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Model-based quantification of the effect of wood modifications on the dynamics of the violin *

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Abstract

In this study, a finite element model is used to simulate the impact of wood modifications on the dynamical behaviour of a violin. Chemical and fungal modifications of the wood selected for violins (tonewood) are considered. In addition, the impact of spruce indented rings anatomic singularities is also studied. Models are used to compute modal bases up to 4000 Hz, and eigenfrequencies, eigenvectors and bridge admittance are used to compare different dynamical behaviours. The impact of wood modifications over the geometric tolerances inherent to instrument makers methods is discussed. This study shows that some modifications or anatomic singularities are not sufficiently efficient to be observed reliably over the geometric uncertainties. In contrary the fungal treatment method also known as mycowood sufficiently modifies the dynamical behaviour to to overcome the luthiers tolerances. Moreover, results give a wood modifications threshold, which can be used as a support for further wood modification methods.

Keywords: Wood modifications, Geometric tolerances, Instrument making, Violin modelling, Violin Dynamics

1 INTRODUCTION

The building of musical instruments is traditionally based on craftsmanship and selection of materials. Instrument makers generally attribute a dominant role to the material properties in regard with the acoustics of the musical instruments. Numerous methods to modify the physical and mechanical properties of tonewood are studied by both researchers. Their densities and elastic and damping parameters are of particular interest. Most of the studies aim at tailoring specific rigidities and acoustic conversion efficiency (ACE) [1], based on the assumption that high ACE is better for the quality of an instrument. Wood properties can be modified through chemical treatments [17], [9], fungal incubation [11] [10], or climatic artificial ageing [8], [7]. Moreover, anatomical singularities like spruce with indented rings also impact the mechanical properties [14], and can be used by instruments makers for this purpose. Meanwhile, all these methods increase the cost of wood preparation. Nevertheless, the objective assessment of the impact of these wood modifications on the perception of musical instruments, and especially the improvement of their "quality" remains a subject to discussion.

The perception of an instrument is subjected to numerous subjective and objective assessments. The link between the attribution of a specific quality or sonority by musicians and measurable features like vibro-acoustical behaviour has still to be established. In this study, it is proposed to study the violin through its dynamical behaviour, prior to acoustical features. The dynamical behaviour of a violin is a result of the choices of the makers in term of design and assembly prestresses, but also depends on the wood properties, relative humidity and temperature conditions. The impact of each of these variables will be studied through dynamical features computed by the numerical models, such as eigenfrequencies, eigenvectors and bridge admittances.

Physics-based models of musical instruments are now able to simulate these dynamical features for a complex geometry and material implementation. Among their capability for virtual prototyping aims, they can also be

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used as a support for conservation of musical instruments and, furthermore, for material studies.

The main objective is to evaluate if a wood modification can overcome the luthiers geometrical uncertainities in regard to the dynamical behaviour, which is part of the acoustical performance and sound perception.

For this purpose, a numerical model is developed and driven to investigate the impact of wood property modifications on the dynamics of a violin while taking into account irreducible uncertainties in the material properties and geometrical tolerances. The aim is to establish a threshold for wood treatments that will insure an observable impact on the dynamic behaviour of instrument.
In the next section, the model, material and geometrical implementation, and analyses are described. Results, discussions and conclusions are given in the last sections.

2 MODEL AND METHODS

In this section, the computer aided design (CAD) of the violin and the finite element model are described. Subsequently, the material parameters implementation is given. Finally, the different dynamical features that have been computed are described.

2.1 Numerical model of violin

The computer aided design of the violin is shown in figure 1, which also gives the nomenclature. The geometry is parametrised using a SOLIDWORKS® feature called family tree. Once the CAD is prepared, parametrised, updated and exported, a detailed numerical model is constructed using the finite elements method based on the commercially available software MSC-PATRAN®. The mesh is created using quadratic tetrahedral elements of 5 mm as global edge length, and orthotropic material parameters are defined.
The different geometrical parameters that have been considered as uncertain are detailed in the table 1. The Relative tolerances are comprised between 0.7 and 9 %, depending on craftsman gesture.

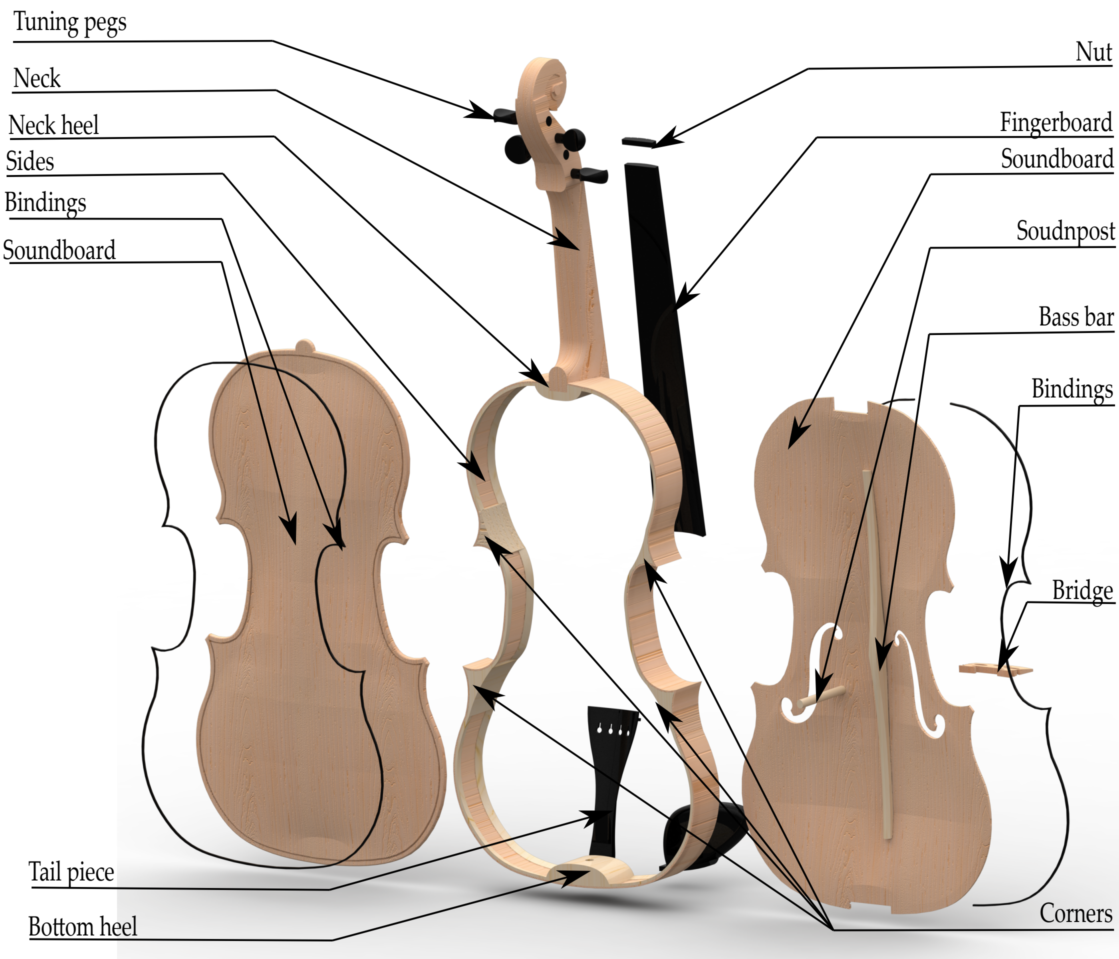
Table 1. Sum up of the relative changes of geometry correpsonding to making tolerances and habits. Relative humidity and temperature changes.

Geometric parameter	Nominal value (mm)	Consider variance [%]
F-hole length	72.5	-1.4 +1.4
F-hole width	4.25	-2.3 +2.3
Bass bar length	270	-0.7 +0.7
Bass bar position	35	-2.8 +2.8
Bass bar width	6.1	-6.5 +6.5
Bass bar height	11	-9 +9
Soundboard averaged thickness	2.8	-3.5 +3.5
Back averaged thickness	2.95	-3.4 +3.4
Relative humidity	45	[-45 +67]
Temperature	21	[-50 +67]

2.2 Material parameters

Tonewood is implemented in the numerical model as a linear elastic orthotropic material. For each solid, wood is oriented in adequation with orientation in real instruments. Mechanically, the wood is described with three main directions, longitudinal (L), radial (R) and tangentail (T). Table 2 gives the initial material properties for all the elements of the violin in their respective local coordinate frame. These parameters are taken from

Figure 1. Scheme of the violin elements and their nomenclature.



[5], [14] and [3]. Numerous different orientations are implemented, and the violin is generally made of solid materials, consisting of three wood species, with five different orientations. The orientation has to be finely taken into account, since wood is highly anisotropic, reaching ratios up to 20.

Table 2. Fixed material parameters values for different wood species and orientations. The values are taken from [5], [14] and [3]

LRT Ebony		LRT Spruce		LRT Maple	
Material parameter	Value	Material parameter	Value	Material parameter	Value
E_L (MPa)	17000	E_L (MPa)	13350	E_L(MPa)	14920
E_R (MPa)	1960	E_R (MPa)	1080	E_R (MPa)	1960
E_T (MPa)	1110	E_T (MPa)	680	E_T (MPa)	1110
ν_{LR}	0.37	ν_{LR}	0.38	ν_{LR}	0.37
ν_{RT}	0.65	ν_{RT}	0.49	ν_{RT}	0.65
ν_{TL}	0.032	ν_{TL}	0.02	ν_{TL}	0.032
G_{LR} (MPa)	1370	G_{LR} (MPa)	930	G_{LR} (MPa)	1370
G_{RT} (MPa)	360	G_{RT} (MPa)	40	G_{RT} (MPa)	360
G_{TL} (MPa)	950	G_{TL} (MPa)	812	G_{TL} (MPa)	950
ρ (g/cm3)	1	ρ (g/cm3)	0.44	ρ (g/cm3)	0.64

The large number of material parameters associated with the different parts of the violin are implemented in the model and a screening analysis has been performed in an earlier study [15] to determine the most influential material parameters. These parameters include the longitudinal and radial (L and R) Young's moduli, the LR shear modulus and density for the soundboard, the bottom plate, the neck and the fingerboard. The moisture content, which is driven by the relative humidity, is related to the water absorbed by the wood. It is potentially one of the most influential material parameters as it affects stiffness, density, geometric dimensions and damping. The variability is modelled with an equi-probabilistic definition of the density, the Young's moduli in longitudinal and radial direction and the shear modulus in LR plane. The hygroscopicity of the wood is implemented as an analytical model that links the relative humidity RH and temperature to the density and mechanical properties for each species. Eq 1 gives the moisture content of the wood samples as a function of the relative humidity, based on [14]. the RH and temperature changes are given in the table 1.

$$MC = 8 + 0.16 \times (RH - 41.5) - 0.03 \times (T - 21) \tag{1}$$

Eq. 2 gives the evolution of the density as a function of the moisture content, based on the results of [13]:

$$\rho_{MC} = \rho_0 \times (1 + 0.01 \times (MC - 10)) \tag{2}$$

Most of the pieces are carved, thus, the orientation of the material properties is quite easy. The local coordinate frames of the elements inside each solid is oriented to match the correct orientation in the global coordinate frame. The sides and linings of a violin are made of bended wood. The ribs of the sides are made with maple and the linings with spruce. The orientation of the material changes along the curvature of the parts. For 3D tetrahedral elements, the correct orientation of the material constituting the bended parts is taken into account.

2.3 Wood modifications

Numerous methods to treat tonewood have been proposed for years. Their effect on the material properties is summarized in the table 3. In LR plane, the evolution of the shear modulus is generally not specified, despite its impact on the dynamical behaviour of the violin [15]. In the computations, each line of the table with data for L and R directions are considered, and modal bases are computed with given deterministic parameters.

Table 3. Summary of relative changes of mechanical properties of spruce and maple for different studies.

Ref.	Specie, treatment	$\Delta\rho$[%]	ΔE_L [%]	ΔE_R [%]	$\Delta\eta_L$ [%]	$\Delta\eta_R$ [%]	$\Delta\frac{E_L}{\rho}$ [%]	$\frac{E_R}{\rho}$ [%]
[11]	Spruce (fungi, 12 weeks)	-11	-17	-30	+20	+70	-6.7	-21
[11]	Maple (fungi, 12 weeks)	-10	-16	-21	0	10	-6.7	-12.2
[12]	Spruce (fungi, 6 months)	-2.1	-3.5	-4.1	+4.1	+5	-1.4	-2
[17]	Spruce, phenolic resin	+4.1	9.4	42.9	-29.1	-43	+5.1	+37.3
[18]	Spruce, Saligenin/formaldehyde	+4.3	6.4	30	-37.6	-46.6	+2.0	+24.6
[14]	Spruce, indented rings	-4	-15	25	-4	-5	-12.7	+33
[8]	Spruce, ageing	-	-	-	-2.5	-	+3	-

2.4 Analyses

The model is used to perform computations with varying material and geometrical parameters. For this application, the design space is explored based both on Morris method [6] and Monte Carlo sampling. For each of these analyses, 240 computations have been performed. The average duration of a run is generally equal to 1 hour, which leads to a total duration for each study of 10 days on an office computer. The eigenmodes of each modal bases of the study are compared with the nominal modal basis of the violin with initial geometrical, material and climatic parameters. The eigenmodes are correlated with a MAC criterion [2]. The minimum value that is retained for the matching of two modes is 0.6. The matched eigenvector error (MEVE) is used to compare the eigenvectors of a given mode of a modal basis to an other. In this case, this gives a normalised evaluation of the difference in the shape of the modes, through the evaluation of the MAC criterion value.

The bridge admittance is synthesised using modal superposition method based on the modal bases of each case. The bridge admittance is a frequency response function giving the displacement normalised by a force as a function of the frequency. The evaluation is located on the bass side of the bridge, in the direction perpendicualr to the strings and coplanar with the soundboard. This is usually measured using an accelerometer or a vibrometer and excited with an impact hammer. The bridge admittance is computed between 20 and 4000 Hz, and is based on nearly 150 modes. The usual increase of the bridge admittance value between 2300 and 3000 Hz is known as the bridge hill and has been widely studied and measured [16], but barely synthesised before [14].

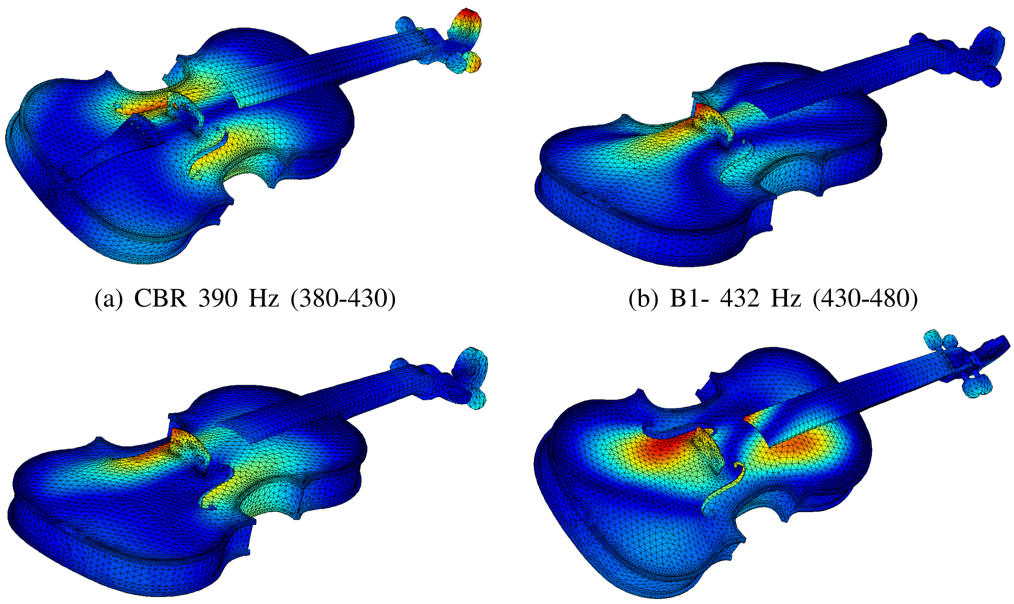
3 RESULTS

This section describes the dynamical results. At first, the modal bases comparisons for each study cases are given, secondly the bridge admittances of each wood modifications are shown together with the bridge admittance dispersion for geometrical uncertainties.

3.1 Modal bases comparison

As an example of the 150 modes computed, several well-known modes are displayed in the figure 2 . The values of the frequencies of the CBR, B1- and B1+ modes are in accordance with the values usually obtained by experimental means [4].

Figure 2. Numerical modes of the violin body in the low frequency domain. The values in the brackets indicate common experimental values [4].



(a) CBR 390 Hz (380-430)

(b) B1- 432 Hz (430-480)

(c) B1+ 492 Hz (510-580)

(d) C4 top 680 Hz (700)

In the table 4, it is shown that geometrical uncertainties lead to an average of the coefficient of variation of the eigenfrequencies equal to 1.1 % for 150 modes computed. Moreover, the MAC drops to 77 % as average for the same number of modes. The impact of the material variability leads to a coefficient of variation equal to 2.0 %, and the MAC value drops to 70 %. These results suggest an higher impact of material variability and moisture content when compared with the geometric tolerances.

Keeping the geometry and wood moisture content constant, the treatment using fungi for soundboard and back leads to a shift in the eigenfrequencies of 5.7 %. Being three times the coefficient of variation that is due to geometric tolerances. This is a strong argument for the observability of such modifications. It has to be noticed that the impact on both soundboard and back together is not equal to the sum of the impact of soundboard and back treatments taken separately, which can be explained by compensation effects when the parts are coupled.

The phenolic treatment leads to an evolution of the eigenfrequencies equal to 2.1 %, which is only two times higher than the coefficient of variation due to geometric uncertainties. This result indicates that, following the "68–95–99.7 rule", it can remain an error equal to 5 % when comparing dynamical behaviour with treated and non treated wood. This error is similar for the indented rings spruce.

Table 4. Evolutions of the modal bases for different cases of uncertainties and wood modifications.

Wood modifications	Frequencies error vs nominal (%)	MAC vs nominal (%)	Number of matched modes Initial: 150 modes
Geometric tolerances	1.1	77	130
Material and MC variability	2.0	70	120
Fungi Sb and B	5.7	61.8	105
Fungi Sb	4.3	68.5	102
Fungi Back	3.6	70.2	105
Phenolic	2.1	72.9	115
Indented rings spruce	2.2	72.8	112

3.2 Bridge admittance Comparison

In this subsection, the bridge admittance of each wood modifications is juxtaposed on all the bridge admittances of the different cases of geometric uncertainties in figure 3. It can be observed that, in accordance with the previous subsection, only the fungi treatments are emerging from the geometric tolerances "noise". But this is not the case for the full frequency band, especially above 3000 Hz. Generally, fungi treatment suggests a general shift to the low frequencies, with a bridge hill center frequency value that decreases from 2600 Hz to 2400 Hz.

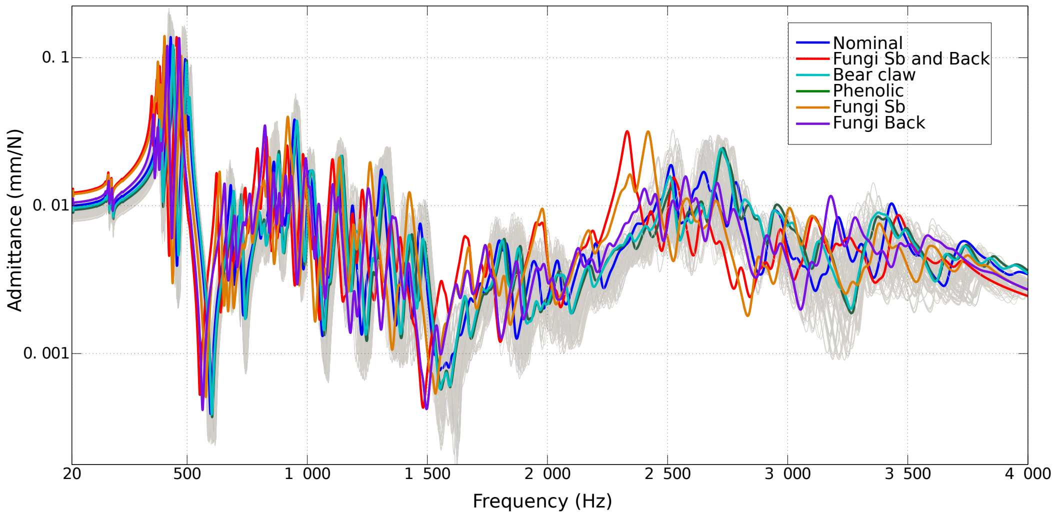
For the remaining treatments, no clear trends are observed outside the geometric tolerances' "noise". therefore, it seems difficult to attribute a specific modifications in dynamical behaviour to weakly influential wood modifications, even in the considered case, that is very optimistic in regard with the variability of the material parameters of the other parts, that has not been considered for this study.

4 DISCUSSION AND CONCLUSION

The objective of this study was to investigate the impact of geometric tolerances and uncertainties on the vibratory behaviour, and to define a threshold of wood modifications to be reliably measured in the dynamical domain. Results have shown that, depending on the wood modifications means, some methods are not sufficiently efficient on the mechanical behaviour of wood to be measured. The coefficient of variation due to geometrical uncertainties is defined to equal to 1.1%, and it is proposed that a wood modifications changes the eigenfrequencies of at least three times the coefficient of variation, in this case 3.3%, which is outreached by the fungal treatment method (mycowood) but not by phenolic treatment and indented rings spruce selection.

Despite these encouraging results for several wood modifications, it is necessary to point out that this study doesn't take into account at the same time the effects full geometric uncertainties like the arching shape, heterogeneities, interfaces parameters and, especially, the remaining material variability. This last effect prevents the possibility to make two identical violins, due to the variability of their constitutive materials. Taking into account these different sources of variability and uncertainty, it can be argued that the modifications to outreach this residual noise in term of violin dynamical behaviour should be higher, but an analysis taking into account

Figure 3. Bridge admittances corresponding to each dimensions tolerances cases and nominal and modified material parameters.



all these sources has yet to be performed. Prior to such study, and considering the high number of potential sources of uncertainties, it should be necessary to reduce the number of material and geometrical parameters using a full screening analysis.

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