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GEOMETRY AND TUNING ASSESSMENT OF TIMBILAS THROUGH NON-DESTRUCTIVE REVERSE ENGINEERING TECHNIQUES

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Resumo

Timbilas são instrumentos musicais tradicionais da família dos xilofones, construidos pelos Chopes, um povo de Moçambique. No contexto de um projecto de investigação relacionado com o estudo de timbilas históricas, desenvolvemos uma abordagem não destructiva para a caracterização da geometria e das propriedades musicais desses instrumentos, combinando técnicas de digitalização 3D e de engenharia reversa. Os dados geométricos são adquiridos por scanner 3D, que oferece uma análise detalhada e precisa da geometria dos vários componentes. Numa segunda fase, os modelos 3D são usados como inputs para construir modelos por Elementos Finitos para análise modal. A análise dos parâmetros modais permite estudar a afinação das barras e analisar a escala musical do instrumento, bem como determinar o diapasão com o qual o instrumento foi afinado pelo constructor. A metodologia é aplicada a uma timbila real e os resultados dos cálculos modais são comparados com valores identificados a partir de medições vibratórias, resultando num acordo razoável.

Palavras-chave: Engenharia reversa, análise modal, Elementos Finitos, scan 3D, xilofones africanos.

Abstract

Timbilas are wooden xylophones finely manufactured and tuned by Chopi people from Mozambique. In the context of a research project concerned with the study of historical timbilas, we developed a methodology for assessing their geometrical and acoustical features based on 3D scanning technology and reverse engineering techniques. We start by performing contact-less geometrical measurements on a nine-bar timbila by using 3D scan that result in a fine description of their design. The collected 3D geometrical data are then used as inputs to build a 3D Finite Element model of each bar in order to perform modal computations for assessing their modal frequencies and mode shapes. For validation of the approach, we apply the methodology to a real-life timbila, for which results stemming from our modal computations compared well with modal data extracted from vibration analysis measurements.

Keywords: Reverse engineering, modal analysis, 3D scanning technology, african xylophones.

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1 Introduction

Timbilas are traditional wooden xylophones finely manufactured and tuned by Chopi people from Mozambique, whose music has been known to the world through the work of ethnomusicologist Hugh Tracey [1]. While being representative of Mozambique and even serving as a national symbol in the mid-20th century, timbila music faced the political, economic and cultural changes that occurred after the independence and declined continuously. In 2007, the Chopi timbila was inscribed on the UNESCO World Heritage List, which has offered it new attentions, with the emergence of new modes of fusion that go well beyond conventional limits of traditional music and a renewed interest by ethnomusicologists.

Despite the numerous references to the instrument since the 16th century [2], only a few researchers have however contributed to its musical values. The pioneer work by Tracey [1] encompasses many features of Timbila music, including concepts, texts and musical forms, as well as quantitative surveys on the instruments tuning. With the loss of most tangible memory of Timbila in Mozambique, recent research has focused on material heritage mainly, kept in museums, among these the National Museum of Ethnology of Lisbon (NME), which represents the world's most important collection of original timbilas, because of the number of instruments and their age. Recently, Warneke [3] performed acoustic measurements on the entire NME's collection but his work remained unspecific on some relevant musical features of the instruments such as the overtone structure and the decay rate of the sounding notes. Henrique [4] performed more detailed measurements for one specimen and successfully identified the modal frequencies, modal damping and mode shapes of each bar of the instrument, by combining impact testing with modal identification algorithm.

Following our previous work on the acoustic characterization of historical percussion instruments [5, 6, 7], we are being involved in a research project that aims at studying the timbilas collection of the NME. In this paper, we present the non-destructive approach devised to systematically analyze timbilas in terms of their vibrational and musical properties. Our approach is rooted on 3D scanning technology combined with reverse engineering techniques, and provides 3D virtual model of the instrument that can be used for further analysis or computer simulations. In general terms, the workflow involves: (1) a 3D geometrical capture of each bar geometry by manual scanning, (2) the construction of a structural model by means of Finite Elements (FE) that is used for modal analysis, and finally (3) an analysis of the computed modal parameters in order to infer musical properties of the instrument. In this work, we develop and apply the technique to a 9-bar laboratory timbila, as displayed in Figure 1, in order to illustrate the benefits of the approach and demonstrate its efficiency. In particular, results stemming from modal computations are compared with those extracted from experimental modal analysis, illustrating the fair behavior of the approach for the objectives of our project.

2 3D surface scanning

Surface scanning technology has grown over the last few years and is now becoming increasingly attractive for a wide range of applications across different disciplines ranging from medical technology to archaeology. 3D scanning combines sophisticated techniques of image capture with efficient processing algorithms that together enable fast and detailed geometry assessment of objects with complex shapes. In this work, we used the Artec Eva 3D hand-held scanner, that uses one projector to send different patterns of LED light on the objects and two cameras for capturing and processing the 3D point clouds. Compared to traditional measuring probes, this scanner proves to be a very precise, easy-to-use and reliable solution for geometry survey, achieving a spatial resolution of 0.5 mm and being capable of capturing surface color and texture information, which makes it particularly attractive for generating detailed full rendered 3D models.

The bars of the laboratory timbila were scanned by sweeping the device along the entire instrument from different angles. Scanning was done sequentially over consecutive regions spanning two or three bars. The procedure was repeated until all the bars were captured and each region was post-processed

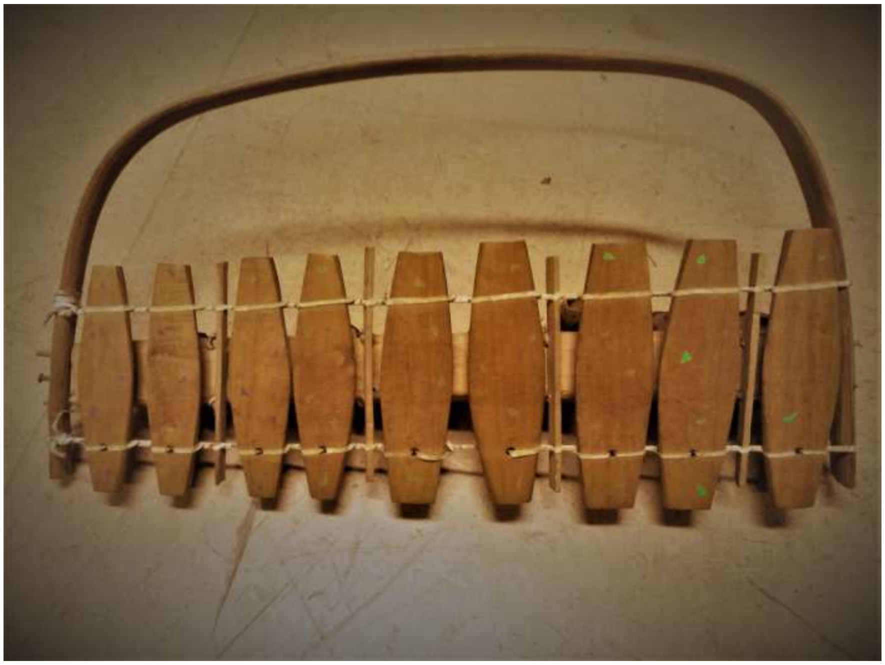


Figure 1: The 9-bar laboratory timbila investigated in this work.

individually in order to isolate each bar. Although relatively simple in practice, scanning can be a time-consuming procedure and must be done with care in order to avoid noisy acquisition, long post-processing and extremely large mesh files. Difficulties during the scanning process include difficult-to-reach areas such as the underside of the bars. Scanning therefore usually involves several scan acquisitions and demands the use of different post processing before obtaining the final polygon mesh of the object, which include: (1) assembling and aligning scans stemming from several captures; (2) cleaning noisy images using eraser, low-pass filter and outlier removal tools, (3) fusing all the scans together to generate the surface mesh, and (4) finally rendering to view the 3D model, possibly with texture. The final 3D surface mesh is built using simplified polygons and is exported in the STL format, which is one of the standards for 3D objects that is supported by many CAD softwares. One example of a surface mesh and its corresponding rendering model built for a bar of the studied timbila is presented in Figure 2.

3 Geometry features extraction

The 3D virtual model is then an adequate representation to perform a detailed analysis of the bar geometry, including its typical dimensions and more relevantly the shape of the undercut, which is fundamental for bar tuning and sound quality. One way for studying the variation of thickness of the bars can be done by computing a series of closed contours representing the cross sections of the bar along a given direction. To that end, we developed a basic uniform slicing algorithm in order to systematically produce contour data of the bars from the STL files. For a given cutting plane, the algorithm first calculates the facets that intersect with the cut plane, then estimates the coordinates of the intersection points and defines the line segment resulting from the facet/plane intersection. Proceeding similarly for all the intersected facets, a set of intersection line segments is obtained. Finally, the closed contour is built by linking the start and end points of the different segments. Figure 3 shows an example of a computed 3D contour image of one bar, together with the corresponding side and top views, obtained using the developed algorithm. Interestingly, these data can be also split into separate cross-section areas - as displayed in Figure 4 - that provide a more detailed analysis of how the material has been removed by the maker during the tuning process. This data

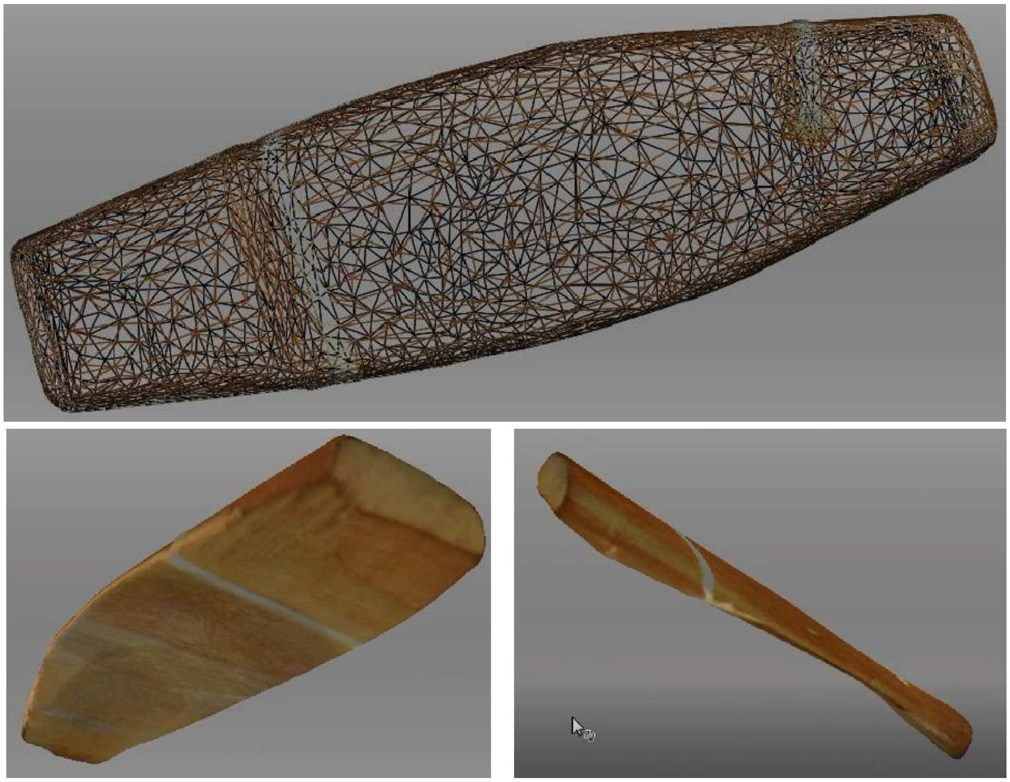


Figure 2: Top: surface mesh. Bottom: details of the 3D rendering with texture. Bar # 4.

can be also further used to study quantitatively the changes in width and area of cross-section or for directly copying original bars through 3D printing, which is actually based on 2D adding layer process and requires slices as inputs. Needless to say, obtaining such precise data for a surface with many irregularities as it is the case for timbila, would be very challenging through classical geometrical measurement techniques.

4 FEM modeling and modal computation

FEM techniques are then applied to investigate the dynamical behavior of the bars in order to compute the frequencies and corresponding mode shapes of the main resonances that are finally used to analyze the tuning and musical scale of the instrument.

From the 3D surface data, a solid 3D mesh is built by means of Finite Elements. The *Partial Differential Equation Toolbox* of Matlab, which allows to import 3D geometries from STL files, was used to construct the FEM model and to carry out the numerical modal computation. For building the mesh, the selected elements were tetrahedrons with 10 nodes. While the number varies with the dimensions of the bar, systematic tests of convergence show that a total number of about 30000 elements leads to a relative accuracy of a few percent. For illustration, a typical example of a built volume mesh is plotted in Figure 5.

A practical problem of our FE modal computations was the selection of the mechanical constants that describe the elastic behavior of the wood, i.e. the Young's moduli, Poisson's ratios and shear moduli. One inherent difficulty in wood mechanics is due to its orthotropic nature, a kind of anisotropy for which properties differ along the main directions and that makes mechanical modeling delicate [8]. Instead of the three parameters that are needed for describing isotropic material, a set of nine parameters is necessary for accurate modeling of wooden bars: three moduli of elasticity (Young's moduli), three moduli of rigidity (shear moduli) and three Poisson's ratios [9].

Timbila are made of *Mwenje*, also named Sneezewood, one of Africa's most resonant woods, extremely

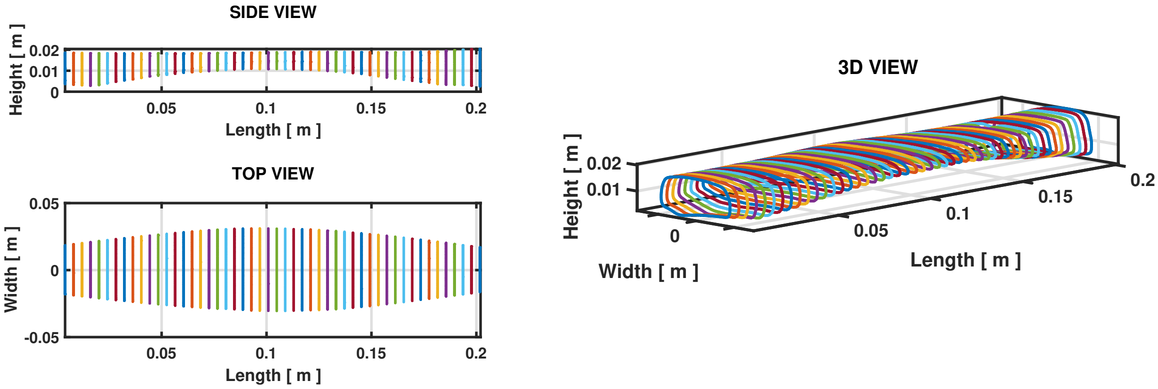


Figure 3: Computed slices of the geometry of bar # 4. Side, top and 3D views.

hard and resinous, for which information in the literature is rare. In addition, if wood databases present properties in the direction parallel to the fiber, they are however not extensive for the other two directions (radial and tangential), and this is the reason to explain why many music acoustics studies concerned with wooden percussion instruments usually modeled wood as an isotropic material [9, 10, 11].

Since only properties in the longitudinal direction were found for the wood *Mwenje*, our preliminary FE computations were performed assuming that the bar material is homogeneous and isotropic, and using average values found in the literature [12]. This obviously remains an approximation of the real physics and limits the validity of the FE modeling. However, it must be noticed that the ratio length/width for musical bar is usually large and that bars are also cut in the longitudinal direction, so that using the longitudinal properties remains a first valid approximation for vibrational analysis. Quantitatively, Bork et al.[9] noticed that for marimba bars, using an isotropic FE modeling was efficient in predicting the frequencies and mode shapes of the first three vertical bending modes, but led to large errors for higher-order modes and torsional modes. If some model updating could be attempted by adjusting the bar density and Young's modulus to modal frequencies identified experimentally, we preferred to perform computations using common values found in order to mimic somehow the conditions that we will find for instruments of the museum, for which information will not be available precisely. We therefore set the Young's modulus to its longitudinal modulus value, which was assumed to be 17.7 GPa, the density to 1000 kg/m^3 and the Poisson ratio to 0.3. Also, for simplicity, modal computations were performed ignoring dissipative phenomena (internal damping losses and sound radiation) and assuming free boundary conditions while in reality bars are fixed to the supporting structure with straps at location close to the nodal position of their fundamental mode.

Figure 6 presents the first six nonzero-frequency modes computed for bar # 4. As can be seen, the bar vibrates in the three directions, in different ways, including flexural, torsional and lateral motions. As anticipated, the mode shapes are very similar to those found for marimba [9]. Modes 1, 3 and 5 correspond to flexural modes mainly, modes 2 and 4 to torsional modes, while mode 6 combines both torsional and lateral motions. Although not presented, the bars also present six low-frequency modes that describe rigid-body motions and correspond to translations and rotations of the bar along the main axis, with near-zero frequencies.

5 Comparison with experimental modal analysis

In order to validate our FE modal computations, experimental modal analysis was performed for all bars of the studied timbila. Tests were performed with the bars mounted in the instrument structure, including the

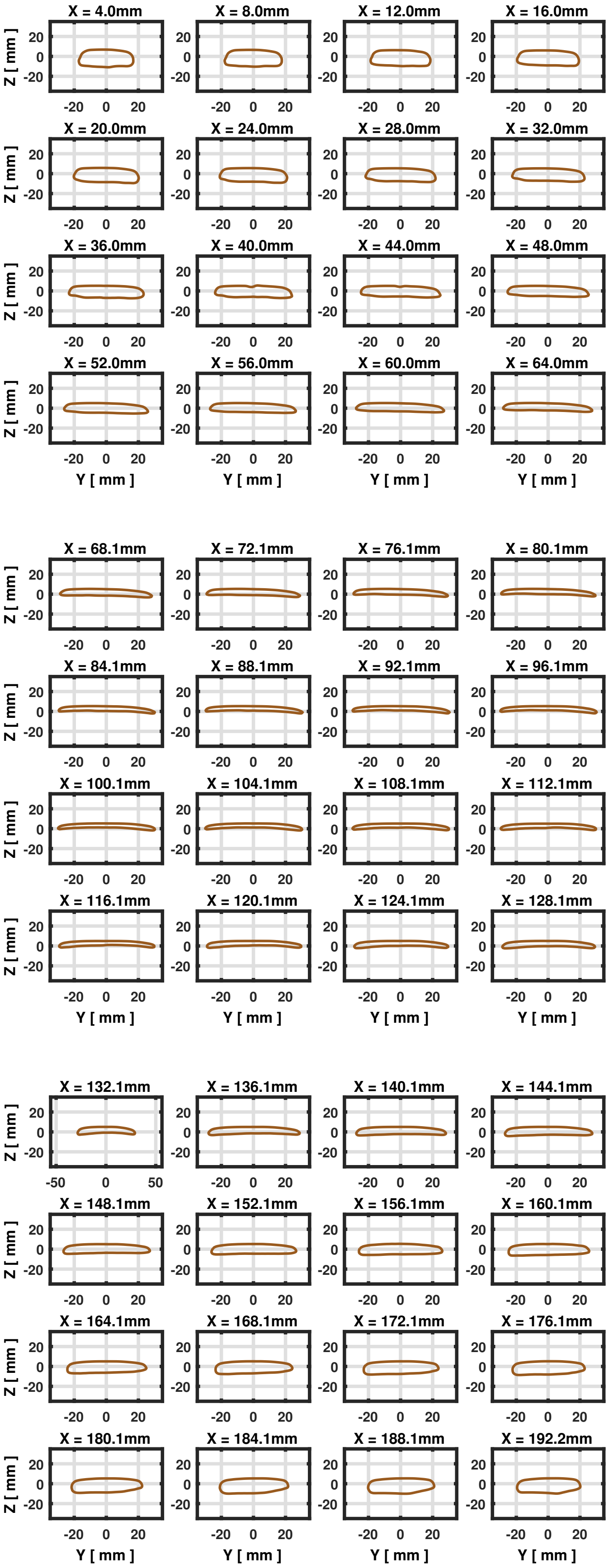


Figure 4: Computed separate slices along the longitudinal direction.

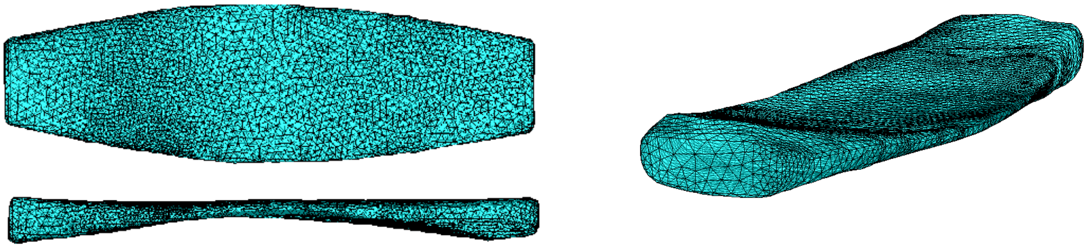


Figure 5: Solid mesh of bar # 4, built using tetrahedron elements.

resonators. Impact excitations were given using an instrumented hammer while a laser vibrometer was used to measure the vibrational response of the bars (Figure 7). Impacts were given in the direction perpendicular to the bar at three different points along the longitudinal axis and off-axis. The vibratory signals were recorded at a sampling frequency of 12600 Hz and pre-processed through the multi-channel data acquisition system Siglab 20-42. The acquired signals were 0.6s long, which is enough to capture the rapid decay of the bar vibration. In order to identify the mode shapes, we also performed a full modal identification of one bar as if it was in free conditions, set on two supports located close to the nodes of the first mode. In these tests, impact excitations were given on a 53-point regular mesh while the vibrational responses were measured at a single point, close to the bar corner (Figure 7).

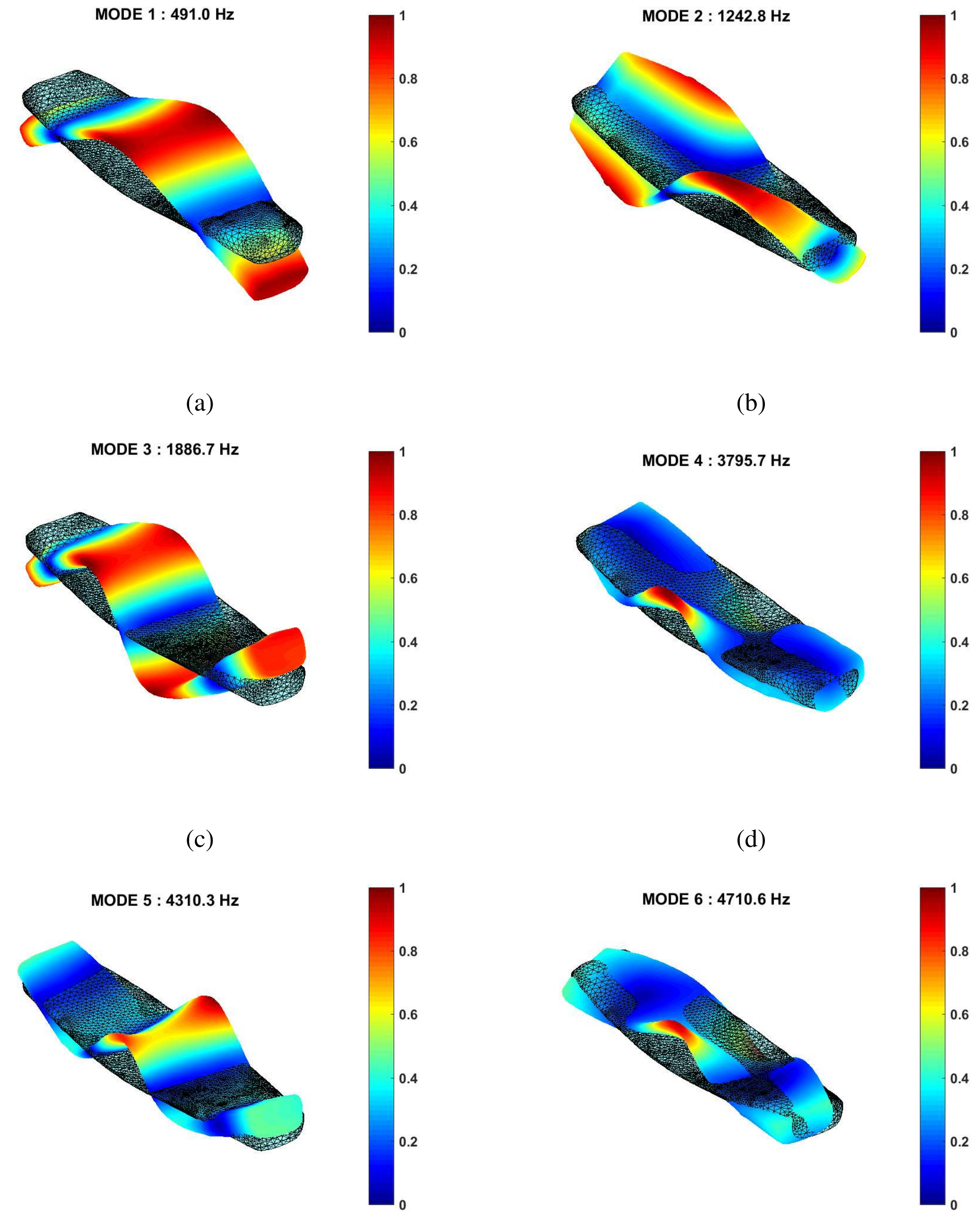
Modal identifications were performed in the time-domain using an implemented version of the Eigensystem Realization Algorithm [13], fed with all the measurements. Retaining a modal representation for describing the linear dynamics of the bar, the impulsive response $h(\mathbf{r_i}, \mathbf{r_j}, t)$ measured at location $\mathbf{r_j}$ for an excitation given at location $\mathbf{r_i}$ can be expressed as a sum of damped modal responses, expressed in terms of velocity/force as:

$$h(\mathbf{r_i}, \mathbf{r_j}, t) = \sum_{n=0}^{N} A_n^{ij} e^{-\omega_n \zeta_n t} \cos(\omega_n \sqrt{1 - \zeta_n^2}\, t) \qquad (1)$$

where $A_n^{ij} = \phi_n(\mathbf{r_i})\phi_n(\mathbf{r_j})/m_n$ represents the modal amplitude of mode n, ϕ_n and m_n being the corresponding mode shape and modal mass respectively, and $\omega_n = 2\pi f_n$ and ζ_n are the (undamped) modal frequency and modal damping respectively. Basically, the objective of the algorithm is to identify the minimum set of modal frequencies and modal damping (of order N) that best-fit the measured impulse responses. Figure 8 shows a typical measured impulse response and transfer function together with the reconstructed functions using the identified modal parameters, showing that the identification was reliable up to 5000 Hz.

When looking at the errors between the FEM-computed and experimentally identified modal frequencies, one notices a relatively good agreement for the bending modes while results largely differ for torsional modes. The mean relative error computed for the bars is less than 0.7% for the first bending mode and then increases with the frequency for higher modes. They are about 4% and 12% for the second and third modes respectively. As anticipated, the computed frequencies for modes involving torsional motions are not correctly predicted and always overestimated. This clearly shows the limits of performing modal computations using an isotropic FE model for bars as previously mentioned. Finally, Figures 6 and 9 provides a quick comparison between FE computed and experimentally identified mode shapes showing that the vertical motions are close to identical in both cases.

Modal damping was found frequency dependent, with values increasing with the frequency, following the general trends observed for wooden bars [11]. It ranges from 0.2 to 2.5 % and notice that large values were identified for the first torsional modes (see Figure 10). This observation can be explained by the



(a) (b)

(c) (d)

(e) (f)

Figure 6: First six non-zero frequency modes computed by FEM ofr bar # 4. Modes are normalized such as $\max(|\varphi_n(\mathbf{r})|) = 1$.

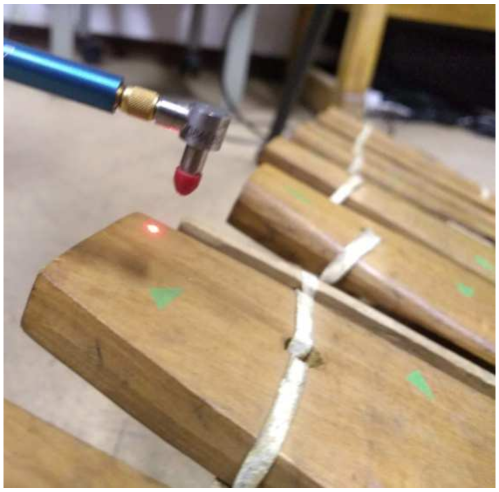


Figure 7: Setup for experimental modal analysis.

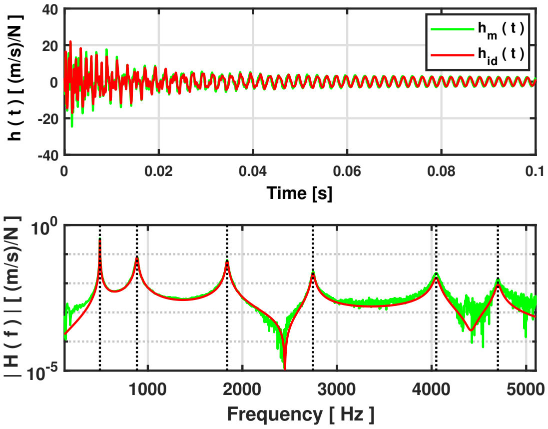


Figure 8: Measured and synthesized impulse (top) and transfer functions (bottom). Vertical dotted gray lines stand for the experimentally identified modal frequencies. Bar # 4.

presence of the attachment cord (see Figure 7), which not only constrains the bar motion in the vertical direction but also favors local dissipation phenomena.

6 Tuning analysis

From the knowledge of the modal frequencies, it is finally possible to study the internal tuning of the bars and the musical scale of the instrument, and infer its reference tuning. Since the sound produced by the bars is essentially due to vertical motions, we focused our analysis on the bending modes. Before attempting any tuning assessment, it must be said that according to measurements done by Tracey on several hundred of instruments [1], timbilas share a common tuning system, an even scale of seven intervals all alike, based on a central note called the *Hombe*, whose frequency is found around 252 Hz, and that other tones are tuned in octave from the central scale.

The internal tuning of the bars are analyzed by looking at the bar overtones, calculating the frequency ratios between the modes in relation to their fundamental. Results presented in Figure 11a show that the tuning of the second and third (bending) modes vary largely over the musical scale, thus suggesting the timbila maker made no attempt to tune the bars overtones. This particularly differs from other percussion bar instruments such as the vibraphone or marimba, for which makers tune the bar overtones according to some musical frequency ratio, usually 1:4:9 or 1:4:10, when tuned according to the equally-tempered scale [9, 14, 15]. From the point of view of pitch perception, the main drawback for timbila sound is that the pitch is not as clearly defined as in the case of an harmonic spectrum because higher partials do not share any temporal periodicity with the fundamental frequency.

Figure 11b shows the musical intervals calculated between successive notes along the musical scale, expressed in cents. As seen, they are fairly constant, around a mean value of 168.3 cents and with a standard deviation of 14 cents. They are therefore close to the theoretical value of 171.42 cents required for an heptatonic scale, and tuning deviations actually compare well with those found on instruments studied by Tracey. Overall, this offers the instrument aesthetic quality to play timbila music.

Finally, one can attempt to estimate the reference frequency of the instrument. A simple approach could consist in looking for the bar which has its fundamental frequency close to the value of the *Hombe* tone. However, a more objective approach could be done by applying the strategy proposed by Debut et al. [5], using the identified modal frequencies of the first mode of all the bars and the target frequencies of the

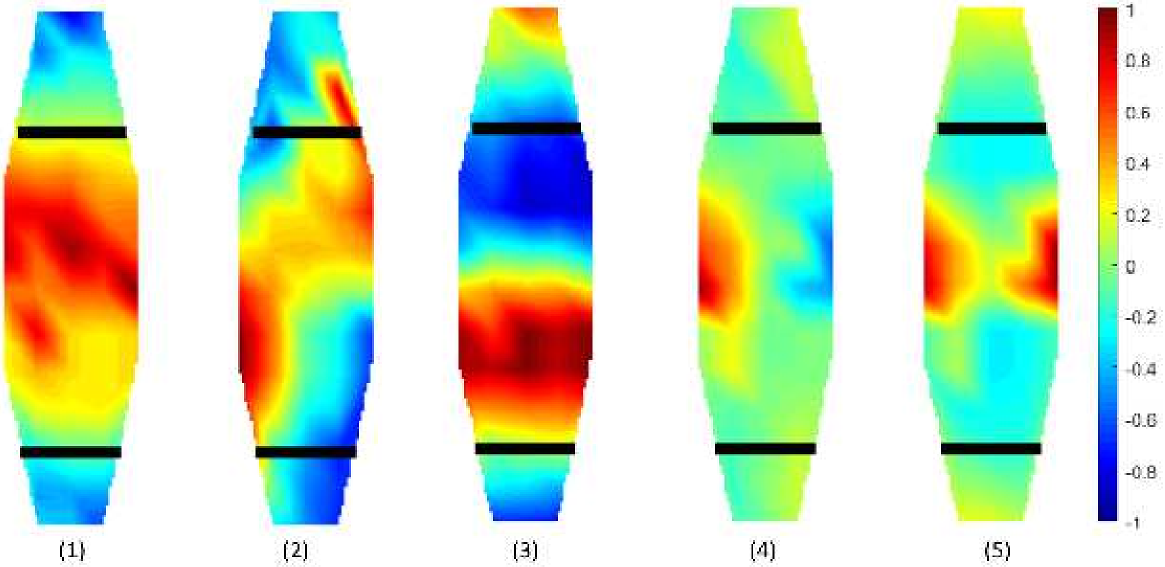


Figure 9: First fifth experimentally identified modes of bar # 4. The black line represents the attachment cord of the bar on the instrument structure.

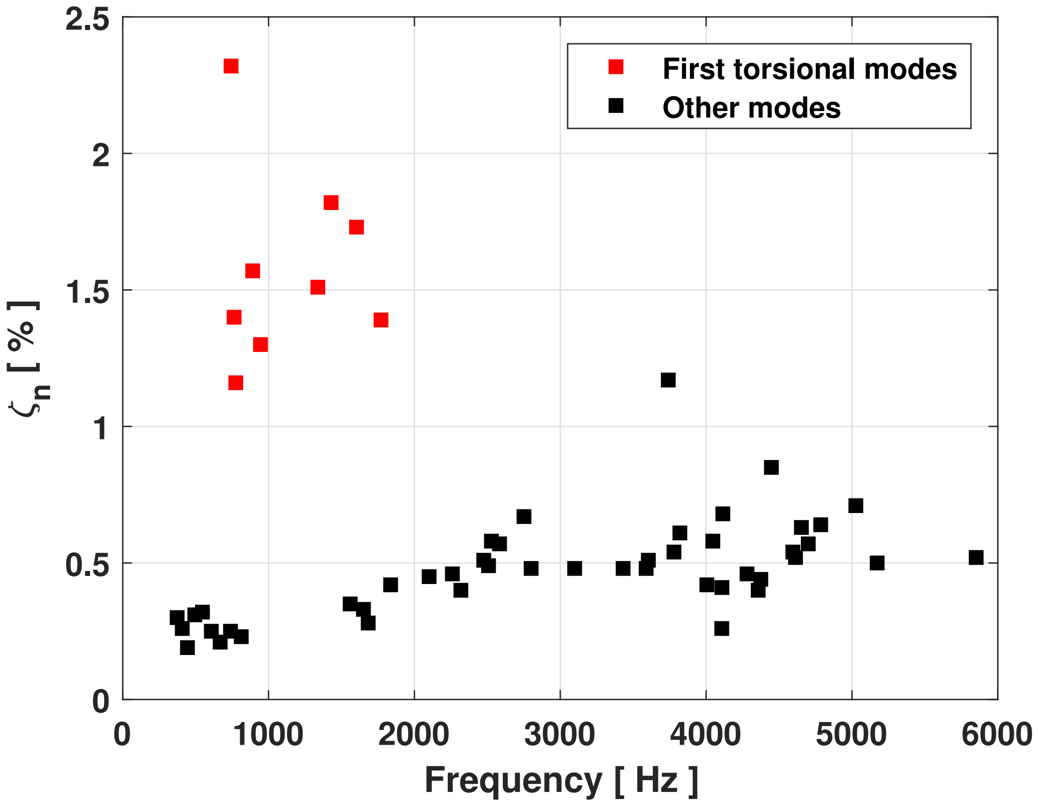
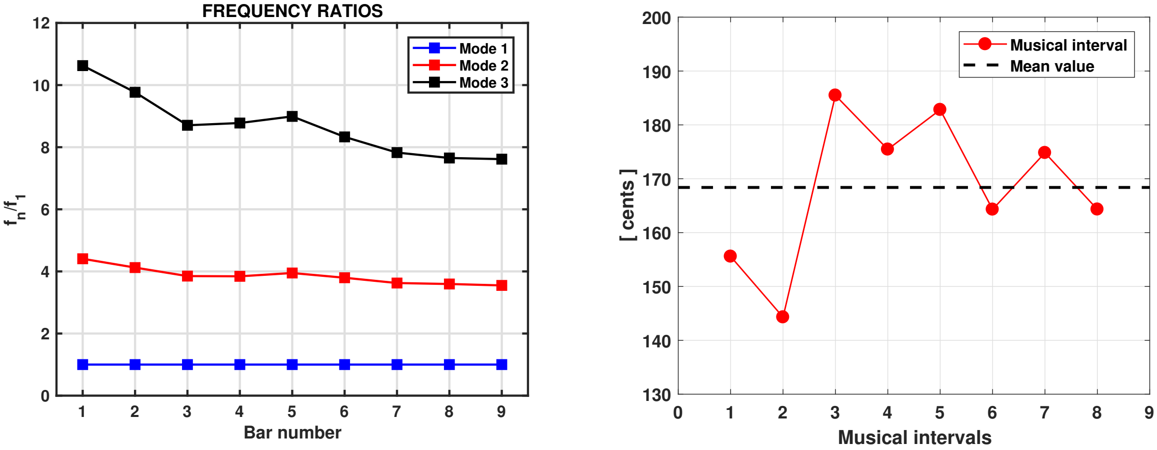


Figure 10: Identified modal damping as a function of frequency.

heptatonic musical system. Instead of looking at the fundamental frequency of a single bar, this approach estimates the reference pitch by accounting for the nine bars comprising the instrument, thus balancing somehow possible mistuning of bars. The standard pitch f_0 of the instrument is given by:

$$f_0 = \mathbf{s}_T^{+} \mathbf{f}_{meas} \tag{2}$$

where $\mathbf{f}_{meas}$ is a vector of the identified frequencies for the fundamental mode of the bars, $\mathbf{s}_T = (2^{0/7}, \ldots, 2^{8/7})$ is a vector containing the targeted musical intervals built according to a perfect heptatonic tuning system, and $+$ denotes the symbol for the MoorePenrose pseudoinverse [16]. The application of Eq. (2) to our frequency data results in a reference pitch of $f_0 = 248.1$ Hz, which is 30 cents lower than the reference value given by Tracey.



(a) (b)

Figure 11: Tuning analysis of the laboratory timbila. Left: internal frequency ratios for the first three bending modes. Right: musical intervals between successive bars.

7 Conclusions

In this paper, we developed a non-destructive characterization technique in order to assess the geometrical and acoustical features of timbila wooden xylophones. Based on 3D scanning measurements of the bars, the technique provides a systematic and detailed analysis of their geometry from which we can infer some relevant musical properties of the instrument. A specific slicing algorithm was developed for contour extraction of the bar cross-sections and successfully implemented in order to highlight and precisely quantify the design of the undercut that is highly relevant for tuning. Combining the 3D scanner data with FE modeling and vibration analysis techniques, we also assessed the proper tuning of each bar, analysed the musical scale of the instrument and identified its reference pitch. By comparison with experimentally identified modal data, the developed approach proved to be accurate on predicting the modal frequency of the most important musical (bending) modes, but improvements in the FE model are needed for good prediction of the torsional modes since a very crude isotropic model for the wood is used in the modal computations. Although here applied to timbilas, the technique can be applied to any percussion bar instruments. Future works will aim at improving such FE model and at developing a physics-based modal synthesis model for timbilas, including all the important components and interaction involved in musical performance, namely the mallet, the bars and the gourd resonators. Other important part of future work will be the application of the proposed methodology to the collection of historical timbilas of the National Museum of Ethnology of Lisbon in order to virtually share such unique collection and promote timbila music and traditional construction process.

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