Numerical simulation of the acoustic guitar for virtual prototyping

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Abstract
This research presents numerical simulation tools used in the research of acoustic guitars in the industrial context. The focus is on describing a virtual prototyping environment that has been successfully used in product development. The main challenge is achieving an acceptable agreement between simulation and measurement of a random guitar taken in the production line. To this end, detailed geometrical modeling and averaged materials parameters values measured from the production line are used. Simulation and measurement results are compared in terms of mode frequencies, frequency responses, and radiation efficiency.

Keywords: Acoustic guitar, Wave-based modelling

1 INTRODUCTION

According to Music Trades[1] in the US alone about 1.5 million acoustic guitars were sold in 2018. At the same time, it can take months to build an acoustic guitar, depending on the amount of development work and details put into it. Large-scale manufacturers typically maintain a large lineup in order to cater for needs of different players, making the management and building processes more complicated. In addition, introducing model changes in the factory production line can be costly. In order to save time and resources, while maintaining high product quality, virtual prototyping has become a very useful tool for musical instrument manufacturing.

Virtual prototyping requires a numerical simulation model, which essentially means solving by approximation the complicated partial differential equations that govern the vibro-acoustic characteristics of the system. Apart from prototyping, numerical simulation has been applied to sound synthesis [20], study of structure-acoustic phenomena [7, 19], conservation of historical instruments [23], and material property estimation [22], among others. Each application requires a little bit different approach to simulation. For example, for sound synthesis, it is possible to use black-box modelling tools that try to match the timbre of the instrument, and often it is required that the simulation work real-time. On the other hand, for prototyping, the interest is on being able to edit the material properties as well as the geometrical properties directly, and ideally within a reasonable computational time. For this purpose, wave-based modelling methods are often employed.

In the field of scientific computing, the verification and validation process is necessary for credibility and ultimately the usability of the simulation tools [14]. Numerical verification is done with a simple case by comparing the simulation against the analytic solution. As for validation, there are many sources of uncertainty when the simulation data is compared with experimental data. For the case of factory-produced acoustic guitars, when comparing a simulated guitar and a random guitar measured from the production line, the biggest sources of discrepancy are probably the inherit variability of wood and the manufacturing tolerance.

In this paper, a combination of wave-based element methods is adopted for simulating the acoustic guitar body. The structural eigenfrequency analysis of a fairly detailed geometrical model is calculated using finite element method (FEM), and that result is used for forced modal analysis with boundary element method (BEM) in the coupled structure-acoustic domain. Different ways of validating the model with measurements are explored while the manufacturing tolerance and perceptual tolerance for frequency responses of the guitars are considered.

2 BACKGROUND

The guitar can coarsely be divided into two vibrating parts: strings and body. The player sets the strings to vibrate and that vibration drives the guitar body to finally generate an audible sound. It is very common

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[1]Music Trades, April 2019 issue, p.62

to consider each of them separately for modelling purposes. First proposal for modelling strings for sound synthesis was done by [8] and since then models have developed, especially for sound synthesis purposes [20, 6].

Guitar body models are useful for prototyping purposes, since guitar building is essentially about crafting the guitar body, including bridge, saddle, neck, and nut. One of the first mathematical models of the guitar body was the resonator model of the first two coupled modes [4]. Since the early stages of scientific computing in the 1960's, especially finite and boundary element models for the guitar body started to appear [16]. Finite difference [15] and spectral method [5] have also been used, but FEM has been by far the most popular method. To mention but a few examples from different decades, guitars at different building stages [7] and the effect of bracing [9], bridge design [18], plate thickness [16], and string-fret collisions [2] have been studied with the help of simulations. Simulations have given rise to extended design methods related to, e.g., frequency response optimization [21], material property identification [22], and platforms for designing musical instruments, such as PAFI[2] and Digital Guitar workshop[3]. The coupling between the body and strings has been explored by [25]. A full model has also been considered by [5].

Commonly, simulation validation is done by comparing simulated mode shapes and frequencies, and transfer functions (input admittance, or sound pressure level at a point in space) to the measured ones. Also, directivity patterns and radiation efficiency have been compared [10, 11, 19].

3 METHODS

3.1 Simulation

3.1.1 Geometrical model and material properties

One guitar can have up to about 40 individual parts and about 10 different materials. The materials may also be oriented in different ways, typically requiring about 10 different local coordinate systems in the model. In addition, the line-up of large manufacturers may be extensive. For example, Yamaha maintains more than 10 different guitar models and within each model the materials vary in order to cater for different needs of players. It is important that each guitar model be modelled with respective properties.

For prototyping purposes, the geometrical model of the guitar needs to be easy to edit. To this end, in-context design with envelopes was used in SolidWorks 2016. The geometrical model was constructed from drawings, but it can also be achieved by measuring a physical copy from the production line with, e.g., 3D imaging techniques.

For the model presented in this paper, some simplifications were made: pegs, frets, and strings were omitted. In addition, the top and back plate were modelled flat, not arched. Glue between parts was not considered, instead continuous mesh across the contact surfaces was assumed.

For the simulation, material properties were measured from the wood used in actual production line. Three or more samples were measured and averaged. Wood is an orthotropic material, so three Young moduli, shear moduli, Poisson ratios, and density are needed as input. The material properties were measured by means of experimental modal analysis with beams at free-free boundary conditions. For example, the Young moduli can be approximated from the first bending mode of the sample, and the shear moduli from the first twisting mode. For procedure, the reader is referred to, e.g., [17]. Damping can also be measured, but it is often frequency-dependent. In order to simplify the simulation process, a constant damping ratio of 0.008 was assumed.

3.1.2 Mesh and process

Structural analysis was performed with finite element method (FEM), and the coupling of that structure with air, as well as radiation was calculated using fast multipole boundary element method (FM-BEM) both on commercially available software, Ansys 18.2 and WAON 4.5 (Cybernet), respectively. A review of FM-BEM

[2] http://plateforme-lutherie.com/
[3] http://www.digitalguitarworkshop.de/

methods is given for example in [13]. The process requires two meshes, one for structural analysis in the vacuum and one for the coupled analysis. The meshes are shown in Fig. 1, and for the BEM model, the field point mesh for post-processing is also included.

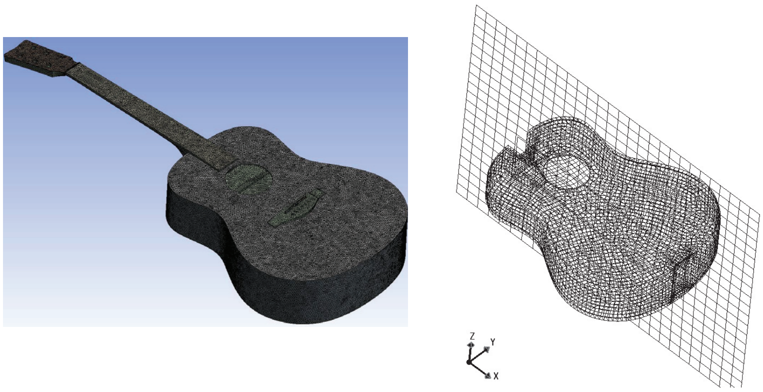

Figure 1. Structural mesh for FEM (left), and the mesh for coupled analysis for BEM with field point mesh included (right).

For the simulated guitar presented in this paper, the structural mesh consisted of solid tetrahedral elements with the maximum size of 4 mm resulting in about 400 000 elements. For the coupled analysis, the structure can be simplified; essentially all structures smaller than the acoustic wavelength can be excluded. In this case, just the enclosed air volume of the guitar was meshed, with tetrahedral elements of a maximum size of 10 mm, resulting in about 5500 elements. The result of eight structural nodal points were averaged and mapped to the each acoustic nodal point. It is recommended to have at least 6 elements per wavelength.

For BEM modelling, there are several algorithms for interior and exterior coupling. In this case, the calculations were performed using the thin panel assumption using the indirect double layer formulation. For examples the reader is referred to [1]. The structure-acoustic simulation took about 30 min for the frequency range of 12-500 Hz with 1-Hz step run with a desktop computer (24 cores, 3 GHz, RAM 256 GB).

Two different excitation methods were used: force of 1 N in the center of the saddle to simulate the impulse hammer excitation, and a point source with amplitude of 2 Pa at a distance of 1 m in order to simulate the acoustic excitation used in the LDV measurements.

3.2 Measurements

In order to understand the material variability in the production line, measurements of eight guitars were performed in an acoustically dry measurement room. Both accelerance (ONOSOKKI PU NP3211) and sound pressure level (microphone ONOSOKKI MI-1234) were recorded with FFT analyzer (ONOSOKKI DS-3000, sampling rate 52100 Hz) by using a miniature impulse hammer (B&K 8203). In addition, one guitar was measured with laser-Doppler vibrometer (LDV) (Polytec PSV-300) in an anechoic room in order to obtain the mode shapes and average top plate velocity for comparison with simulation. It is also possible to reconstruct the radiated sound power and the radiation efficiency of each of the mode shape when the surface velocity is known [24]. The excitation method was random noise through a speaker (Yamaha MSR100). During the measurements of the assembled guitars, the strings were damped, and the guitar was supported from the neck only.

4 COMPARISON OF SIMULATION AND MEASUREMENTS

Firstly, the material property variation in the production line was analyzed. Figure 2 shows the mobility of eight guitars taken from the same production line. The variation of the peak frequencies is limited to a few percent.

This sets a limit for the acceptable difference between simulated and measured mode frequencies.

After careful material measurements and geometrical modelling, an example of the simulated and measured sound pressure level in the near-field of the guitar is shown in Fig. 3. The simulated mode frequencies are within 2 % of their measured values. Some of the simulated mode peaks have a higher Q value than the measured ones, owing to approximating the damping with a constant damping ratio.

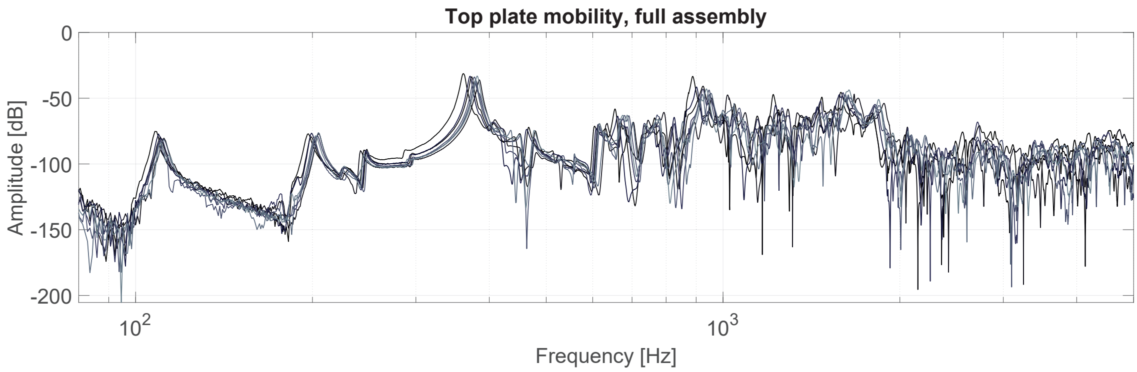

Figure 2. Top plate mobility measured in eight different guitars in the production line.

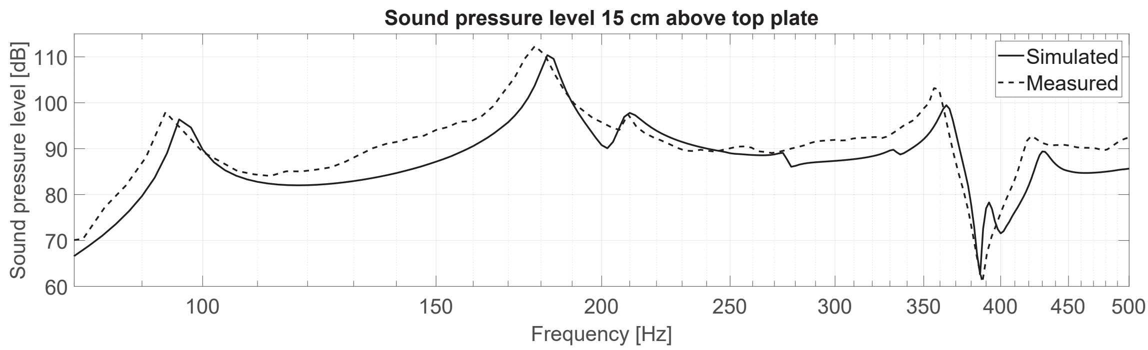

Figure 3. Comparison of simulated and measured sound pressure level at 15 cm above the low bout of an acoustic guitar.

In addition to the frequency response, some of the simulated and measured modes shapes are shown in Fig. 4. The data is real velocity data, and the color scales of the simulated and measured data have been normalised. The mode shape are very similar.

Furthermore, the average velocity of the top plate and radiation efficiency of the mode shapes are compared in Fig. 5. The simulated and experimental average velocity are very similar. The radiation efficiencies, while not matching in all cases, follow similar trends. Again, the simple approximation for damping may be the cause of the differences.

5 DISCUSSION

It can be concluded that even with some geometrical simplifications, and with a simple damping model, the acoustic guitar body can be simulated reasonably accurately. In addition, with the combined FEM-FMBEM approach, the air cavity does not need to be modelled with as much detail as the structural model.

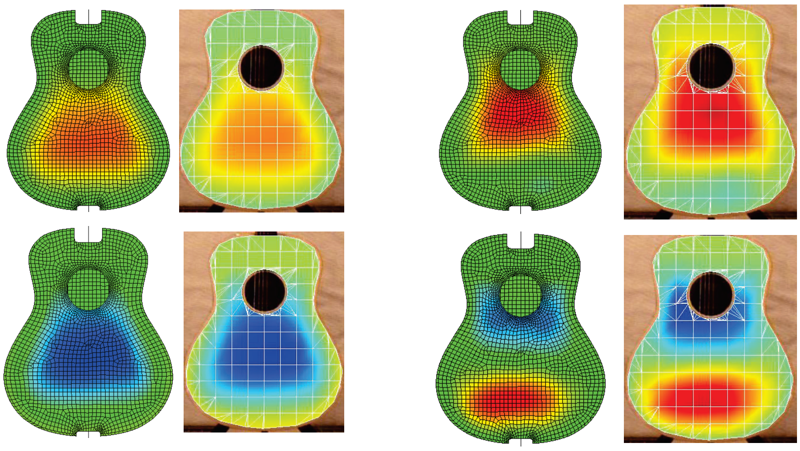

Figure 4. Some of the simulated and measured mode shapes with acoustic excitation.

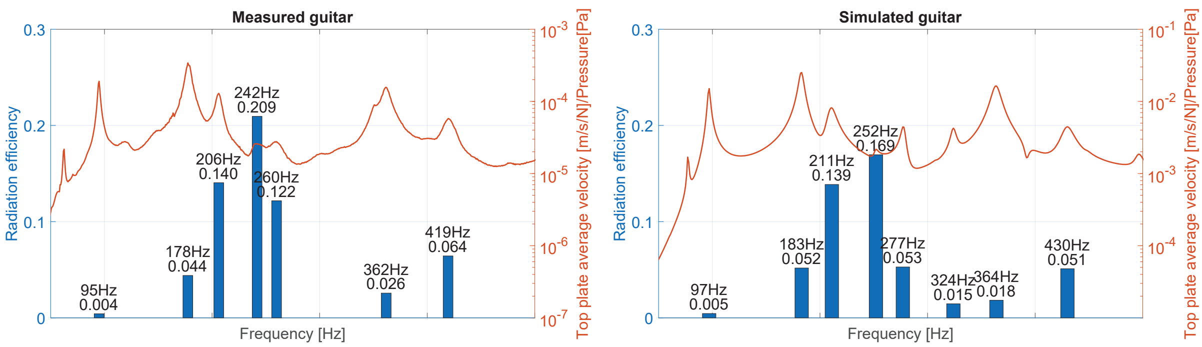

Figure 5. Comparison of simulated and measured average top plate velocity and radiation efficiency of an acoustic guitar with acoustic excitation.

The differences between simulated and measured mode frequencies fall within the variability of the manufactured guitars in the production line when averaged material properties from the production line are used. The measured and simulated mode shapes are also very similar. The more global parameters like average top plate velocity or radiation efficiency of the modes can differ more. Differences can be seen especially in the modal damping and in modes that do not seem to radiate well. This information, together with understanding the origins of the coupled modes, can be used to improve the simulation model.

Perceptually, it seems possible to differentiate between two guitars, if all the mode frequencies are shifted about 2-3 % [25]. However, recent playing and listening tests with actual guitars suggest that even a larger shift might be acceptable when not all modes frequencies are shifted consistently [3]. Furthermore, while studying guitars from the same production line, about 5% reduction in the frequency of the first mode was needed in order the guitar to perceived as more bassy [12]. The frequency response of the current simulated guitar falls within such variation from that of the measured guitar.

After verifying the simulation results, the simulation model can be used in virtual prototyping. The design process for the A-series aiming at louder low-mid frequency range sound with bracing changes is an example of involving virtual prototyping at Yamaha. The numerical simulation serves in a supporting role, meaning that ultimately actual prototypes are built and evaluated.

The feedback loop between simulation and measurement is completed by measuring the prototypes and confirming the simulation result. Consequently, improving the matching between simulation and measurements is an ongoing process at Yamaha. With a large database of measured and simulated guitars, it is possible to spot trends in the mismatch between simulation and measurement, and to improve the simulation model. Generally, a good agreement between simulation and measurements can be reached at much higher frequencies than presented here. The contribution of individual modes can distinguishable up to about 1 kHz, as can be seen in the top plate mobility measurements in Fig. 2.

Examples of further considerations for the simulation include pre-stress from the string tension, although at low frequencies, it does not change the results considerably. Orthotropic damping has also been considered.

6 CONCLUSIONS

A modelling scheme using FEM and FM-BEM was adopted for simulating the acoustic guitar body. By using averaged material properties measured from the wood used in the production line and the detailed geometrical modelling from drawings, it is possible to reach an acceptable agreement between simulated and measured frequency response that falls within the manufacturing variability and the perceivable tolerance of frequency response shifts, when the measured guitar is taken randomly from the production line.

Comparison of the simulated and measured guitars shows that while the mode frequencies and shapes are very similar, average top plate velocity and radiation efficiency of the modes can vary more. One of the reasons is simplified damping properties of wood used in the simulation.

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