DETERMINATION OF IMPORTANT WOOD PROPERTIES FOR BLANKS FOR VIOLIN TOPS BY THE USE OF NUMERICAL OPTIMIZATION

Mats Tinnsten and Peter Carlsson

Department of Information Technology and Media
Mid Sweden University
`mats.tinnsten@mh.se`

ABSTRACT

In the strive of understanding how different parameters affects the vibration properties and the characteristics of the sound emanating from a violin, i.e. what makes a good violin good, numerical methods as FEM (finite element method) and BEM (boundary element method) are used. Numerical models of whole violins and/or part of it is created and studied. Crucial for the results from these studies is the correctness of the input data for the numerical analysis.

One important group of input data is the wooden material parameters for the part of the violin subjected to analysis. In this study a new method for determining these important material parameters for blanks for violin tops is proposed. In the proposed method a FEM-code is linked together with a stochastic optimization algorithm in order to, in an automatic fashion, determine the material parameters. The method requires the geometrical dimensions, the density, and measured normal modes for the blank and it consider the fact that the Young's modulus in the axial direction varies with respect to the radial direction.

1. INTRODUCTION

The characteristics of the sound emanating from a vibrating structure and its vibration properties, as mode shapes and eigenfrequencies, depends of its design properties and if these are changed the sound characteristics and the vibration properties are also changed. The influence of changes in structural design variables such as geometric dimensions [1], shell thickness [2], material parameters [3], discrete masses [4], and, for fiber reinforced material, fiber orientation [5] have been studied earlier with interesting results but more research is needed in order to understand how musical instruments, especially wooden, should be modeled to give numerical results to correspond to measured ones.

An instrument made out of wood comprises a very complex material where the material parameters, which also have a natural distribution, have great influence on the vibration properties and the characteristics of the sound emanating from it. Earlier studies, [6], on blanks for violin tops gives a good idea of the sensitivity of the vibration properties with respect to the material parameters and it stands clear that even if the material in the blank is regarded as othotropic there is no simple answer on how to determine the different material parameters in order to get acceptable correspondence between measured and calculated results. In [6] the different material parameters were assumed to be constant with regard to spatial coordinates and with the help of the sensitivity analyses, the values of the parameters were determined to give correspondence between measured and calculated results. This is not an easy task and it has proven in earlier analyses, [7], that even if the number of variables is low it is hard to determine the values of each variable by the use of sensitivity analysis to get acceptable results.

In this study the possibility to estimate these important material parameters, for an individual blank, by the use of optimization methods is investigated. Firstly, a material model for wood the so-called honeycomb model, [8], is used in order to determine the material parameters that then is used in the blank for numerical modal analysis. The results are thereafter compared with the measured results according to [6]. The next step is to use an optimization method in order to determine the material parameters that give the correct eigenfrequencies and mode shapes according to the measurements in [6]. Here the material parameters are assumed to be constant with regard to spatial coordinates. Finally optimization is used in order to determine the parameters when the Young's modulus in the first direction is allowed to vary linearly with respect to the second direction, see Figure 1.

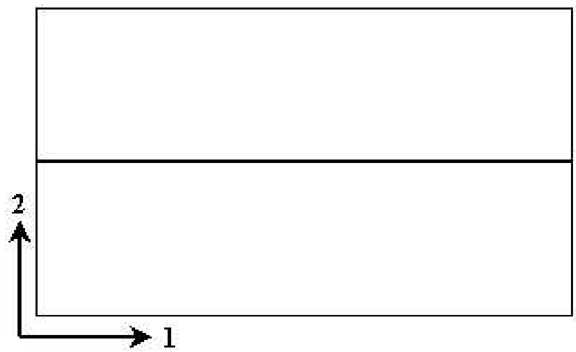

Figure 1: *Blank for a violin top. The first direction indicates the axial direction (the direction of the fibre) and the second the radial direction.*

2. ANALYSIS METHOD

It is possible to change the vibration properties as mode shapes and eigenfrequencies, and the characteristics of the sound emanating from a vibrating structure, by changing structural design variables. Of course, changes in one or more of these variables will result in changes in other structural characteristics. To find the best design, i.e. the one that satisfies all the demands put upon the structure is a question of optimization. This often requires a multi disciplinary approach, i.e. analytical tools from different disciplines must be used in concert. A typical problem formulation could be: minimize the structural weight under the constraints that the sound intensity in certain spatial domains and the maximum stress in the structure do not exceed some given values.

The modal analysis in this investigation has been performed with the commercial finite element code Ansys 7.0 (mode extraction method: block Lanczos). The FE-code has been linked together with the stochastic optimization algorithm simulated annealing (SA) [9] in order to, in an automatic fashion, determine the different material parameters. The method requires the geometrical dimensions, the density, and the measured normal modes for the individual blank.

3. IMPORTANT MATERIAL PARAMETERS FOR BLANKS

Wood has a cellular structure. If knots, annual rings and other deviations are neglected, a hexagonal honeycomb model gives a good description of the mechanical properties of wood (see [8] for more detailed information). If the wood material is modeled with the honeycomb model it is possible to show that the mechanical properties of wood depend primarily on the properties on the cell wall, the cell wall density, and the shape of the cells. Although wood as balsa or beech differs a lot in density, mechanical properties, and strength, the properties of the material in the cell wall itself are still about the same. This fact makes it possible to estimate several global wood properties from information on the cell wall.

3.1. Reference material parameters determination

In the following equations, the thickness of the cell wall is related to the density of the wood (the density of the wood is proportional to the actual cell wall thickness). The honeycomb model gives the following approximate equations for some mechanical properties of wood:

$$\frac{E_1}{E_S} = \frac{\rho}{\rho_S}, \quad \frac{E_2}{E_S} = 0.81 \left(\frac{\rho}{\rho_S}\right)^3 \tag{1}$$

$$\frac{G_{12}}{E_S} = 0.074 \frac{\rho}{\rho_S} \tag{2}$$

where E_1 and E_2 are the Young's modulus in axial (first direction) and radial directions (second direction) of the wood (blank), see Figure 1, G_{12} the shear modulus, E_S the axial Young's modulus for the cell wall, ρ_S the density of the cell wall, and ρ the density of the actual wood. From Eq. (1) we note that the axial Young's modulus (E_1) is proportional to the density (i.e. the relative density), while the radial modulus (E_2) is proportional to the cube of the density. The values for E_S and ρ_S were taken as 35 [GPa] and 1500 [kg/m^3] respectively, [8], and the value of ρ to 482 [kg/m^3], [6]. These values together with (1) and (2) gives the reference material parameter set according to: E_1=11.2467, E_2=0.9406, G_{12}=0.8323 [GPa]. The Poisson's ratio ν_{12} was chosen to 0.02, [6].

3.2. The use of optimization in determining the actual material parameters

Earlier studies, [7], on the use of optimization in connection to violins suggests that it could be possible to compensate for changes in the material parameters (from one top to another) by adjusting the thickness distribution and the arching on the violin top in order to retrieve a desired vibrational behavior. In [7] the material parameters were assumed to be known and the variables in the optimization analyses were the thickness distribution and the arching on a top. The objective with the optimization was to calculate the compensation in these variables when the material parameters for the top slightly was changed. Also in [7] the honeycomb model according to section 3.1 was used to calculate the changes in the Young's modulus when the density in the top material was changed. In the present investigation however optimization is used in order to determine the actual material parameters for the blank so that desired (or measured) normal modes are obtained. In the optimization analysis performed here there is no variables concerning geometrical dimension, instead the variables here are the material parameters.

4. PROBLEM DEFINITION

The optimization (which comprises modal analyses) is performed on a blank for a violin top (spruce). The blank has the following geometrical dimensions, vibrational properties, and weight, [6]: length = 386, width = 215, height at edge = 8.5, and height at centerline = 20 [mm] where length and width is the geometrical extension in the first and second direction respectively (Figure 1). The density of the blank is 482 [kg/m^3]. The value of the measured three first eigenfrequencies are: f_1=272, f_2=562, and f_3=631 [Hz]. The nodal lines (white) from the measurements are showed in the figures in section 5. In the FE analysis (the modal analysis) an orthotropic four-node shell element is used and the analysis is performed on a free blank, i.e. without any supports.

4.1. Reference material (given by the honeycomb material model)

The reference material set given by the honeycomb model is according to section 3.1: E_1=11.2467, E_2=0.9406, G_{12}=0.8323 [GPa] and the Poisson's ratio ν_{12} is chosen to 0.02. Here no optimization is carried out, only a modal analysis on the blank.

4.2. Constant material parameter distribution

This optimization is performed with the assumption that the Young's modulus in both directions (E_1 and E_2) are constant with respect to spatial dimensions. The objective with the optimization is to minimize the difference of the three first eigenfrequencies and the difference of the nodal line for mode 2 compared to the measured ones [6]. The optimization comprises four variables: E_1, E_2, G_{12}, and ν_{12}.

4.3. Varying material parameter distribution

Here one variable is added in allowing the Young's modulus in the first direction, E_1, to vary linearly with respect to direction 2. The objective with the optimization is the same as in section 4.2 with the difference that the optimization comprises five variables: E_1, E_2, G_{12}, ν_{12}, and the variation of E_1: $evar$.

5. RESULTS

5.1. Reference material

The modal analysis with this material set gives the following eigenfrequencies: f_1=288.9, f_2=500.6, and f_3=610.3 [Hz] (to be compared with the measured ones: f_1=272, f_2=562, and f_3=631 [Hz].).

The nodal lines for mode 2 and 3 (the first mode correspond with the measured) are showed in Figure 2 and 3.

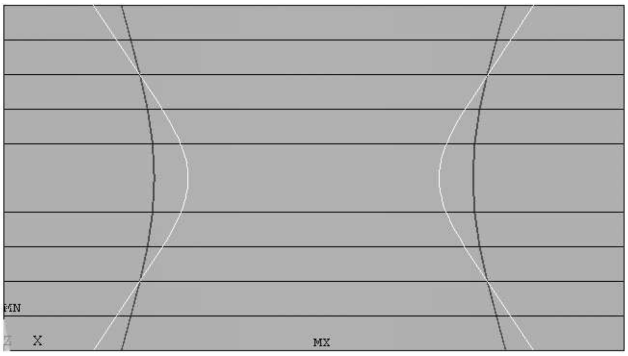

Figure 2: Reference material. Nodal lines for mode 2 (white curved lines represent measured nodal lines and black calculated).

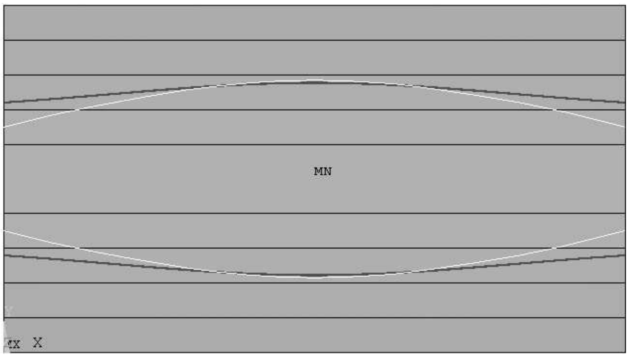

Figure 3: Reference material. Nodal lines for mode 3 (white curved lines represent measured nodal lines and black calculated).

5.2. Constant material

The initial (the starting point for optimization) material parameters is set to the values according to the reference material (section 3.1) and the optimization converged to the following results: f_1=272.0, f_2=562.0, and f_3=631.0 [Hz] (to be compared with the measured ones: f_1=272, f_2=562, and f_3=631 [Hz].). The variable set for the optimal state is: E_1=14.4720, E_2=0.9984, G_{12}=0.7251 [GPa], and ν_{12}=0.0189. The nodal lines for mode 2 and 3 (the first mode correspond with the measured) are showed in Figure 4 and 5.

5.3. Varying material

Also here the initial (the starting point for optimization) material parameters is set to the values according to section 3.1 and the optimization converged to the following results: f_1=271.9, f_2=562.0, and f_3=631.0 [Hz] (to be compared with the measured ones: f_1=272, f_2=562, and f_3=631 [Hz].). The variable set for the optimal state is: E_1=11.7230 (at the edge), E_2=0.9844, G_{12}=0.7276 [GPa], ν_{12}=0.0246, and $evar$=39.1%. The nodal lines for mode 2 and 3 (the first mode correspond with the measured) are showed in Figure 6 and 7.

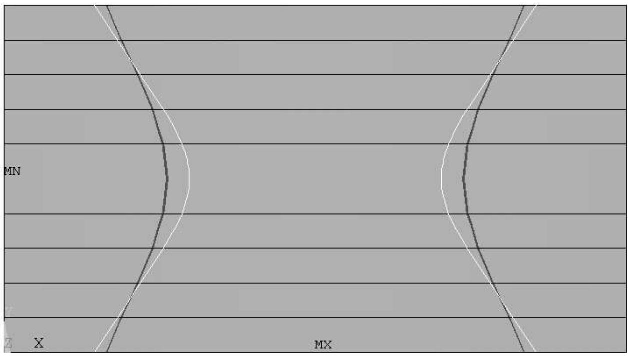

Figure 4: Constant material. Nodal lines for mode 2 (white curved lines represent measured nodal lines and black calculated).

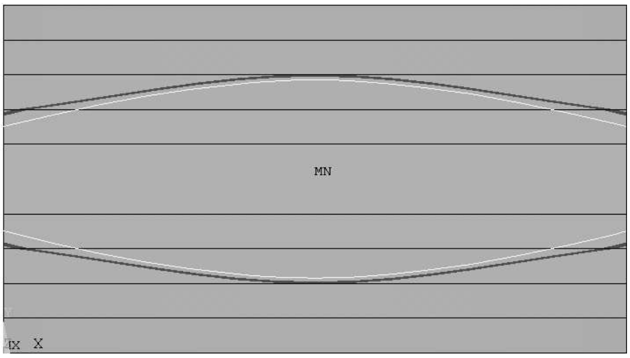

Figure 5: Constant material. Nodal lines for mode 3 (white curved lines represent measured nodal lines and black calculated).

6. DISCUSSION AND CONCLUSIONS

Present investigation on blanks for violin tops has been performed on a blank with the same geometrical dimensions and weight (see section 4) as was used in [6]. The FE-analyses in [6] was performed with the finite element code FEMP developed at Luleå University of Technology and the blank was discretizised with triangle (shell) element. The method proposed in [6] resulted in the following material parameters for the blank in question: E_1=15.50, E_2=1.03, G_{12}=0.75 [GPa], and ν_{12}=0.02. The FE-analysis (FEMP) gave the following values for the first three eigenfrequencies: f_1=277, f_2=553, and f_3=644 [Hz]. In the present investigation the commercial FE-code Ansys 7.0 has been used and the first analysis here was on a blank discretizised in triangle elements with the same material parameters as above and exactly the same pattern as in [6]. This analysis gave the following values for the first three eigenfrequencies: f_1=276.8, f_2=580.9, and f_3=645.5 [Hz]. If we compare the results we see that the first and third value correspond quite well but there is a significant difference in the second value. In spite of this we decided to relay on the results from Ansys 7.0. Generally the four-node elements give more accurate results than the three-node element and because of this the former element type has been used in this investigation. An analysis on the blank with the same material parameters as above but discretizised with four-node elements gave the following results: f_1=276.8, f_2=579.6,

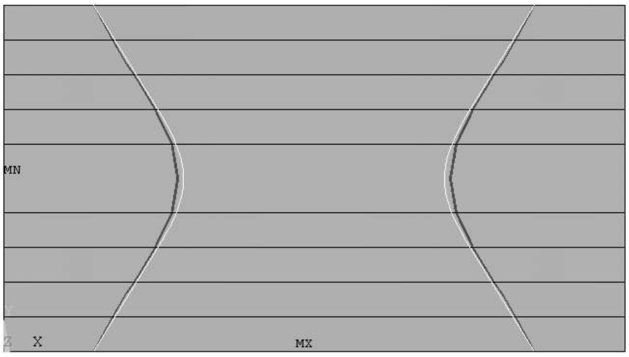

Figure 6: *Varying material. Nodal lines for mode 2 (white curved lines represent measured nodal lines and black calculated).*

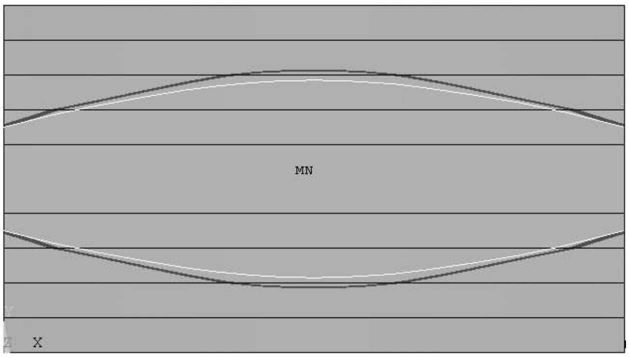

Figure 7: *Varying material. Nodal lines for mode 3 (white curved lines represent measured nodal lines and black calculated).*

and f_3=642.6 [Hz] which seems to be in order since triangle elements tends to give a stiffer structure (overstiff) than four-node elements. In all the presented modal results in this investigation, the Ansys 7.0 four-node shell element (SHELL63) has been used.

In the optimization analyses performed here the objective has been to determine a material set (material parameters in different direction) that gives the values of the first three eigenfrequencies and the nodal line for mode 2 according to measured results [6].

From the modal analysis on the blank with material parameters determined by the honeycomb model (section 5.1 and Figure 2 and 3) it can be concluded that this model is not sufficient to this application since both the values of the eigenfrequencies and the mode shapes differs significantly.

The first optimization analysis with constant material parameters (with regard to spatial dimensions), section 5.2, gives quite interesting results. Here the values of the eigenfrequencies correspond very well with the measured ones but the mode shapes, especially for mode 2, differs significantly (see Figure 4 and 5).

In the second optimization analysis (section 5.3) the Young's modulus in the first direction was allowed to vary linearly with respect to the second direction and this variation was added to the variable set. The results from this analysis are quite promising, the values of the eigenfrequencies corresponds very well with the measurement and also the mode shapes correspond quite well (see Figure 6 and 7).

It seems that the variation of E_1 is needed to get both the values of the eigenfrequencies and the mode shapes to correspond with measured results. The optimization determined this variation to 39.1% which could seem as a high value on a distance not longer than 10.75 [cm] but there is support in the literature for variation of these levels [10].

7. REFERENCES

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