Virtual Prototyping: A Potential Tool for Wooden Cultural Heritage Studies

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Abstract

In this paper, numerical methods developed in the industrial domain are discussed, in order to evaluate their utility towards instrument making and conservation. The aim of the overall work is to provide virtual prototyping tools as a decision support for instrument makers and curators, such as material parameters sensitivity analyses coupled with retro-engineering, simulations of stress induced by hygroscopic changes and mounting, and numerical support to instruments testing. The violin is the main subject of this work, and a numerical model of violin based on computer aided design has been developed to illustrate these methods. Experimental measurements are also presented to explore test-analysis correlation.

1. Introduction

Wood, because of its use in both construction and the fine arts domains has been linked to societal evolutions. Nowadays, it is still used in the same way as centuries ago especially for the arts and crafts domain, such as instrument making; and is present as a cultural heritage, a witness of a period. Much more recently, numerical models have emerged from the industrial domain, especially under the impulsion of the automobile and aerospace domains. These virtual models aim to simulate the behaviour of complex structures, where the simple analytical formulations are not sufficient. Along with these models, numerical prototyping has been developed to use these models for different purposes, mostly corresponding to industrial domain issues. In 1976, SCHWAB developed one of the first numerical model of musical instrument [1]. Since then, numerous models have been developed, with a progressive increase in the level of details [2].

2. Topics

2.1 Numerical modelling

The numerical model developed for these studies is based on a computer aided design (CAD) of a violin. Constructed using Solidworks, the CAD design is then exported in the pre-processor Patran and the used solver is Nastran. Most of the post-processing operations, such as effects screening are performed on in-house software developed by the research department. Figure 1 below shows details of the numerical model. This model is composed of 21 solids, whose properties are listed in Table 1. Orientations are applied in the reference coordinate frame in Figure 1.

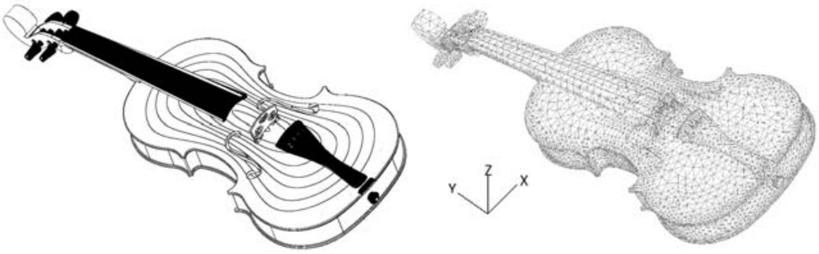

Figure 1: CAD and numerical model used for simulations

Table 1: Solid components of numerical model

Solid	Species	Orientation
Soundboard	Spruce	RLT
Back	Maple	RLT
Ribs	Maple	RLT
Linings	Spruce	RLT
Corner	Spruce	RTL
Heels	Spruce	RTL
Bass bar	Spruce	RLT
Soundpost	Spruce	TLR
Neck	Maple	TLR
Fingerboard	Ebony	TLR
Tuning pegs	Ebony	LRT
Bridge	Maple	LTR
Tailpiece	Ebony	RLT
Strings	Steel and other materials when rounded	ISOTROPIC

2.2 Material modelling

Tonewood properties are necessary to simulate the behaviour of musical instruments, as it is widely used in musical instruments making. They are finely selected, straight wood, which is meant to show particular dynamical behaviour that can be subjective/qualitative or objective/quantitative (case of the specific modulus [3, 4]). For this study, material properties are obtained by the measurements of 10 maple quarters’ and 10 spruce quarters’ eigenmodes, and the orthotropic material properties are identified by the model updating of same geometry and density numerical models of those quarters [5, 6].

Table 2 shows material properties and variabilities for both spruce and maple. E_i correspond to Young’s moduli in i direction, G_{ij} correspond to shear moduli in i, j directions.

Poisson’s ratios used in simulations are taken from Guitard’s laws, according to the density for both softwoods and hardwoods [7].

Specific anatomical characteristics, such as bear-claw are not incorporated in those results, but it is a high level of interest when considering wood variability, since it has a strong impact on wood anisotropy [8].

Table 2: Material properties implemented in the numerical model

Species	Material property	Value	Bounds
Spruce	**Elastic constant**	**(MPa)**	**(%)**
	EL	13500	±20
	ER	1120	±20
	ET	700	±12
	GLR	835	±35
	GRT	88	±15
	GTL	700	±20
	Density	0.46	±8
Maple	**Elastic constant**	**(MPa)**	**(%)**
	EL	13500	±20
	ER	1120	±20
	ET	700	±20
	GLR	835	±17
	GRT	88	±18
	GTL	700	±12
	Density	0.66	±13

2.3 Hygroscopic stress simulations

Climatic variations surrounding musical instruments occur during their utilisation, thus they undergo moisture content variations that affect their vibrations and damping [9]. As wood is a hygroscopic material, it will be sensitive to variations in relative humidity (RH) of the surrounding air and water will be sorbed in the cell walls.

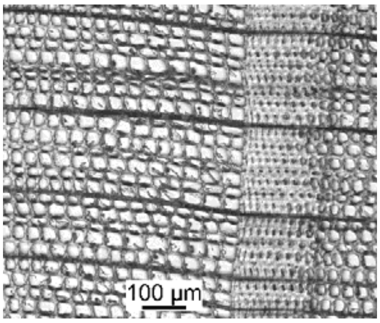

Figure 2: Microscopic observation of RT plane of spruce

Figure 2 shows a transverse cross-section of spruce heartwood. We can see on this picture both earlywood (left side) and latewood (right side). During all the life of the instruments, wood will undergo adsorption/desorption cycles that lead to changes both in density, stiffness and strains of the material at all its scales of observations. Experiments have shown that violin undergoes strains when strings are tuned and both strains and mass variations occur when conservation climate changes [10]. Those changes can lead to severe damages within the instruments and main changes in their vibrational behaviour. Relative humidity has thus an impact on static and dynamical behaviour of the instrument. Static behaviour of the instrument has to be taken into account in order to prevent damages, and ensure that under a stress due to strings, the instrument will be able to sustain new stresses due to climate changes. Water sorption-induced dynamical changes must be taken into account to quantify the effects of climate changes on the dynamical behaviour of the instrument, in particular to evaluate the stability of the vibrations. For this study, biological deteriorations, irreversible modifications and effects of ageing on hygroscopicity of the wood are not implemented but still remain to be investigated in future work.

As the moisture content variations induced by relative humidity changes have to be taken into account, the adsorption and desorption isotherms have been measured for spruce tonewood. Figure 3 shows the moisture content determined for different levels of relative humidity. For the following simulations, a variation of ±15% RH around a mean value of 50% will be considered, leading to a variation of approximately -2% and +3% around an average value of 10% in moisture content.

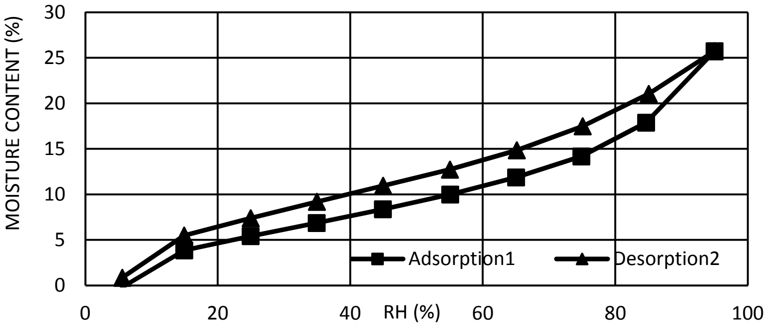

Figure 3: Sorption isotherm (25°C) of spruce tonewood

An increase in moisture content of 1% will imply:

- Decrease in stiffness: -3% for ER, ET, GLR, GRT, GTL, -1.5% for EL [7]
- Increase in density : +1% for ρ
- Dimensional variations:
  + 0.015% Longitudinal direction
  + 0.2% Radial direction
  + 0.3% Tangential

Geometrical and density variations' coefficients have been measured through the variations in dimensions of spruce plates during climatic changes, correlating relative humidity and moisture content. Due to hygroscopic variability of wood, those values might vary, in the purpose of the study global indicators are used.

As the geometric variations are orthotropic, they will lead to different changes as a function of the material directions. This is implemented in the numerical models by means of an orthotropic definition of the compliance matrix of the material, and three different coefficients corresponding to orthotropic hygro-expansion.

After the static analysis computations, the translational constraint forces are obtained, as well as the VON MISES stress field in the structure, thus providing the stress level induced by both the prestresses of assembly (strings bass bar and soundpost) and moisture content variations. A decrease in RH drives a lowering of moisture content in the wood, yielding to negative strains and an increase in the stiffness parameters, this configuration yields the maximum stress level in the instrument, and may cause damage, such as cracks. Another effect of the static stress-induced effecs in the instrument is the modification of the dynamical behaviour of the instrument. As well as the stiffness and density affects the eigenmodes' frequencies and shapes, the stress field drives to a prestressed behaviour that numerically is implemented by taking into account the new stiffness matrix computed by the static analysis in the dynamical solving process.

2.4 Effects of prestresses on dynamical behaviour

Frequency response functions are synthesised for prestressed modal analysis, giving the admittance at different points of the structure. For this example, the bridge admittance is evaluated by applying an input force on the bass side of the bridge in the X direction (according to Figure 1) and observing the response (velocity) on the opposite node in the same direction. The bridge admittance is often measured for violins, as it leads to an easily measurable signature of the instrument. Experimentally, it can be measured by applying with a hammer a force and measuring the displacement, velocity or acceleration of the structure when excited by this force. The measurements can be performed using either laser vibrometer, piezoelectric accelerometer or linear variable differential transformer (LVDT) displacement sensor. These studies have been described in different publications [12, 13].

Figure 4 shows the admittance computed for the prestressed complete violin. Two cases are considered, where the strain of the soundpost is doubled, yielding to an increase in the prestress field under the treble foot of the bridge. This effect leads to changes in the vibrational behaviour of the instrument, and differences in the admittance of the bridge. For this study, modal damping is needed to compute frequency response function, the value is obtained by measuring the average damping factor of different tested violins. Post processing of measured frequency response function (FRF) enables to identify modes of the structure, as well as their modal damping factors. For readability issues, smoothing of the curve is obtained by giving a 5% modal damping ratio for each mode used in the FRF synthesis.

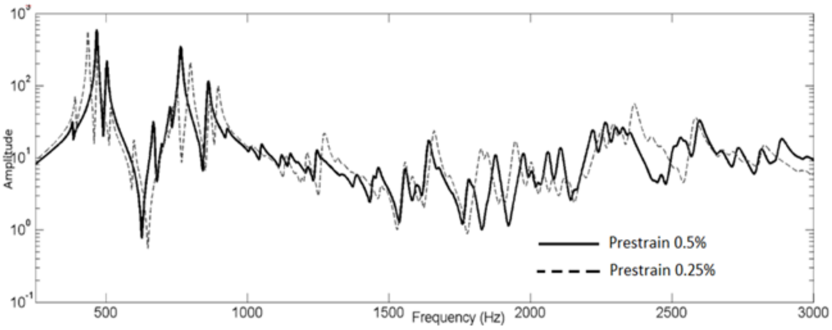

Figure 4: Admittance at the bridge for two different soundpost prestrains

The figure shows shifts in eigenfrequencies of the violin, and changes in the different amplitude of FRF peaks, leading to a quantifiable effect of different cases of prestrains of the bridge. The next considered step is to drive the numerical using directly the geometry, to evaluate impact of position of the soundpost, and not only its prestrain. As well as the admittance of the bridge, shifts in matched eigenfrequencies and eigenvectors can be evaluated, using modal assurance criterion (MAC) [11]. This is a quantitative indicator of well-known designs and preset configurations familiar to instruments.

2.5 Model based effects screening of stringed instruments

As numerical models allows to perform changes for a single material parameter, it allows to perform effects screening analyses. These analyses aim to define which inputs have the highest influence on a defined input. In our case we use the Morris sensitivity analysis [14] to perform the effect screening analysis. Our variables design of interest are the moisture content, the density, the stiffness parameters and the prestress of bassbar and soundpost and strings. Our outputs, meaning the effects that we compute are the eigenfrequencies and eigenvectors of eigenmodes of the structure, and the stress field that those changes yield. This study enables us to screen the most important parameter that drive mainly the static and dynamic behaviour of the violin.

The results shown in this paper consider an unmounted violin, and 91 different variables, density, moisture content and stiffness material parameters for nine different materials implemented in the numerical model. The variability of each parameter is taken into account, corresponding to usual variations in RH that a violin can undergo, and material variabilities, either measured or assessed in wood literature.

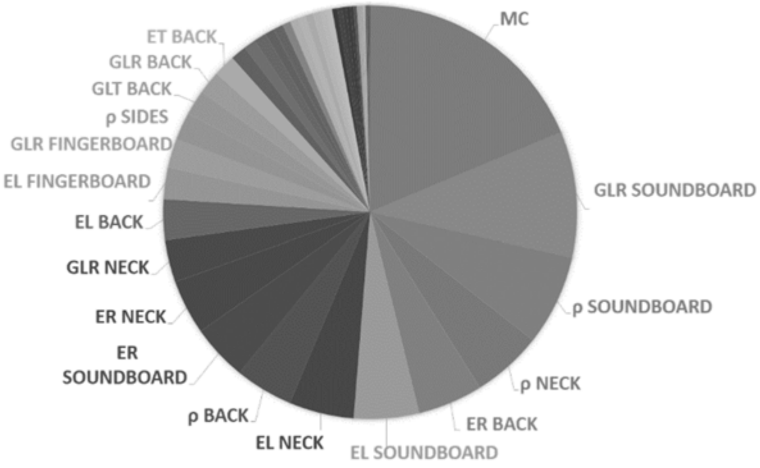

Figure 5: Ranking of all variables according to eigenfrequencies

As density affects the stiffness parameters and the eigenfrequencies of the structure, and the moisture content affects material properties, those effects are preponderant in the modal behaviour of the structure. Considering a fixed moisture content of the wood and a fixed density, this study can rank only orthotropic constants that are hard to rank in traditional prototyping, since changing unique material property of a constructed violin is not possible.

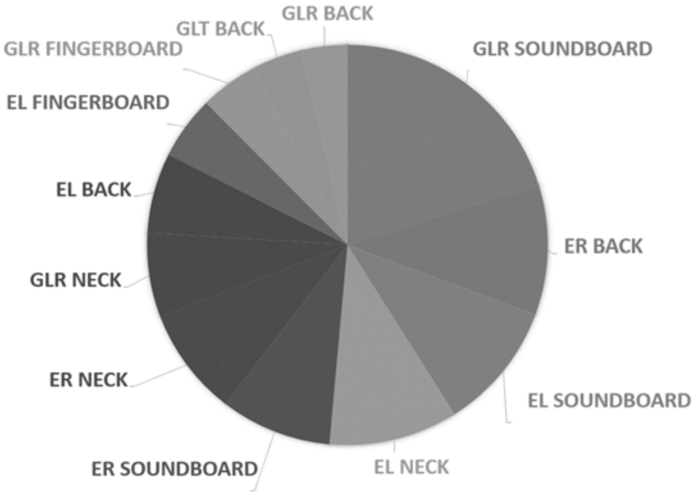

Figure 6: Ranking of stiffness parameters according to eigenfrequencies of the violin

This result shows a preponderant effect of the shear modulus of the soundboard, which is, during violin making, taken into account, as instruments makers apply torsional effort on the soundboard and back while making, and tune the thicknesses of these plates to reach wanted both static and dynamic characteristics.

Effects screening analysis is able to perform more specific sensitivity analysis and coupling effects analysis that are time-dependant to the number of the input variables. Screening these variables to focus on the most influential ones improves the readability of these studies. This example takes into account all the different eigenmodes of the structure, but more specific modes can be studied, especially those that show an acoustic interest, such as the different mode of the soundboard or a musician feeling interest, as the neck and fingerboard modes of the violin that drive the vibrations felt by musicians when playing.

3. Conclusion and perspectives

The different studies presented above aim to transfer numerical tools from industry to the arts and crafts domain, which is submitted to different issues. Once numerical models are developed, one has to validate them in order to assess their domain of validity, since numerical modelling is sensitive to numerous issues, such as the boundary conditions. Test-analysis correlation enables us to compare numerical models to reality, using quantitative criteria, comparing numerical degrees of freedom to experimentally measured degrees of freedom of structures. For this purpose, a testing bench has been developed to represent the boundaries of a guitar soundboard when it is clamped on the sides. Also, correlation results show that fluid structure interaction must be taken into account for better correlations, as it will in the case of a cavity with an opening leads to highly coupled structure-fluid modes that share the same patterns, yielding to shift of soundboard eigenfrequencies. This ongoing work aims to compare guitar soundboard and numerical models for critic steps of building, such as bar shapes, prestresses and positions.

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