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Numerical approach for the tuning of tubes in musical instruments

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Numerical approach for the tuning of tubes in musical instruments

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Abstract. Musical instrument design is still a relatively complex task. It frequently relies on empirical and oversimplified analytical approaches. The current computation era may be coupled with these processes to generate easy using tools to aid the design and creation of musical instrument. This study uses numerical routines, based on the modal analysis of simple geometries employed in musical instruments, as a tool to help the intended instrument design. Aluminum tubes, with flexural vibrations designed to resonate in a C4 register were first tested by experimental modal analysis and these results were used as reference to validate the referred numerical approach. Overall, it is shown that the numerical results highly replicate the experimental results and may be further optimized to display an even better correlation. It is, therefore, concluded that this type of computational method may be a fast and easy tool for the tuning of musical instruments.

1. Introduction

Musical instrument design is still nowadays a complex process, being frequently associated with highly empirical knowledge and analytical approaches [1].

For instance, musical instruments such as idiophones are subjected complex vibro-acoustic phenomena dependent on material interaction, instrument design and type of excitation [2]. It is, therefore, difficult to find an analytical relation that is able to portray all these multi-physical issues.

Current computation and engineering provide researchers with powerful tools to represent physical phenomena in virtual scenarios, including musical instrument vibratory and acoustical behaviour [3]. For instance, the frequency response of a structure that represents a part or a complete musical instrument may, in some cases,be simulated using finite element analysis, if the correct boundary conditions and system properties are provided [4].

Thus, it is fundamental that these numerical techniques are coupled with modern and traditional musical instrument design and tuning, allowing a very flexible tool to simulate numerous scenarios in a manageable interval of time.

Based on this premise, this study displays the analysis of vibrating metal tubes, designed to resonate in a C4 register, that are subjected to a numerical modal analysis to determine the validity of this method as a tool for the tuning of this type of samples.

2. Materials and methods

2.1 Detail of tube samples

The focus of this study was the detailed analysis of an aluminium (AA6060) tube designed to have its 1st flexural vibratory modal frequency at 261.63 Hz corresponding to the C4 register [5]. Table 1 describes the overall geometrical, physical and elastic properties of the samples.

Table 1. Detail of tube samples.

Detail	Value
External diameter (mm)	22
Internal diameter (mm)	19
Length (mm)	699
Density (Kg/m^3)	2720
Young’s modulus (GPa)	68.9
Poisson’s ratio (-)	0.33

2.2 Experimental modal analysis

Figure 1 (a) illustrates the experimental apparatus that was used to perform the modal analysis to the tube samples. These tubes were excited with a mechanical approach, using an impact hammer (PCB Modally Tuned, Figure 1 (b)), while their vibration response was monitored by a Laser Döppler Vibrometer (Polytec OFV-5000). This response was measured in 19 points (Figure 1 (c)), where P1 is located in the vicinity of the tube extremity (5 mm), while the remaining points (P1 to P19) are equidistantly distributed in 40 mm intervals along the tube length. The tube was supported by two elastic (nylon ribbons) threads in the two nodal points of the 1st flexural global vibratory mode. To avoid external result tampering effects, these tests were performed inside an anechoic chamber with temperature and relative humidity ranges of, respectively, 18ºC-23ºC and 49%-58%. Overall, five samples were tested using this apparatus.

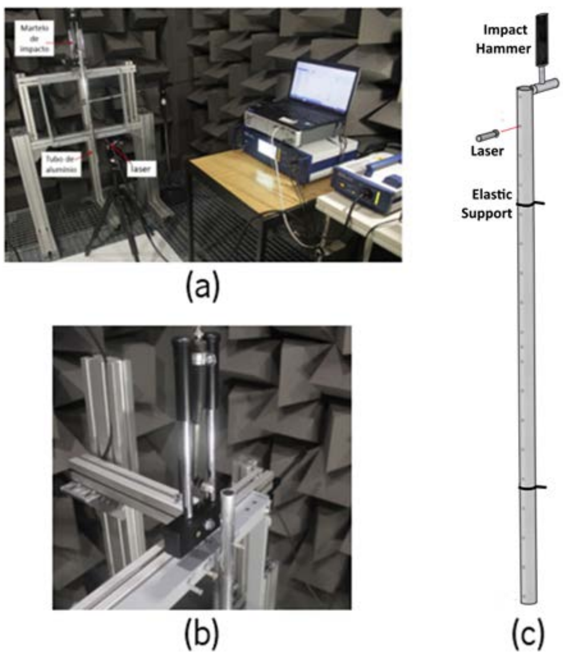


Figure 1. Experimental apparatus: (a) general assembly, (b) detail of impact hammer and (c) measurement points.

Sample vibration response was performed by the monitoring of displacement velocity in the referred points ans recorded by a Spectral Analyser (LMS Scadas Mobile). Velocity signals were used as input data, whose interpretation was performed using the software TestXpress V10 to determine eigenmodes and eigenfrequencies. The Dynamic Young's modulus of the samples was based on the classic Euler-Bernoulli beam theory [6], using Equation 1.

$$E = \left[\frac{\omega_n}{(\beta_n l)^2}\right]^2 \left(\frac{\rho A}{I_z}\right) l^4 \tag{1}$$

2.3 Numerical modal analysis

The numerical approach was performed by applying the Modal Analysis module of the software ANSYS 17.0. Samples were modeled using the Design Modeler tool of the same software. Base materials were defined as Hookean (i.e. linear elastic), uniform and isotropic with the properties defined in Table 1. Boundary conditions were defined as free, as the analysis is supposed to represent free-vibration conditions, and a Sparse Direct Equation Solver was used to calculate the results. The default modal analysis suggested a coarse mesh (Figure 2 (a)), thus Edge Sizing (12 sub-divisions) and Size (0.75 mm) were defined to optimize mesh discretization with SOLID186 elements (Figure 2 (b)).

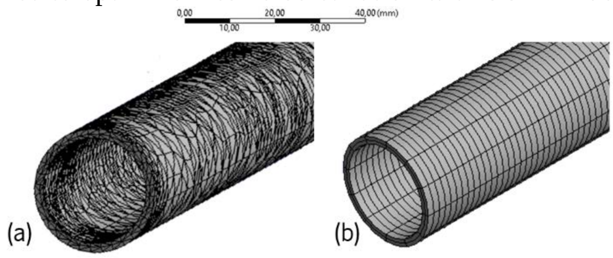


Figure 2. Mesh detail: (a) default coarse and (b) refined.

3. Results and Discussion

3.1 Experimental modal analysis

Figure 3 displays the overall experimental vibration response (P1 to P19) in the tested samples by showing their frequency response function (FRF).

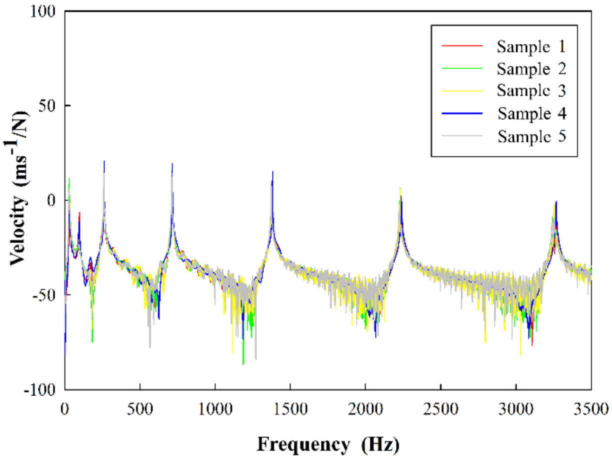
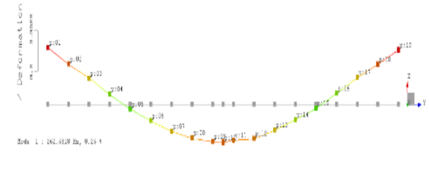
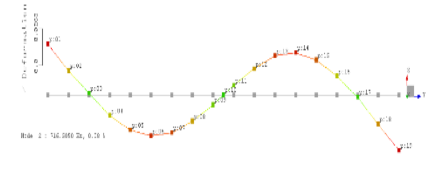
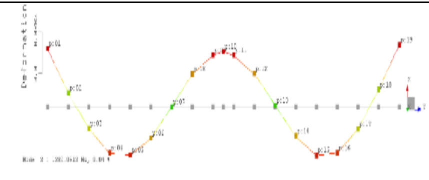
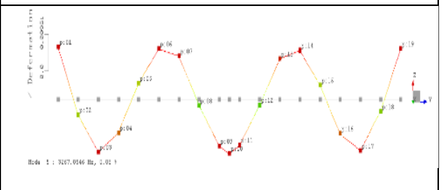


Figure 3. FRF of the tested samples.

Table 2 presents the eigenfrequencies and eigenmode shapes for the tested samples from the analysis of the FRF of Figure 3. Recurring to this data, it is possible to correlate the shapes that the samples are vibrating in each eigenfrequency.

Table 2. Experimental eigenfrequencies and eigenmodes.

Eigenfrequency	Eigenmode shape
261.5±0.9 Hz	
714.2±1.6 Hz	
1372.1±1.7 Hz	
2231.2±4.6 Hz	
3259.4±6.7 Hz	

The results reveal that the average value for the first eigenfrequency is 261.5 Hz, being very close to the fundamental frequency for a C4 register (261.63 Hz). An analysis on this difference, considering its effect in a human ear perception point of view, it is determined that it is not significant for the overall register of the tube.
The experimental results (Figure 3) were also used to determine the frequency dependent (i.e. dynamic) Young's modulus (Equation 1). These values are represented in Table 3.
The experimental results show that there is a considerable variation in the Dynamic Young's Modulus of the samples with the increase in frequency. It is observed that the real stiffness of the samples tends to decrease with the increase in frequency. In fact, this has already been found for other materials such as porous ceramics, perlite and rocks [7-9]. It may be, however, easily understood that these matters are more relevant when this changes the behaviour of the application such as in musical instruments.

Table 3. Experimental eigenfrequencies and eigenmodes.

Eigenmode	Eigenfrequency	Young's Modulus
1	261.5±0.9 Hz	66.8±0.4 GPa
2	714.2±1.6 Hz	65.9±0.3 GPa
3	1372.1±1.7 Hz	63.6±0.2 GPa
4	2231.2±4.6 Hz	60.9±0.3 GPa

5	3259.4±6.7 Hz	58.3±0.2 GPa

3.2 Numerical modal analysis

Table 4 shows a comparison between the experimental and numerical results. The numerical results display a slight deviation (Δmax=0.5%) that may be attributed to small dimensional/geometric deviations in the samples and small anisotropy in the base material processing.

It has been found that these results, however, may be enhanced with a small correction of the Young's Modulus to 68.5 GPa. Table 5 shows the results for the corrected sample stiffness

Table 4. Numerical eigenfrequencies and deviations.

Eigenmode	Eigenfrequency	Deviation
1	261.3 Hz	0.5 %
2	712.1 Hz	0.3 %
3	1373.4 Hz	0.1 %
4	2223.2 Hz	0.3 %
5	3239.2 Hz	0.2 %

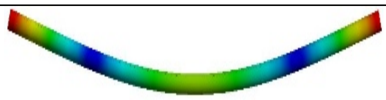
Table 5. Corrected numerical eigenfrequencies and deviations.

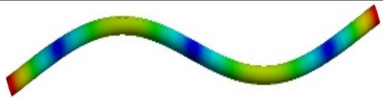
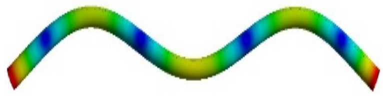
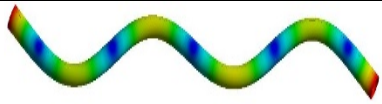
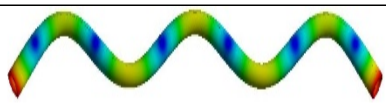
Eigenmode	Eigenfrequency	Deviation
1	262.5 Hz	0.0 %
2	715.6 Hz	-0.2 %
3	1380.2 Hz	-0.6 %
4	2234.7 Hz	-0.2 %
5	3256.7 Hz	0.1 %

This way, a perfect correlation may be obtained between the experimental and numerical results for the first eigenfrequency, which, in some instruments, is the preponderant in a musical context. In other metallic idiophones, for instance in tubular bells, it is not the first eigenmode that determines the perceived pitch of the instrument [10]. Instead, it is the ratio between the eigenfrequencies of several modes. Other numerical methods, using optimization techniques, have proved successful in tuning the shape of musical instrument components to reach a specific set of eigenfrequencies ratios [11, 12]. These techniques can also be used not only for vibratory components but also for acoustic elements, such as the resonators used in marimbas and vibraphones [13] of bass-traps for room acoustics [14].

The shapes of the numerical eigenmodes may be visualized in Table 6. By their direct comparison with the shapes in Table 2, it is determined that they display the same shape has the experimental approach.

Table 6. Shapes obtained by the numerical approach.

Eigenmode	Shape
1	

2	
3	
4	
5	

4. Conclusions

This study proposes a numerical approach to optimize the routine of tube tuning for musical instruments, combining classic experimental approaches with numerical routines using the finite element method.

Experimental modal analysis is performed in aluminium tubes that are designed to resonate in a C4 (262.63 Hz) register. It is shown that the experimental approach reveals resonant eigenfrequencies in the first (predominant) mode that are very close to the intended value. The overall elastic behaviour of the tubes, however, is more complex has the frequency increases.

A virtual model that represents the tested samples was modelled in ANSYS 17.0 and numerical modal analysis was performed to determine if this would be a promising routine for the intended tuning purpose. It is shown that the results of the numerical routine display small variations relatively to the experimental results. These deviations, however, while being very small, may be optimized, allowing the process to obtain a perfect correlation, at least for some eigenfrequencies. In conclusion, the proposed process is validated, and the numerical approach is reinforced as a solution for fast and easy tuning processes in this type of samples.

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