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# CREATION OF AN EXPERIMENTAL DATABASE, FOR THE VALIDATION OF RESONATOR MODELS, COMPARISON OF GEOMETRIES AND MATERIALS, AND QUANTIFICATION OF MEASUREMENT ERRORS

**Jérémy CABARET**[1] **Jean-Pierre DALMONT**[2] **Augustin ERNOULT**[3]
**Vincent FRÉOUR**[4] **Romain VIALA**[1*,2]
[1] ITEMM, 71 avenue Olivier MESSIAEN, 72000 Le Mans, France
[2] Laboratoire d'Acoustique de l'Université du Mans
UMR CNRS 6613, Le Mans Université, 72085 Le Mans, France
[3] Makutu team, Inria centre at the university of Bordeaux
200 avenue de la vieille Tour, 33405 Talence, France
[4] YAMAHA Corporation, Research and Development Division, 10-1
Nakazawacho, Hamamatsu, 430-8650 Shizuoka,

## ABSTRACT

With an objective of providing wind instrument makers with design and simulation tools, many methods for both characterization and simulation of the behavior of acoustic properties have been developed. Some of these tools are made available to makers via softwares and devices. In parallel with a benchmark of numerical approaches for their verification detailed in a companion paper, an experimental campaign is presented here in order to create a reference database for the validation of models, and to estimate the uncertainties associated with the input impedance measurements. In particular, the random inter / intra sample uncertainty is quantified. The experimental campaign is based on batches of five specimens each of tubes and cones. The experimental plan allows to obtain consolidated experimental results concerning materials and making processes. The specimens produced are tested in different laboratories with varying characterization methods. The campaigns that took place defined a measurement protocol and evaluated biases and irreducible uncertainties. These measurements give first estimates of the variability of the results and provide precision thresholds of modifications to be significantly measured. Generally, for a batch of five specimens made with the same process, the orders of magnitude for the coefficient of variation is equal to 5 cents and 5 dB.

**Keywords:** *Wind instruments, Impedance, Benchmark, Verification and validation*

## 1. INTRODUCTION

Musical instrument bores are essential components in wind instruments such as flutes, clarinets, saxophones, trumpets, etc. The input impedance of the bores is an important parameter that characterizes its acoustical behavior, and is associated with playability and acoustic features. In the context of dedicated tools to instrument makers, affordable devices to measure input impedance are in development. In order to evaluate the specifications of such devices in terms of precision, the uncertainties associated with the objects usually measured and the current precision of reference devices is yet to be quantified. Moreover, simulation tools are also developed for instrument makers, and the numerical models are currently verified in a verification and validation process. Verification and validation (V&V) refers to

*Corresponding author: romain.viala@itemm.fr.

the process of ensuring that a model or simulation is implemented correctly and accurately represents the underlying physics or phenomenon. Validation, on the other hand, refers to the process of ensuring that a model or simulation accurately represents the real-world system it is meant to describe. [1] discusses the importance of both verification and validation in scientific computing, and emphasizes the role of benchmarking in both processes. Along with the verification approach, the presented uncertainty quantification will also be used as a support for the validation of the models and to evaluate potential epistemic errors. To address both topics, we present an experimental benchmark of specimens whose input impedance are measured to evaluate the actual dispersion of results. The study examines both intra- and inter-variability in the measurement of input impedance, with the goal of providing insights into the V&V process for measuring acoustical parameters in musical acoustic. In the next section, we describe the materials and methods used in the study, including the experimental setup, data collection, and data analysis procedures. We discuss the implications of our findings for the V&V process in musical acoustics, and the importance of precision in the design and evaluation of musical instruments.

## 2. MATERIAL AND METHODS

Each sample is composed of five tubes of 180 mm length as a target value. The tubes were designed to exhibit dimensions similar to the usual bore of some parts of wind instruments. The three materials chosen for the experiments are brass, wood and Acrylonitrile Butadiene Styren (ABS), a usual polymer used for 3D printing. The Table 1 describes the details of the different batch of tubes. Moreover, the geometrical parameters are obtained with a ruler for the length, a caliper for the external diameter, and a telescopic gauge and caliper for the internal diameter. The resolutions are 0.5 mm for the ruler and 0.1 mm for the caliper.

The presented data come from different operators from four different laboratories and different measurement devices, labeled as operators 1 2 3 and 4. Nevertheless, three devices were similar and produced by the CTTM at Le Mans [2] for operators 2, 3 and 4. The device for operator 1 is designed in its own laboratory. The tubes are attached to the impedance measuring device (impedance head) with connection printed in polylactic acid (operator 1) or thermoplastic polyurethane (TPU) for operators 2 3 and 4. One can notice that for a given specimen, the result of the impedance measurement depends on the waterproofness at the contact between the impedance head and the specimen. To avoid leak, we usually use cork grease (for wind instruments) on the top of the device. Also, the connection piece is made to make the replacement of the different tubes easier.

The temperature and relative humidity have been measured to apply correction on the speed of sound in the post processing step. The frequency axis is scaled to correspond to a dry air at 25°C [3]. Operators 2,3 and 4 used a frequency sweep from 20 Hz to 5 kHz and operator 1 from 50 Hz to 10 kHz to measure the amplitude of the input impedance of the tubes at different frequencies. For a batch of five tubes, the measurements have been repeated five times for a given tube to estimate the intra specimen variability (labeled as intra thereafter) for a given tube. Then, the four remaining tubes have been measured to estimate the inter specimens variability (labeled as inter). Each batch has been measured this way for closed-closed and closed-opened boundary conditions The experimental results are post processed to quantify the discrepancy between the amplitude of the module of the impedance measured and the one predicted by a model based on transfer matrix method, as proposed in [4, 5]. Therefore, the intra and inter specimen variability is quantified for both amplitude of the impedance module and resonance frequencies of the closed-closed and closed-opened tubes.

## 3. RESULTS AND DISCUSSION

The dimensions of each batch are given in table 2.

The mean of each dimension is given for each type of sample. The standard deviation is given to estimate the variability of the length, diameter of the bore and thickness. The standard deviation of the length measured with a rule is comprised between 0 and 0.5 mm. The standard deviation of the diameter measured with bore gauges is comprised between 0.03 (for ABS and brass) and 0.08 mm for wood. The standard deviation of the thickness measured with caliper is comprised between 0.06 mm (for ABS) and 0.15 mm for brass, which exhibits highest variability, despite being a manufactured product. It is interesting to note that 3D printed tubes exhibit the best repeatability, compared with wood turned on a lathe and brass tube provided by manufacture. The figure 1 displays the frequency deviation at resonance for brass

**Table 1**. Description of samples with target values. Each sample contains five tubes of 180 mm length

| Case | Description |
|---|---|
| Brass C | Brass tube, 7 mm inner radius, 2 mm thickness, closed end |
| Brass O | Brass tube, 7 mm inner radius, 2 mm thickness, open end |
| Wood C | Boxwood tube, 7 mm inner radius, 7 mm thickness, closed end |
| Wood O | Boxwood tube, 7 mm inner radius, 7 mm thickness, open end |
| 3D C | Z-ABS printed tube, 7 mm inner radius, 7 mm thickness, closed end |
| 3D O | Z-ABS printed tube, 7 mm inner radius, 7 mm thickness, open end |

**Table 2**. Mean (μ) and standard deviation (SD) of length (L.), inner diameter (D.) and thickness (Th.) for each sample of five tubes.

| Case | L. μ (mm) | L. SD (mm) | D. μ (mm) | D. SD (mm) | Th. μ (mm) | Th. SD (mm) |
|---|---|---|---|---|---|---|
| Brass C | 180.0 | 0.0 | 13.92 | 0.03 | 2.16 | 0.15 |
| Wood C | 179.8 | 0.5 | 14.00 | 0.08 | 6.5 | 0.1 |
| 3D | 179.7 | 0.25 | 14.03 | 0.03 | 6.59 | 0.06 |

samples in closed-closed conditions, respectively.

The deviations are similar for both intra and inter evaluations, as expected. It is also interesting to note that generally, the intra variability is lower than the inter variability, but in some cases, the values are similar, suggesting that the experiment variability for one sample can be close to the variability between different samples. This highlights the importance of the measurement protocol for such studies. The results also show an important fact : the variability between operators and / or devices (it is not possible to discriminate at this point) is higher than the variability between samples. This can be explained by either different devices or different measurement means. More specifically, this can also be attributed to the calibration of the devices, which remained constant for all the measurement process. The figure 2 displays the deviation from the theoretical model. The squares or circles refer to the mean and upper and lower whiskers to the standard deviation of all the resonance peaks from 50 Hz to 5 kHz, for each sample of five specimens.

Considering the deviation of the frequency, for most cases and operators, the mean of the deviation falls between plus and minus 5 cents, which is close to 0.3 % in relative frequency, near the detection threshold. Nevertheless, the variability at one standard deviation of a sample is comprised between 3 cents and up to 20 cents. The results demonstrate the importance of accurate measurement of the input impedance of musical instrument tubes and the need to consider the actual dispersion of the results in the design and evaluation of musical instruments, especially for the development of dedicated resonance models. The verification and comparison of such models is the object of the companion paper [6].

## 4. CONCLUSION

In this paper, we presented an experimental benchmark of tubes used to measure their input impedance and to evaluate the actual dispersion of results. The results demonstrate the importance of the evaluation of the variability and the impact of the operator or the device on the quantification of the input impedance of samples. The experimental setup and the methodology presented in this paper can be used to benchmark and compare different types of specimens and to evaluate their acoustical properties. Moreover, the specimens can be sent interested teams that would like to compare their measurement methods / devices or operators and therefore enlarge the overview of the actual diversity of methods. The results of this study highlight the importance of considering both intra- and inter-variability when measuring the input impedance of

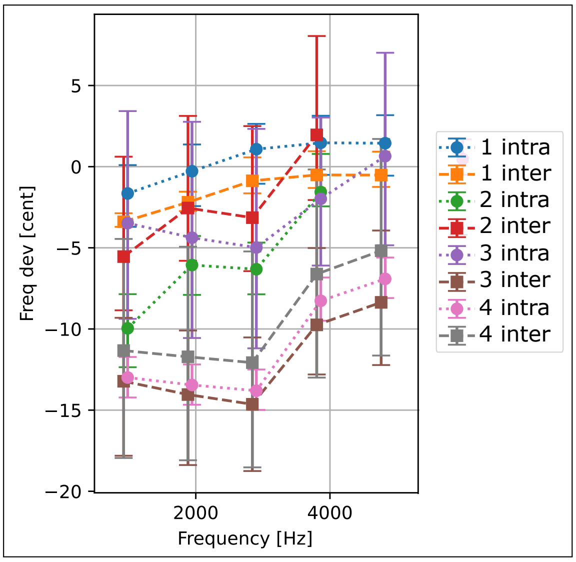


**Figure 1**. Frequency deviation at resonance for brass closed-closed tubes sample

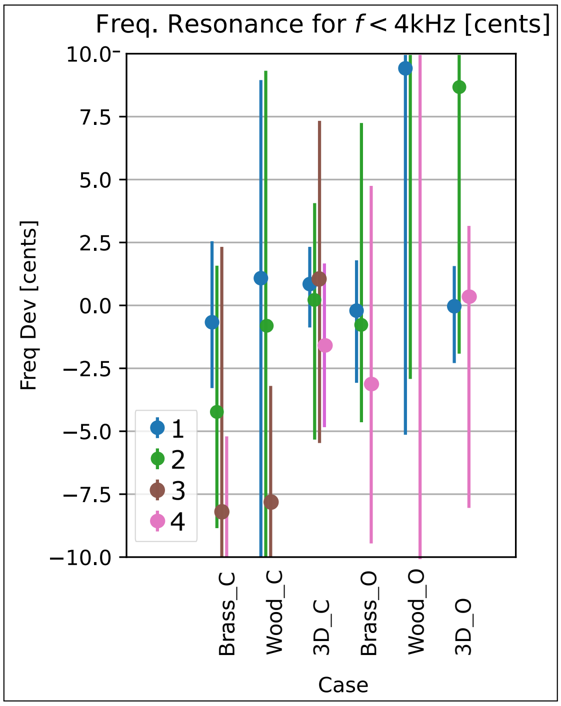


**Figure 2**. Deviation of the frequency at resonance

musical instrument tubes. The intra-variability observed emphasizes the need for careful and repeated measurements to ensure accurate and reliable results, even if this seems not sufficient since even for low variability for an operator, its results may differ strongly with another operator which also shows low variability. The dispersion of the results within each tube, suggests that a larger number of measurements may be necessary to capture the full range of variation. This is especially important for designing and evaluating musical instruments, where small variations in input impedance are supposed to have a significant impact on the appreciation of the musician. The inter-variability observed in our study suggests that different tubes can exhibit significantly different input impedances, even when they have similar physical dimensions and are made from the same material and the same process or by the same maker. It suggests that a larger sample size may be necessary to capture the full range of variation across different specimens. The experimental setup and methodology presented in this paper can be used to benchmark and compare different types of specimens. The objectives of this collaborative work is to reach a consensus on the models and assumptions to adopt to measure and simulate the impedance of wind instruments in a context of instrument making, and also to give a reference for the sensitivity of an affordable device in development for instrument makers.

## 5. REFERENCES


[1] W. Oberkampf and C. Roy, *Verification and Validation in Scientific Computing*. January 2010.

[2] J.-C. L. Roux, M. Pachebat, and J.-P. Dalmont, “Un capteur de nouvelle génération pour la mesure d’impédance acoustique en contexte industriel,” *Acoustique et Techniques : trimestriel d’information des professionnels de l’acoustique*, vol. 68, 2012, hal-00834134.

[3] A. Ernoult, “Effect of air humidity and carbon dioxide in the sound propagation for the modeling of wind musical instruments,” Tech. Rep. RR-9500, Inria, Feb. 2023.

[4] R. Tournemenne and J. Chabassier, “A comparison of a one-dimensional finite element method and the transfer matrix method for the computation of wind music instrument impedance,” *Acta Acustica united with Acustica*, vol. 5, 2019.

[5] A. Chaigne and J. Kergomard, *Acoustics of musical instruments*. Springer: Modern Acoustics and Signal Processing, 2016.

[6] A. Ernoult, H. Boutin, J. Chabassier, T. Colinot, J.-P. Dalmont, J.-B. Doc, B. Fabre, V. Fréour, F. Silva, and R. Viala, "Collaborative benchmark study of models for impedance simulation of wind instruments.," in *Proc. of the Forum Acusticum 2023*, (Turin, Italy), 2023.