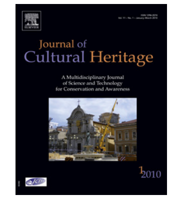
ARTICLE IN PRESS

Journal of Cultural Heritage xxx (2016) xxx–xxx

Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en



Historical and dynamical study of piano actions: A multibody modelling approach

Baudouin Bokiau [a,b,*], Anne-Emmanuelle Ceulemans [b], Paul Fisette [a]

[a] *Centre for Research in Mechatronics, Université catholique de Louvain, 2, Place du Levant, 1348 Louvain-la-Neuve, Belgium*
[b] *Centre de recherche en musique-musicologie, Université catholique de Louvain, 1, Place Blaise Pascal, 1348 Louvain-la-Neuve, Belgium*

ARTICLE INFO

Article history:
Received 10 March 2015
Accepted 19 April 2016
Available online xxx

Keywords:
Multibody dynamics
Modelling
Piano mechanism
Piano action
Double escapement action
Grand piano
Johann Andreas Stein
Prellzungenmechanik
Arnaut de Zwolle
Dulce melos

ABSTRACT

Piano actions are striking mechanisms whose functioning is based on dynamic principles; producing a sound on a struck keyboard instrument by pressing a key slowly is impossible because the hammer needs momentum to hit the strings. This is also the reason why mechanisms intended for struck keyboard instruments are difficult to study; their normal functioning speed is beyond human observation capabilities. For this reason, many modern studies on the piano take advantage of engineering tools in order to measure the exact behaviour of their actions in terms of time response, involved forces and displacement values. A complementary approach to study piano actions consists in modelling them, giving us a virtual mechanism to work with. In this case, the above-mentioned motion and behaviour are computed instead of being measured. The modelling technique used and described in this paper, called multibody dynamics, consists in computing the motion and the forces acting upon each component of the action. Subsequently, the response of the mechanism to a certain keystroke can be computed and a slow-motion animation can be produced. The aim of this paper is to give an overview of an ongoing research project in which two distinctive piano actions are modelled. Each of them is studied with a different objective in mind. Starting with the most modern, well-known but also most complex, the model of a double escapement action found in grand pianos is used to explain its functioning. This pedagogical goal is achieved with three progressive models; the first one is a simplified version of the action to which components of the complete action have been (virtually) removed. The stepwise progression leads to a single escapement action for the second model, and finally to the full double escapement action for the third. Timing of the action events and response to different types of touch are studied and compared with literature. The results show that our model is able to reproduce the same behaviour as real actions. Going back in time, the second instrument that is studied is a *Prellzungenmechanik* built by Johan Andreas Stein at the end of the 1780s. In this context, a model has been achieved to evaluate the influence of the so-called "escapement height" (a regulation parameter of the action) on the playing characteristics of the action. As with the grand piano action, timing analysis and touch comparison are performed with the model.

1. Research aims

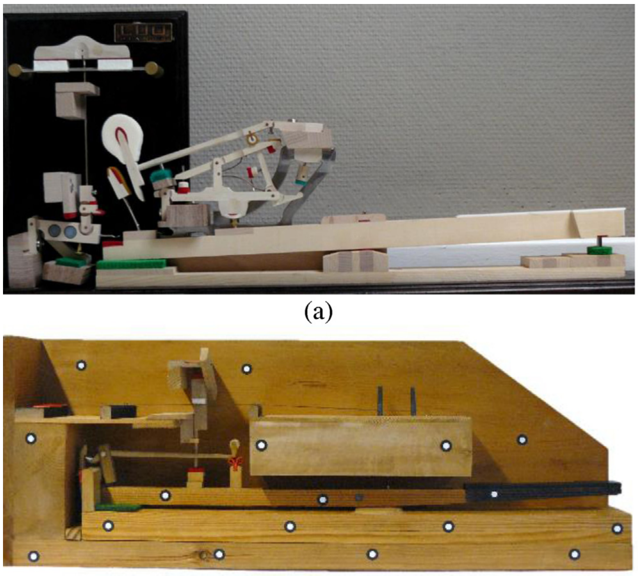
The aim of this research project consists in studying the dynamic behaviour of modern and ancient piano actions by means of the so-called "multibody" modelling approach. Most musicological studies concerning piano actions are limited to a static observation or subjective evaluation of their performance. A multibody model enables to predict the time evolution of the physical parameters of the action (relative displacements, force between components ...). The computation of these variables can help to quantify these performances. In the general framework of this interdisciplinary project, three different actions are envisaged: the double escapement action found in modern grand pianos, an 18th century *Prellzungenmechanik* (PZM) by Johann Andreas Stein and Henri Arnaut de Zwolle's striking mechanism. The present paper focusses on the two first actions.

2. Introduction

The history of the piano is a succession of inventions. Apart from the *gravecembalo col piano e forte* of Bartolomeo Cristofori

* Corresponding author. Centre for Research in Mechatronics, Université catholique de Louvain, 2, Place du Levant, 1348 Louvain-la-Neuve, Belgium.
E-mail addresses: baudouin.bokiau@uclouvain.be (B. Bokiau), anne-emmanuelle.ceulemans@uclouvain.be (A.-E. Ceulemans), paul.fisette@uclouvain.be (P. Fisette).

http://dx.doi.org/10.1016/j.culher.2016.04.010
1296-2074/



(a)

(b)

Fig. 1. The two actions studied in this paper: (a) a grand piano action with the double escapement system and (b) a *Prellzungenmechanik* by Johann Andreas Stein.

which was a very complex but accomplished instrument, the global evolution of the instrument pictures a continuous increase in sophistication. This observation is particularly true for the action, the part responsible for transmitting the musical intention of the pianist through his fingers all the way up to the strings. Even if there exists a great diversity of action designs, their common point is that their functioning relies on highly dynamic principles. Unfortunately, this characteristic also limits our ability to grasp the details of their functioning. Indeed, under normal playing conditions, it is impossible to visualise the sequence of motion of the action because of its very high working speed. When the key is depressed slowly, the hammer will not gain enough momentum to hit the strings. For this reason, many excellent studies concerning the piano take advantage of engineering tools like high-speed imaging and force sensors to observe their behaviour [1–4].

The present paper highlights a modelling method called multibody dynamics which enables to compute the motion of any polyarticulated system and to virtually interact with the action. Besides imitating the one shot experiments in which data are measured, with a model, it is possible to compare actions in which some parts have been virtually modified through simulations in identical situations. These simulations enable to compute the data that were highlighted in [1–4] rather than measuring them. Moreover, a 3D visualisation system provides the user with a user-friendly graphical tool to observe the action from the desired viewpoint.

The objective of this paper is to give an overview on an ongoing research project concerning two types of piano actions (Fig. 1), via the use of the multibody approach. The first one is the modern grand piano action, for which much technical literature is available. Even if it is the most complex one from a morphological point of view, it is certainly the best-known action. Second, we are interested in an 18th century PZM by Johann Andreas Stein, typically used by the Viennese and South-German classical piano school. The instruments which use this kind of action are fairly well preserved and frequently rebuilt by piano makers.

3. Modelling piano actions

In this section, we introduce the main principles of multibody dynamics and its application to piano actions. Thereafter, we illustrate how the models are validated. Throughout this section, we use the double escapement action as a guideline. Needless to say, exactly the same techniques are applied to the other action.

3.1. Introduction to multibody dynamics

Multibody dynamics is a branch of mechanical engineering which consists in predicting the motion of polyarticulated bodies, that is, systems composed of multiple bodies connected by joints (e.g. Hinges, telescopic arms, ball joints, etc.). Classical applications for this method range from road and rail vehicles to robotics, biomechanics, transmissions, etc. The piano action is also a polyarticulated system as it consists of multiple bodies linked to each other through rotational joints.

Multibody dynamics is based on equations known since the 18th century, namely Newton's equation of motion which yields $\boldsymbol{F} = m\ddot{\boldsymbol{x}}$, and its equivalent in rotation, Euler's law $\boldsymbol{T} = \boldsymbol{J} \times \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J} \times \boldsymbol{\omega}$ written for each body of the system. In the previous equations, $\boldsymbol{F}$ and $\boldsymbol{T}$ respectively stand for the external applied force and torque resultant with respect to its mass centre, m and $\boldsymbol{J}$ are the mass and the inertia tensor of the body with respect to its mass centre and $\ddot{\boldsymbol{x}}$ and $\dot{\boldsymbol{\omega}}$ represent the absolute linear and angular accelerations of the body. Whatever the formalism used to generate these equations of motion for the multibody structure, the system kinematics is always described in terms of so-called generalized coordinates, $\boldsymbol{q}$, from which position, orientation, velocities and accelerations will depend. In particular, $\ddot{\boldsymbol{x}} = \ddot{\boldsymbol{x}}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)$ and $\dot{\boldsymbol{\omega}} = \dot{\boldsymbol{\omega}}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)$.

Using these generalized coordinates as system variables, the multibody equations of motion can be written in the following matrix form:

$$\boldsymbol{M}\left(\boldsymbol{q}\right)\ddot{\boldsymbol{q}} + \boldsymbol{F}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \boldsymbol{f}, \boldsymbol{\tau}\right) = \boldsymbol{0} \qquad (1)$$

where $\boldsymbol{M}$ is the so-called mass matrix and $\boldsymbol{F}$ contains the centrifugal, Coriolis and gyroscopic effects as well as the forces $\boldsymbol{f}$ and torques $\boldsymbol{\tau}$ applied to the bodies.

The system of equations (1) can be written by hand for small academic examples, but becomes too complex for large and realistic systems for which the equations are generally non-linear with respect to $\boldsymbol{q}$ and $\dot{\boldsymbol{q}}$. We therefore use an in-house software called Robotran [5]. Starting from the system to analyse (Fig. 2a), a schematic representation can be achieved; in the schematic representation of a multibody system in Fig. 2b, ellipses stand for bodies and lines for joints. Then, on the basis of a formalism and given all the system parameters (dimensions, mass, centre of mass, inertia, etc.), Robotran automatically writes the equations of motion (1) in a symbolic manner (Fig. 2c).

At this stage, by analogy with a model of the human body, the user has in his possession a human body in free fall and without muscles, but with the correct body characteristics and joint kinematics. The next step consists in writing the law forces $\boldsymbol{f}$ and torques $\boldsymbol{\tau}$ appearing in (1) according to their underlying physical laws.

Once forces and torques are fully described, the differential system (1) can be easily simulated with a suitable numerical time integrator to provide the desired results (Fig. 2d).

3.2. Multibody modelling of piano actions

The main hypotheses underlying the action models are the following: the motion is planar, bodies are rigid,[1] joints are geometrically perfect (no backlash) and the string damper is not considered.

In the multibody model of a grand piano action (Fig. 3), the various rotational motions of the bodies are the generalized coordinates

[1] Regarding the body rigidity assumption, the hammer shank flexibility has also been neglected. Its flexibility will be considered in future work.