



Simulation of a non-smooth dynamical model of the piano key

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$$M(q) \, \mathrm{d}\dot{q} + F(t, q, \dot{q}) \, \mathrm{d}t = \mathrm{d}i \quad (2)$$

where q is the vector of generalised coordinates made of the angles of each rigid body, $M(q)$ is the mass matrix, $F(t, q, \dot{q})$ are the internal forces, dt is the Lebesgue measure and di is the reaction measure. The Lebesgue's decomposition theorem yields:

$$d\dot{q} = \gamma dt + (\dot{q}^+ - \dot{q}^-) d\nu + dv_s \quad (3)$$

$$di = f dt + p d\nu + di_s \quad (4)$$

where $d\nu$ is a countable sum of weighted Dirac distributions and dv_s and di_s are neglected singular measures. Equation 3 is discretized in time using a theta-method [5]. Typical results of the simulation are presented in Figure 3, either for a force-driven simulation (top frames) or for a position-driven simulation (bottom frames). We discuss the fact that, for the same model, the qualitative differences between the simulation and the measurements are greater for position-driven simulations.

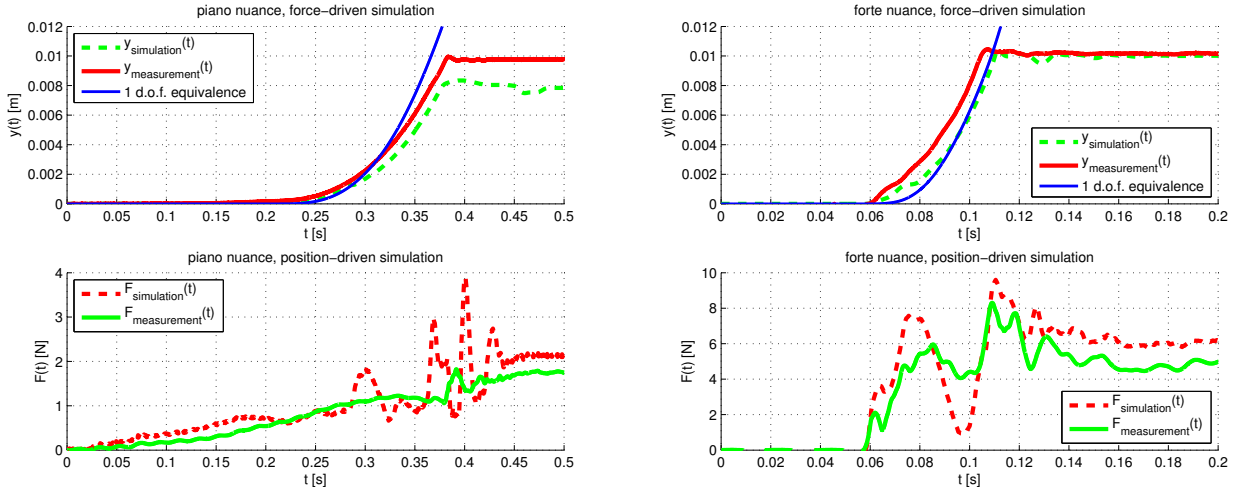


Figure 3. Experimental and simulation results $F(t)$ and $y(t)$ (see Figure 2). Left: p nuance. Right: f nuance. Top: control by the measured $F(t)$. Bottom: control by the measured $y(t)$. In blue: the displacement calculated from the measured $F(t)$ on a simple model of the key with only one degree of freedom.

The time series $F(t)$ or $y(t)$ which has not been used for driving the simulation is considered as the output of the system. The dynamics of the whole mechanism is dominated by inertia and gravity (see the equivalent system of 1 d.o.f. subject only to inertia and gravity, blue curve in figure 3). Therefore, it mainly acts as a low-pass second order filter of the exerted force $F(t)$ or as a second-order high-pass filter of the displacement $y(t)$. Playing on recent numerical keyboards with "heavy touch" demonstrates that inertia and gravity alone are not enough to provide a realistic haptic feedback. Therefore, we hypothesize that the realistic quality of a key relies on small variations, of high-frequency content, in the time-series $\{F(t), y(t)\}$. Since the force control is mostly insensitive to such details (by virtue of the low-pass filtering), it follows that the model must be position-driven in order to account for significant details.

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