Model-based decision support for assessing the playability of heritage musical instruments

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IMAC-XXXVII Conference

01/31/2019

Overview

I. Introduction

II. Model-based decision support methodology

III. Preliminary study on Laux Maler lute

IV. Conclusions and perspectives

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Introduction

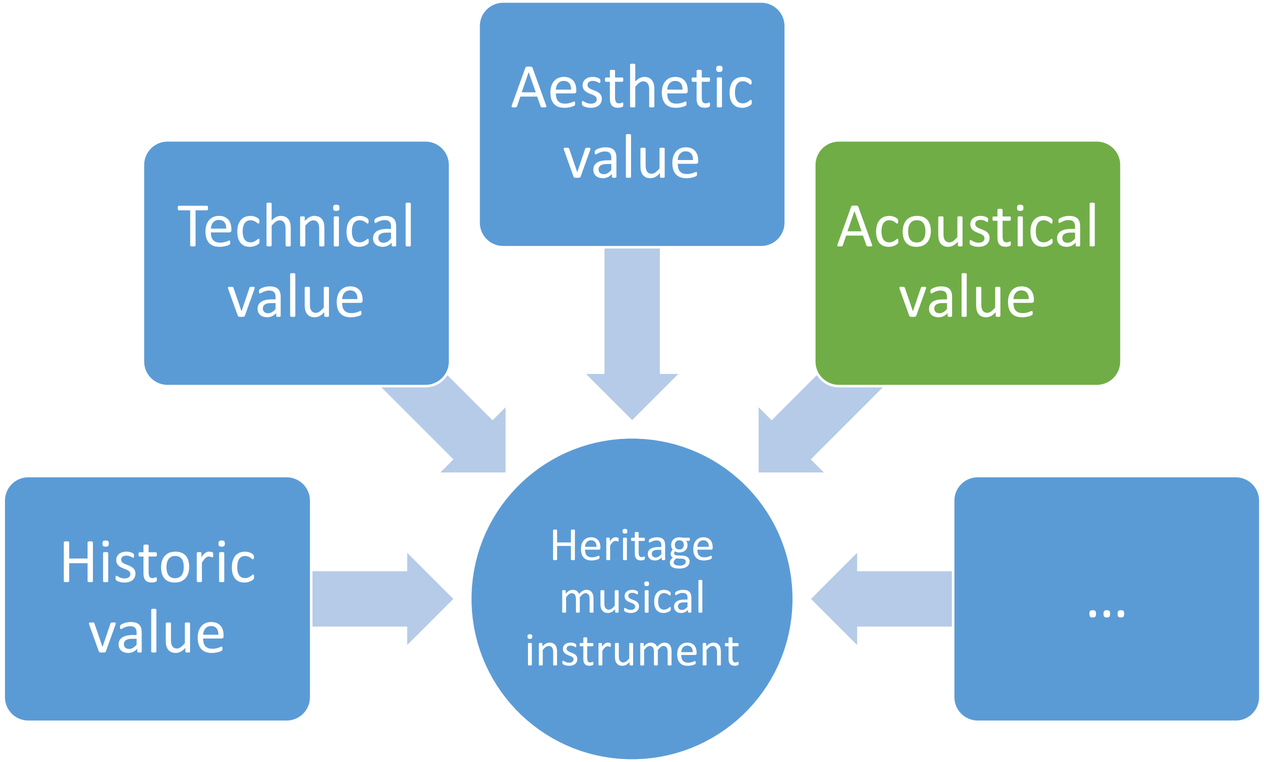
Museum problematics

Music museum of Paris

- Describe the story of music through its instruments
- Conserve and restore heritage musical instruments
- Assess the playability of heritage musical instruments

Introduction

Assessing playability in museum context



- Heritage musical instruments present many cultural values.
- These cultural values are compared based on arbitrary notation.

→ If acoustical value of an instrument is predominant, we want to assess its playability.

Introduction

Focus on stringed musical instruments

- Assess the playability of heritage **stringed** musical instruments
- Music museum of Paris → collection of 7000 instruments but only 5% in playable state

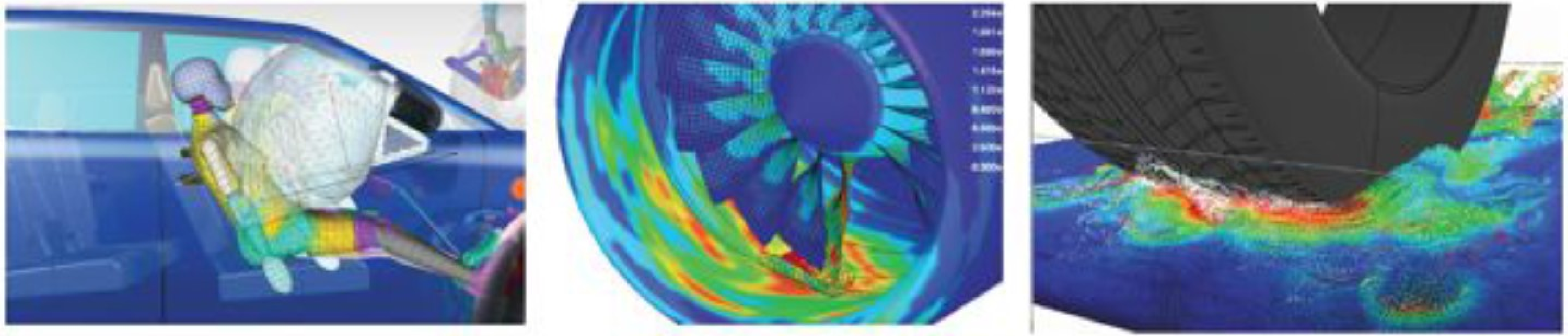
→ Account for any irreversible phenomenon when the strings will be tuned again

Cracks on 1924 Grapelli violin soundboard

Crack on 1761 Hemsch harpsichord soundboard

Introduction

Virtual prototyping in industry



http://www.mscsoftware.com/application

Prototyping tools

- Direct analysis
- Optimization
- Uncertainty quantification
- Test design
- Model calibration
- Inputs identification

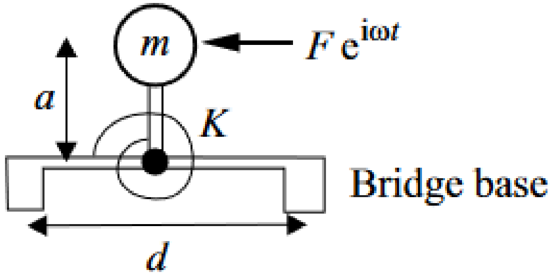
Limitations

- Requires accurate material properties and behavior laws
- Geometric accuracy does not guarantee fidelity
- Forecasting under untested configurations

→ **V&V to quantify credibility of the simulation**

Introduction

Mechanical study of stringed musical instruments



Idealized model of a violin bridge (J. Woodhouse 2005)

Experimental approach

- Testing of acoustic stringed musical instruments *(M. French & al. 2001)*
- Analysis of bridge mobility of violins *(B. Elie & al. 2013)*
- Antique violins: effect of the player on the moisture content *(G. Goli & al. 2017)*

Analytical approach

- On the “Bridge Hill” of the violin *(J. Woodhouse 2005)*
- Static model of a violin bow *(F.Ablitzer & al. 2011)*

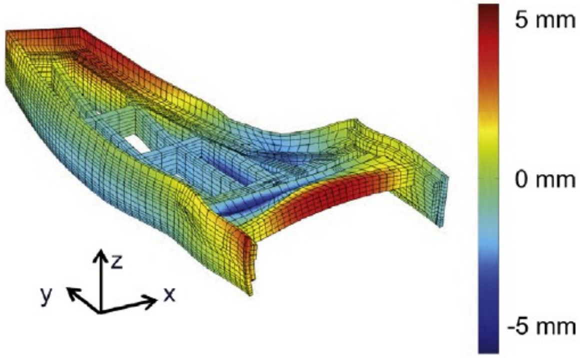
→ **Not suited to make decisions on local behaviors**

Violin mute used for the study (B. Elie et al. 2013)

Virtual prototyping approach

- Restoration of a 17th-century harpsichord to playable condition *(S. Le Conte & al. 2012)*
- Vibrational modes of the violin family *(C. Gough 2013)*
- Numerical modelling of wooden structures *(D. Konopka & al. 2015)*

→ **This approach can provide a real complement compared to the two previous**



Simulated vertical deformation uz (mm) of the pianoforte at a1= 415 Hz and RH/T: 70/28. (D.Konopka et al. 2015)

Introduction

Objective

Develop a decision support tool

- To study the impact of the long-term state of playability of heritage stringed musical instruments
- Based on virtual prototyping
- Usable in museum framework
- Complex numerical model (behavior, geometry, loading)
- Account for uncertainties (aleatory and epistemic)

Specific sources of uncertainties

- Visible and invisible damage (cracks, worms holes, glue joints, …)
- Material properties of aged wood
- Prestress state
- Environmental loading

Introduction

Corpus of interest

Various lutes

Application case :
1532 Laux Maler lute E.2006.3.1

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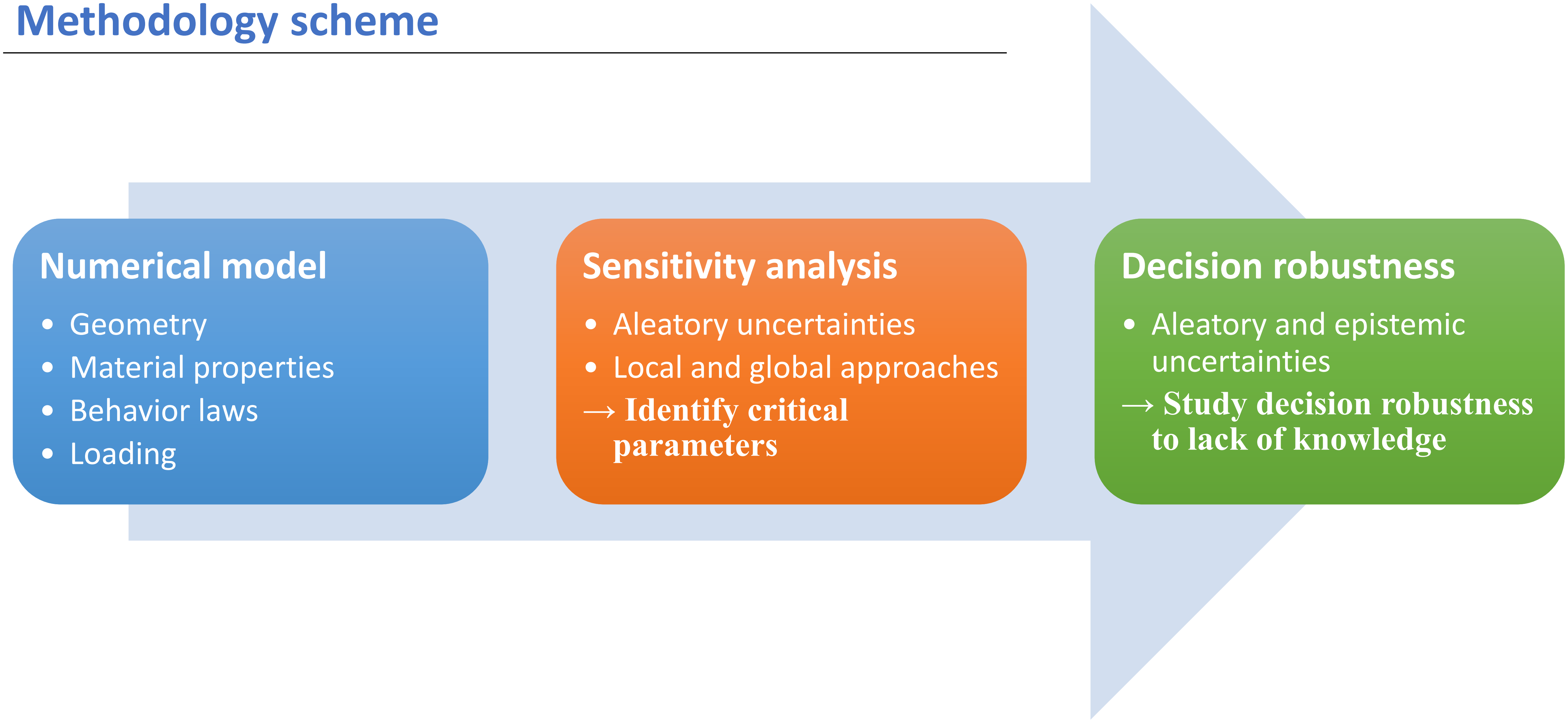
Model-based decision support

Methodology scheme



Numerical model

- Geometry
- Material properties
- Behavior laws
- Loading

Sensitivity analysis

- Aleatory uncertainties
- Local and global approaches

→ **Identify critical parameters**

Decision robustness

- Aleatory and epistemic uncertainties

→ **Study decision robustness to lack of knowledge**

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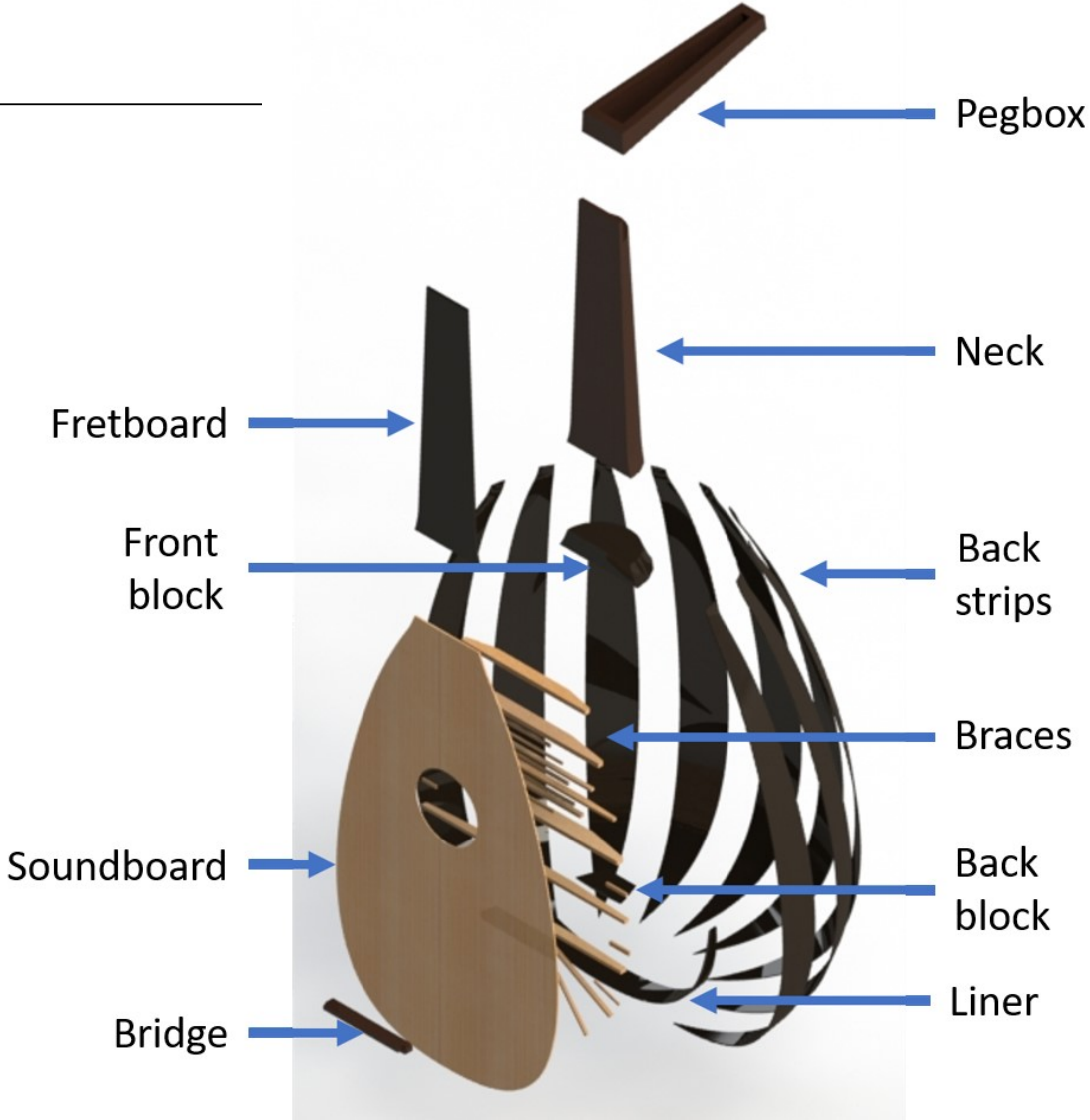
Geometric model

Hypotheses

- Simplified geometry without defects
- Connections are supposed perfect

Laux Maler lute pictures

3D CAD model



Exploded view and nomenclature

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Behavior model and parameters

Part	Wood species
Soundboard	Spruce
Back strips	Ash
Liner	Ash
Back block	Ash
Bridge	Pear tree
Fretboard	Ebony
Neck	Lime
Pegbox	Poirier
Front block	Lime
Braces	Spruce

Wood species associated with lute parts

Constant	Spruce	Ash	Pear tree	Ebony	Lime
E_L (MPa)	10200	9850	11500	18000	9200
E_R (MPa)	850	1125	1350	2450	1025
E_T (MPa)	500	550	700	1550	475
ν_{LR}	0,39	0,37	0,38	0,4	0,37
ν_{LT}	0,43	0,47	0,47	0,46	0,47
ν_{RT}	0,5	0,6	0,59	0,56	0,61
G_{LR} (MPa)	750	825	975	1650	775
G_{LT} (MPa)	675	600	725	1300	550
G_{RT} (MPa)	75	200	250	550	175

Elastic constant of wood species

Hygro-expansion coefficient	Value
α_L $(\%mc^{-1})$	3×10^{-5}
α_R $(\%mc^{-1})$	7×10^{-4}
α_T $(\%mc^{-1})$	$2{,}4 \times 10^{-3}$

Used hygro-expansion coefficient

Wood material is modeled with an orthotropic elastic linear and hygro-expansion behavior

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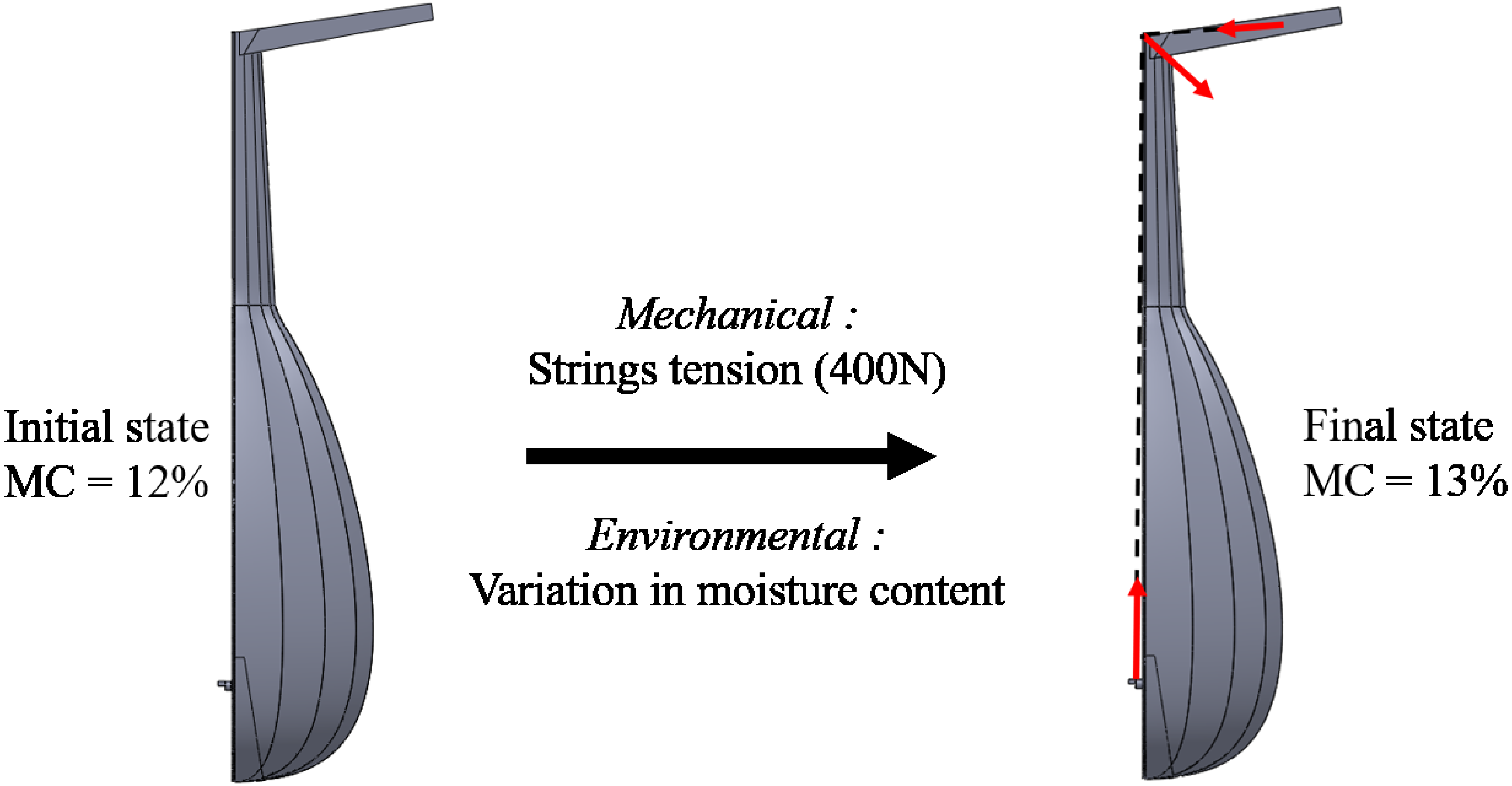
Loading



Initial state
MC = 12%

Mechanical :
Strings tension (400N)

Environmental :
Variation in moisture content

Final state
MC = 13%

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Output features

Quadratic Hill yield criterion *(R. Hill. 1948)*

$$\sigma_{Hill} = F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + \mathrm{H}(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2$$

$$F = \frac{1}{2}\left[\frac{1}{\left(\sigma_2^y\right)^2} + \frac{1}{\left(\sigma_3^y\right)^2} - \frac{1}{\left(\sigma_1^y\right)^2}\right] \quad ; \quad G = \frac{1}{2}\left[\frac{1}{\left(\sigma_3^y\right)^2} + \frac{1}{\left(\sigma_1^y\right)^2} - \frac{1}{\left(\sigma_2^y\right)^2}\right]$$

$$H = \frac{1}{2}\left[\frac{1}{\left(\sigma_1^y\right)^2} + \frac{1}{\left(\sigma_2^y\right)^2} - \frac{1}{\left(\sigma_3^y\right)^2}\right]$$

$$L = \frac{1}{2\left(\sigma_{23}^y\right)^2} \quad ; \quad M = \frac{1}{2\left(\sigma_{31}^y\right)^2} \quad ; \quad N = \frac{1}{2\left(\sigma_{12}^y\right)^2}$$

Yield stress (MPa)	Traction	Compression
σ_L^y	65.5	-50.3
σ_R^y	3.75	-6
σ_T^y	2.79	-6
σ_{LR}^y	6.34	
σ_{LT}^y	5.34	
σ_{RT}^y	1.83	

Yield stress for Norway spruce wood
at MC = 12% and 20°C
(J. Schmidt et al. 2009)

Frequency of the first 5 soundboard eigenmodes

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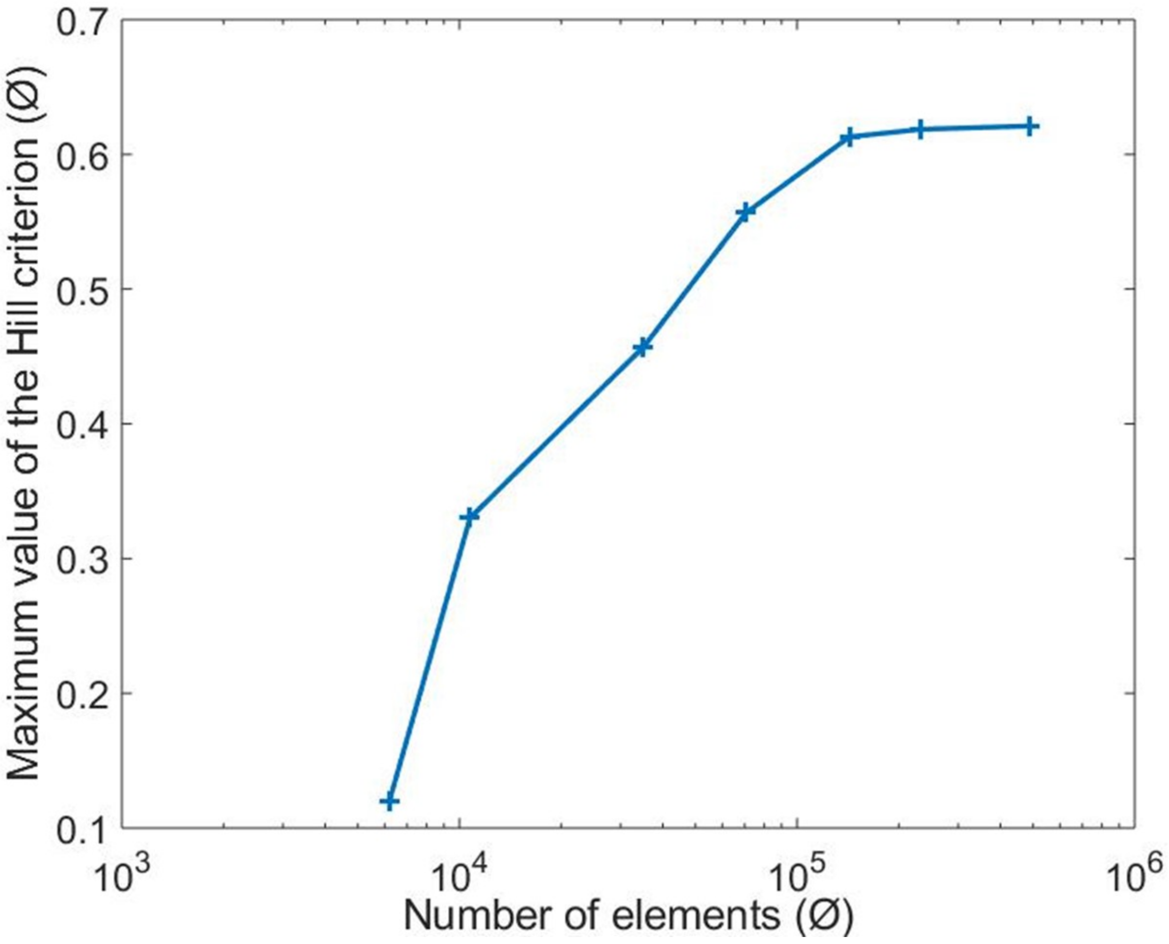
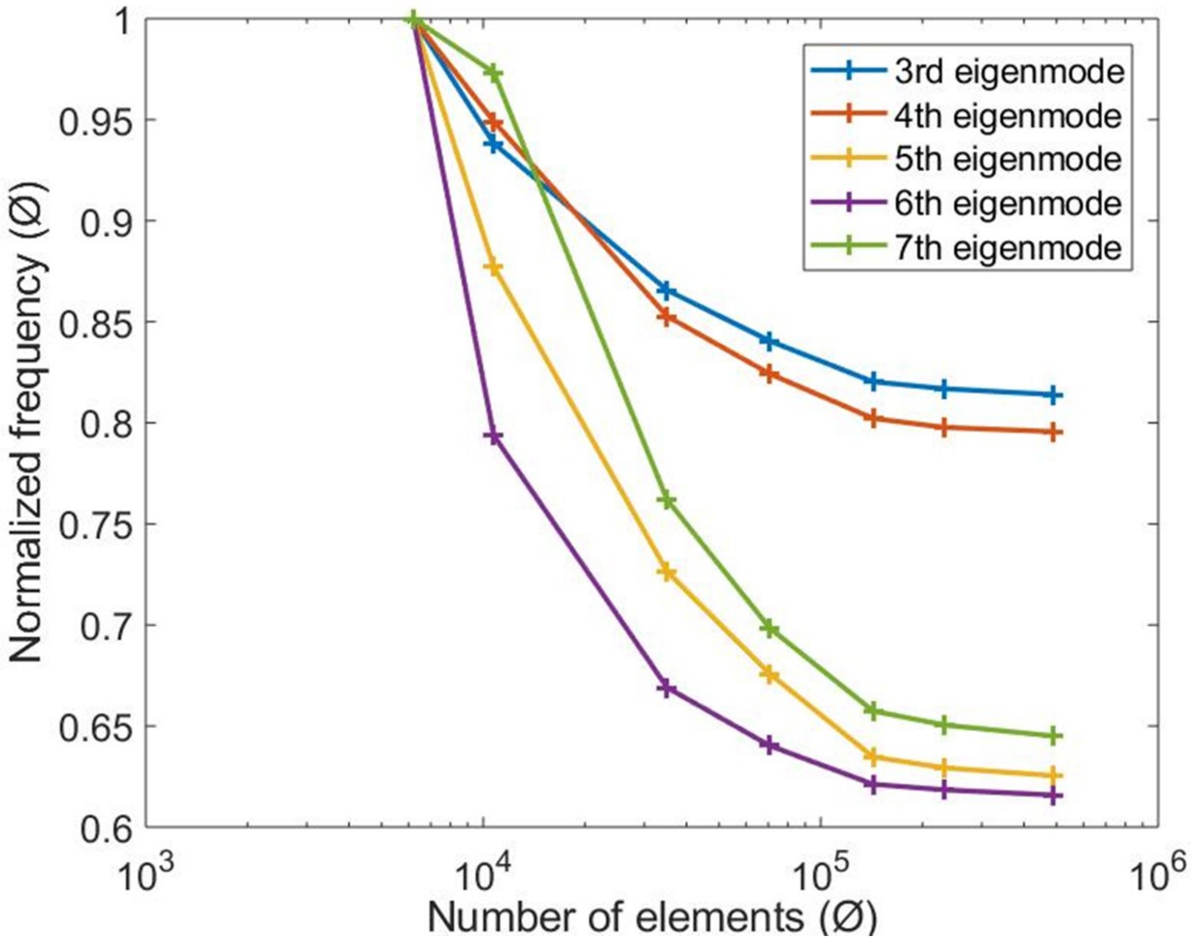
Model verification





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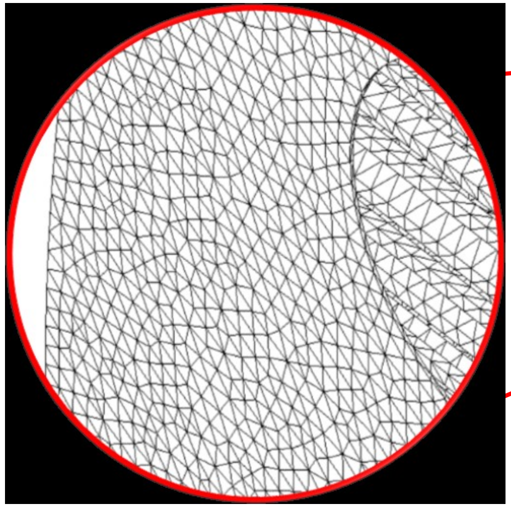
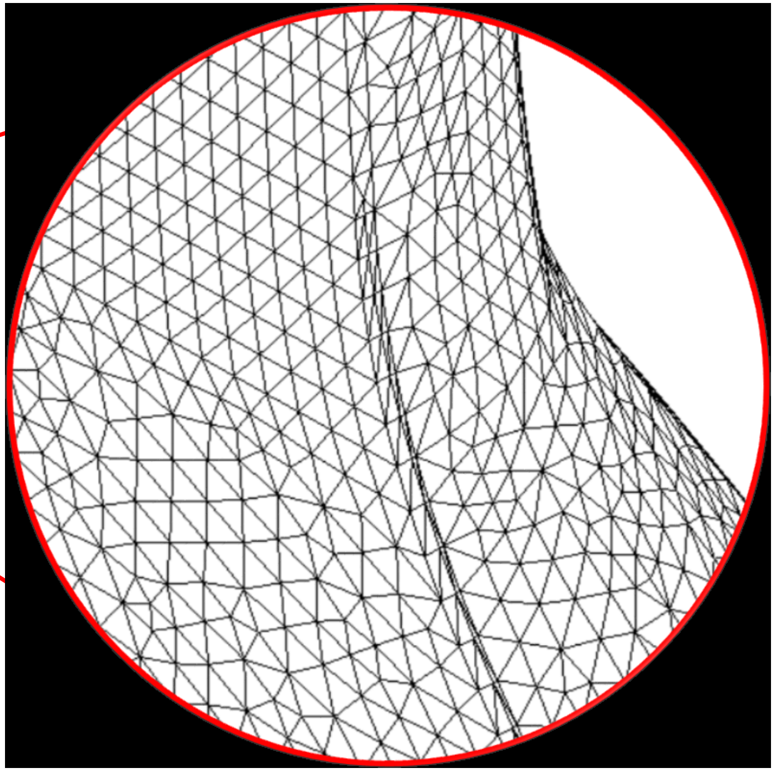
Model verification

Elements type	Quadratic second-order thetrahedral elements (C3D10)
Number of elements	150 000
Number of dof	1 500 000
Number of part	41
Number of different material parameters	48
Maximum value of the Hill criterion (Ø)	0.613
Eigenfrequencies (Hz)	212 ; 243 ; 244 ; 266 ; 328

Summary of the finite element model





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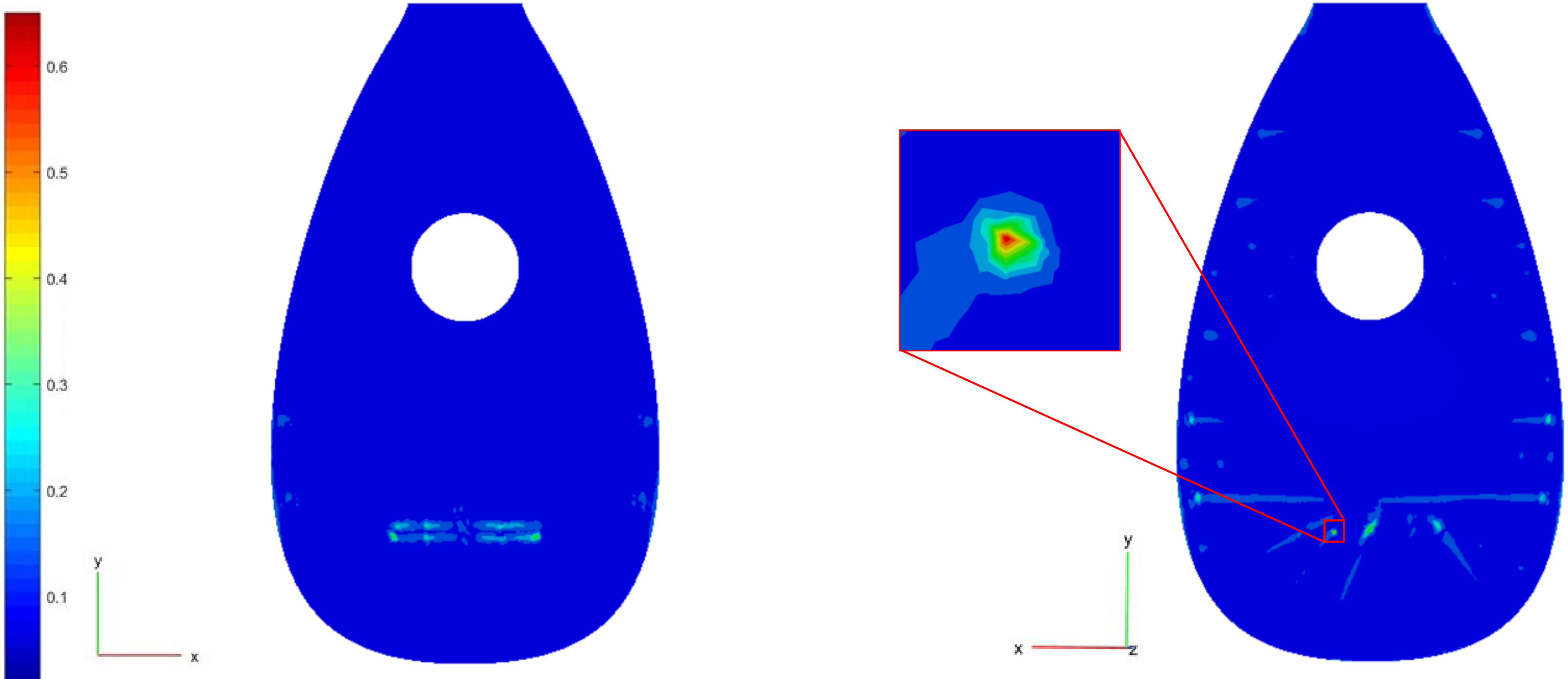
Static analysis

Soundboard hill criterion field



Front view

Back view

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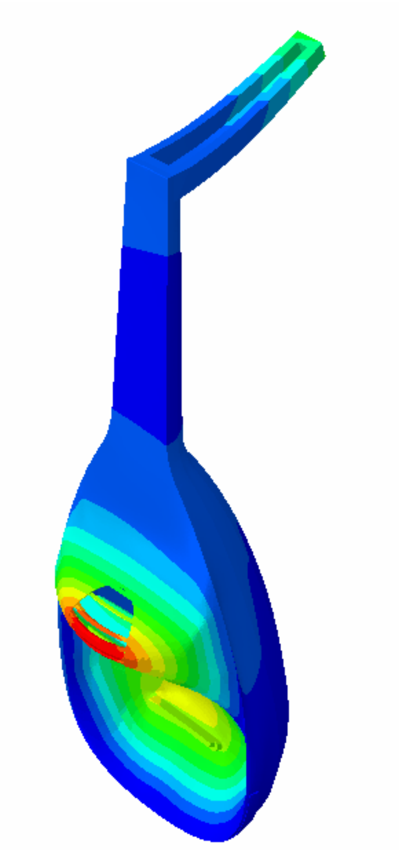
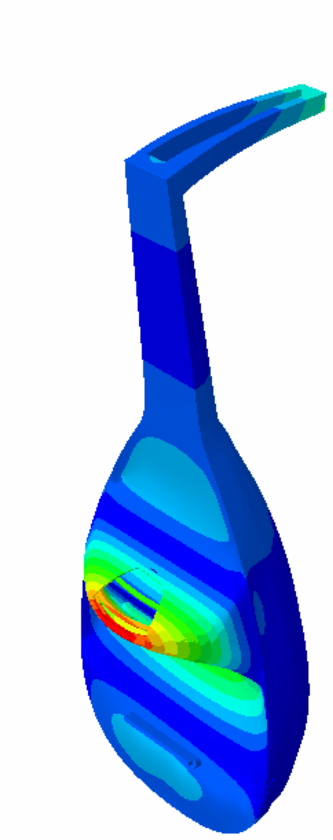
Modal analysis

Shape and frequency of the first 5 soundboard eigenmodes

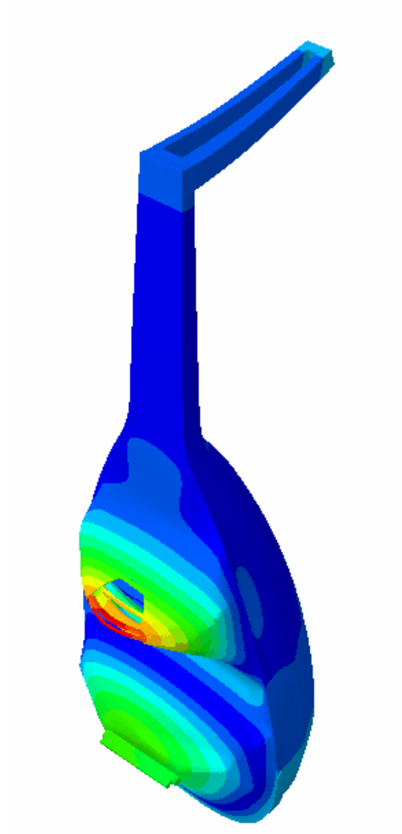


3rd eigenmodes
212 Hz

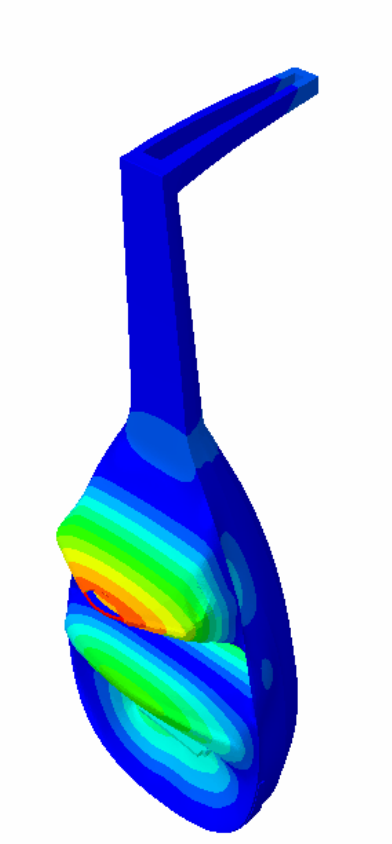
4th eigenmodes
239 Hz



5th eigenmodes
244 Hz



6th eigenmodes
266 Hz



7th eigenmodes
324 Hz

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Sensitivity analysis : Inputs and outputs

	Inputs
Environmental input	Moisture content
Geometric inputs	Soundboard thick.
	Back thick.
	Bridge position
	Main braces thick.
	Sound hole braces thick.
	Fan-shaped braces thick.

	Inputs	
Material inputs	EL	GLR
	ER	GLT
	ET	GRT
	νLR	α_L
	νLT	α_R
	νRT	α_T
	ρ	

Inputs

137 inputs (1 env. + 6 geo. + 130 mat.)

Outputs

- Maximum value of the Hill yield criterion
- Frequency of the first 5 soundboard eigenmodes

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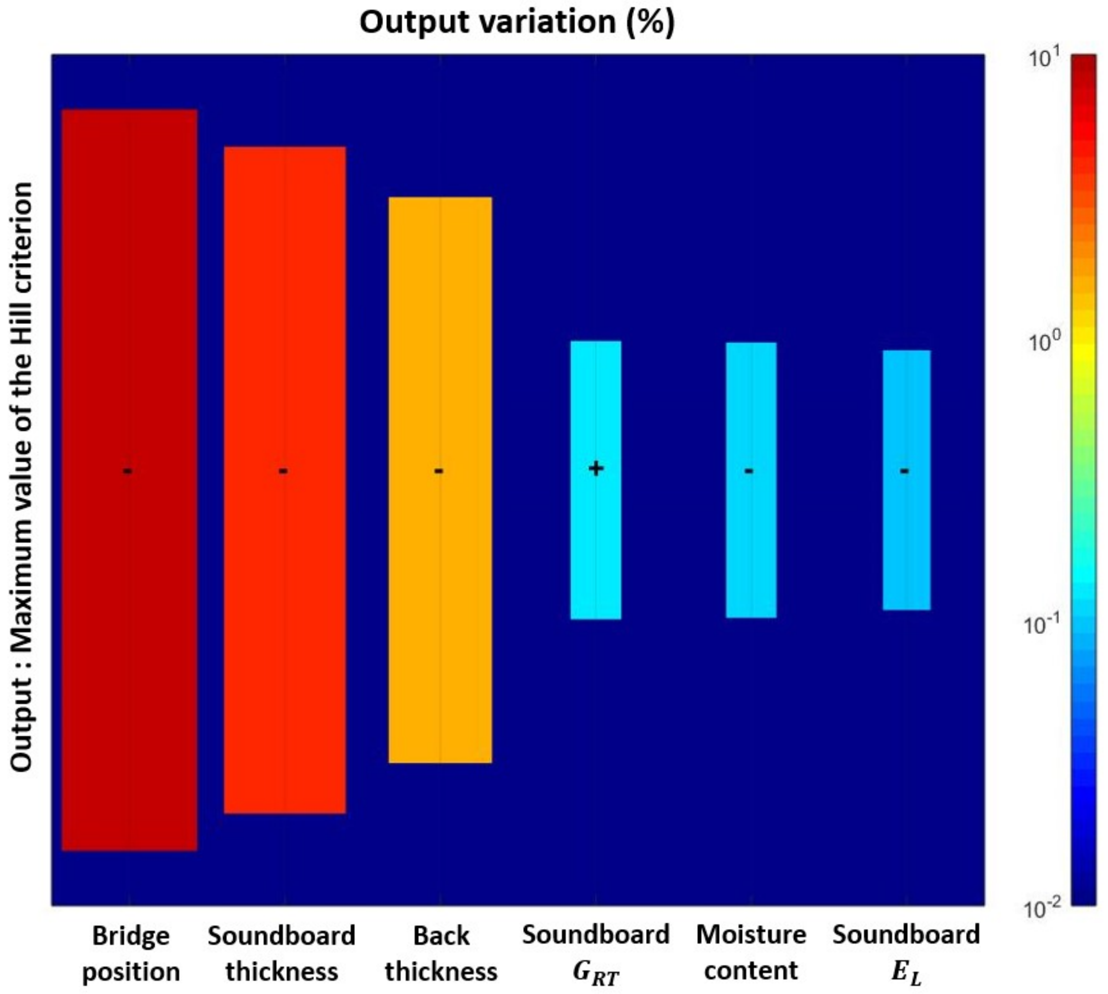
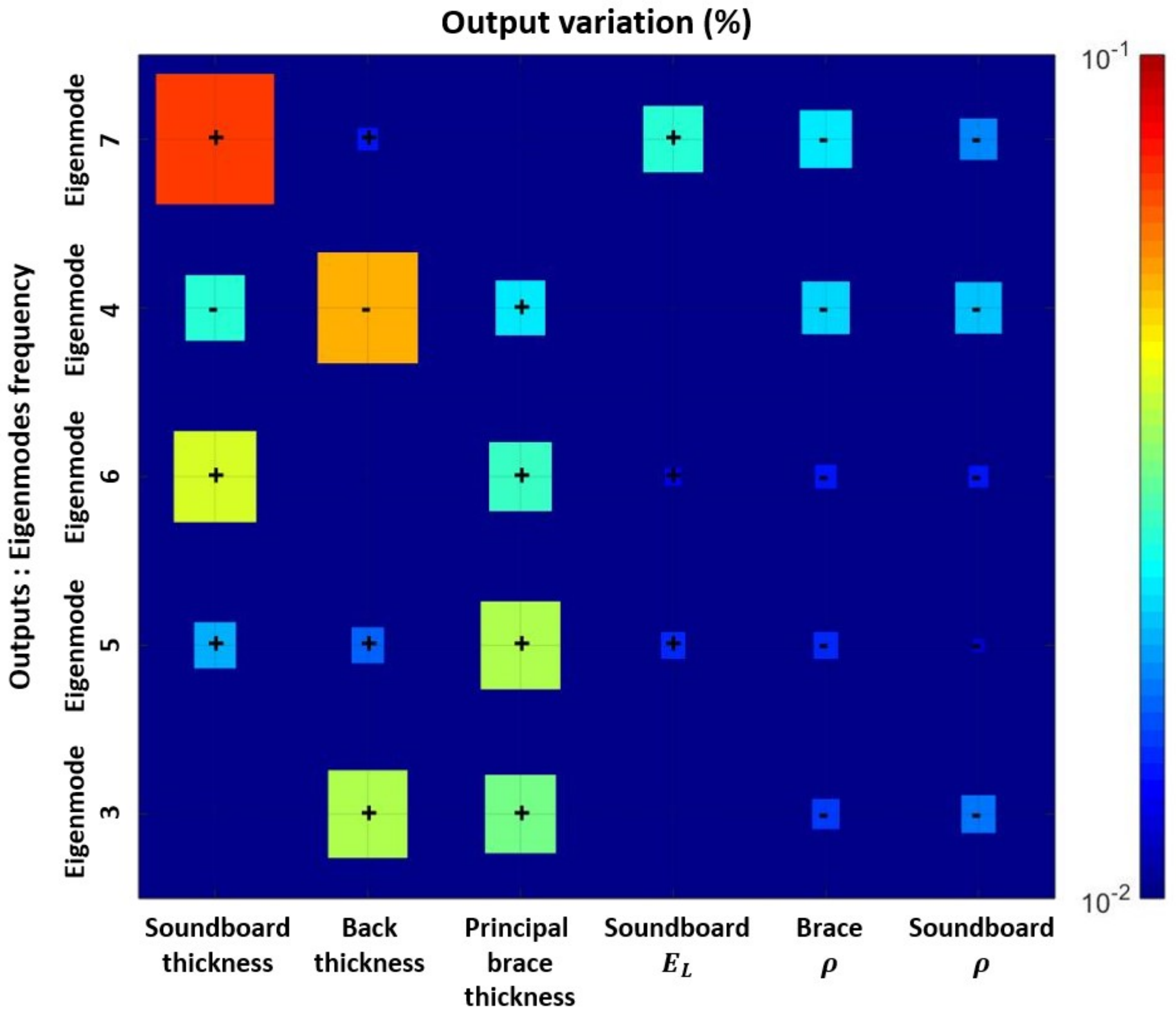
Finite difference sensitivity analysis with δ = 0,1%



*Only inputs generating greater variation than **0.1%** of the output are shown.*



*Only inputs generating greater variation than **0.01%** of the output are shown.*

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Info-gap robustness analysis

System model

Defines the relation between system inputs and outputs

→ **Finite elements model**

Uncertainty model

Represents the uncertainty in the variables x as a function of the horizon of uncertainty h

→ $\boldsymbol{U(x,h) = x * (1+h),\ with\ h = [0\,;0.1]}$

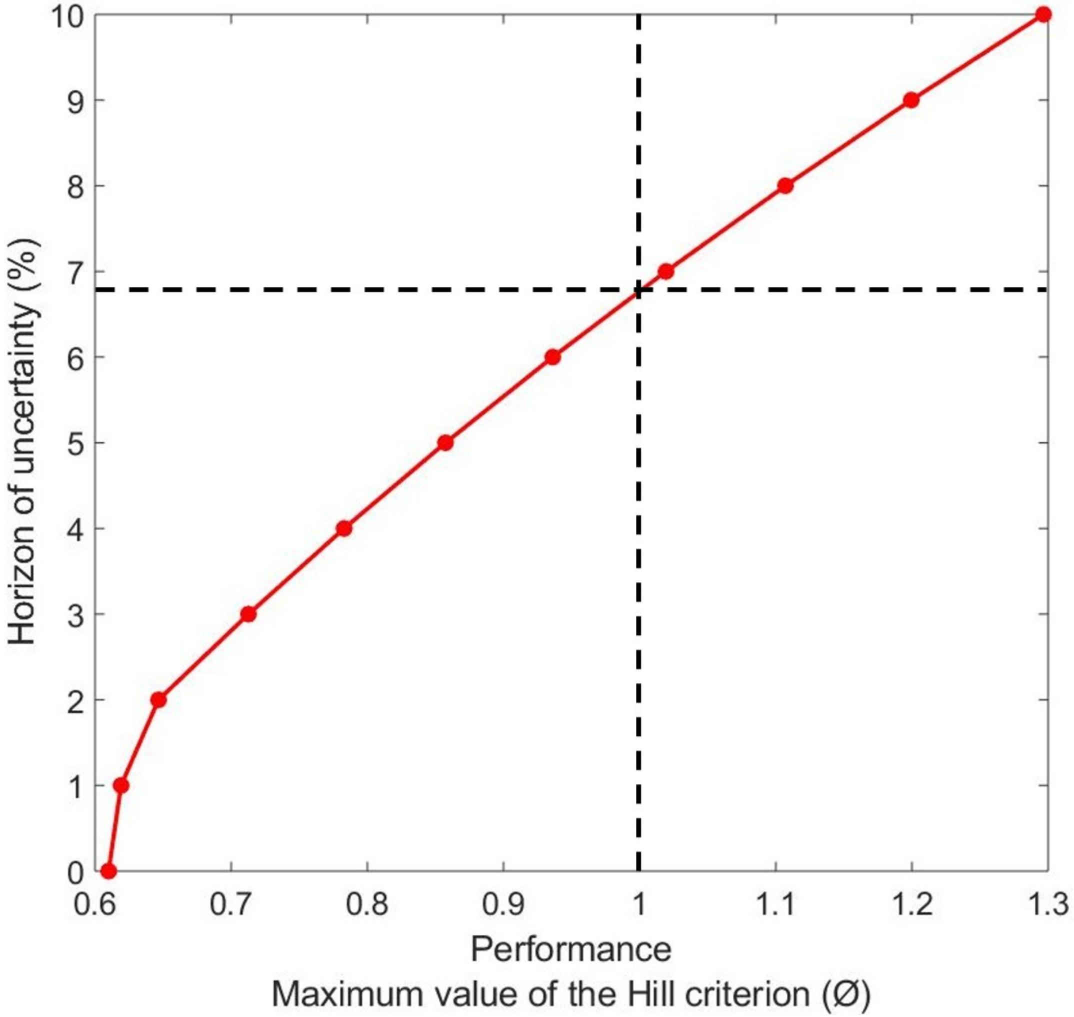
Performance requirement

→ **Maximum value of the Hill criterion < 1**

Robustness analysis

→ **Info-gap robustness analysis with minmax design**

Info-gap decision theory: decisions under severe uncertainty (Y Ben-Haim 2006)



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Conclusions and perspectives

Conclusions

- Propose a methodology for model-based decision support in a museum context
- Account for aleatory and epistemic uncertainties
- Preliminary study on a generic model of the lute Laux Maler

Perspectives

- Develop a more accurate model of the lute (geometry, behavior laws and loading)
- Model the sources of lack of knowledge
- Study the impact of prestress on static and dynamic responses
- Perform an experimental and numerical confrontation

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