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Experimental and simulative examination of the string-soundboard coupling of an acoustic guitar

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Abstract

The acoustic guitar is a popular string instrument in which the sound results from a coupled mechanical process. The oscillation of the plucked strings is transferred through the bridge to the body which acts as an amplifier to radiate the sound of the guitar. In this contribution, the vibration of a guitar body is examined experimentally and by means of numerical simulation. An experimental setup not only capable of determining eigenmodes and eigenfrequencies but also demonstrating the transient coupling between the strings and the body is presented. This capability is achieved with a plucking mechanism that allows reproducible plucks of a single string and synchronized measurements of multiple plucks at different positions of the guitar body using a scanning laser Doppler vibrometer. Besides the experimental setup, a finite element model of the guitar is developed. The numerical model consists of the body and the neck of the guitar. Furthermore, the struts to reinforce the soundboard and the back of the guitar are included. A comparison between the numerical model and the experimental measurements is conducted.

Keywords: Guitar, Modal Analysis, Finite Elements

1 INTRODUCTION

The acoustic guitar is a popular string instrument in which the sound results from a complex transient process beginning with the oscillation of a plucked string that is then coupled with the guitar body that radiates the sound to the surrounding air. To better understand this transient process, not only measurements shall be carried out, but also a finite element (FE) model shall be created that is able to approximate the vibration of the guitar. In this contribution the guitar body is examined without any influence from forces of the strings with the goal to create an FE model that approximates the eigenfrequencies and eigenmodes of a real guitar. The oscillation of a single string is examined in previous works of the authors [1, 2]. For this reason, an experimental modal analysis is carried out to gather knowledge of the eigenfrequencies and the eigenmodes of the particular examined guitar. This particular examined guitar is then modeled in a high level of detail and the eigenmodes and eigenfrequencies of the model are compared with the ones identified in the experiment.

2 MODAL ANALYSIS OF AN ACOUSTIC GUITAR

The sound of an acoustic guitar results from an interaction between the guitar body and the string through the bridge. In this work the guitar body shall be examined without any influence of the strings as it is necessary to understand the two mechanical systems decoupled to create a coupled model afterwards. For this reason a modal analysis of the guitar body is carried out with the strings unmounted to identify the eigenfrequencies and the eigenmodes as well as the damping and the transmission behavior of the system.

2.1 Experimental setup

The experimental setup contains basically the guitar mounted with rubber bands on a fixture, an electrodynamical shaker and a Polytec PSV-500 scanning laser Doppler vibrometer (LDV). Figure 1 shows the complete experimental setup.

The examined guitar is a rather small traveling guitar equipped with nylon strings and a simple bracing pattern

Figure 1. Experimental setup for the modal analysis.

on the soundboard and the back plate that consists of only three horizontal struts approximatively dividing the soundboard and the back plate in four similarly large parts, respectively. The strings are unmounted during the modal analysis to ensure that coupling effects between strings and body are excluded. As the guitar is a low priced model the soundboard and the back are made of some laminate of which the choice of woods is not known. In the experiment the guitar is held in place by rubber bands which are attached at the head and the strap button. At the head the guitar is fixed with one loop of rubber band while on the strap button three loops of rubber bands are mounted to reduce rotational movement when the guitar is excited eccentrically. The support can be interpreted as a proximate free support because the allowed movement through the rubber bands is expected to be in a very low frequency range that does not interfere with the elastic body modes of the guitar body.

To excite the guitar an electrodynamical shaker is used. The shaker is mounted decoupled from the guitar support and weighted with sand bags to guarantee that there is no significant movement of the shaker support. Since usual frequency sweeps that are carried out with a shaker are rather time consuming in combination with the need of many points to measure, the shaker is used in such a way that it acts like an impulse hammer. Therefore, the shaker is triggered by a function generator with a short trigger signal which leads to a single hammering motion of the shaker. A soft rubber tip is used to not damage the guitar and the shaker is applied on a position close to the lower edge on the left hand side of the soundboard. A shaker position close to the edge is chosen for two reasons. First and foremost, the position should be chosen such that the shaker is not in the way of the laser rays which would prohibit the measurement of certain points. Secondly, close to the edge it is easier to robustly prevent double hits. Behind the tip, a PCB piezoelectric force sensor is adjusted to measure the force input on the guitar body. Before being transmitted to an oscilloscope or the Polytec controller the force signal is preprocessed and amplified by an ICP conditioner.

The oscillation of the guitar body is measured with a scanning LDV. With the scanning LDV it is possible to measure the velocity on a predefined mesh of points on the guitar successively in a convenient way. Generally, an LDV can measure the velocity of a point of a structure owing to a frequency difference between a reference ray and the reflected ray on the structure, which is caused by the Doppler effect. In a scanning LDV, addition-

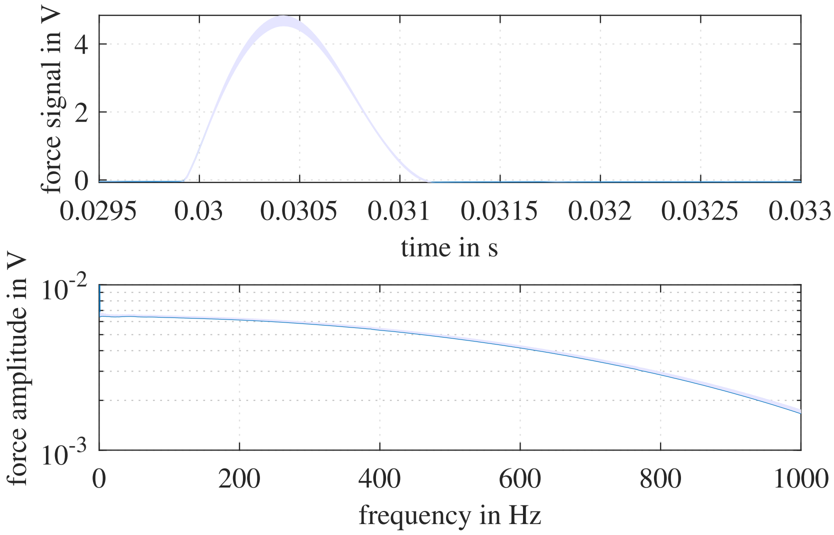

Figure 2. Force signal with confidence interval transient (above) and its Fourier transform (below).

ally, the direction of the laser ray can be controlled via a system of mirrors making it possible to change the measured position quickly and conveniently without changing the position of the LDV itself. The experiment is carried out using a mesh of 73 points distributed over the soundboard. In the current status only the velocity on the soundboard is measured, the neck and the back plate are omitted.

2.2 Modal analysis results

To carry out a modal analysis there is large number of procedures available in the frequency domain as well as in the time domain. An overview over different procedures can be found for example in [3, 4]. For the modal analysis in this work the peak amplitude method combined with an adjusted version of the half-power bandwidth is chosen. This is one of the standard procedures to choose for a modal analysis in the frequency domain and it belongs to the single degree of freedom methods.

The carried out modal analysis identifies not only the eigenfrequencies but also the eigenmodes and the damping. To ensure that the identified data is correct, the transfer function of a reconstructed system is compared with the measured transfer function.

To begin with, the system input, being the force acting from the shaker tip on the guitar body, is displayed in Figure 2. The plot shows the band of forces including 99.73 % of the measured forces on the 73 points in the time domain and in the frequency domain. In the time domain, it is visible that the shaker produces an almost sine shaped impulse and double hits can not be seen. From the plot in the frequency domain one can learn up to which frequency the hammer excites the system with a sufficiently strong impulse such that the measurement is meaningful. From Figure 2 it can be seen that this is at least the case up to 700 Hz.

For the rest of this contribution only the frequency domain will be examined. In the experiment the force action from the shaker tip on the guitar soundboard and the velocity of the guitar body on several points are measured. Due to that, the calculated transfer function

$$Y_{\mathrm{jk}}(\omega) = \frac{V_{\mathrm{jk}}(\omega)}{F_{\mathrm{jk}}(\omega)} \tag{1}$$

is the mobility of the system from an excited point k to a measured point j with the velocity V_{jk} and the force F_{jk}. In a standard peak picking procedure this transfer function is used to identify the eigenfrequencies which

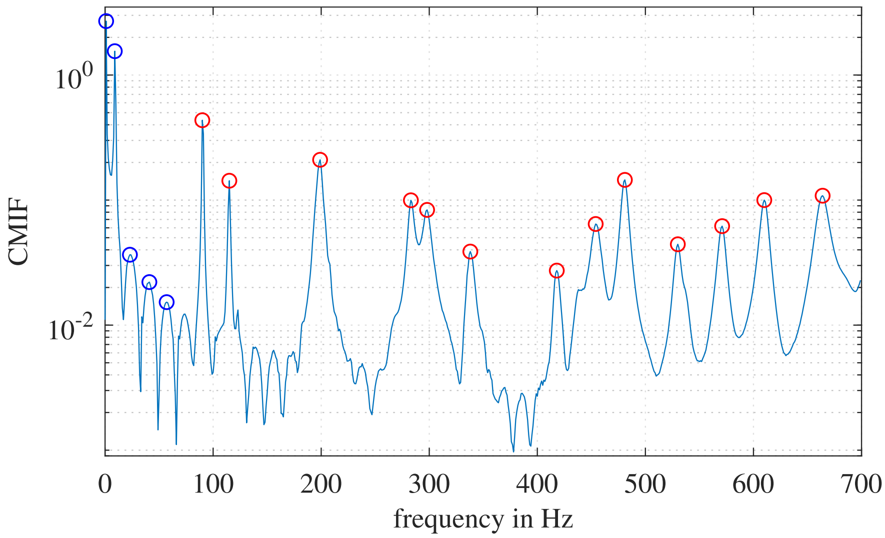

Figure 3. Complex mode indicator function of the measured signals.

are approximately at the peaks of the transfer function if the damping is low enough. An even better approach for finding the eigenfrequencies yields the complex mode indicator function

$$CMIF_1(\omega) = \Sigma_1(\omega), \tag{2}$$

where $\Sigma_1(\omega)$ is the first entry of $\mathbf{\Sigma}(\omega)$ which is calculated via a singular value decomposition of the matrix of all transfer functions

$$\boldsymbol{Y}(\omega) = \boldsymbol{U}(\omega)\mathbf{\Sigma}(\omega)\boldsymbol{V}(\omega). \tag{3}$$

If the experiment was carried out with different inputs, more CMIFs could be calculated containing even more information about the system [5]. For the conducted measurements the resulting CMIF is displayed in Figure 3. The peaks in the figure are highlighted with circles which indicate the approximate eigenfrequencies. There are several clear peaks in the regarded frequency range. The first two peaks are clearly assigned to the rigid body motion of the guitar allowed by the rubber bands, while the next three peaks come probably from noise in the measurements. The first structural eigenfrequency is then visible around 90 Hz and in total 13 eigenfrequencies are clearly visible in the frequency range up to 700 Hz.

With the given information about the eigenfrequencies, the transfer function is evaluated and reconstructed as a summation of N single degree of freedom systems

$$\tilde{Y}_{\mathrm{jk}}(\omega) = \sum_{r=1}^{N} \frac{{}_{\mathrm{r}}A_{\mathrm{jk}}(\omega)}{\omega_{\mathrm{r}}^2 - \omega^2 + 2i\omega_{\mathrm{r}}\omega\zeta_{\mathrm{r}}}, \tag{4}$$

where N is the number of identified eigenfrequencies, ${}_{\mathrm{r}}A_{\mathrm{jk}}(\omega)$ are the modal constants, ω_{r} are the eigenfrequencies, and ζ_{r} are the modal damping coefficients. The damping coefficients ζ_{r} are calculated with an adjusted version of the half-power bandwidth method as

$$\zeta_{\mathrm{r}} = \frac{b_{\mathrm{r}}}{2\omega_{\mathrm{r}}\sqrt{a^2 - 1}} \tag{5}$$

with the width b_{r} of the peak in the transfer function at the eigenfrequency ω_{r} at a fraction of the height $1/a$. Using this result the modal constants result to

$${}_{\mathrm{r}}A_{\mathrm{jk}} = 2Y_{\mathrm{j}}(\omega_{\mathrm{r}})\zeta_{\mathrm{r}}. \tag{6}$$

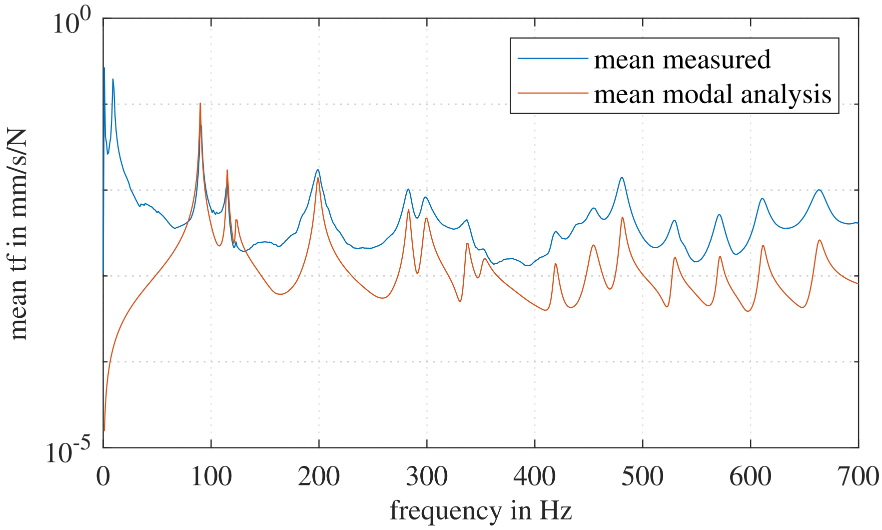

Figure 4. Comparison between mean measured transfer function (mobility) and reconstructed transfer function.

According to the equations above, the transfer function can be reconstructed with the identified eigenfrequencies, modal damping parameters, and modal constants. This resulting reconstructed transfer function is compared against the measured mobility in Figure 4. The results visible in the graph are good. Firstly, the peaks corresponding to the eigenfrequencies are at the same frequencies as they are in the measurement and, secondly, the resulting overall shape of the reconstructed curve is in good accordance with the measured one. Nevertheless there is still room for improvement because not only the identified modal damping parameters seem to be slightly too low, but also the amplitudes of the higher eigenfrequencies are underestimated. This might be solved with different identification methods and a higher frequency resolution [4].

In Figure 5 four identified modes are displayed. Furthermore, the mesh of measured points is visible in these graphs. There are two similar eigenmodes at 115 Hz and 199 Hz, where mostly the lower part of the guitar is moving. These eigenmodes can be explained by an in-phase and an out-of-phase movement of the soundboard and the back plate of the guitar that leads to two eigenmodes. In general, the found modes are in good agreement with the existing literature, see for example [6, 7].

3 NUMERICAL MODEL OF AN ACOUSTIC GUITAR

Besides the experimental study, a numerical finite element model is developed. The model of the guitar is geometrically very similar to the guitar examined in the modal analysis. It contains all parts of the guitar except strings, namely the soundboard and the backboard, both including the bracing pattern of the guitar, the bridge, and furthermore, a detailed model of the neck including the heel and the head of the guitar. Due to that, it should be possible to compare the eigenmodes of the experimental guitar with the ones calculated in the finite element model as a first step of verification.

3.1 Modeling procedure

The modeling of the geometry as well as the meshing and the simulation are carried out using the commercial software `Abaqus`. Figure 6 shows a picture of the whole model on the left which shows the high level of detail in the geometric modeling as well as the mesh used for the simulation. Within the model, two types of elements are used. To create an efficient numerical model, all thin, plate-like parts are modeled with shell elements and volume elements are only used when necessary. Hence, the soundboard, the backplate, and the

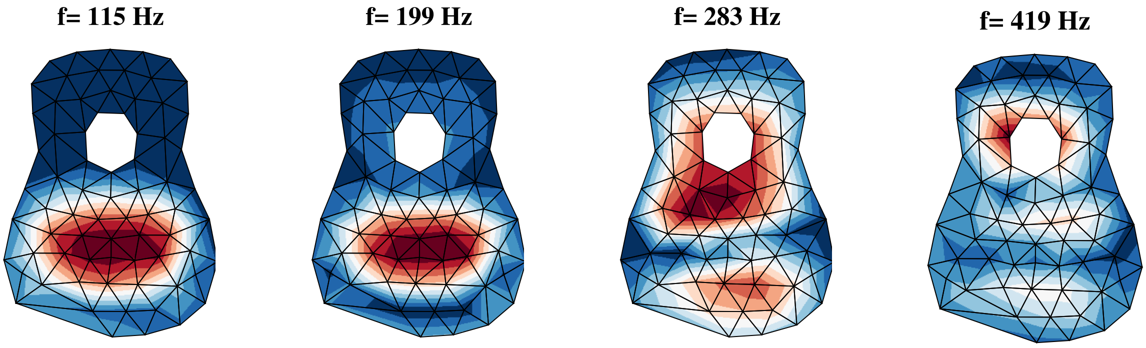

Figure 5. Four modes identified with the modal analysis.

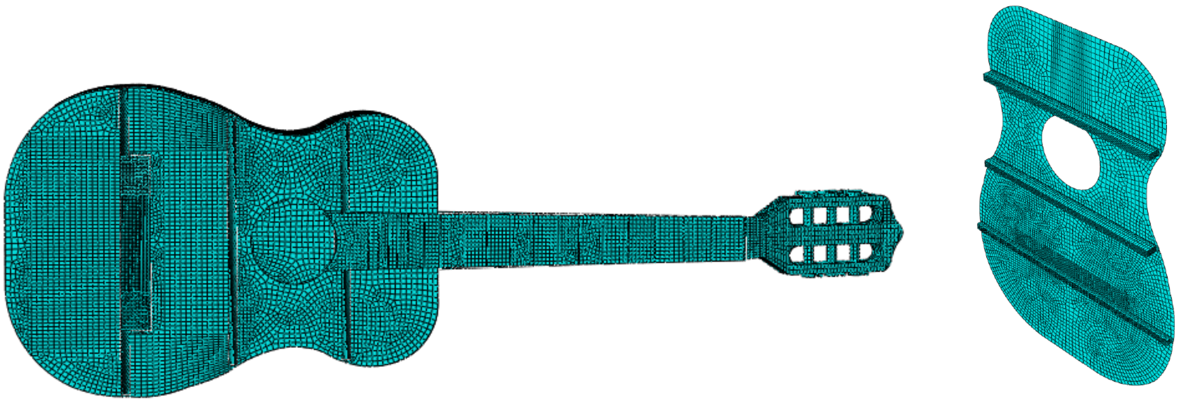

Figure 6. FE Model of the whole guitar (left) and soundboard with bracing (right).

sides are modeled with shell elements of type `S4` while the neck, the head, the fretboard, and the bracing are discretized using volume elements of type `C3D8`.

The shape of the soundboard and the back plate are equal except for the hole in the soundboard and it is modeled using splines between measured points on the experimental guitar. To both, the soundboard and the back plate, three struts are attached, as shown in Figure 6 on the right. The struts in the particular guitar are simple straight rods without any shape variation. They are coupled with the soundboard and the back plate via tie constraints which means that the additional degrees of freedom at the nodes in contact are deleted such that the two parts in contact share these nodes.

In a same level of detail the neck, including the head as well as the heel and the fretboard, is modeled. Only few simplifications are made to make it possible to create a finite element mesh on the complex geometry. In particular, the neck and the heel are modeled conical with trapezoidal cross sections and a rounded lower side instead of the complex curved shape on the real guitar. These details are assumed to be important rather for playability and ergonomic issues but the level of detail should be high enough to get good results for the eigenmodes and eigenfrequencies. For coupling the parts of the neck a different strategy than on the soundboard

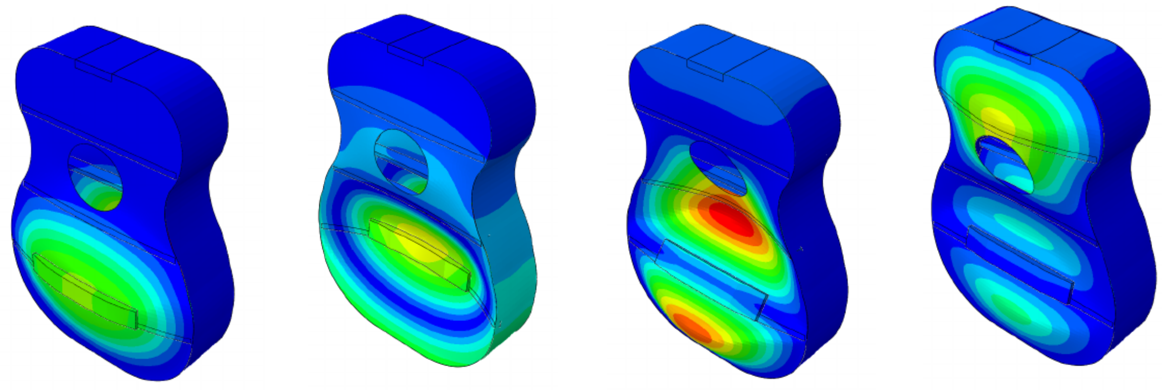

Figure 7. Four modes extracted from the simulated FE model.

and back plate is chosen. Instead of coupling the meshed parts, the neck is created as a single part and meshed afterwards. Only the fretboard is modeled as a separate part and then coupled to the neck via tie constraints. In the end, the complete neck is coupled with the guitar body on the sides and on the soundboard using tie constraints again.

On the contrary to the detailed geometry model, the material model is rather coarse at the current state. A linear elastic, isotropic material is assumed and further, the material is assumed to be equal for all parts of the guitar. This assumption is made because the particular material of the parts is unknown for the experimental guitar and for that reason the material parameters are design parameters at the current state. Hence, the material properties are chosen, such that the first bending eigenmode, occurring at 90 Hz in the experimental modal analysis, appears to be at the same frequency in the finite element model. This results in the Young's modulus $E = 7200\ \mathrm{N/mm^2}$ and the density $\rho = 640\ \mathrm{kg/m^3}$. The Poisson ratio is chosen as $\nu = 0.314$. These values result in a first bending mode, which lies at 90 Hz and additionally, the chosen values are near to the realistic values usually measured for wood.

3.2 Simulation Results

As a first step to verify the ability of the FE model to approximate the behavior of a real guitar, the comparison of eigenmodes and eigenfrequencies is chosen. In Figure 7 four eigenmodes calculated from the model are presented. The modes are chosen such that they fit to the modes extracted from the modal analysis in Figure 5.

For all four modes it can be concluded, that the shapes of the model fit remarkably well to the modes observed in the experiment. However, the two modes on the right hand side are perfectly symmetric in the model while they are not in the experimentally calculated modes. This might occur either due to a not fine enough mesh of measured points in the experiment but it is far more likely to be caused by some non-homogeneous material in the experimental guitar. Furthermore, with the model, it is visible that the two modes, in which the lower part of the soundboard has one antinode, refer to an out-of-phase movement (leftmost picture) and an in-phase movement (second from left picture) of the soundboard and the back plate. This detail cannot be seen in the modal analysis because the oscillation of the back plate is not measured.

Besides the mode-shapes themselves, the frequencies belonging to the mode-shapes are important for the behavior of the system. Figure 8 shows the eigenfrequencies observed in the experiment and the eigenfrequencies calculated from the FE model. Each compared pair of frequencies belongs to a mode shape that matches between experiment and simulation. The material parameters in the FE model are chosen such that the first eigenfrequency matches the one measured in the experiment. Using that procedure, it can be concluded, that all the other frequencies in the model are higher than the ones in the experiment. While some frequencies,

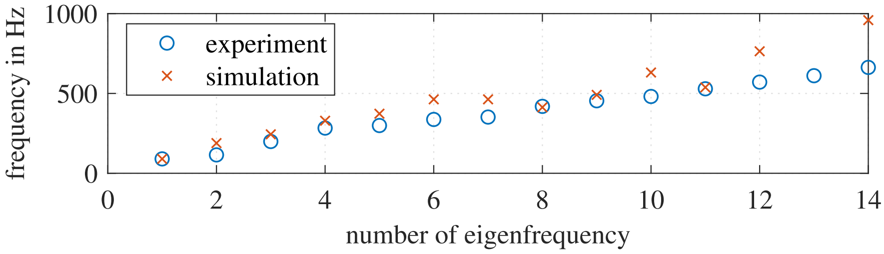

Figure 8. Eigenfrequencies with matching modal shapes compared between experiment and simulation.

like eigenfrequency number 8 and 11, fit quite well, others like eigenfrequency number 12 and 14 are rather far away from the measured value. Furthermore, the eigenfrequencies in the model do not occur in the same order as in the experiment. Hence, the frequency of the eigenmodes belonging to the model in Figure 8 is not monotonically increasing. The different eigenfrequencies might be caused by the assumption of a single material for the whole guitar in the model.

4 CONCLUSIONS

The goal of the authors was, to create an FE model of a guitar which is able to approximate transient behavior of the guitar. In this work the first steps towards this goals are presented. An experimental modal analysis has been carried out which shows good results in comparison to the existing literature referring to the eigenmodes and the transmission behavior of the guitar. The particular guitar examined in the experiment has then been modeled in a high level of detail in the FE software `Abaqus`. Good results regarding the eigenmodes and eigenfrequencies can be seen already in the early stages of the modeling procedure.

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