Multi-instrument virtual keyboard – The MIKEY project

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Abstract
The design of a virtual keyboard, capable of reproducing the tactile feedback of several musical instruments is reported. The key is driven by a direct drive motor, which allows friction free operations. The force to be generated by the motor is calculated in real time by a dynamic simulator, which contains the model of mechanisms' components and constraints. Each model is tuned on the basis of measurements performed on the real system. So far, grand piano action, harpsichord and Hammond organ have been implemented successfully on the system presented here.

Keywords
Virtual mechanisms, dynamic simulation

INTRODUCTION
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 with the instrument stimulates several senses in the player: tactile, kinesthetic, proprioceptive etc. It constitutes a bi-directional communication channel between player and instrument. In fact, the player manipulates (by hand or mouth) the instrument, and the force exerted on it correspond to a motion of the manipulated part and, in turn, to a specific generated sound. On the other hand, the instrument reacts with a force to a particular motion, and this reaction contains useful information on the instrument behavior. For instance, by paying attention to the interaction force that arises during key descent, the piano player can detect the escapement re-triggering and, in turn, vary the key motion in order to obtain the fastest repetition of the note. Roughly speaking, the haptic information allows the player to perceive the "state" of the mechanism being manipulated through the key. By using this knowledge on the state of the mechanism and correlating it with the sound generated, the player learns a strategy to obtain the desired tones. This tight correspondence between acoustic response and touch response, however, is lost in electronic instruments, like synthesizers, in which the sound generation is related only to the speed of the key. In this type of synthetic instrument, the touch feedback is independent from the instrument being simulated. For instance, the interaction with different instruments like harpsichord, piano or pipe organ give to the player the same haptic information. This constitutes a severe limitation for the musician, who looses expressive control on the instrument and, in turn, on the generated sound.

The above consideration sparked 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 [1] [2] [3] [5] [6] [7]. Such kind of system falls in the category of "virtual mechanisms", i.e. haptic displays devoted to the reproduction of the touch feedback that a user would experience when interacting with a mechanism constituted by several parts, interacting one another and with constraints. In this field, relevant results have been obtained by Cadoz and his group [2] [3], who have developed a high performance force feedback interface, suitable for the realization of virtual instruments.

Among all the possible keyboard-operated instruments, the grand piano has by far the most complicated mechanism [8]. The grand piano action, in fact, is composed of dozens of components and this has impeded the realization of a real-time dynamic simulator for it. A remarkable work from Gillespie shows in [7] 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 a piano mechanism. However, the obtained model, even if it results in good agreement with experimental data, can run only off-line. Given the difficulty of having a complete real time dynamic simulation, several researchers have focused their work on the reproduction of only one or few specific behaviours of the mechanism. For instance, Baker in [1] proposes the simulation of user programmable inertial and viscous characteristics, in order to adapt the keyboard to the player's taste. Gillespie, instead, has studied in [5] and [6] the modelling of a simplified piano action, composed of only two bodies, namely the key and the hammer. Even with this very simple model, it is possible to reproduce part of the hammer motion, composed essentially 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, and such characteristics are very useful in order to re-gain the previously mentioned correspondence between acoustic response and touch response.

In this paper, we present the preliminary results obtained within the MIKEY (Multi-Instrument active KEYboard) project, 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 trade-off between model accuracy and real-time operability had to be made at the beginning of the project, especially for the grand piano. In our case, we started from the work of Gillespie and we added some additional feature, namely the hammer-string impact, various state-dependent hammer-key impacts and the escapement effect. Also, in order to improve the quality of the haptic feedback, direct-drive, ultra-low friction motor have 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.

MECHANISMS MODELLING

The realization of a realistic haptic interaction with an active keyboard requires the use of a model of the mechanism to be emulated. We will describe in the following three different mechanisms emulated by the MIKEY system, pointing out the simplification done on the complete model, in order to have a dynamic simulation that runs in real time. The three models considered are the grand piano, the harpsichord and the Hammond organ.

Grand piano action

The grand piano action is shown in Fig.1. As mentioned in the previous section, this is a mechanism composed of several parts, which characteristics are not always easily attained. This is the case, for instance, of the “soft” parts, like felts, characterized by high energy dissipation and non-linear stiffness. We mention here the main parts composing the mechanism. In Fig.1 we can see the hammer, free to rotate around the pivot P1, and resting on a soft damper D1. The hammer swings up under the action of the jack and the escapement lever, both pushing against the rubber-covered knuckle. When the key is pressed, the whippen goes up and the jack stays in its position, thanks to the action of a spring. 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, also the jack is stopped by the regulator JR at one end and starts to rotate clockwise around the pivot P2, loosing contact with the hammer. If the key motion is fast enough, the hammer starts its flight toward the string. The impact with the string has a quite complicated dynamics, but it can be summarized as a finite time impact with loss of energy. Literature in this field says that the impact time is roughly one eighth of the period of the note, while about 20% of the hammer energy is lost during impact [4]. The hammer, then, bounces back and may have different impacts with the whippen, according to the key position. If the key is still fully pressed, the hammer tails impacts the back-check and dissipates all its energy, without touching the whippen (no haptic feedback is generated by this impact). Should the key a little bit raised (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 in this phase is the same as when a ball hits a pad, rebounds and hits again. Due to the dissipation of energy, only one rebound usually occurs. Finally, should the key be in rest position, the hammer hits both the whippen and a rest felt D1. The hammer rebounds and, since a reduced force is acting on the whippen, this moves upward and a little downward motion of the key can be observed at the player’s side.

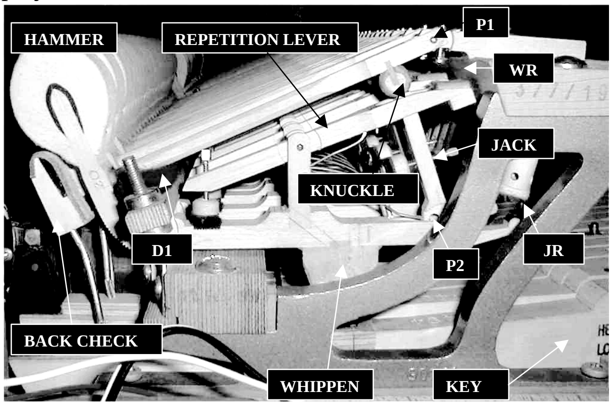

Figure 1. Grand piano action

This qualitative description of the piano action behavior has, of course, an analytical counterpart. So far, Gillespie has developed the most accurate dynamic model of the piano action [7]. However, due to limitation in computational power, the equation of his model can be integrated only off-line. Real time experiments performed by the same author [5] used a simplified model of the piano key, constituted only by the key and the hammer. The model, reported in Fig.2, considers a hammer swinging around a pivot and interacting with the key through a spring-like contact.

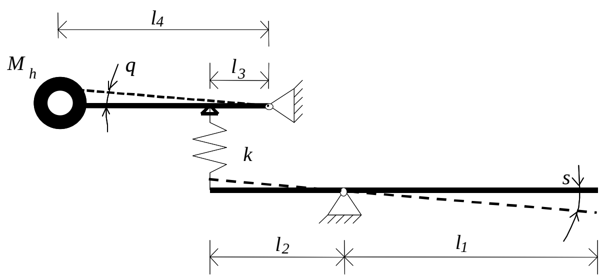

Fig.2 - Simplified model of the piano action

The model is fully described by contact stiffness k, key lengths l_1 and l_2, hammer mass M_h, inertia $I_h=M_h l_4^2$, length l_4 and distance between hammer pivot and contact point l_3. *è* and *s* are the angular displacements of the hammer and the key, respectively. As a further simplification, all rotational motions are approximated as linear, so that the force exchanged between key and hammer results:

$$f_h = k(l_2 s - l_3 q) \quad (1)$$

The dynamic simulator accounts for two sub-models, corresponding to the conditions of contact and non-contact between hammer and key, respectively. During contact, hammer motion is described by the following equation:

$$I_h \ddot{q} = k l_3 (l_2 s - l_3 q) - M_h l_4 g \quad (2)$$

while during free fly, only gravity acts on the hammer:

$$I_h \ddot{q} = -M_h l_4 g \quad (3)$$

The switch between the models is driven by the sign of the force transmitted by the spring *k*. In fact, a negative force cannot be applied by the spring and when the dynamic simulator, during integration of Eq.(2) detects the following condition:

$$(l_2 s - l_3 q) < 0 \quad (4)$$

this means that the hammer is no longer in contact with the key, i.e. it is flying toward the string and Eq.(3) is integrated from then on, until Eq.(4) become false again, revealing a new contact between hammer and key. As for the haptic feedback, the force to be generated by an actuator replacing the hammer should be equal to Eq.(1).

It is worth noticing that this model does not include neither escapement nor hammer-string impact modeling, and this results in a unrealistic haptic interaction. Also, no friction is considered in the model, resulting a an overestimated hammer speed. It can be expected that computational power limitation will be partially removed by technological improvements, but high cost of the devices needed is still a major limitation to the realization of a commercial product, in which all the characteristics of the piano action are incorporated in the real-time dynamic simulator.

Given the above consideration, it is clear that the design of a low-cost active keyboard with realistic haptic feedback must consider some trade-offs. In MIKEY project we wanted to have a system in which the hammer angular position and velocity could be accurately computed, in order 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 (both reduced when the hammer is flying toward the string). The solution adopted to satisfy both requests has been the use of a simplified hammer-key model for the dynamic simulation as described above, in which the hammer-string impact is added, while the haptic feedback is generated by summing the output of a simplified dynamic model to a set of position-dependant events, like impacts, rebounds and escapement. In particular, the dynamic simulator must calculate the coordinate of the hammer according to Eq. (2) and (3) and, during the free fly phase, consider the occurrence of hammer-string impact, when the hammer bounces back with 80% the velocity it had before the impact. The impact duration, as mentioned before, is about 20% of the note period. In addition to this, the simulator must signal the occurrence of hammer-key impacts. The interaction force to be generated by the motor depends on the actual mechanism to be replaced by the virtual one. In MIKEY project, only the key is left and the force generated by the motor is applied at its rear end, i.e. in the original point of interaction between whippen and key, as it will be shown in the next Section. The force to be generated by the motor can be described by the following equation:

$$i(t) = I(t)\ddot{q}(t) + B(t)\dot{q}(t) + G(t) + X(t) \quad (5)$$

where *I* and *B* represent the time-varying overall inertia and friction of the virtual action at the contact point between key and whippen, *G* represents gravity effects and *X* accounts for extra terms like impacts, escapement etc. The value of each coefficient in Eq.(5) depends on the state of key-hammer assembly. If the hammer is in contact with the key, the inertial, viscous and gravity terms are higher than those to be used when the hammer is flying toward the string. As for the extra term, as described at the beginning of the paragraph, three different types of hammer-key impacts may occur. When the key is completely pressed, the hammer's rear end 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 hammer's velocity goes below a certain threshold, its value is set to zero at 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. Moreover, the force impulse exchanged between hammer and key depends on the relative velocity of hammer and key.

Finally, *X* contains a position-dependant term, which accounts for the escapement. This is essentially a non-linear spring, which 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 Fig. 3.

When the key reaches the position x_1, the force applied by the actuator linearly increases until it reaches x_2. At this point, the force is linearly decreases, until it reaches zero in x_3. On the way back to the origin, the force is kept to zero, since the jack re-load 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 Fig.4.

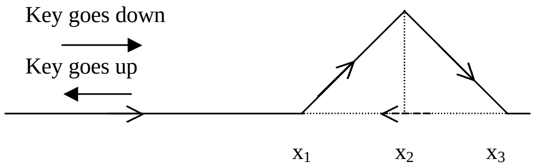

Figure 3. Simplified model of escapement – Force vs. position

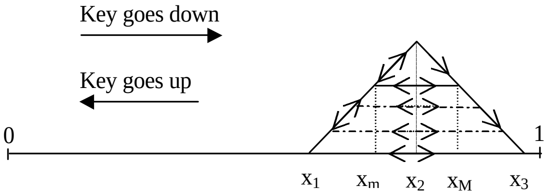

Figure 4. Management of inversions during escapement phase

If the inversion occurs between x_1 and x_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 x_M in Fig.4), the force is kept constant, at the value it had at moment of inversion, until the key gets at the position xm in which the force of the positive slope is equal to such constant. Then, should the position decrease further, the force goes down with it. If during the motion from x_M to x_m another inversion occurs, the force is kept constant until the key position gets again to x_M. With this simple model, the force perceived during escapement first increases and then rapidly decreases, as 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 to handle 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 on the state of the jack and, in turn, may alter the value of the mechanical advantage between key's and hammer's motion accordingly.

Experimental results reported in the next section and test with performers confirm that the haptic feedback obtained by summing the above described contribution is quite realistic.

Harpsichord

Harpsichord mechanism is shown in Fig.6. When the key is pressed, one or more jacks are raised. The number of jacks to raise can be usually selected by properly positioning a set of stop rails. Using such rails, the key can be "programmed" to raise more than one jack, each of them plucking a different string. When the key goes down, the string is pushed against an elastic plectrum and the force perceived increases as the key goes down, until the plectrum plucks the string. After this event, the force goes at a very low value. Then, the key is raised and the plectrum easily slides aside, under the action of the string, so that the mechanism is ready to pluck the string again. The haptic feedback for harpsichord is very similar to the escapement in grand piano, with a position-dependant increasing force that rapidly decreases when a certain threshold is reached. For this reason the force to be generated by the actuator in the MIKEY system when emulating the harpsichord is obtained by a model as in Fig.4, where thresholds and forces have been set at proper values. As for multi-plectrum systems, they have been obtained by simply putting together several plectrum simulations, each of them with non-overlapping thresholds, as shown in Fig.6.

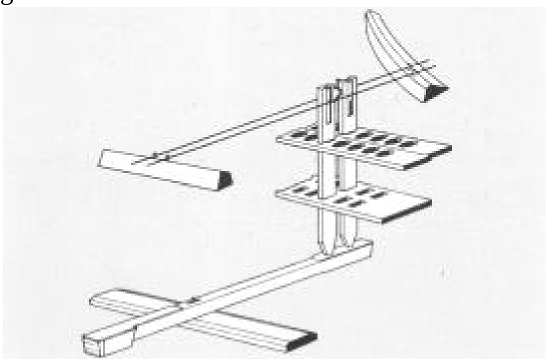

Figure 5. Harpsichord mechanism

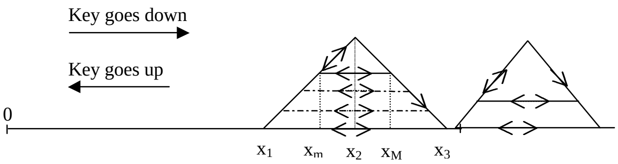

Figure 6. Multi-plectrum harpsichord – force to be generated vs. position

In addition to the position-dependant force, a viscous term can be added to the motor's command, in order to simulate the friction of the real key.

Hammond organ

The last keyboard-operated instrument considered in MIKEY project is the Hammond organ. This instrument has been conceived with the target of giving to the player the same haptic feedback ad in pipe organs with electric command. 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 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 has to be proportional to key's position. Furthermore, to make the key lighter, a negative, constant term can be added, so that the force becomes:

$$i(t) = kq(t) - const \qquad (6)$$

As in the harpsichord, a viscous term can be added to Eq.6, in order to take account of friction that is usually present in the real keyboard.

EXPERIMENTAL SETUP

The electro-mechanical system for the active keyboard is shown in Fig.7. Three keys are connected to rotational voice coils motors through rigid links and low friction ball bearings. The motors 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 0.007 Nm/A. Key's position is measured by using a low-cost reflective sensor, placed under the key, on the player's side. Its output is pretty linear and its range is normalized between 0 and 1 by an automated tuning procedure. It is worth noticing that from this measurement both key velocity and acceleration are obtained, by using multi-sample filtered differentiation. Also, key's position is filtered by a low-pass Butterworth filter to reduce the noise.

According to the block diagram of Fig.8, each sensor's output is sampled by a 16 bit, 44.1 kHz A/D converter, which sends the digital data to a DSP board, built around a Motorola 56000 chip. 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 transconductance amplifier, capable of forcing a current up to 2 A into the voice coil motor, with a bandwidth of 40 kHz.

It can be noticed in Fig.7 that weights have been added to the original key's structure. This solution is required in order to limit the request of force to be generated by the motor. For instance, it is useless and power consuming to give the motor the duty to generate the gravitational effect originally due to the whippen, since this constant term can be easily replaced by a properly placed weight. Finally, key regulators have been added in order 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.

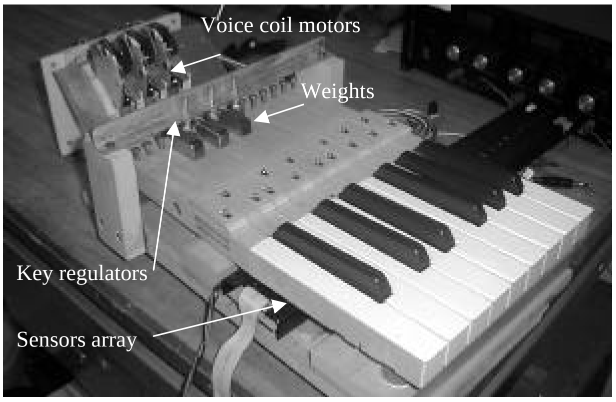

Figure 7. MIKEY keyboard

It is worth noticing that the system consists of low-cost, mass-production components. In particular, the voice coil motor has been detached from a hard disk drive and it can be produced at very low cost. The A/D-D/A converters have been realized with a low-cost single chip device, usually adopted in PC sound boards. The transconductance amplifier is also derived from hard disk current drivers. Finally, the DSP is a low-end device. As a result, the hardware for each key has a cost below 10 USD.

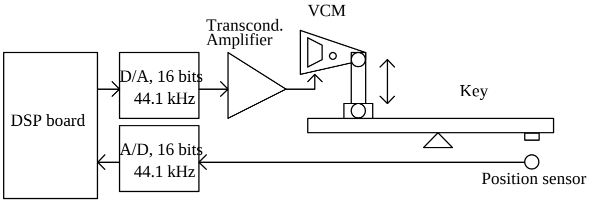

Figure 8. Key control unit – Block diagram

EXPERIMENTAL RESULTS

An active keyboard is designed to generate an active feedback as close as possible to that of a real keyboard. Then, it is difficult to present quantitative results on a system designed to stimulate the haptic senses of the performer. It is possible, anyway, to show that the designed system properly generates the force command to the motors. We present in the following the current references generated by the DSP program only when simulating the grand piano and the harpsichord, since the Hammond organ is trivially obtained by generating a force proportional to key's position. In addition, only for the grand piano, we present the hammer's position evaluated in real-time by the dynamic simulator.

Grand piano

When the key is pressed slowly, the hammer does not loose contact with the key, then its position, computed by the dynamic simulator, follows closely that of the key. (top of fig.9). When the velocity is a little bit higher, the hammer flies toward the string. If the velocity of the key is not high enough, the hammer goes back to the key, with a parabolic trajectory (fig.9, center). If the key is still down, the hammer stops at key's position, without rebounds. Should key's speed be higher, the hammer impacts the string (fig.9, bottom). In this case, impact time has been set to one sample.

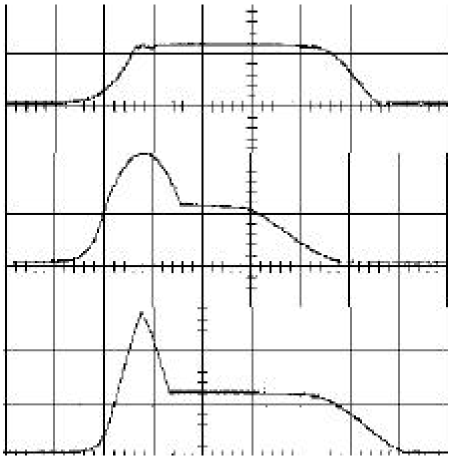

Figure 9. Hammer's motion – No fly, fly without impact and fly with impact against string

As for the force generated by the motor, it is the sum of several components, which in turn depend on the state of the key, its escapement etc. In Fig.10 we show the profile of the force generated by the motor when the key is completely down when the hammer bounces back from the string. In t1, the key descent starts and the force generated is relative to the viscous term. After a while, the escapement phase starts, the force rises and then goes rapidly to zero in t2, when the key stops. The key remains down till t3, when it is released by the performer. When going up, the key is under the action of a viscous force. When it gets at the final rest position, the hammer rebounds on the rest felt in t4, and a small key rebound is observed.

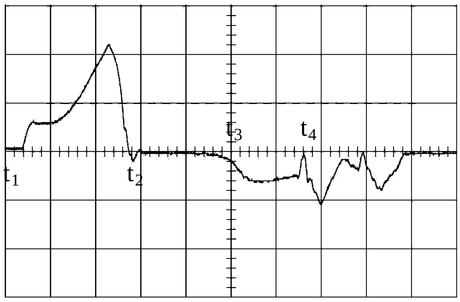

Figure 10. Full key's dip and release – generated force

Harpsichord

The force to be generated by the motor in the virtual harpsichord is reported in Fig. 11, where a single jack harpsichord is considered. The key descent starts in t1 and the force applied to the key emulates a viscous friction. In t2, the plectrum engages with the string and plucks it. This event ends in t3. In t4, the key is completely down and stops. In t5, the key is raised and a viscous effect is generated, until the key gets back to rest position in t6.

CONCLUSIONS

The realization of a multi-instrument active keyboard may require the design of a complex dynamic simulator, in which all the 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 MIKEY project we demonstrated that it is possible to have a realistic feedback and good accuracy in dynamic simulation (e.g. in evaluating the hammer's position in grand piano), by using a simplified dynamic simulator, which generates a set of events (impacts, states). In turn such events generate a set of haptic feedbacks. As a result, the MIKEY system is capable of generating the haptic feedback for three different keyboard-operated instruments. Experimental results confirm 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.

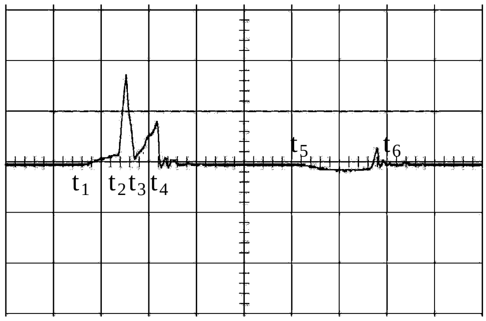

Figure 11. Single plectrum harpsichord – generated force

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