ISMRA 2016
INTERNATIONAL SYMPOSIUM on MUSICAL and ROOM ACOUSTICS
September 11-13, 2016
La Plata, Buenos Aires, Argentina

Physics of musical instruments and voice: Paper ISMRA2016-68

Acoustics of pianos: An historical perspective

Antoine Chaigne

University of Music and Performing Arts Vienna, Austria, chaigne@mdw.ac.at

Abstract

The art of piano making shows a considerable evolution during the nineteenth century. Around 1800, the instruments were build almost in the same manner as harpsichords, whereas the pianos made at the end of the century are very similar to modern pianos. This evolution is of major interest for musical acousticians, since the pianos made at successive milestones provide us with clearly distinct tone qualities. The challenge is then to establish the links between these tonal properties and the main physical parameters of the instruments. Precise knowledge and understanding of these links pave the way for a predictive approach in piano making. The lecture will start with the presentation of some of the most important aspects of the evolution of piano making, in terms of hammers, strings, soundboard and case. Consequences of this evolution for the string scaling, hammer forces, rib design and modal properties of the soundboard will be discussed. With the help of dedicated simulations of some representative models of pianos, it will be shown to what extent the observed differences in physical parameters can affect the efficiency of string-soundboard coupling, the spectral content of the transients, and the temporal evolution of the tones. [Work supported by the Lise-Meitner Fellowship M1653-N30 of the Austrian Science Fund].

Keywords: Piano acoustics

Acoustics of pianos: An historical perspective

1 Past: A short survey of piano history

The first pianoforte appears around 1710 (Cristofori, Padova, Italy). The main difference with the existing harpsichords is the striking action of the hammer, compared to the previous plucking. This results in a significantly modified tone color. In addition, the player has a better control on the sound level. In these early days, no noticeable differences could be viewed in the strings, soundboard and shape of both instruments, although clear divergences will appear later. It will takes some times before the piano action mechanism stabilizes. A continuous evolution can be seen during the nineteenth century, where two major systems coexist: the English action, and the Viennese (or German) action. The latter has the reputation to give a softer and more delicate sound than the former one.

Between 1790 and 1870, an important evolution of the piano is the continuous increase in string tension. In average, the tension is multiplied by a factor of 4 during this period, whereas the string length increases only moderately. As a consequence, the strings become progressively thicker, and the characteristic impedance Z_c of the string increases. The prime motivation for such an evolution is an increase in sound power of the instrument: the piano plays more and more as soloist with orchestras of growing sizes, and in bigger halls than in the previous intimacy of private houses. In parallel, the number of strings also increases. As an example, an instrument built by N. Streicher in Vienna in 1805 has 65 keys and 154 strings. A modern Steinway built in 1980 has 88 keys and 243 strings. To withstand the global tension of strings, the makers used different strategies. Before 1840, one can rarely see metallic parts inside the piano: wood was used for the reinforcement and fixation of the soundboard. The soundboard became thicker, which, in terms of tone color, results in appreciable changes due to modification of the modes and of the modal density. The ribs and the bridges also became progressively thicker. Around 1850, acting on the soundboard itself becomes insufficient, and metallic bars are added to withstand the strings (see Fig. 1). This progressively leads to the

Figure 1: Pianoforte made by J.B. Streicher in 1851, showing the two metallic bars parallel to the strings.

complete metallic plates, which support the tension of the strings entirely, as we can see on modern instruments today.

Another important change in piano design must be mentioned here: In the seventeenth and eighteenth century, the usual rule was to stretch the strings in the direction perpendicular to the keyboard, which was also the direction of the fibers in the soundboard. As a consequence, distinct zones of the soundboard were vibrating, depending on the instrument was played in the bass, medium or treble register. This resulted in specific tone color for each register, since different families of modes were excited in each case. Today, on the contrary, most of the modern grand pianos are built with overlapping strings, and almost all notes mainly excite the central part of the soundboard. This might induce a better homogenization of the timbre properties along the compass, however with a lost of clarity when different voices are superimposed in polyphonic compositions. Notice that a number of contemporary makers are aware of such a problem (S. Paulello, C. Maene and D. Barenboim), and they build on purpose modern instruments with parallel stringing. The example of Brahms's piano (built by J.B. Streicher in 1868) will be presented during the lecture to illustrate this point.

2 Present: A scientific approach of the piano

It is only at the end of the twentieth century that numerical simulations started to be used rather systematically in the physics of musical instruments. Before that period, the approach was mostly experimental, and the theoretical results were only limited to simplified parts of the instruments. The theory of strings, for example, was well established since the end of the eighteenth century, but there is no example at that time of a complete model of the piano.

Once it has been validated, important expected results of a model are to quantify the phenomena and predict the consequences of structural modifications. In this context, the models based on the fundamental principles of mechanics and acoustics developed over the last thirty years are of great help for understanding the behavior of the piano [1]. The simulated piano tones obtained by means of such models clearly mimic real tones, although their quality cannot be compared with top-level instruments. One first possible explanation follows from the fact that the underlying models are still too crude for reproducing the complexity of piano tones convincingly, in view of the extreme sensitivity of the human ear. A second argument is that our experimental methods are still today unable to measure the necessary parameters to feed the models with enough accuracy.

It can be reasonably anticipated that differences between real and simulated tones will still be detectable for decades. However, a joint program of simulations, measurements and listening tests remain an attractive cocktail for reducing this gap. Systematic variations of parameters can be investigated with a help of a numerical model, which would hardly be conducted experimentally. Listening tests can be of help for detecting threshold of audibility of the physical parameters, and thus for highlighting those parameters which induce noticeable changes in tone color.

In previous studies, our goal was to reproduce one specific instrument (a Steinway D grand piano) after development of a complete model and careful measurements [2, 3]. Our objective here is different: the idea is to measure various pianos with clearly different tone color. For

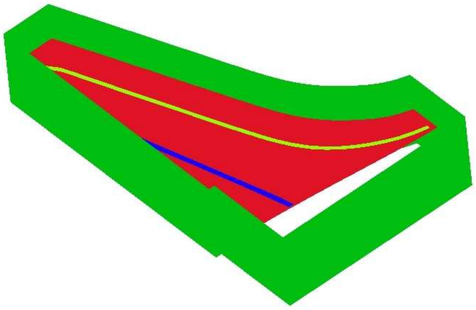

Figure 2: Sketch of the numerical model for a pianoforte made by N. Streicher in 1819 (NS19).

that purpose, an attractive panel is given by pianofortes made at successive period of times by a Viennese dynasty of makers (the Streicher family: see Fig. 2) [4]. With such a choice, it was anticipated that the selected instrument significantly differ from each other, while remaining in the same global tradition of making, thus allowing a more easier detection of evolution steps in the construction of the instruments. For each of the 6 selected instruments, measurements are performed on hammers, strings, bridge, soundboard and in the acoustic field in order to extract the necessary geometrical and material parameters (density, elasticity, damping) of each constitutive part (see an example in Fig. 3). These parameters are obtained through various

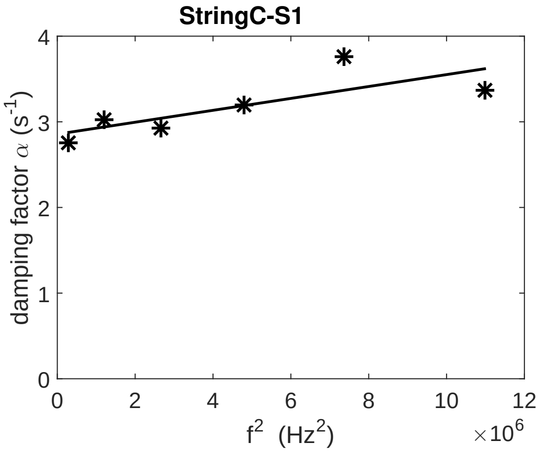

Figure 3: Example of analysis for extracting the damping factor coefficients for a C♯5 string coupled to a NS19 soundboard.

time and spectral analysis tools. An original method has been especially developed for reconstructing the hammer force from measurements of the string velocity [5]. For each instrument, a numerical model of the soundboard is made, in order to compare with the measured modes (see an example in Fig. 4). These modes are present in the starting transients of the tones and contribute to the tone color of the instrument (see Fig. 5).

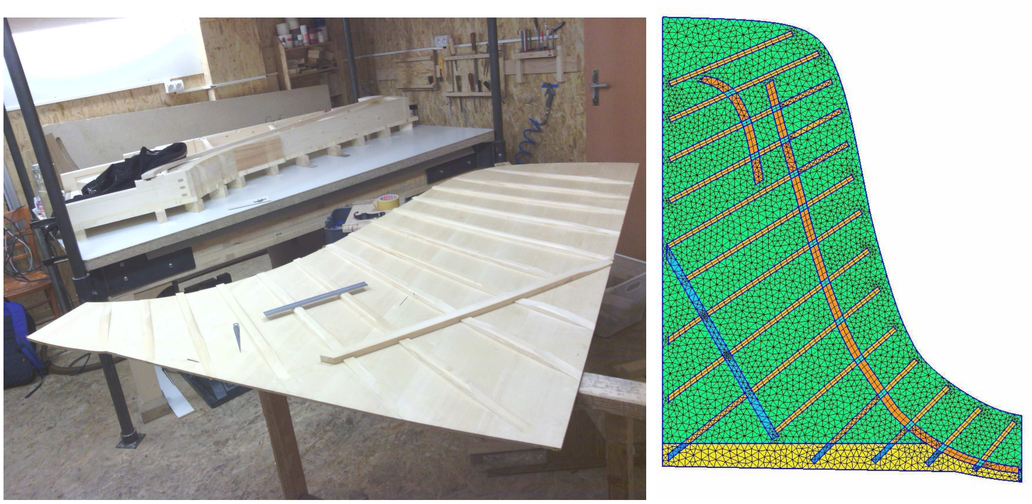

Figure 4: Copy of a J. B. Streicher soundboard (the Brahms's piano) made by the pianoforte maker Paul McNulty, and its numerical modeling.

The numerical modal analysis also yields useful information on the localization of the modes in the frequency range above 1 kHz due to the presence of ribs and bridges [6]. The complete numerical model of each piano couples together the strings, the soundboard and the acoustic field. The soundboard is inserted in a rigid case with the appropriate boundary conditions. In its present version, the input variable of the model is the hammer force exerted at the hammer striking point [2].

One interesting feature of our model lies in the calculation of energetic quantities for strings, soundboard and acoustic field. This allows to represent the time evolution of a given piano note irrespective of the measurement point. These energetic quantities are global characteristics of a given piano, which facilitates the comparison between different instruments [7]. In this version of the model, a number of weak points are identified. First, due to the lack of reliable experimental data, the material parameters of hammers and strings are crudely estimated. Secondly, the string model has only one polarization, as well as the bridge. A current extension to 3D model of strings and bridges is under way.

3 Future: Building bridges between science and piano making

The new results obtained in the physics of pianos over the last decades not only serve a better understanding of the acoustic pianos, but also were used intensively for the development of digital pianos and physics-based digital processing. Today, each main component of an acoustic piano can be convincingly replaced by its digital counterpart, thus opening the way to a large number of hybrid solutions, from the "full" acoustic concert prototype to the "full" digital versatile keyboard. This diversity seems very promising since it offers a wide range of different instruments, each of them being dedicated to a specific purpose. In view of the today's knowledge, we will now briefly examine the specificities of acoustic, digital and hybrid pianos,

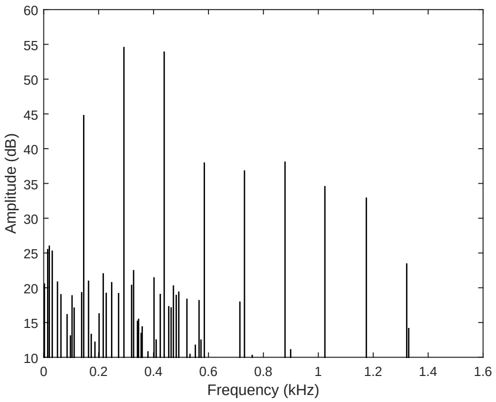

Figure 5: Spectral analysis of a D♯3 note played on a J. B. Streicher pianoforte, showing the presence of the soundboard modes below 500 Hz.

with some projections on their possible development.

In acoustic pianos, the sound quality highly depends on the selection of materials (strings, hammers, soundboard) and on the careful adjustment of all parts. This usually result in a high cost: think, for example that 12000 components are necessary for building a Steinway D piano! As a consequence, it seems that such instruments are primary intended for concert halls and professional use. Even if the making of such pianos still obey more or less to the same rules as in the past, one can notice the continuous emergence of innovative concepts over the last years. A number of examples on stringing and soundboard design were mentioned in the previous sections. In an attempt to preserve the heritage, there is also a growing interest in restoration and copying of historic pianos, which contributes to give more authenticity in the interpretation of the musical compositions of the past. Here again, the progresses in musical acoustics can be of help for discriminating between the features of a piano which need to be copied from the less important others.

In fully digital pianos, recorded piano tones form the database. The quality of the samples has been considerably improved over the last decades, and even cheap keyboards show today a large diversity of sounds. Also the action, which was for a long time considered as a weak point of these devices, made significant improvements so that they are more and more used in classical music. Obviously, the main advantage of digital keyboards is that they do not use to be tuned, and there is no necessity of voicing the hammers! The main weak point is the radiation, due to the limited number and frequency range of the loudspeakers. However, relative better results are obtained by using headphones. In physics-based digital piano, we can have access to the string parameters to modify the sound. It can be anticipated that refined soundboard parameters could be accessible in the near future.

Recent advances in mechatronics make it now possible to replace the historic wooden action mechanisms by electromechanical devices [8]. In addition, the mechanical properties of new materials (such as polymers) make them less sensible to humidity with reduced risks of shrinking. Models of damped stiff strings are now well-known, and thus the stringing can also be entirely removed and replaced by electronic circuits where the string motion is calculated in real-time. However, some theoretical and numerical efforts remain to be done for modeling the whirling nonlinear motion of real strings, which has an important effect on the temporal envelope of the sounds. Nonlinear models would also be necessary in order to reproduce the phantom partials in an adequate manner. Today, a great deal of effort is made in the musical acoustics community for accurate modeling of soundboard vibrations and string-soundboard coupling [9]. This is a key and challenging problem, since the soundboard is a 2D/3D system with space-varying elastic and damping parameters. As such, this is also more difficult than strings for real-time applications. One can however reasonably anticipate that future physics-based pianos will want to incorporate such soundboard models which are potentially able to produce a large variety of sounds, directly linked to a given design. At this stage, it is important to mention that only the *dynamical* part of the physical equations need to be discretized for simulating sounds and vibrations: in other words, we do not need to reproduce the *static* balance between all elements. Finally, there is also active research in the 3D reproduction of sound field with loudspeakers arrays, which could be nicely applied to the piano case. Today, the results are mainly limited by the required spatial mesh, in order to reproduce the high frequency range with sufficient accuracy.

4 Conclusion

Piano manufacturing is one of the few examples of industry which did not significantly evolve during the last century. After 100 years of relative stagnation, it seems that engineering creativity and new musical demands are pushing again the industry of pianos forward to many innovations. Depending on the opportunities left by the economical and financial context (which can change rapidly!), interesting tracks for the design of new instruments are possible today, in view of the recent progresses in acoustics, robotics and electronics. Like for the good wines, it would be very damaging that the recent progresses both in piano physics and making result in a unique instrument only!

Acknowledgements
This work was supported by the Lise-Meitner-Fellowship M1653-N30 of the Austrian Science Fund (FWF). The author wishes to thank Alex Mayer (MDW), Caroline Haas and Michael Kirchweger (Technical Museum Vienna), Paul McNulty (Divisov), and Gert Hecher (Das Klavier-Atelier, Vienna) for discussion and help in the measurements. The simulations presented in this paper were carried out using the PLAFRIM experimental platform, being developed under the Inria PlaFRIM development action with support from Bordeaux INP, LABRI and IMB and other entities: Conseil Régional d'Aquitaine, Université de Bordeaux and CNRS (and ANR in accordance to the programme d'investissements d'avenir (see http://www.plafrim.fr/).

References

[1] Chaigne, A.; Kergomard, J. Acoustics of Musical Instruments, Springer, New York (USA), 2016.

[2] Chabassier, J.; Chaigne, A.; Joly, P. Modeling and simulation of a grand piano. J. Acoust. Soc. Am., Vol 134 (1), 2013, pp 648-665.

[3] Chabassier, J.; Chaigne, A.; Joly, P. Time domain simulation of a piano. Part 1: model description. European Series in Appl. and Ind. Math:M2AN, Vol 48 (5), pp 1241-1278.

[4] Chaigne, A.; Hennet, M.; Chabassier, J.; Duruflé, M. Comparison between three different Viennese pianos of the nineteenth century. Proceedings of the 22nd International Congress on Acoustics, Buenos Aires, paper ICA2016-25.

[5] Chaigne, A. Reconstructing the piano hammer force from measurements and filtering of the string velocity, J. Acoust. Soc. Am., Vol 139 (4), Pt. 2, 2016, p 2011.

[6] Chaigne, A.; Cotté, B.; Viggiano, R. Dynamical properties of piano soundboards. J. Acoust. Soc. Am., Vol. 133 (4), 2013, pp 2456-2466.

[7] Chaigne, A.; Chabassier, J.; Duruflé, M. Energy Analysis of Structural Changes in Pianos. Proceedings of the Third Vienna Talk on Music Acoustics, Vienna, Austria, 16-19 September 2015, pp 184-191.

[8] Thorin, A.; Boutillon, X.; Lozada, J.; Merlhiot,X. Non-smooth dynamics for an efficient simulation of the grand piano action. Hal-01331941, 2016.

[9] Boutillon, X.; Ege, K. Vibroacoustics of the piano soundboard: Reduced models, mobility synthesis and acoustical radiation regime. J. Sound Vib., Vol. 332, 2013, pp 4261-4279.