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EVALUATING THE REPRODUCIBILITY OF IMPEDANCE MEASUREMENTS OF WIND INSTRUMENTS

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ABSTRACT

Input impedance is a physical quantity that allows the objective characterization of wind instruments. It is now a common measurement in research labs and wind instrument factories. To be relevant, these measurements must achieve a precision higher than what a musician can detect. Although the sensitivity of musicians to slight impedance variations is not known, it is important to have an idea of the precision of impedance measurements in realistic situations. In order to evaluate the accuracy and different type of variability (e.g.: intra- and inter-operator) of impedance measurements and to identify key sources of error in the process, a collaborative study has been conducted involving multiple operators using the experimental setups developed by the CTTM. Measurements were performed on simple pipe geometries, including cylindrical, with a focus on boundary conditions, material properties, and calibration procedures. Variability in experimental results is linked to the calibration steps, the pipes manipulation, and challenges with wall surfaces, particularly in wooden pipes. The study also revealed significant inter-operator variability and emphasizes the importance of rigorous calibration procedures and standardized measurement practices. These findings provide actionable insights for enhancing the reliability of experimental methods and support further research into more complex and realistic geometries.

Keywords: *wind instrument, input acoustic impedance, metrology.*

1. INTRODUCTION

Input impedance measurements of wind instruments are now commonly used tools in research laboratories and wind instrument manufacturing companies [1-3]. This tool can be used both during the prototyping phase of an instrument and for manufacturing control. However, the question of the accuracy that can be expected from such tools has rarely been asked. The objective of this work is therefore to provide quantitative elements on this accuracy and compare it with the accuracy that can be achieved in machining. This work focuses on the sensor developed jointly by LAUM and CTTM (now Almacoustic) [4].
To assess measurement uncertainty, standards are required. These standards are cylindrical tubes for which the errors related to the theoretical model are significantly lower than the uncertainties expected with the measurement. A number of tubes were manufactured in different materials and in multiple copies. Different operators with different sensors measured the different tubes several times, which allowed the repeatability uncertainty of each operator to be assessed,

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as well as the uncertainties related to the operators. Sample variability could also be assessed and compared with the measurement uncertainties.

2. THE SAMPLE PANEL

Tubes in different materials have been fabricated with a target length of 180mm and a target inner diameter of 14mm. Each sample consists of five specimens, so that measurements can be compared with simulations, taking into account manufacturing uncertainties. The three materials chosen for the cylinders are brass, boxwood, and Acrylonitrile Butadiene Styrene (ABS), a common polymer used in 3D printing.
After manufacturing, the actual geometrical parameters are measured with a ruler for the length and a telescopic gauge and caliper for the internal diameter (the wall thickness being deduced from internal and external diameters). The mean μ and standard deviation σ_{tot} of each dimension is given for each type of sample in Table 1. The standard deviations are estimated from the measurement tools resolutions (0.5 mm for the ruler and 0.1 mm for the caliper) and the measured variability. The same pipes are used for the open (O) and closed (C) conditions, using 3D-printed caps for the closed conditions and grease for the airtightness.

Table 1 Samples dimensions

Material	**Length** (mm)	**Diameter** (mm)
Brass	180.0 ± 0.3	13.92 ± 0.03
Wood	179.9 ± 0.65	13.97 ± 0.07
ABS	179.85 ± 0.3	14.03 ± 0.09

From Table 1, it appears that the brass tube sample is the most uniform. The boxwood sample, made by hand, has the largest length deviation, and the 3D printed samples have the largest wall thickness variation. The temperature (°C) and relative humidity (%) have been also measured to apply corrections on the speed of sound in the post processing step. The scientific sensors have generally a great precision (0.1°C and 1%), however due to possible air heterogeneity between the measured point and the air inside the tube the uncertainty on the speed of sound may remain large and might lead to rather large deviation between experiments made in different conditions.

3. MEASUREMENTS

The Measurements have been performed with impedance sensors produced by the CTTM [4]. This device necessitates one calibration step (measurement of a cap with an "infinite" impedance) and has a 16 mm output diameter. Logarithmic sine sweep which frequency range was 100-4000 Hz. Most of operators (2 to 4) attached the tubes to the impedance head with a connector printed in flexible material (thermoplastic polyurethane, TPU) to facilitate their alignment and to deal with small external diameter variations between specimens. Operator 5 preferred to place the tube by hand. The quality of the impedance measurement strongly depending on the air tightness at the contact between the impedance head and the sample, cork grease (for Wind instruments) has been used at this junction (or clay for O5). For a batch of five tubes, the measurements have been repeated five times for a given tube, the first one, to estimate the intra specimen variability for a given tube. Then, the four remaining tubes have been measured to estimate the inter specimen variability. Each batch has been measured this way for closed-closed and closed-opened boundary conditions. The complete protocol being time consuming, some experimenters have focused on some configurations (at least closed cylinders), but by measuring all the requested repetitions (intra + inter = 9). It is specified that operator 4 didn't measure the tube in the open configuration. Each operator was free to redo some measurements using his/her own criteria.

4. RESULTS

In this section, the reference values used to display the observables are taken from the calculation of the analytical solution for the closed cylinder [5-6]. All these simulations have been calculated for the average geometry of each sample (Table 1).
Both sound velocity and air density depend on air temperature *T* and relative humidity *RH*. This dependence affects the magnitude of the impedance and shifts the frequency axis. The calibration steps naturally scale the obtained data by the lossless characteristic impedance Z_c, removing the main magnitude dependence. However, in order to compare the data, it is necessary to correct the effect on the frequency axis, by applying to frequency a correction factor $c_{25}/c_{T,RH}$ where c_{25} is the speed of sound in dry air at 25°C and $c_{T,RH}$ is the speed of sound during the measurement taking into account temperature value and relative humidity.
Frequency and amplitude deviations from theory of first four maxima and minima of the input impedance are

analyzed. The deviations are expressed in cents for the frequencies, that is $1200\log_2(f_{meas}/f_{theo})$, and in dB for the amplitude, that is $20\log_{10}(Z_{meas}/Z_{theo})$.

4.1 Measurements of a single brass tube

In this section the modal characteristics of a single closed brass tube are analysed. Results are shown in Figure 1. For each operator and each configuration, the standard deviation of each observable is computed along the five measurements on the same specimen. These deviations do not seem to be related to the absolute frequency of the peak. For most operators, the deviations are even similar for all "resonances" (max amplitude) and for all "anti-resonances" (min amplitude). This suggest that deviation are related to small temperature or geometrical variations.

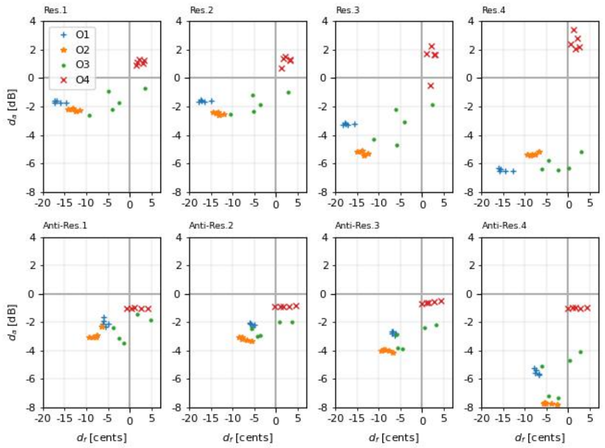

Figure 1. Deviation to the reference values of the frequency (d_f in cents) and magnitude (d_a in dB) of the 4 resonances and 4 anti-resonances, for the 5 repeated measurement of a given closed Brass cylinders. Each operator is associated to a marker shape and a color.

A result is that intra operator (same operator) deviations are much lower than inter operator deviations. Indeed, the standard deviation for all peaks and dips is less than 2 cents for operators 1, 2 and 4 and less than 4 cents for operator 3 for frequency and for amplitude it is 0.3 dB pour operator 1 et 2, 1 dB pour operator 4 et 1.5dB pour op. 3. This corresponds to the value obtained in previous studies [1-3]. The deviations between operators are much larger since it is around 10 cents in frequency and 2 dB in amplitude. The large difference for the amplitude is probably due to the difficulty to ensure a perfect closure of the tube since it is observed that the deviations are lower when the tube is open (1dB).

The origin of the inter-operator deviations is difficult to pinpoint. It can be due to a biased estimation of the temperature in the tube, a different placement of the sample on the sensor or differences between sensors. In practice to explain a 10 cents deviation a 3°C error on the temperature or a 1mm error on the tube length are needed. This deviation could also come from a deviation between sensors. To test this hypothesis, an operator measured the same pipe with five different sensors. This experiment being carried out a posteriori, a different tube has been used (about 1 m long and a 20 mm inner diameter). The obtained standard deviation between the sensors is about 3 cents and 0.5 dB. This is similar to the intra-specimen variability which suggests that the difference between the sensors cannot alone explain the inter-operator variability. The inter-operator variability is certainly due to the conjunction of multiples factors.

4.2 Measurements of various tubes

In order to compare the variability linked to manufacturing processes and the uncertainties of impedance measurement various tube have machined and their impedance measured (see table 1). It appears that the inter-specimen deviations are in the range or larger than the intra-operator variability. For 3D printed and brass tubes deviations in frequency cannot be assessed while for wooden tube significant deviation can be detected. Also, significant amplitude deviations can be detected for the wooden and 3D printed tubes. This validates the fact that the impedance measurement is capable of detecting small machining variations. However, this is only possible if measurements are performed by the same operator in the same experimental conditions.

Table 2 Median value over all operators of the inter-specimen standard deviation (open tubes)

Standard deviation	Brass	3D	Wood
Frequency (cents)	3	4	8
Amplitude (dB)	0.2	0.5	1.3

5. CONCLUSION

It appears that input impedance measurements – at least with the sensor we used - allow the determination of eigenfrequencies with a relative accuracy of about 3 cents on frequency and 0.5 dB on amplitude. This means that it is possible to detect differences between two instruments as small as this provided that both instruments are measured under the same conditions. Measurements with different sensors and different operators suggest that below 10 cents and 1 dB it would be doubtful to conclude that the deviations betray a significant difference between the measured instruments. It can be estimated that the absolute accuracy of the measurements is of this same order of magnitude as long as the measured impedances are adapted to the sensor used. Here, the sensor has an input diameter of 16 mm and the measured tubes have a diameter of 14 mm. In the case of significantly narrower or wider tubes, the absolute errors will a priori be larger.

In another work, the sensor will be used to evaluate the accuracy obtained on the input impedance calculated from numerical models. It should be possible to assess if models can reach an accuracy of less than 5 cents on eigenfrequencies.

A question remains open: to what extent is a musician able to detect a difference between two similar instruments? This question has been little explored [2, 3] and the answer to this question will obviously depend on the instrument considered. We find an example in reference [2]: on saxophone necks, measurements were able to unambiguously highlight differences of the order of 8 cents on the first eigenfrequency. For his part, the musician tester was able to distinguish without difficulty the necks which had the lowest frequencies. Are musicians able to be more accurate than impedance measurements? The question remains open.

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