Haptic Piano Key based on a Real-Time Multibody Model of the Double Escapement Grand Piano Action

Sébastien Timmermans[1], Anne-Emmanuelle Ceulemans[2], Bruno Dehez[1] and Paul Fisette[1]

[1] *Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, {sebastien.timmermans, bruno.dehez, paul.fisette}@uclouvain.be*
[2] *Centre de recherche en musique-musicologie, Université catholique de Louvain, anne-emmanuelle.ceulemans@uclouvain.be*

Touch in an acoustic grand piano is a critical sensory information which results from the high dynamics of the piano action. The tactile feedback allows the pianist to finely control his playing and his nuances. Increasingly accepted by musicians, present-day digital instruments offer the possibility of nuancing the sound thanks to a limited key dynamics which attempt to imitate that of a traditional piano. However, the result is far from reproducing the fineness required by pianists.

Several attempts have been made with different final quality and resulting in various touch sensitiveness ([1] and [2] among others). However, these haptic feedback keyboards that do not include real-time model simulation, suffer from an unsatisfactory touch response in terms of pianistic perception.

Our project aims at developing a haptic feedback piano key for digital keyboards, based on real-time multibody models of piano actions. Assuming that the dynamics of the model can be quasi-instantaneously computed and the corresponding force transmitted to the key, it would give the pianist the same force feedback as a traditional piano action. We present here the dynamic model of the traditional piano action developed in [3] that we improve in order to simulate it in a real-time process. Next a first haptic prototype of one key equipped with a linear voice coil actuator is described.

Resulting from 200 years of historical evolution, the double escapement action is now equipping all grand pianos. Using the Robotran symbolic generator [4], Bokiau and al. developed a multibody model of a grand piano action to explain its functioning – especially the role of the escapement principle – adequately matching high-speed imaging experiments (Fig. 1).

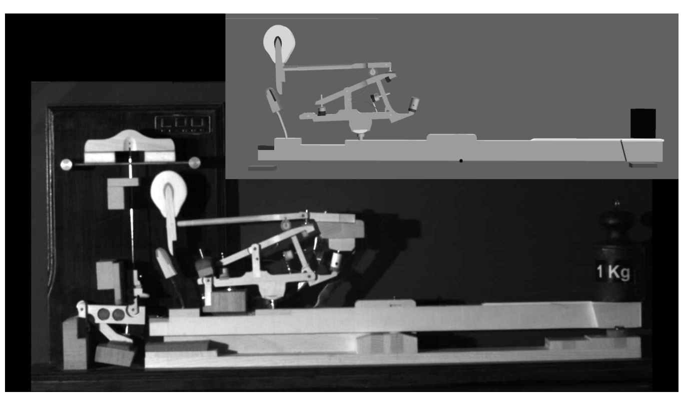

Fig. 1: Motion snapshot of the double escapement piano action and its corresponding multibody model (upper right corner) (from [3])

Starting from this multibody model, our first task was to improve the computational speed without deteriorating its dynamic behaviour that could, a posteriori, effect the pianist's feeling. In other words, a trade-off between the real-time performances and the refinement of the model should be found.

To simulate the dynamics faster than the system's response, a time computation ratio of about 50 %[1] would allow to provide the force feedback response on time, taking into account the communication delays of the hardware.

[1] Meaning that, considering a sampling time of 1 [ms], the corresponding MBS prediction should run in less than 0.5 [ms].

Besides simplifying the MBS model, the choice of the time integrator to solve the multibody equations is crucial for such a real-time application. For instance, MATLAB/Simulink® adaptive time step stiff solver[2] *ODE15s* combined with C-compiled code for the multibody model allows currently 1 [s] of simulation to be processed in $\approx$ 1.15 [s], which is a promising result. Although still insufficient for now, Bokiau and al. demonstrated in [5] with a simpler, Viennese action – also modelled in our lab with Robotran – that real-time processing is reachable with today's processor capabilities. A similar demonstration of the double escapement action will be achieved and shown during the presentation.

In addition to this real-time modeling challenge, an electro-mechanical device intended to reproduce haptic feedback on one piano key is under development and involves various challenging issues :

- The accurate reproduction of the action's high dynamics given any key motion,
- The conservation of the key's characteristics (mass, centre of mass, inertia, visual and physical aspects),
- The limitation of the mass, the volume, the energy consumption and the cost of the global device.

The design of this active key prototype (Fig. 2, left) will allow us to validate the entire process ranging from sensing the kinematics of the key (position, speed, acceleration) to computing the multibody model response (force) and transmitting the latter to the user in real-time. A voice coil linear actuator is presently optimized by a genetic algorithm and validated with a FEM analysis in COMSOL Multiphysics® to verify the capability of reproducing the magnitude of the feedback force, with a special attention on the nonlinearities and the high dynamics of the movement (Fig. 2, middle and right).

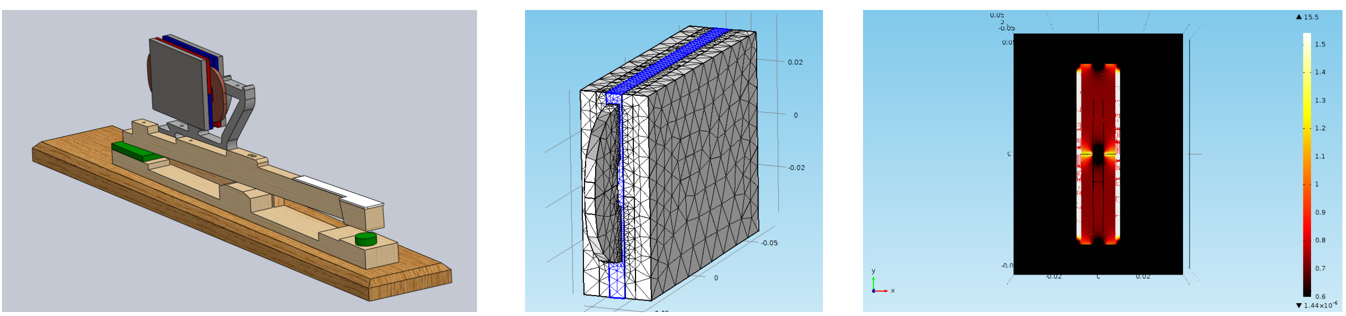

Fig. 2: Design of one-key active feedback device : 3D current CAD view (left) - FEM mesh in COMSOL® of the voice coil actuator (middle) - Magnetic field in the system (right)

Our project takes advantages of today's performances in symbolic multibody modeling along with those of haptic devices. This allows us to dream of an universal keyboard capable of restoring, not only the sound – as most of current digital piano can do – but also the touch, with the possibility to virtually tune and/or modify it in real-time, or even to pass from one model to another.

References

[1] P. Horvàth, "Towards to haptic keyboard: Modeling the piano action," in *Mechatronics*, Springer, 2013.

[2] W. Miedema, *Active haptic feedback within a musical keyboard*. PhD thesis, University of Twente, June 2016.

[3] B. Bokiau, A.-E. Ceulemans, and P. Fisette, "Historical and dynamical study of piano actions: A multibody modelling approach," *Journal of Cultural Heritage*, vol. 275, pp. S120–S130, May 2017.

[4] J.-C. Samin and P. Fisette, *Symbolic modeling of multibody systems*. Springer, Dordrecht, Netherlands, 2003.

[5] B. Bokiau, T. Habra, A.-E. Ceulemans, and P. Fisette, "Real-time simulation of ancient piano actions : A step towards the technicians experience," in *Ecomas*, 2015.

[2] Deliberately restrained with a maximum time step of 10^{-4} [s] to match with the sampling frequency requirement. We are aware that this real-time constraint must be satisfied at every sampling time.