

# Acoustic Impedance Probe for Oboes, Bassoons, and Similar Narrow-bored Wind Instruments

Dustin Eddy

*Erich Thienhaus Institut - HfM Detmold, 32756 Detmold, Deutschland, Email: dueddy7@gmail.com*

## Introduction

Acoustic impedance measurements are extremely useful in assessing how musical instruments are prone to resonate independent of human excitations. These air column resonances largely determine the intonation and sound characteristics of wind instruments [1]. And developing a consistent measurement setup allows us to compare existing instruments and to investigate aspects of the musician-instrument interaction.

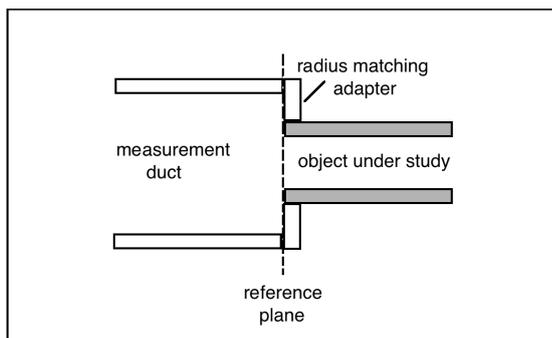
When measuring acoustic impedances of air ducts, one must typically define a reference plane at which to measure. If then there exists an abrupt change in the diameters of the measurement device and the object under study (OUS) as shown in figure 1, size adaptors must be used which introduce irreversible effects that exceed limitations of a plane wave model [2]. This is problematic for musical instruments with narrow-bored tubes at their entrance, such as oboes and bassoons, since there are currently no available impedance probes specifically tailored to them.

In our work, we utilize previous theory and findings to create a practical tool for measurement purposes tailored specifically for oboes and bassoons that is more accurate at broader frequency ranges than typical impedance probes found today for these applications.

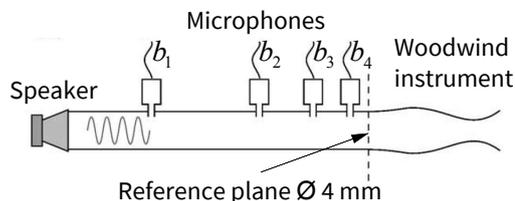
## Method

From reviewing previous literature and experimenting with different approaches, we developed a Four Microphone Four Calibration (FMFC) narrow tube impedance probe as illustrated in figure 2.

To construct the probe, a single Beyerdynamic DT 48 headphone driver was mounted to an air tight cone adapter leading to a heavy brass pipe 40 cm in length



**Figure 1:** Example of radius discontinuity at reference plane.



**Figure 2:** Four Microphone Four Calibration method setup. Modified picture taken from [5].

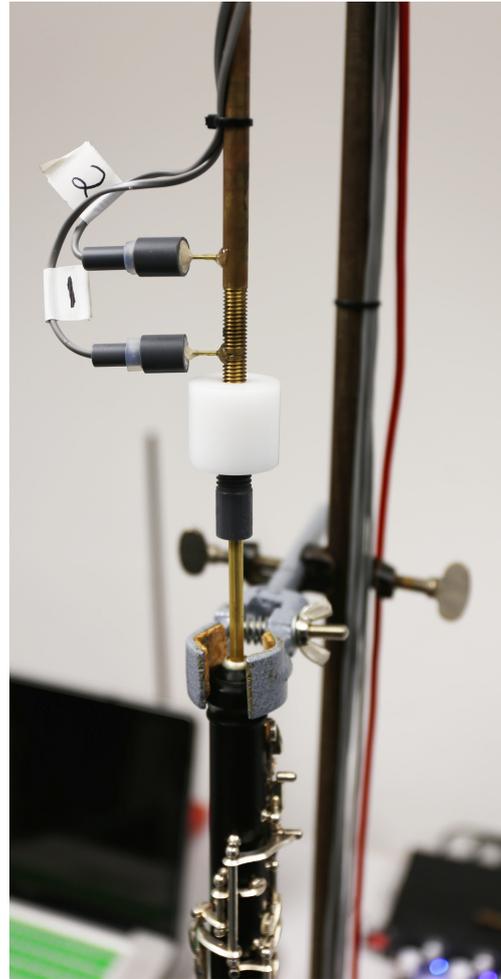
with an inner diameter of 4 mm, matching closely to the opening size of our OUS's. Four small holes were drilled at strategic positions attempting to avoid possible singularities in the measurement tube itself. After which four Sennheiser KE-4 microphone capsules were attached via air tight adaptors and capillary tubes that were then sealed to the measurement duct. The physical setup can be seen in figures 3 and 4. The adapter between the measurement duct and Oboe seen in figure 4 will be explained further in the Oboe – Measurements section.

Data acquisition and signal processing was accomplished with MATLAB using the ita toolbox [3]. For AD/DA conversion and speaker amplification, the RME UCX was used. Four external SM Pro Audio PR8E microphone amplifiers were used and calibrated to the same levels before measurement probe calibrations and measurements. A swept sign from 100 Hz to 5000 Hz with an fft degree of 17 was determined as our choice excitation signal for both the calibrations and following measurements. These calibrations cancel out any unwanted effects from the speaker, air cavity within the probe itself, and microphones, giving the acoustic impedance at the reference plane at the end of the probe.

This device is a slight adaptation from a previous Two Microphone Three Calibration (TMTC) method [4], and utilizes a set of resonance free calibrations [5]. We first attempted our measurements by calibrating with an older TMTC method using sets of calibration tubes of known lengths with a special spatial relation to each other around the reference plane. We confirmed this method to be impractical since it required multiple sets of calibration tubes covering different frequency ranges due to singularities, and the requirement of a cutting precision of 0.02 mm [2], [5]. The resonance free calibration loads consist theoretically of three types of prerequisites at the reference plane: An “infinitely long” tube to provide infinite resistance by having no reflections, a closed end, and an open end with an “infinitely large” flange. Practically speaking, the flange can be ignored without giving any significant error. Compared to the TMTC method



**Figure 3:** Full FMFC physical setup



**Figure 4:** Oboe adapter

of calibration, the resonance free method suggested by Dickens, Smith, and Wolfe [5] proved to be much more practical, covering a wide frequency range with one set of calibrations, and proved also to be highly accurate.

To achieve a reflection free “infinitely” long calibration, a 10 m coiled PVC tube of the same inner diameter as the probe was used and attached to the measurement head after long straight pipes of three varying lengths to average out any discrepancies in the small bumps in radii changes between physical attachments. It was found that allowing the “infinite” tube to coil had no effect on the results as opposed to drawing out the calibration coil straight. When accounting for wall losses that are much more relevant in such a small diameter tube, 10 m proved to be both experimentally and theoretically long enough to provide a virtually reflection free load for all frequencies down to about 70 Hz. Absorption material was also added to the open end of the coil for good measure. It is these three averaged “infinite” calibrations, along with a calibration that was left open at the reference plane that make up the four calibrations in our FMFC probe.

## Results – Validation

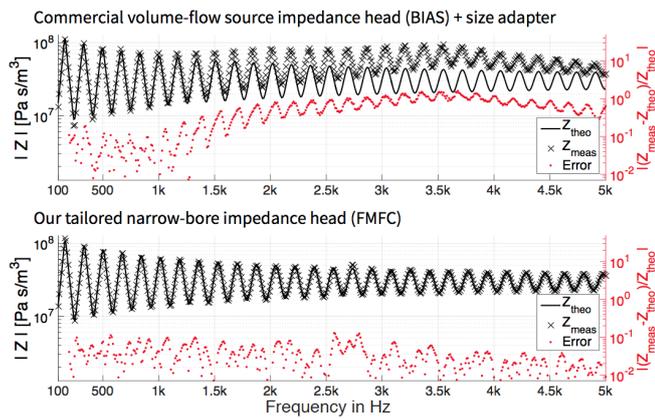
In order to validate our measurement setup after the calibrations, multiple measurements were made with simple

straight pipes of the same diameter and known lengths in both the open and closed states. These measurements were then compared directly to transmission line simulations to verify their accuracy. It should be noted that due to unexpected temperature changes in this validation measurement process, a temperature best-fit algorithm was used.

Additionally, we compared our validations with the commercially available BIAS system [6] using a radius matching adaptor.

Though we made validation measurements for pipes of 1 m, 60.1 cm, and 33.9 cm in both the open and closed states, only the results for the 1m validation are shown in figure 5, as they are indicative of the results for all validation measurements.

As seen in this validation plot, our tailored narrow-bore impedance head matches much closer to the simulated curves in a much higher frequency range than traditional commercial options with matching adapters. This is especially seen in frequencies above 1000 Hz where the wavelength of the frequencies become small compared to the adapting radii, and prone to distortions that are difficult to counter when there are propagating modes coupled to modes in the OUS [2].



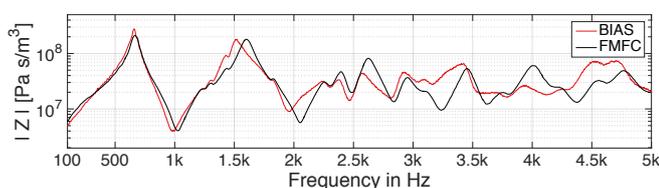
**Figure 5:** Comparative validation measurements of a 100 cm closed cylindrical pipe of 4 mm diameter

Upon closer examination, one will observe shifts in peak frequencies which are not so apparent visually from such a wide view, but are easily audible to the human ear. These frequency shifts are certainly important for musical instrument builders striving for consistency or reliable data when considering improvements in their craft [7].

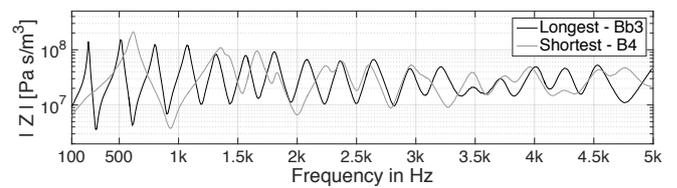
## Results – Oboe Measurements

Using a simple straight pipe adapter of 10.85 cm with professionally attached cork matching that of a typical oboe staple, it was possible to measure an oboe directly with our FMFC impedance probe as seen in figure 4. The influence of the straight adapter can be canceled out numerically, leaving the acoustical impedance of the oboe where the adapter ends within the oboe's entrance bore, effectively where the staple would end within the instrument.

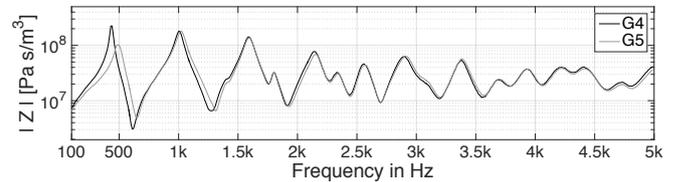
Acoustic impedance curves for wind instruments simply show the ratio of pressure to air volume flow,  $Z = \frac{p}{U}$ . What this means for each type of instrument may differ depending on the manner in which the air column resonates within the instrument. For almost all wind instruments, the input impedance will show the frequencies likely to resonate at positive peaks where the pressures are at maximum. This is because all common wind instruments are essentially open-closed pipes where one end remains mostly closed with small, intermittent bursts of air through a vibrating reed or lip where high pressures are required for sustained vibrations. The most common exception to this rule is the flute, which has a mostly open-open behavior with low pressure and high volume flow at resonant frequencies around the mouthpiece. In



**Figure 6:** Comparing two measurement systems on an Oboe



**Figure 7:** Resonances in the oboe for the longest and shortest air column



**Figure 8:** The effect of the register key is to weaken the fundamental resonance

the case of the flute, one would read the low valleys in the impedance curves as the resonances. However, for our case with the oboe (and potentially the bassoon), it is the pressure maxima that are of interest.

The measured fingerings chosen were standard fingerings only [8], which either matched to notes measured in previous studies for comparison, or those which have an interesting relationship or quality i.e. octaves, all closed, all open, etc...

The accuracy discrepancies between the BIAS head and our TMTC probe are seen in figure 6 in frequencies above roughly 1.2 kHz which are consistent with the validation plot discussed in the previous section. This comparison plot is for the note C5 which should have its sounding fundamental frequency at 523.25 Hz.

When observing figure 7, one may see effectively the longest and shortest air columns of any of the standard fingerings. The results are consistent with impedance curves of simple short air columns in pipes compared to longer columns. The sounding frequency for the lowest (with the longest air column) note Bb3 is 233.08 Hz. The highest standard note we measured, which had the least tone holes covered without the octave key pressed, was the B4 which should have the sounding frequency of 493.88 Hz.

In figure 8 we show the effect of the register (octave) key for the notes G4 to G5, theoretically 392 and 783.99 Hz respectively. A clear impedance decrease in the fundamental frequency is seen, encouraging frequency locking in the next harmonic for the G5.

While the theoretical sounded frequencies stated are often close with the measured frequency peaks in the impedance curves, it does not actually make sense to compare these directly without the effect of the staple and reed cavity interaction. Also, since this is a measure of input impedance, the radiation impedances from instruments are also not taken into account aside from any internal feedback effects.

## Discussion

In borrowing from previous theory and work, we managed to build a semi-rugged prototype of a FMFC impedance probe that offers significantly more precision for narrow-bored objects, such as oboes and bassoons, than a commercial system coupled with radius matching adapters. Using theory which is modular for any number of calibrations with any number of microphones, high accuracy across a wide frequency range is easily obtained with one open resonant free calibration and three reflection free “infinitely” long calibrations. The key to its accuracy also lies in matching the radius of the measurement duct to that of the object under study, avoiding non-planewave disturbances which are difficult or even impossible to account for and remove.

As a practical improvement, an internal thermometer would be necessary to insure accuracy in changing environments during both calibrations and measurements. Even a slight deviation in the internal temperature will create large audible shifts in measured curves and simply knowing what the real temperature is within the probe will easily solve that issue.

Since the response of the measurement duct itself is calibrated out of the equation, it might be possible to make a more rugged and portable version using a stable coiled tube for the probe, though this should be tested. Another advantage to this FMFC method is that, compared to volume flow devices such as BIAS, greater excitation signals are possible for higher signal-to-noise ratios in louder environments. This combination of potential portability and imperviousness to louder environments makes this tool an ideal candidate for commercial applications in instrument workshops. For this to happen, a more rugged and self-contained version would be needed with permanently fixed microphones, and ideally with built in preamplifiers and analog to digital conversion.

Additionally, it is possible to measure the input impedance of the staple with and without reeds from the opposite direction. This could allow us to have another view of how different staple shapes and reed configurations affect the preferred resonances of the system.

With these improvements, our FMFC narrow-bored impedance probe could provide very useful precision and reliability for instruments such as oboes and bassoons regarding music acoustics research for sound synthesis and instrument building alike.

## Acknowledgements

The author wishes to thank his supervisor Timo Grothe for enduring support with all steps in this project, and especially in manufacturing the impedance head and in implementing the calibration algorithms.

The author and his supervisor also thank Prof. Dr.-Ing. Malte Kob for lending us the microphones, Bernhard Laufhütte for lending us the Marigaux Oboe, and Peter Wolf for manufacturing the oboe staple adaptor.

## References

- [1] Grothe, T.; Baumgart, J.: A Comparison of Intonation Estimates for Reed Woodwinds. *Fortschritte der Akustik*, 42. Jahrestagung für Akustik (DAGA2016)
- [2] Walstijn, M.; Campbell, M.; Kemp, J.; Sharp, D.: Wideband measurement of the acoustic impedance of tubular objects. *Acta acustica united with acustica* 91 (2005), 590-604
- [3] Dietrich, P.; Guski, M.; Pollow, M.; Masiero, B.; Müller-Trapet, M.; Scharrer, R.; Vorländer, M: ITA-toolbox-An open source MATLAB toolbox for acousticians. *Fortschritte der Akustik*, 38. Jahrestagung für Akustik (DAGA2012), 151-152
- [4] Gibiat, V.; Laloë, F.: Acoustical impedance measurements by the two-microphone-three-calibration (TMTC) method. *The Journal of the Acoustical Society of America* 88 (1990), 2533-2545
- [5] Dickens, P.; Smith, J.; Wolfe, J.: Improved precision in measurements of acoustic impedance spectra using resonance-free calibration loads and controlled error distribution. *Journal of the Acoustical Society of America* 121 (2007), 1471-1481
- [6] Ossman, T.; Pichler, H.; Widholm, G.: BIAS: A Computer-Aided Test System for Brass Wind Instruments. *Audio Engineering Society Convention* 87 (1989)
- [7] Mamou-Mani, A.; Sharp, D.; Meurisse, T.; Ring, W.: Investigating the consistency of woodwind instrument manufacturing by comparing five nominally identical oboes. *The Journal of the Acoustical Society of America* 131 (2012), 728-736
- [8] Oboe Fingering Chart - ohmusic. <https://sites.google.com/site/ohmusicstudent/band-instruments/oboe/oboe-fingering-chart> (2015)