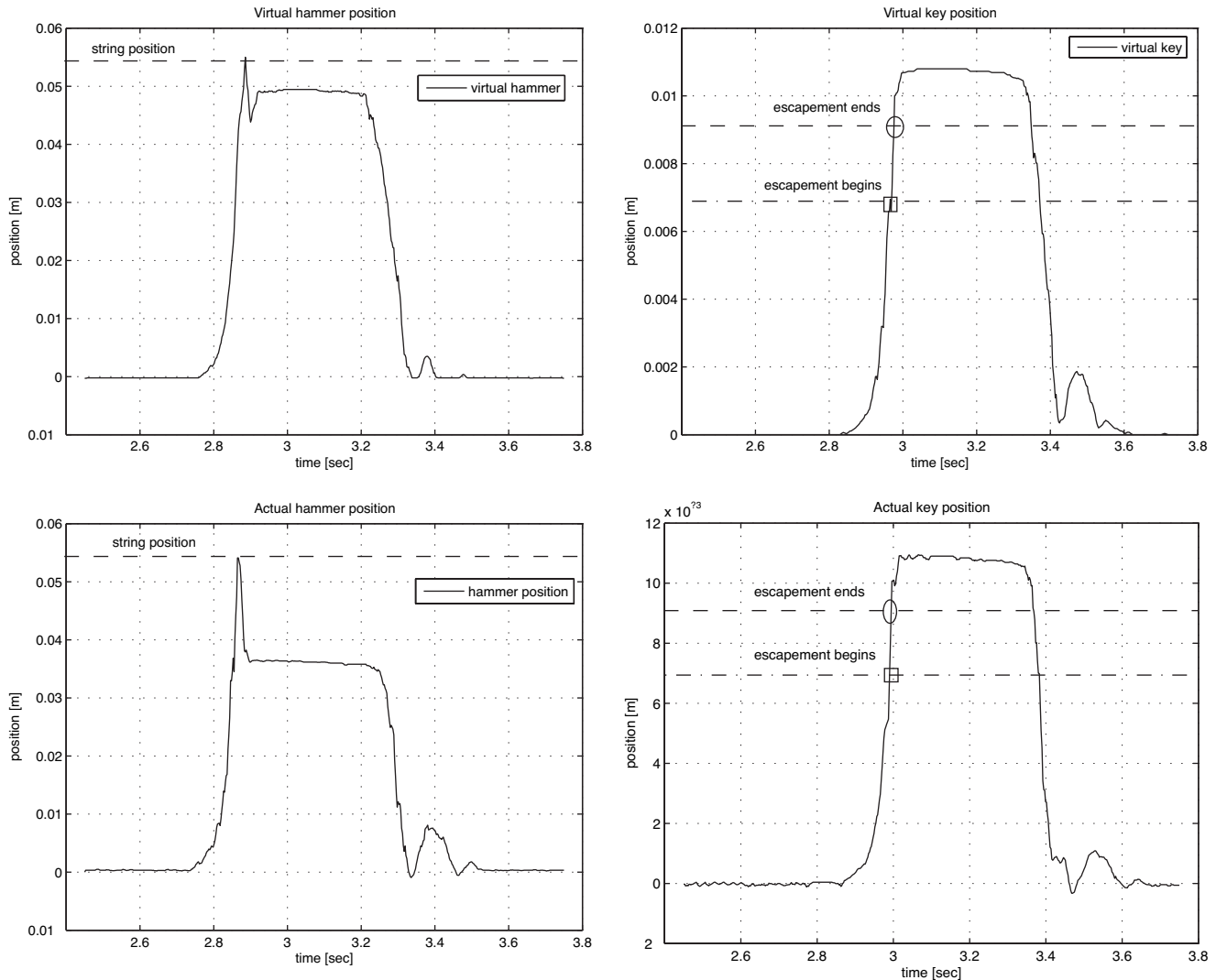
tion. The hammer leaves the key and, after a short flight, impacts the key at time t_3. The force impulse ends at t_4. When the key is released at t_5, the force represents a viscous effect until at t_6 the hammer rebounds on the rest felt, causing a motion of the key that ends at t_7. Note that the final rebound is smaller when the key is only half pressed, because the simulator accounts for the smaller energy of the hammer at the time of impact with the rest felt.

The behavior of the dynamic simulator has been validated in two ways. The first type of test was aimed at comparing the simulated hammer motion

with the actual one under the same key motion. This type of validation experiment is used to confirm the correctness of the inertial, kinematic, and friction parameters used in the mathematical model of the key. To implement this type of experiment, it is necessary to move the keys of both keyboards (the standard and the active one) with a servo actuator, programmed to generate a typical profile. (This is obtained by recording the key motion while a player was playing on the standard keyboard.)

Figure 18 illustrates the experimental results obtained, confirming that the dynamic simulator

Figure 19. Force response
of the hammer motion.
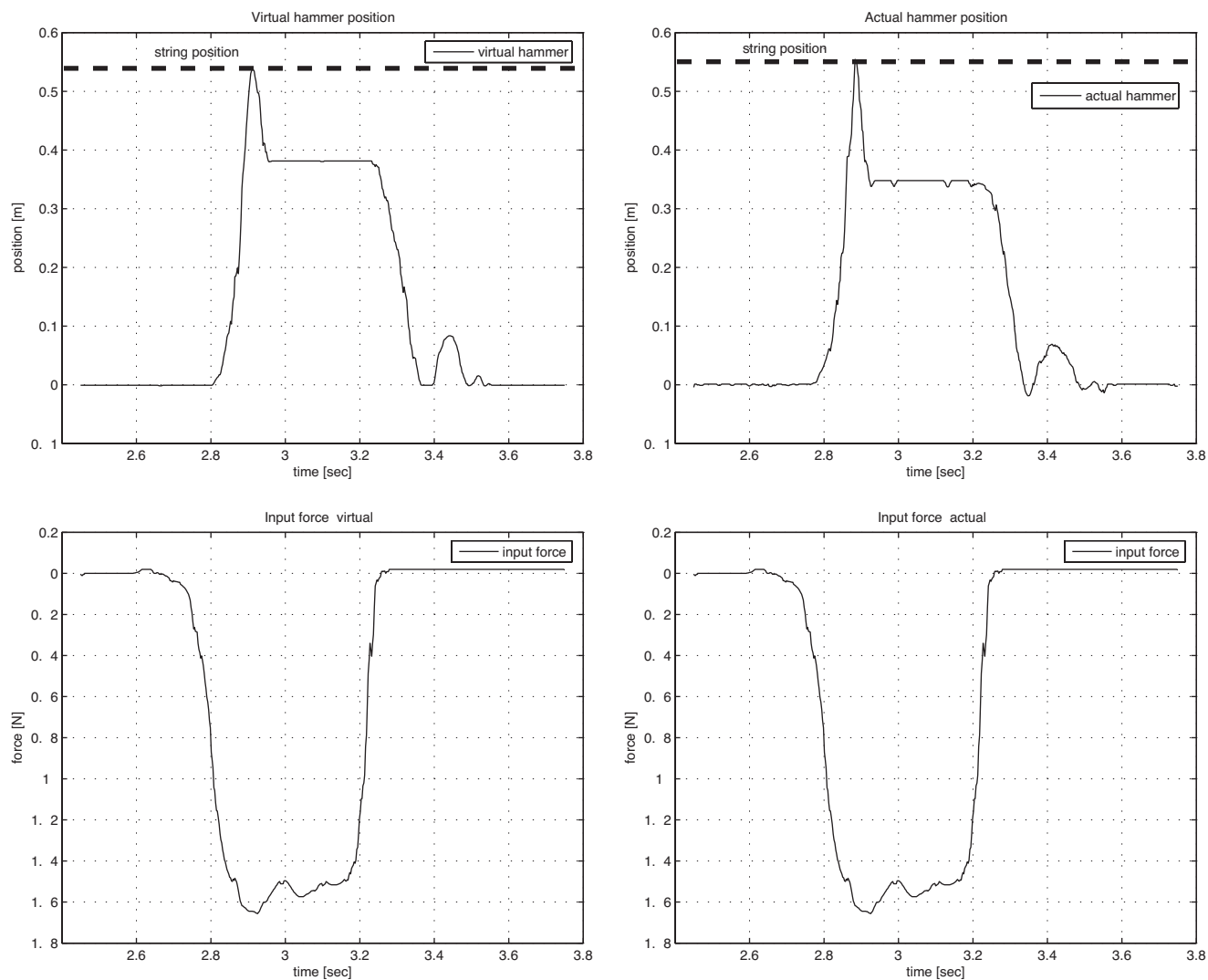
designed correctly replicates the behavior of the actual mechanism. It is worth noting, however, that this result does not provide much information on the force perceived by the player, because the dynamic simulator does not take into account the key inertia, but only its angular position (and derivatives).

Thus, the second type of experiment was aimed at showing that the actual and the simulated hammer have similar motion when the same force was applied to the key. This has been realized by first recording the force exerted by the player on the actual keyboard and then by applying the same force

(by using a force-controlled actuator) to the key of the MIKEY keyboard. The results obtained are reported in Figure 19, and they confirm that the virtual mechanism closely replicates the behavior of the grand piano action from the point of view of the dynamic response.

Harpsichord

The force to be generated by the motor in the virtual harpsichord is shown in Figures 20 and 21. In

Computer Music Journal

*Figure 20. Generated force
from the single-plectrum
harpsichord.*

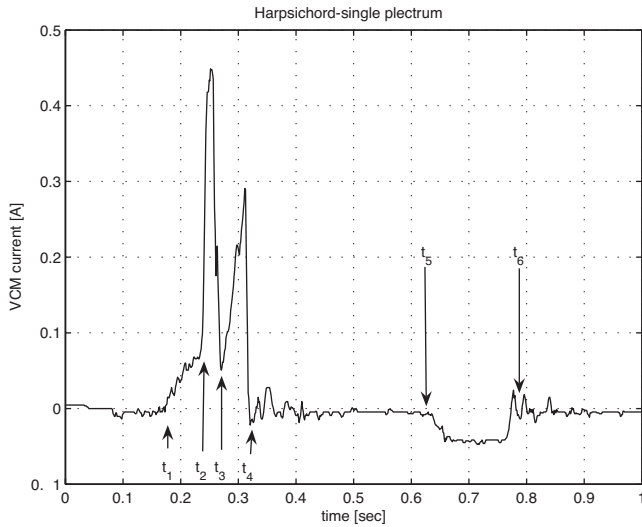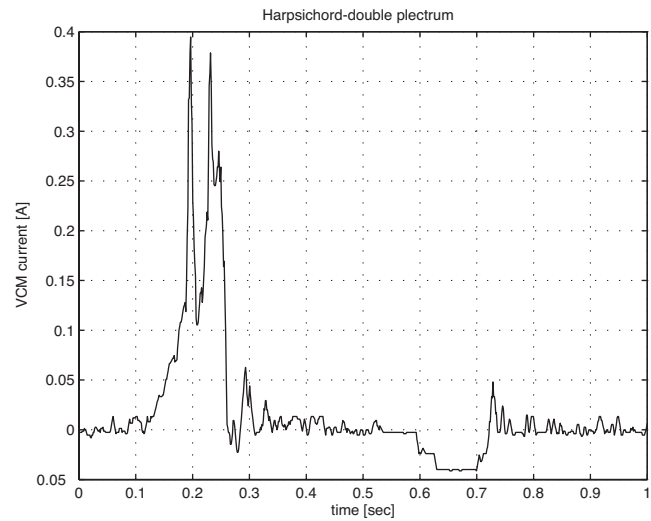*Figure 21. Generated force
from the double-plectrum
harpsichord.*

Figure 20, a single-jack harpsichord is considered. The key descent starts at time t_1, and the force applied to the key emulates a viscous friction. At t_2, the plectrum engages with the string and plucks it. This event ends at t_3. At t_4, the key is completely down and stops. At t_5, the key is raised, and a viscous effect is generated until the key gets back to the rest position at t_6.

In Figure 21, the force for a double-jack harpsichord is reported. It is worth noting that the two virtual plectrums are purposely set with a large gap to show two distinct spikes during key descent.

Conclusion

The realization of a multi-instrument active keyboard may require the design of a complex dynamic simulator, in which all parts composing the real mechanism are included. This approach, however, is very expensive in terms of computation and may be unsuitable for real-time operation. In the MIKEY project, we have demonstrated that it is possible to have a realistic feedback and good accuracy in dynamic simulation (e.g., in evaluating the hammer position in grand piano) by using a simplified dynamic simulator that generates a set of events (e.g., impacts and states). In turn, such events generate a set of haptic feedbacks. As a result, the MIKEY sys-

tem is capable of generating the haptic feedback for three different keyboard-operated instruments. Experimental results confirm that such feedback contains many of the characteristics of the real instrument. Moreover, the system has been realized by using low-cost electronics, demonstrating that a mass production of an active keyboard is now possible with the proposed approach.

Acknowledgments

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