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To cite this version:

Benjamin Elie, Xavier Boutillon, Juliette Chabassier, Kerem Ege, Bernard Laulagnet, et al.. MAESSTRO: A sound synthesis framework for Computer-Aided Design of piano soundboards. ISMA 2019, Sep 2019, Detmold, Germany. hal-02281818v2

HAL Id: hal-02281818
https://hal.science/hal-02281818v2

Submitted on 18 Dec 2019

PROCEEDINGS of ISMA 2019
International Symposium on Music Acoustics

13 - 17 September 2019 in Detmold, Germany

MAESSTRO: A sound synthesis framework for Computer-Aided Design of piano soundboards

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Abstract

The design of pianos is mainly based on empirical knowledge due to the lack of a simple tool that could predict sound changes induced by changes of the geometry and/or the mechanical properties of the soundboard. We present the framework of a program for the Computer-Aided Design of piano soundboards that is intended to bridge that gap by giving piano makers a tool to synthesize tones of virtual pianos. The sound synthesis is solely based on physical models of the instrument in playing situation. The calculation of the sound is split into several modules: computation of the modal basis of the stiffened soundboard, computation of the string dynamics, simulation of the soundboard dynamics excited by the string vibration, and calculation of the sound radiation. Reference tests of sound synthesis of real pianos as well as sound synthesis of modified pianos are used to assess our main objective, namely to reflect faithfully structural modifications in the produced sound, and thus to make this tool helpful for both piano makers and researchers of the musical acoustics community.

Keywords: Piano soundboard, Assistance to musical instrument manufacturing, Sound synthesis

1 INTRODUCTION

When they design stringed musical instruments, manufacturers traditionally use empirical approaches. This usually leads to marginal improvements of existing schemes. One of the main reason explaining the difficulty for a revolution to take place, in musical instrument design, is the lack of a simple tool that might predict sound changes induced by virtual changes of the geometry, and/or the mechanical properties of the instrument.

In the case of the piano, many studies have been made in the past in order to fully comprehend all of the physical phenomena that are involved in the tone production, which is necessary for manufacturers to overstep empirical approaches. For instance, many authors have studied the vibro-acoustic behavior of the piano soundboard, either by experimental characterization [1–5], or by proposing simplified models [6–9] or finite element models [5, 10]. The string behavior, including the hammer-string interaction and the string-bridge coupling, has also been studied by several authors [10–15].

All of the aforementioned studies contributed to a better understanding of the piano functioning and several models are now available to numerically simulate separately the mechanisms of the piano tone production chain, from the hammer activation to the radiated sound. By gathering some of these different numerical methods, a framework of a program for the Computer-Aided Design (CAD) of piano soundboards is presented in this paper. It is solely based on physical models of the instrument in playing situation, and thus provide to piano makers a simple tool to predict the acoustic characteristics of a virtual piano, in regards to its specific geometry and to the mechanical properties of the materials that compose the soundboard and the strings.

This CAD program is made available for any piano maker or academic researcher in the form of a software, called MAESSTRO[1], which present several functionalities to assist the piano maker in the design process. The software architecture is presented in Sec. 2. Case studies are presented in Sec. 3 to highlight the functionalities of MAESSTRO, and analyzes of piano tones synthesized by MAESSTRO are presented in Sec. 4.

2 SOFTWARE ARCHITECTURE

2.1 General principles

The different functionalities of the sound synthesis framework MAESSTRO are the following: i) entering the geometry and the materials of the virtual soundboard thanks to a Graphical User Interface (GUI), ii) feeding MAESSTRO with MIDI files to be synthesized, iii) simulating numerically the physical phenomena involved in the production of piano tones, iv) post-processing the software outputs, and v) creating audio files of synthesized piano tones.

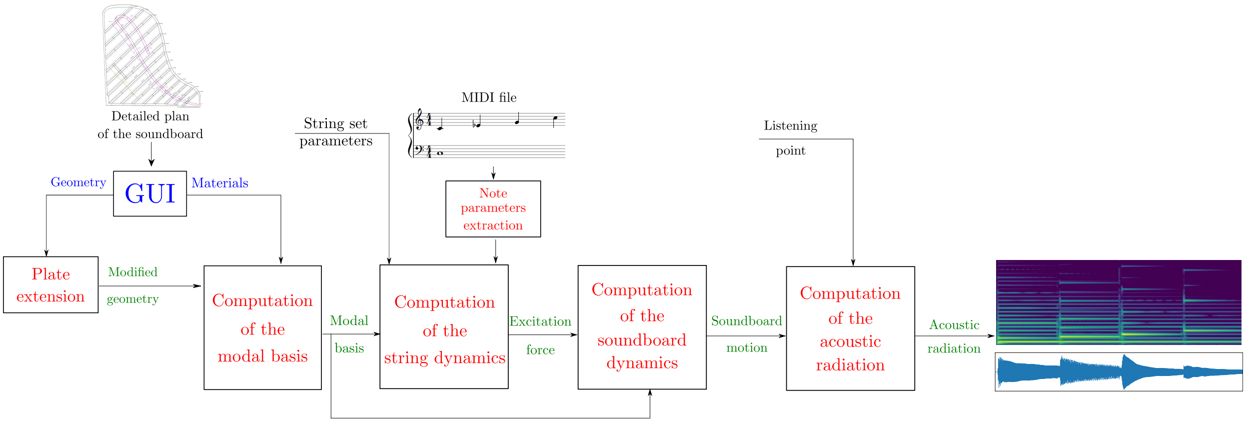

Figure 1. Block-diagram showing the software architecture. The input data provided by the user are represented by a black font color. Blue corresponds to user data entered in the GUI. The software operations and the software outputs are represented by the red and green font colors, respectively.

Fig. 1 represents the global functioning of the software. It consists in a sequence of software operations that yields output synthesized piano tones from inputs specified by the users, including the geometry and the materials of the virtual soundboards, the string set parameters, and the tones to be played. First, the normalized data about the geometry and the materials of the virtual soundboard can be defined with the help of a specifically designed GUI (see Sec. 2.2). Then, the modal basis of the virtual soundboard is computed with a semi-analytical model [9]. To synthesize specific tunes, the user may directly give a MIDI file in which MAESSTRO will extract the tone information, namely the note index, the key activation and release instants, as well as the hammer initial velocity. A non-linear finite-element model of string dynamics [10] is then used to compute the bridge excitation force applied by the struck strings. Using the elements of the modal basis of the virtual soundboard, we can then compute the soundboard dynamics and the acoustic radiation at any listening point specified by the user. The different software operations are detailed in the next sections.

2.2 Computer-Aided-Design of the virtual soundboard

The software needs data about the geometry of the virtual soundboard and about the mechanical properties of its materials, which are gathered into a geometry file in a normalized format (JSON). In order to assist the user to build this geometry file, we specifically designed a Graphical User Interface[2], developed in Typescript+React.

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[1] More information available at `https://www.maesstro.cnrs.fr`

[2] It is available from any web browser at the following url: `https://maesstro.demo.logilab.fr/`

The choice of developing our own GUI has been motivated by the fact that adapting geometry data from standard 3D CAD commercial software to our geometric modeling would have added too much complexity, including naming convention of the soundboard components (panel, bridge, ribs...) to extract the corresponding volumes.

The computation of the soundboard dynamics considers three main classes of structural components of the soundboard geometry, namely the main panel, the bridges and the ribs. The GUI can then be used to define the characteristics that are specific to each class. For instance, this includes the coordinates of the points defining the panel contour, or the evolution of the width and the thickness of the bridge along its median line, and so on.

2.3 Computation of the modal basis

The computation of the modal basis is based on a simplified model of the soundboard geometry that allows us to compute analytically the modal basis of ribbed orthotropic clamped panels with any contour [9]. The general principle is to consider a simply supported rectangular plate with special orthotropy in which the considered panel contour is entirely included. This contour can then be defined inside the so-called *extended plate* with a spring distribution, as shown in Fig. 2.

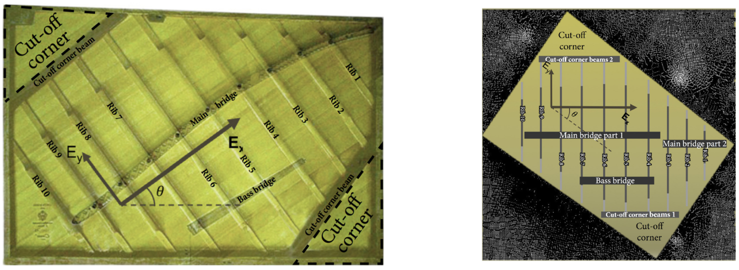


Figure 2. Exemple of modification of the geometry for a Pleyel P131 piano used to compute of the modal basis. Left is the original geometry. Right is the modified geometry. The black region in the right figure is the spring distribution used to define the contour of the analyzed panel in the extended plate geometry. Figure extracted from [9].

2.4 Simulation of the string dynamics

The string dynamics is simulated with a specifically designed module which uses the finite-element code Montjoie [10]. It considers a Timoshenko model to account for the string stiffness, and the geometrically exact model to account for non-linearity due to local geometric deformation of the string. In order to accurately model the string-soundboard coupling, the modal basis of the soundboard should be computed prior to simulate the string displacement.

2.5 Computation of the soundboard dynamics

Once the displacement of the string is simulated, the transverse force applied to the bridge can be computed, as well as the resulting soundboard dynamics. Thus, the soundboard motion for the j^{th} mode, denoted $\phi^j(x,y)$, in the extended plate coordinate system is given by

$$\Phi^j(x,y) = \sum_{n,m} A^j_{n,m} \sin\left[\frac{n\pi x}{L_x}\right] \sin\left[\frac{m\pi y}{L_y}\right], \tag{1}$$

where $A^j_{n,m}$ is the eigenvector associated to the j^{th} mode, and L_x and L_y are the length and width of the extended plate. Then, the motion of the table at time t in response to the transverse force applied by the string i is given by

$$u_i^j(x,y,t) = \sum_j q_i^j(t)\Phi^j(x,y), \tag{2}$$

where $q_i^j(t)$ is the modal coordinate at time t associated to the j^{th} mode.

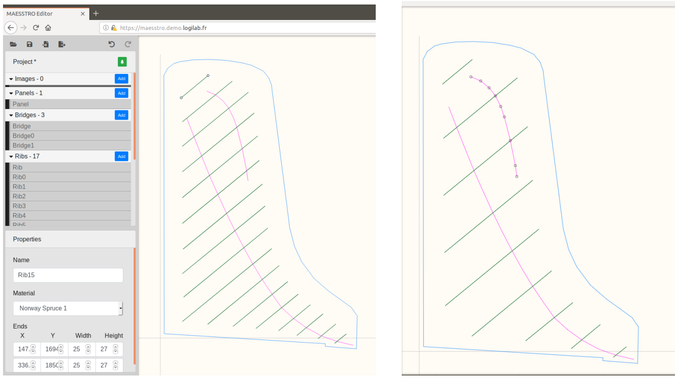
2.6 Computation of the sound radiation

Finally, considering a point M in a 3D pressure field around the extended plate, defined by its coordinates $\{x_{ac}, y_{ac}, z_{ac}\}$, the radiated sound pressure $p(M,t)$ is computed using the Rayleigh integral and assuming the soundboard is baffled.

3 CASE STUDIES

This section presents the different cases that are used in this paper to show some possibilities of the MAESSTRO software. It consists in building a virtual reference piano, here a Steinway D, which is subject to several modifications to evaluate the acoustic impact of these structural modifications. The chosen modifications include increase of the panel thickness, removal of half the ribs, and removal of all the ribs. This results in 4 cases, namely the reference piano (RP), and the 3 modified pianos (MP1, MP2, and MP3).

The reference piano geometry is a simplified version of the Steinway D. The geometric data has been extracted via the MAESSTRO GUI, as shown in Fig. 3.



Name: Rib15

Material: Norway Spruce 1

Ends

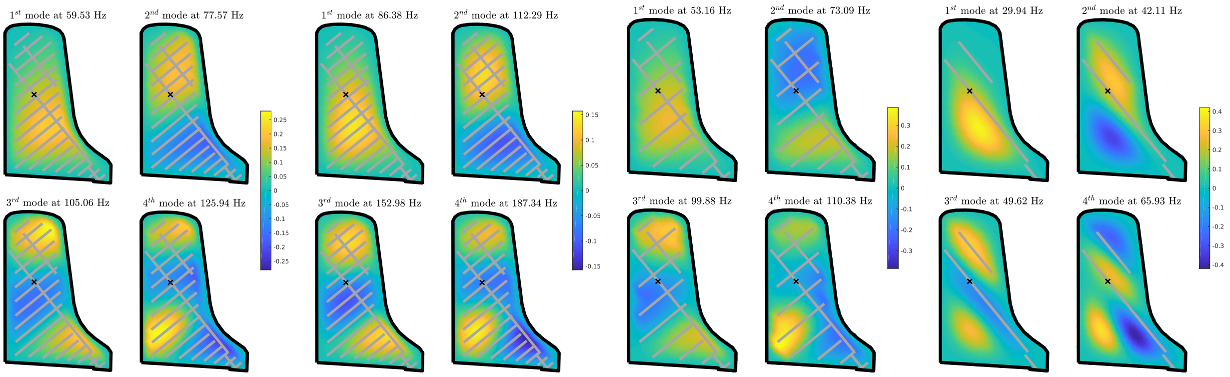
X	Y	Width	Height
147.	1694	25	27
336.	185C	25	27

(a) Reference piano (b) Modified piano #2

Figure 3. Screen shot of the GUI after completion of the design of the virtual Steinway D. The panel contour is shown in blue, the median line of the bridges in pink and the median lines of the ribs in green. Left is the reference piano, right is the modified piano 2, labeled as MP2

The first modified piano (labeled as MP1) is similar to the reference piano RP except that the thickness of the soundboard is twice as the one of RP, namely 18 mm, while it is 9 mm for RP. The second modified piano, MP2, is similar to RP but with inter-rib spacing twice as RP (see Fig. 3 (b)). Finally, the third modified piano, MP3, is similar to RP but with no ribs: all ribs have been removed and the bridges are the only superstructures. Qualitatively, in comparison with RP, MP1 is similar to a stiffer piano, whereas MP2 and MP3 are similar to a slightly softer reference piano and to a highly softer piano, respectively.

Although this is unlikely to be representative of what piano manufacturer would try in real life, we chose these caricatural structural modifications of the reference piano in order to emphasize their acoustic impact in the resulting tones. Besides, these gross modifications make the qualitative prediction of the variations in the



(a) Reference piano (b) Modified piano #1 (c) Modified piano #2 (d) Modified piano #3

Figure 4. First mode shapes of the reference piano and the modified ones computed with the method detailed in Sec. 2.3. The coupling point of the C3 string at the bridge is denoted by the black cross.

mechanical behavior and some acoustic features possible.

For all of the virtual pianos, the strings are assumed to be the same. The parameters of the string set are taken from a technical report [16], which provides all of the required information to compute the dynamics of any string of the virtual reference piano, including string geometry and tension, Young modulus of the string materials, internal damping, and location of the bridge coupling points. It also provides the mechanical parameters of the hammers, namely the mass, the stiffness, and the impact location on the string. For this study, we used the wrapped strings model of [16].

4 RESULTS

For the sake of concision, we present results of a single piano tone that have been synthesized using the four virtual soundboards. The tone is C_3, with a fundamental frequency of 131.11 Hz. The initial velocity is kept at 1 m/s for the four synthesized tones, and the tone is sustained as if the key were not released until the complete note extinction. We present first the computed mechanical properties of the tested soundboards, and then the synthesized tones.

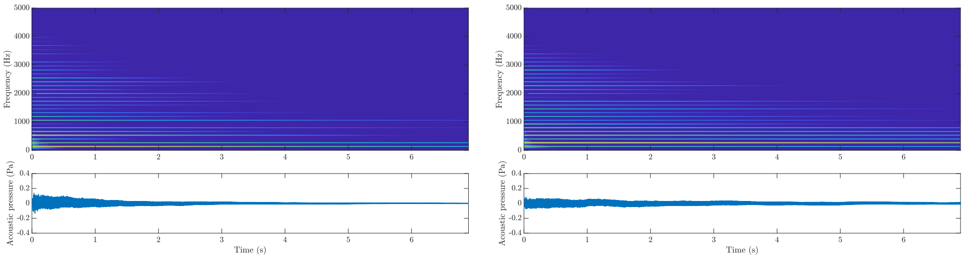
The synthesis has been done on a UNIX machine with 4 CPU processors at 2.3 GHz. The computation times for each module, corresponding to the synthesis of a tone of 7 seconds, are the following: 132 s for the computation of the modal basis, 1007 s for the string dynamics, 70 s for the soundboard dynamics, and 68 s for the acoustic radiation, hence a total of 1277 s.

4.1 Mechanical properties

Fig. 4 shows the first 4 modes associated to the different configurations. Although removing the ribs lowers the mass of the soundboard, its main effect is to lower the global stiffness of the soundboard, hence the fact that the mode frequencies are smaller in the half- and no-ribs configurations. Conversely, a thicker plate, such as for MP1, increases both the mass and the stiffness, but whereas mass increase is proportional to the thickness h, the stiffness increase varies with h^3. As a consequence, the thick plate MP1 has higher modal frequencies than other thinner plates, and consequently, a lower modal density.

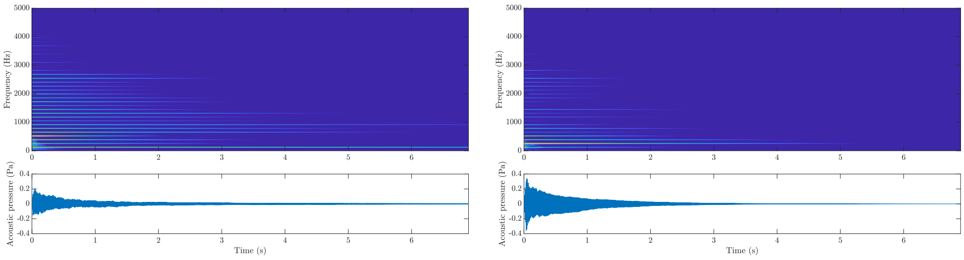
Following the mean-value theorem by Skudrzyk [17], for structures with similar mass, the mean-value of the mobility lowers as the stiffness increases. Consequently, MP1 has the lowest mobility while MP3 has the largest.

4.2 Synthetized tones



(a) Reference piano

(b) Modified piano #1



(c) Modified piano #2

(d) Modified piano #3

Figure 5. Synthesized tone waveforms and their corresponding narrow-band spectrograms for the 4 different piano configurations.

Fig. 5 displays the narrow-band spectrograms and acoustic pressure waveform of the 4 synthesized C_3 corresponding to the 4 different piano configurations. One can notice salient differences: the synthesized tones from MP2 and MP3 decay much faster than other tones. Interestingly, for MP2 and MP3, individual decays vary significantly from a partial to the next: the second partial of MP3 (at $2\ f_0$) presents the largest sustain while it is fundamental for MP2. Additionally, although MP3 presents the fastest decay, it also has the highest acoustic pressure level at the beginning of the tone. These observations are in agreement with our expectations, since in addition to the intrinsic dissipative mechanisms in the string, a coupling with a mobile structure adds an additional damping that increases with the structural mobility. Sounds may be heard by clicking on the subplot legends.

Indeed, as stated in Sec. 4.1, MP2 and MP3 have mobility levels higher than RP and MP1, which results in higher additive string damping terms, and consequently in faster decays of the synthesized tones. Also, as the damping mechanism due to the coupling gets large, it may eventually become predominant in comparison with the intrinsic string damping mechanisms. In that case, the total damping term associated with a partial is directly proportional to the mobility at the partial frequency. Consequently, the decay distribution along the different partials present the large variations similar to the mobility curve along the frequency axis.

4.3 Acoustic analysis

We choose to analyze the synthesized tones through its energy decay. This choice is motivated by the fact, as said in Sec. 4.2, that the energy decay is related to the mechanical behavior of the soundboard. The energy decay profile of the acoustic pressure $p(t)$ is computed as the Energy Decay Curves introduced by Schroeder [18] as

$$EDC_{dB}(t) = 10\log_{10}\left(\int_t^{+\infty} p^2(\tau)d\tau\right). \tag{3}$$

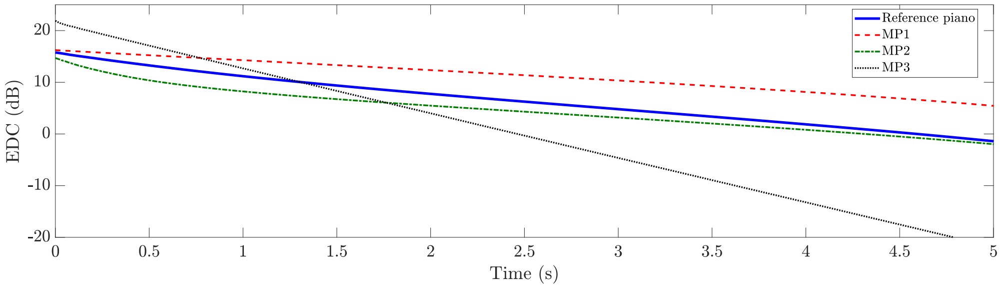


Figure 6. Energy decay curves of the synthesized tones.

Fig. 6 shows the EDC of the synthesized tones. They confirm the qualitative observations made from spectrograms in Sec. 4.2. The global energy decays faster for MP2 and MP3 than for RP and MP1. The decay of MP1 is also slightly slower than RP, which is also in agreement with our expectation since MP1 has a higher stiffness.

5 CONCLUSION

This paper has presented a framework of a program for the Computer-Aided Design of piano soundboards that is intended to help piano makers in the design process by giving them a tool to synthesize tones of virtual pianos. Case studies show the interest of the software in predicting acoustic impacts of structural modifications of a piano soundboard. Indeed, starting from a reference piano, we synthesized tones from three virtual pianos, which are modified versions of the reference piano. Modifications have been chosen to reflect variations of the global stiffness. The impact of these stiffness variations on the soundboard mechanical behavior and on the energy decay profile of the synthesized tone are in agreement with the theory. Stiffer soundboards present higher modal frequencies, which results in a lower modal density and in a lower mobility at the bridge. As a consequence, synthesized tones from stiffer soundboards present slower decays than soft soundboards.

Through a broad utilization of the software, piano makers will be able to virtually test new designs, and thus significantly enhance the pace of the trial and error process. This software might also be a useful tool of communication between piano makers and academic researchers. Thus, we are convinced that significant evolution of the traditional architecture of piano soundboards would emerge in the next future. The resulting synthesized piano sounds may however be still perceived as non-realistic, mainly because of the lack of fine and precise modeling of dissipative phenomena in both the soundboard and the strings, that could be addressed in the future. The coupling between the strings and the plate at the bridge rely on a very simple model (continuity of the vertical velocity) but measurements on real pianos point towards a more complex model allowing rocking and horizontal motion of the bridge. Finally, one major evolution could be the use of composite materials for the soundboards: the software could be used to predict the sound of a piano with soundboard made in specific composite materials, or even be used to find the mechanical properties which yield to the sound desired by the piano maker.

ACKNOWLEDGEMENTS

This work is part to the project MAESSTRO, with the financial support of the French ANR (Agence Nationale de la Recherche). The authors would also like to thank Denis Laxalde, Frank Bessou, and Viet-Hung Nhu from Logilab for the development and implementation of many modules of the software.

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