The challenges of classical guitar FEM modelling

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Abstract. The aim of the present paper is to discuss the most problematic aspects of modelling the classical guitar using the Finite Elements Method (FEM). In spite of being a powerful tool that can be used for designing, modifying and simulating the musical instruments, the numerical modelling is also a very complex method, demanding the profound understanding of physics of the modelled objects. Moreover, being a model that only imitates the reality, the FEM also assumes several simplifications. As a solution for the discussed problems, the concept of a modular guitar is introduced. It brings the possibility of defining the influence of particular guitar construction elements on the acoustic parameters of the instrument and therefore leads to more aware use of FEM while modelling the classical guitar. The awareness of the limitations of the method itself, combined with the understanding of the mechanics and acoustics of the instrument can result in creating a very effective solution both for luthiers experimenting with new construction concepts and scientists working in the field of musical instruments acoustics.

Keywords. Classical guitar, Finite Elements Method, modular guitar, numerical modelling

1 Introduction

The musical instruments modelling using the Finite Elements Method (FEM) is a powerful tool that can be applied e.g. for testing the brand new concepts or modifications of instruments construction in an abstract, digital domain. It enables to simulate the mechanical behaviour of an instrument and the acoustic effects it creates. Modern luthiers often attempt to control the acoustic parameters of the classical guitar by slightly reshaping its construction to obtain the tone desired. To achieve this goal it is essential to understand the mechanics and acoustics of the instrument. But even with this knowledge, gathered by each luthier during experimenting with different models for a long time, it is impossible to avoid the waste of time and materials for unsuccessful attempts. This time-consuming nature of luthier craft can be also a reason of the excessive attachment to traditional design and the unwillingness to experiment more radically, both caused by the fear of wasting time and materials for the constructions whose effects are unpredictable. The FEM seems to be a panacea for all this problems. Changes in the instrument geometry can be made virtually and their influence on the sound checked just in the time needed to perform the computation. But also, as the modelling method, FEM assumes a number of simplifications. In the case of the classical guitar, they are mostly related to the accuracy of geometry modelling and the type of excitation used for simulation. Without the knowledge of the meaning of the particular guitar construction elements for the acoustic parameters of the instrument, it is impossible to create a precise model and perform a simulation giving the credible results. The further sections of the present paper discuss the challenges of modelling the classical guitar using FEM and the possible solution for the problems encountered.

2 Scope and purpose of the study

The main purpose of the study was a comparison between the classical guitar FEM model and the measurement of the real instrument, followed by an indication of the differences and finding out their reasons. The simulated/measured parameter was the SPL (Sound Pressure Level) of the guitar. The two instruments shown in Fig. 1 were engaged in the study.

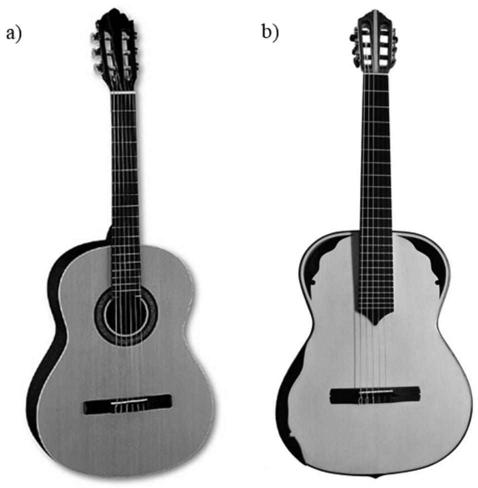

Fig. 1 The objects of the study: a) Greg Bennett, Barcelona Series C-2 [1], b) Piotr Aleksander Nowak, *Björk* [2]

The first one (guitar A) is the Barcelona Series C-2 traditional classical construction made by Greg Bennett. The second guitar (guitar B) is the modern guitar *Björk* designed and build by Piotr A. Nowak. The wood species used for both instruments are listed in Table I.

TABLE I: WOOD SPECIES USED IN THE EXAMINED INSTRUMENTS

Guitar	Top plate	Ribs	Back plate	Neck	Fingerboard	Bridge
A	Sitka Spruce	Ovangkol	Ovangkol	Gaboon Ebony	Brazilian Rosewood	Brazilian Rosewood
B	Norway Spruce	Yellow Birch and Red Maple	Yellow Birch	European Ash	Brazilian Rosewood	Gaboon Ebony

The experiment was performed in two stages. The first one was the SPL measurement of the guitars A and B in the anechoic chamber of Mechanics and Vibroacoustics Department of AGH University of Science and Technology in Cracow. The measured instrument was placed on a polyurethane foam in a horizontal position, what could slightly attenuate the back plate vibrations. The strings were excited one by one manually with the displacement of "3mm" on the 16th fret. The sound of each string was recorded several times, to reduce the inaccuracy of the manual excitation. Seven uniformly distributed free field G.R.A.S 46AE microphones were used to collect the data, each placed "1m" from the bridge on the semi-sphere above the guitar body. The recorded signals were processed to calculate the SPL of each string and the FFT (Fast Fourier Transform) was used to determine the frequency spectrum.
The second stage of the study concerned modelling the geometries of the guitars A and B and performing the SPL simulation using FEM software. A detailed description of these processes is contained in the next section of the present paper.

3 The most problematic aspects of FEM modelling

Both steps of FEM modelling, i.e. creating the geometrical and physical models of the examined objects and phenomena, demand some simplifications. The geometrical models of the guitars A and B used for the simulation are shown in Fig. 2 and Fig. 3.

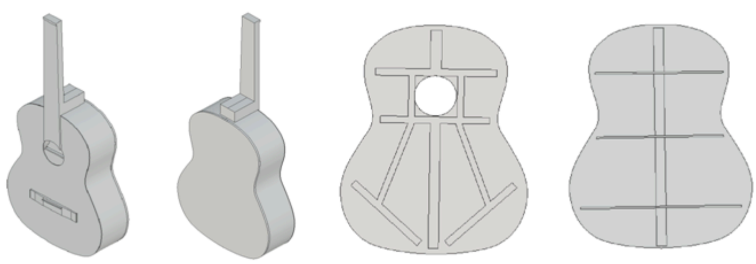

Fig. 2 The geometrical model of guitar A

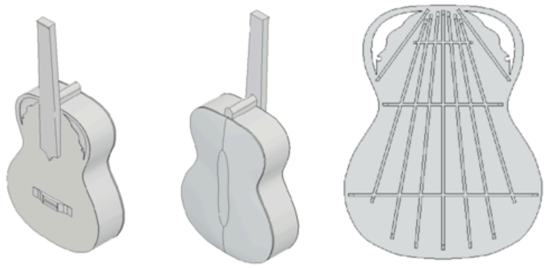

Fig. 3 The geometrical model of guitar B

Although both models are the best possible approximations of real geometries, there are several differences between them and the real ones. The most important is that not all construction elements were modelled. The geometry was limited to both plates with bracing, ribs, bridge and the neck with fingerboard. The headstocks were omitted because of their negligible mass. The difference covers also the thickness of plates – in reality it is not constant but usually decreases towards the edges. The modelled geometries have constant thicknesses of the plates selected to result in the same mass of the plates as the real ones. Moreover, the plates of the guitar B are bended in reality. The top plate deflection is unnoticeable so it was modelled as the flat one. The back plate in maximum point is bended up to "1.5cm" and this was taken into account. But it was impossible to model a perfect copy of the plate curvature so it was simplified to the one shown in Fig 3.

Another issue in modelling the geometry of an instrument is the connection of elements. In reality they are usually glued to each other. The result of this process is a rigid connection, but not perfectly rigid – the layers of glue contribute to the sound propagation within the guitar body. Between all elements in the model the perfectly rigid connection was applied.

The physical model in FEM software is a coupling between mechanical and acoustic phenomena, i.e. between guitar body and surrounding air. The first decision to be made is the choice of a mesh size which determines the frequency range of the study. The finer mesh, the higher upper limit of the range and higher accuracy, but also – the longer calculation. The analysis of the recorded sound of strings led to the conclusion that the most influential harmonics of the guitar sound are located between "100Hz" and "2.5kHz". The size of a mesh was adjusted to meet this condition.

The next step in FEM modelling is to assign the material properties to the object. And that is probably one of the most challenging tasks in the classical guitar modelling. Wood is an orthotropic material – its properties are different in three perpendicular directions - axial, radial, and circumferential [3]. Besides, wood properties are influenced majorly by temperature and humidity. It is impossible to include all these conditions in a model – there is not enough data about wood parameters, even for common wood species, not mentioning rare examples, e.g. an African ovangkol. For this reason, modelling the wood simplified its nature significantly – it was assumed isotropic, and the used parameters, i.e. density ρ, Young modulus E and Poisson ratio μ, related to 12% humidity. The values of the parameters applied to the model are listed in Table II.

TABLE II: PARAMETERS OF MATERIALS USED IN THE MODELS

Material	Latin name	*E* (GPa)	*μ* -	*ρ* (kg/m^3)
Yellow Birch	*Betula alleghaniensis*	13.96	0.50	640
Gaboon Ebony	*Diospyros crassiflora*	16.89	0.30	955
European Ash	*Fraxinus excelsior*	12.31	0.33	680
Ovangkol	*Guibourtia ehie*	18.60	0.40	825
Brazilian Rosewood	*Dalbergia nigra*	13.93	0.33	835
Yellow Birch-Red Maple plywood	-	16.27	0.51	830
Norway Spruce	*Picea abies*	9.70	0.34	405
Sitka Spruce	*Picea sitchensis*	11.03	0.38	425

The final stage of classical guitar modelling using FEM is the application of physics. It is the most demanding part, requiring the awareness of each step. Unlike the material parameters, which can be optimised to the most credible values, physics is only applied once and determines the whole computation. In the present research and in the modelling of musical instruments in general, the most important part is the definition of an excitation. A plucked string starts to vibrates and transmits the energy mainly through the bridge to the sound box [4]. According to Rossing, the maximum transverse force from the string to the bridge is roughly 40 times greater than the maximum longitudinal force [4]. For this reason, the excitation used in the study was the force applied perpendicularly to the bridge as shown in Fig. 4. Similarly to [5], the modelling of strings was omitted. This approach caused one more inaccuracy – the strings' tension is not taken into consideration. It slightly changes the resonant frequencies, but should not have a great influence on SPL.

4 Measurement and FEM simulation results comparison

Because of all assumed simplifications, the raw results of the SPL simulation differed from the measurement significantly. After some adjustments in the material parameters and the amplitude of the excitation, the differences do not exceed "5dB". A comparison of measurement and simulation results for the guitars A and B is shown in Table III.

TABLE III. SPL MEASUREMENT AND SIMULATION RESULTS COMPARISON

String name	**Guitar**	**SPL (dB)**		
		Measurement	**Simulation**	**Absolute error**
E	A	38	41.5	**3.5**
	B	40.2	43.1	**2.8**
A	A	40.9	42.1	**1.3**
	B	46.8	42.8	**3.9**
d	A	41.3	42.7	**1.4**

	B	45.1	44.5	**0.6**
g	A	42.9	44.9	**2**
	B	53.5	48.8	**4.8**
b	A	42.2	45.1	**2.9**
	B	49.1	46.8	**2.3**
e1	A	45	43.6	**1.4**
	B	45.2	45.5	**0.4**

5 Conclusion

The main problem encountered during the present study was the inability of evaluating the uncertainty of the model designed. Without determining the influence of each step of the study on the final result it is unclear which elements are more important, requiring more accuracy and which can be significantly simplified. The state of the art does not solve the problem, there are still not enough studies concerning the interactions between guitar construction elements. To face the problem, a new approach is in preparation. The concept concerns the construction of a special measuring instrument – a modular guitar, which special features will make it possible to determine the influence of the classical guitar construction elements on its acoustic parameters and its final tone. With this knowledge, the instrument modelling using FEM method will be more aware and will contribute to obtaining more accurate results, allowing scientist and luthiers to simulate their ideas and making the process of instrument building much more efficient.

Acknowledgments

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