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

Victor ALMANZA
V. Placet, S. Cogan, E. Foltête, S. Serfaty, S. Vaiedelich and S. Le Conte

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
Overview

I. Introduction

II. Model-based decision support methodology

III. Preliminary study on Laux Maler lute

IV. Conclusions and perspectives
Model-based decision support for assessing the playability of heritage musical instruments

Introduction
Museum problematics

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

Music museum of Paris

15/04/2019
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

Crack on 1761 Hemsch harpsichord soundboard

Cracks on 1924 Grapelli violin soundboard
Introduction

Virtual prototyping in industry

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

http://www.mscsoftware.com/application
Introduction

Mechanical study of stringed musical instruments

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

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
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
Overview

I. Introduction

II. Model-based decision support methodology

III. Preliminary study on Laux Maler lute

IV. Conclusions and perspectives
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
Overview

I. Introduction

II. Model-based decision support methodology

III. Preliminary study on Laux Maler lute

IV. Conclusions and perspectives
Preliminary study on Laux Maler lute

Hypotheses

- Simplified geometry without defects
- Connections are supposed perfect
# Preliminary study on Laux Maler lute

## Behavior model and parameters

<table>
<thead>
<tr>
<th>Part</th>
<th>Wood species</th>
<th>Constant</th>
<th>Spruce</th>
<th>Ash</th>
<th>Pear tree</th>
<th>Ebony</th>
<th>Lime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soundboard</td>
<td>Spruce</td>
<td>$E_L$ (MPa)</td>
<td>10200</td>
<td>9850</td>
<td>11500</td>
<td>18000</td>
<td>9200</td>
</tr>
<tr>
<td>Back strips</td>
<td>Ash</td>
<td>$E_R$ (MPa)</td>
<td>850</td>
<td>1125</td>
<td>1350</td>
<td>2450</td>
<td>1025</td>
</tr>
<tr>
<td>Liner</td>
<td>Ash</td>
<td>$E_T$ (MPa)</td>
<td>500</td>
<td>550</td>
<td>700</td>
<td>1550</td>
<td>475</td>
</tr>
<tr>
<td>Back block</td>
<td>Ash</td>
<td>$\nu_{LR}$</td>
<td>0.39</td>
<td>0.37</td>
<td>0.38</td>
<td>0.4</td>
<td>0.37</td>
</tr>
<tr>
<td>Bridge</td>
<td>Pear tree</td>
<td>$\nu_{LT}$</td>
<td>0.43</td>
<td>0.47</td>
<td>0.47</td>
<td>0.46</td>
<td>0.47</td>
</tr>
<tr>
<td>Fretboard</td>
<td>Ebony</td>
<td>$\nu_{RT}$</td>
<td>0.5</td>
<td>0.6</td>
<td>0.59</td>
<td>0.56</td>
<td>0.61</td>
</tr>
<tr>
<td>Neck</td>
<td>Lime</td>
<td>$G_{LR}$ (MPa)</td>
<td>750</td>
<td>825</td>
<td>975</td>
<td>1650</td>
<td>775</td>
</tr>
<tr>
<td>Pegbox</td>
<td>Poirier</td>
<td>$G_{LT}$ (MPa)</td>
<td>675</td>
<td>600</td>
<td>725</td>
<td>1300</td>
<td>550</td>
</tr>
<tr>
<td>Front block</td>
<td>Lime</td>
<td>$G_{RT}$ (MPa)</td>
<td>75</td>
<td>200</td>
<td>250</td>
<td>550</td>
<td>175</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hygro-expansion coefficient</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_L$ (%mc$^{-1}$)</td>
<td>$3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\alpha_R$ (%mc$^{-1}$)</td>
<td>$7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\alpha_T$ (%mc$^{-1}$)</td>
<td>$2.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

## Elastic constant of wood species

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

<table>
<thead>
<tr>
<th>Wood species associated with lute parts</th>
<th>Spruce</th>
<th>Ash</th>
<th>Pear tree</th>
<th>Ebony</th>
<th>Lime</th>
</tr>
</thead>
</table>

---

Model-based decision support for assessing the playability of heritage musical instruments
Preliminary study on Laux Maler lute

Initial state
MC = 12%

Mechanical:
Strings tension (400N)

Environmental:
Variation in moisture content

Final state
MC = 13%
Quadratic Hill yield criterion (R. Hill. 1948)

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

\[
F = \frac{1}{2}\left[\frac{1}{(\sigma'_y)^2} + \frac{1}{(\sigma'_z)^2} - \frac{1}{(\sigma'_x)^2}\right] ; \quad G = \frac{1}{2}\left[\frac{1}{(\sigma'_y)^2} + \frac{1}{(\sigma'_z)^2} - \frac{1}{(\sigma'_x)^2}\right]
\]

\[
H = \frac{1}{2}\left[\frac{1}{(\sigma'_x)^2} + \frac{1}{(\sigma'_z)^2} - \frac{1}{(\sigma'_y)^2}\right]
\]

\[
L = \frac{1}{2(\sigma'_{23})^2} ; \quad M = \frac{1}{2(\sigma'_{31})^2} ; \quad N = \frac{1}{2(\sigma'_{12})^2}
\]

Frequency of the first 5 soundboard eigenmodes

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

<table>
<thead>
<tr>
<th>Yield stress (MPa)</th>
<th>Traction</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma'_L)</td>
<td>65.5</td>
<td>-50.3</td>
</tr>
<tr>
<td>(\sigma'_R)</td>
<td>3.75</td>
<td>-6</td>
</tr>
<tr>
<td>(\sigma'_T)</td>
<td>2.79</td>
<td>-6</td>
</tr>
<tr>
<td>(\sigma'_{LR})</td>
<td>6.34</td>
<td></td>
</tr>
<tr>
<td>(\sigma'_{LT})</td>
<td>5.34</td>
<td></td>
</tr>
<tr>
<td>(\sigma'_{RT})</td>
<td>1.83</td>
<td></td>
</tr>
</tbody>
</table>
Preliminary study on Laux Maler lute

Model verification

Model-based decision support for assessing the playability of heritage musical instruments
Preliminary study on Laux Maler lute

Model verification

<table>
<thead>
<tr>
<th>Elements type</th>
<th>Quadratic second-order tetrahedral elements (C3D10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>150 000</td>
</tr>
<tr>
<td>Number of dof</td>
<td>1 500 000</td>
</tr>
<tr>
<td>Number of part</td>
<td>41</td>
</tr>
<tr>
<td>Number of different material parameters</td>
<td>48</td>
</tr>
<tr>
<td>Maximum value of the Hill criterion (Ø)</td>
<td>0.613</td>
</tr>
<tr>
<td>Eigenfrequencies (Hz)</td>
<td>212 ; 243 ; 244 ; 266 ; 328</td>
</tr>
</tbody>
</table>

Summary of the finite element model
Preliminary study on Laux Maler lute

Static analysis

Soundboard hill criterion field

Front view

Back view
Preliminary study on Laux Maler lute

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
## Preliminary study on Laux Maler lute

### Sensitivity analysis: Inputs and outputs

<table>
<thead>
<tr>
<th>Environmental input</th>
<th>Material inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>EL, GLR</td>
</tr>
<tr>
<td>Soundboard thick.</td>
<td>ER, GLT</td>
</tr>
<tr>
<td>Back thick.</td>
<td>ET, GRT</td>
</tr>
<tr>
<td>Bridge position</td>
<td>νLR, χ_L</td>
</tr>
<tr>
<td>Main braces thick.</td>
<td>νLT, χ_R</td>
</tr>
<tr>
<td>Sound hole braces thick.</td>
<td>νRT, χ_T</td>
</tr>
<tr>
<td>Fan-shaped braces thick.</td>
<td>ρ</td>
</tr>
</tbody>
</table>

### Inputs

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

### Outputs

- Maximum value of the Hill yield criterion
- Frequency of the first 5 soundboard eigenmodes
Preliminary study on Laux Maler lute
Finite difference sensitivity analysis with $\delta = 0.1\%$

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.
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 $h$
→ $U(x, h) = x \ast (1 + h)$, 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)*
Overview

I. Introduction

II. Model-based decision support methodology

III. Preliminary study on Laux Maler lute

IV. Conclusions and perspectives
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
Thank you for your attention!