Sound Production Analysis of the Oboe

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ABSTRACT

In an effort to advance the understanding of how an oboe produces its unique sound, a survey of the oboe's acoustical properties and the sound output was performed. The specific acoustical impedance was measured using a previously developed piezoelectric transducer run data acquisition system. Sound output analysis was carried out using a phase-sensitive wave analysis program. The tests were run on two different oboes to find trends that were unique to the different models and the materials from which they were constructed. Results show two distinctive harmonic signatures that share similar main features as well as multiple trends for both oboes in the impedance measurements.

I. Introduction

The class of wind instruments that produce sound through the vibration of reeds consists of two groups: those excited by a "lip" reed, such as brass instruments, and those excited by cane reeds.[1] The group that uses cane reeds to excite the air column can further be divided into those that use a single reed like clarinets and saxophones and those that make use of a double reed like oboes and bassoons. The focus of this paper will be on an instrument in the latter group, the oboe.

When a musician forces air through the double reed, the airflow excites the reed and causes vibrations that send pressure waves down the bore. The long, narrow channel of the reed introduces high flow resistance and Bernoulli forces that cause the two blades to beat against each other.[2] The nonlinear nature of the double reed makes analysis of the oboe very difficult and thus relatively little information is to be found concerning it. Using several different techniques, this paper will continue to explore the nature of the oboe itself, both with and without a reed, and the distinctions in the sounds it produces when different materials are used in its construction.

II. Background

As the oboe is a complex and relatively unknown instrument, it is useful to start with a brief physical description of the instrument and the associated terms so that the author can reference them at later points. The structure of the oboe mainly consists of three sections: the bell, the middle joint, and the top joint. The inner surface, also known as the "bore," is nearly a perfect conical shape with the exception that the tip does not close. The defining feature of the oboe is the mouthpiece, or reed. The piece that is directly inserted into the top of the oboe is a conical piece of brass or silver with a cork covering at the bottom, which from hereon will be called the "staple." The cork creates a seal between the opening in the top of the oboe ("the reed well") and the tube so that the conical nature of the bore continues up through the reed as seamlessly as possible. A piece of

Figure 1. Picture of a Lorée AK model oboe and its various parts.

properly shaped cane is bent in half, tied to the top part of the staple, and then scraped and the tip clipped until it is deemed playable by the musician.[2]

During the course of this study, tests were run on two different oboes. The first was a Lorée AK Standard model oboe, which was made of grenadilla wood.[7] Grenadilla is the wood of choice for the manufacture of oboes -- not necessarily for its tone but rather for its hardness as this eases the task of creating a bore and attaching the key mechanisms.[2] The AK denotation expresses a specific bore model. AK oboes have a more conical bore than a standard model, so the top is slightly smaller and the bell is slightly wider. Other bores produced by Lorée include the DM, which has a relatively cylindrical bore, and the Royal, which has a thicker bore wall.[9] The second oboe was a Fox Renard Model 330 Artist which is made of a plastic resin. Even though it is made of plastic, the bore was reamed out by hand, so this oboe may have minute imperfections like an oboe that was hand-reamed from a hardwood.[8]

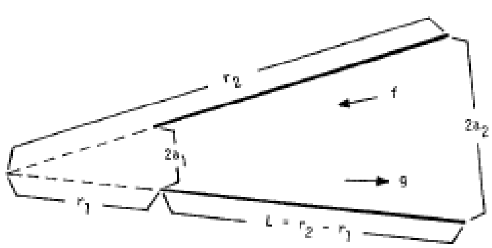


Figure 2. Parameters for the dimensions of a cone.[5]

Though the outside appearance of an oboe leads one to believe that the bell flares out like a clarinet or trumpet, the inner dimension of the bore actually forms a conical shape all the way to the end of the instrument. It is not a perfect cone as the reed tip is open most of the time,[2] but the sound waves still propagate like they would in a closed cone. This is due to the fact that the apex of a cone, either virtual or real, is neither a source nor a sink for the sound waves. Ultimately, each conical shape behaves like an open-ended tube, which can be proven by the following. Any given frequency of an open-ended tube is

$$f_n = \frac{nc}{2L} \qquad (1)$$

where L is the length of the tube, c is the speed of sound in the tube, and n is the harmonic number.[4] Using separation of variables to solve the linear wave equation of acoustics,

$$\nabla^2 p(r,t) - \frac{1}{c^2}\frac{\partial^2 p(r,t)}{\partial t^2} = 0 \qquad (2)$$

where p is pressure, c is the speed of sound in the tube, and t is time, as a function of r, the linear position, we find the Helmholtz equation.

$$\nabla^2 p(r) + \omega^2 c^{-2} p(r) = 0 \qquad (3)$$

When discussing a cone with two open ends, a model with a wave impedance of zero at both ends is used. This means that there is a boundary condition of $p = 0$ at each end. In this situation the standing wave solution is

$$p(r) = \frac{\sin[k_n(r - r_1)]}{r} \qquad (4)$$

where

$$k_n(r_2 - r_1) = n\pi \qquad (5)$$

resulting in frequencies that can be found by

$$f_n = \frac{k_n c}{2\pi} = \frac{nc}{[2(r_2 - r_1)]} = \frac{nc}{2L} \qquad (6)$$

where L is the length of the cone along its side. A direct comparison with Eq. (1) shows they are identical.[5]

In studying how an oboe makes a sound, the focus was mainly on acoustic impedance, Z, which can be defined as a measure of resistance to putting a pressure wave through a tube.[3] The complex acoustical impedance, hereon referred to as "impedance," is a direct relation between the complex pressure, p, and the complex particle velocity, u.

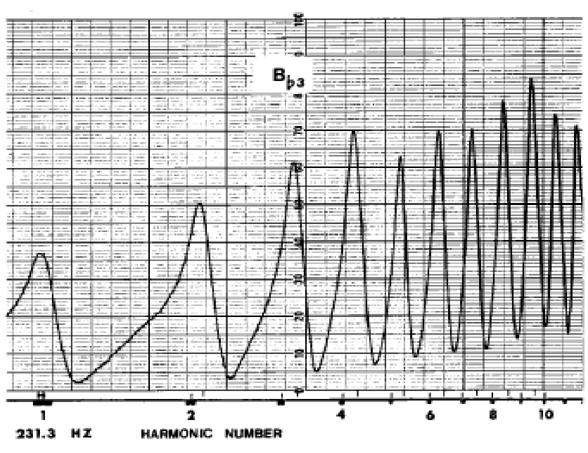
$$\tilde{Z}(r) = \frac{\tilde{p}(r)}{\tilde{u}(r)} \qquad (7)$$

Backus calculated this quantity by supplying a constant acoustic current to the mouthpiece using an adapter attached to the staple and then measuring the resultant pressure changes as detected by a response microphone at the top of the instrument.[1] The plots of this measured input impedance as a function of frequency show the impedance resonances in the instrument. Pignotti expanded upon this technique in his study of the trumpet by using a piezo-transducer disk to supply the acoustic current. His method, largely adopted for this study, differed in a few other ways as well. Rather than relying on a constant acoustic current for his calculations, he took the particle velocity measurements directly using a differential pressure microphone. Using several lock-in amplifiers, he was able to study not only the input and output impedance of the trumpet, but also the phase changes of these measurements.

III. Experimental Apparatus

A. Piezoelectric Excitation Method

The small size of the oboe staple and the lack of the addition volume added by the reed made it difficult to mimic Pignotti's method by directly gluing a piezoelectric transducer to the top of the staple. In an effort to simplify the complicated reed system, the cup portion of a trumpet mouthpiece was cut from the shank and an oboe staple was inserted into



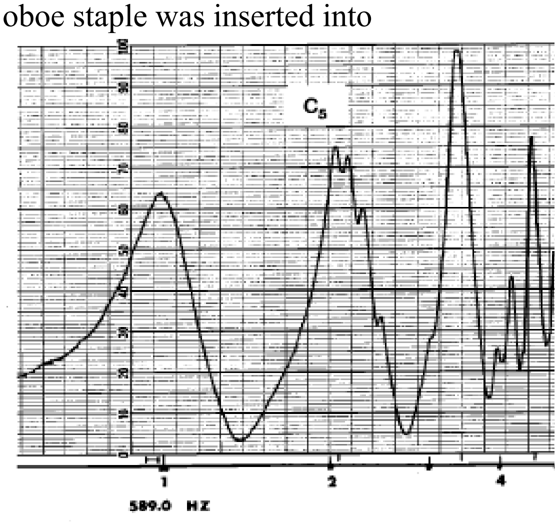


Figure 3 and 4. Input impedances of B-flat 3 (left) and C5 (right) as a function of frequency (x-axis) and harmonic number (y-axis).[1]

Figure 5. Picture, starting on the left, of a complete reed, a staple, and the modified mouthpiece.

the bottom. A small portion of the shank was left on so that the top of the staple reached the very bottom of the cup. Since the throat of the trumpet mouthpiece was slightly larger than the outside dimension of the staple, a short length of heat-shrink tubing was attached to the metal insert of the staple. This created an airtight seal between the two pieces.

The newly attached trumpet cup was then set up using the method established in Pignotti's thesis. Holes were drilled into two opposite sides of the mouthpiece for the insertion of the p and u microphones. A 1" diameter piezo-transducer was attached to the top rim of the trumpet cup using cyanoacrylate glue. The completed oboe-trumpet mouthpiece was pushed into the reed well of the oboe and the entire instrument was placed in a large plywood box lined with foam. The room in which tests were run experienced a large amount of 1/f noise due to the ventilation system, so the thick plywood of the box served as a low-frequency insulator to increase the signal-to-noise ratio. The foam on the inside of the box soaked up excess sound waves created during the tests so that waves emerging from the bell of the oboe did not bounce back and interfere with the microphone readings at the mouthpiece or the bell Once the oboe was placed securely in the box, the pressure and particle velocity mics were positioned in the mouthpiece and secured using an apiezon sealing compound to create an airtight seal. Another set of pressure and particle velocity mics were placed in the plane of the bell. The pressure mics used were 1/10" Knowles Acoustics FG-23329 high performance microphones and the pressure differential mics were modified Knowles Acoustics EK-23132 high performance microphones. In both situations, the pressure mics used were omni-direction, so their placement was arbitrary. The modifications done to the pressure differential mics eliminated this ability so they had to be placed perpendicular to the direction of the airflow. More information on the microphones can be found in Pignotti's thesis.[3]

Custom-built integrating operational amplifier circuits were used to find the particle velocity measurements. These originate from the one-dimensional version of Euler's equation for inviscid fluid flow,

$$\rho_0 \frac{\partial U_Z(z,t)}{\partial t} = -\frac{\partial P(z,t)}{\partial z} \qquad (8)$$

which upon finding the time-integral using the differential pressure signal results in a value that is linearly proportional to the particle velocity:

$$u_z(z,t) = -\frac{1}{\rho_0}\int_{-\infty}^{t} \frac{\partial p(z,t')}{\partial z} dt' \qquad (9)$$

The variable ρ_0 is the ambient density of air and is approximately 1.2 kg/m^3.[3]

The experiment was run from an adapted version of the University of Illinois at Urbana-Champaign Physics 498POM PC-based data acquisition system for guitar pickup and loudspeaker electrical impedance measurements.[10] The complex specific acoustical impedance can be directly related to complex electrical impedance,

$$\tilde{Z}_{acoustic}(r) = \frac{\tilde{p}(r)}{\tilde{u}(r)} \quad \Leftrightarrow \quad \tilde{Z}_{electric} = \frac{\tilde{I}}{\tilde{V}} \quad (10)$$

so that the pressure, *p*, is correlated with the current, *I*, and the particle velocity, *u*, is correlated with the voltage, *V*. This relationship means that converting the existing programming for electrical impedance to that which can measure acoustical impedance was a straightforward task. [3]

The modified version of the UIUC program controlled an Agilent 33220A function generator, which output a sine wave starting at a user-defined frequency and incremented the frequency by 1 Hz steps until the user-defined endpoint. For the purpose of this experiment, the start and end point settings were 29.5 Hz and 4030.5 Hz respectively. Due to a resonance in the piezo transducer at about 3200 Hz, the input on one of the mics would typically overload one of the eight ADC's associated with digitizing the outputs from the four SRS-830 lock-in amplifiers used to collect data, so the program rarely ran to completion. The area of interest for the oboe is about 100 Hz to 2000 Hz, after which very little occurs, so the lost data was of little consequence.

The sine wave from the function generator was fed to the piezo-transducer and the lock-in amplifiers. The lock-in amplifiers used this signal as a reference against which any phase change could be detected. The piezo-transducer received the signal after it had gone through a custom built voltage amplifier, which increased the output signal by a factor of 10, and a negative impedance converter (NIC) circuit, which provided true constant current and a phase shift of -90° over the frequency range of interest.

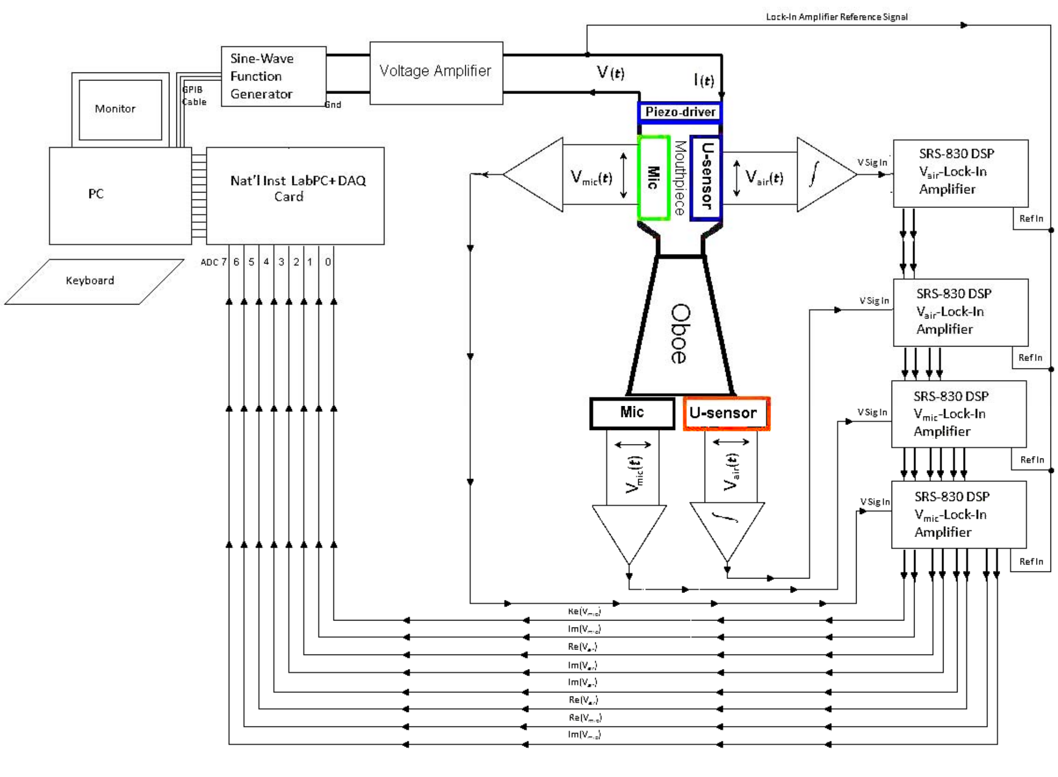


Figure 6. The modified UIUC Physics 498 data acquisition system. [3]

The real and imaginary parts of the voltage signals from all four mics were digitized using eight 12-bit ADC channels on a National Instruments LabPC+ DAQ card and stored in software arrays.[3] The program took about 12 hours to run as there was a multiple-second wait for each lock-in to settle on its final value for each step. Once the program had ended, the data was saved as a text file for analysis in a MATLAB based program.

B. Human Excitation Method

To further analyze the sound output that occurs when the oboe is played, several notes played by the author were recorded. A Peavey PVM-45 dynamic microphone was placed at the bell of the oboe and connected to a digital tape recorder. Several attempts were made to record the harmonics present inside the mouthpiece while the oboe was being played. However, despite using pressure microphones with different sensitivities (the particle velocity mic was too big to fit inside the staple), they were overpowered by the high amplitude of the sound, over 130 dB, so no data could be taken. The .WAV format sound files of the output sounds were examined through a phase-sensitive wave analysis program written by Joseph Yasi.[6]

IV. Results and Discussion

A. Waveform Analysis

Once the .WAV files were analyzed with Yasi's program, several trends started to surface. Plots of the amplitude of the sound waves as a function of frequency reveal the harmonics present in the audio

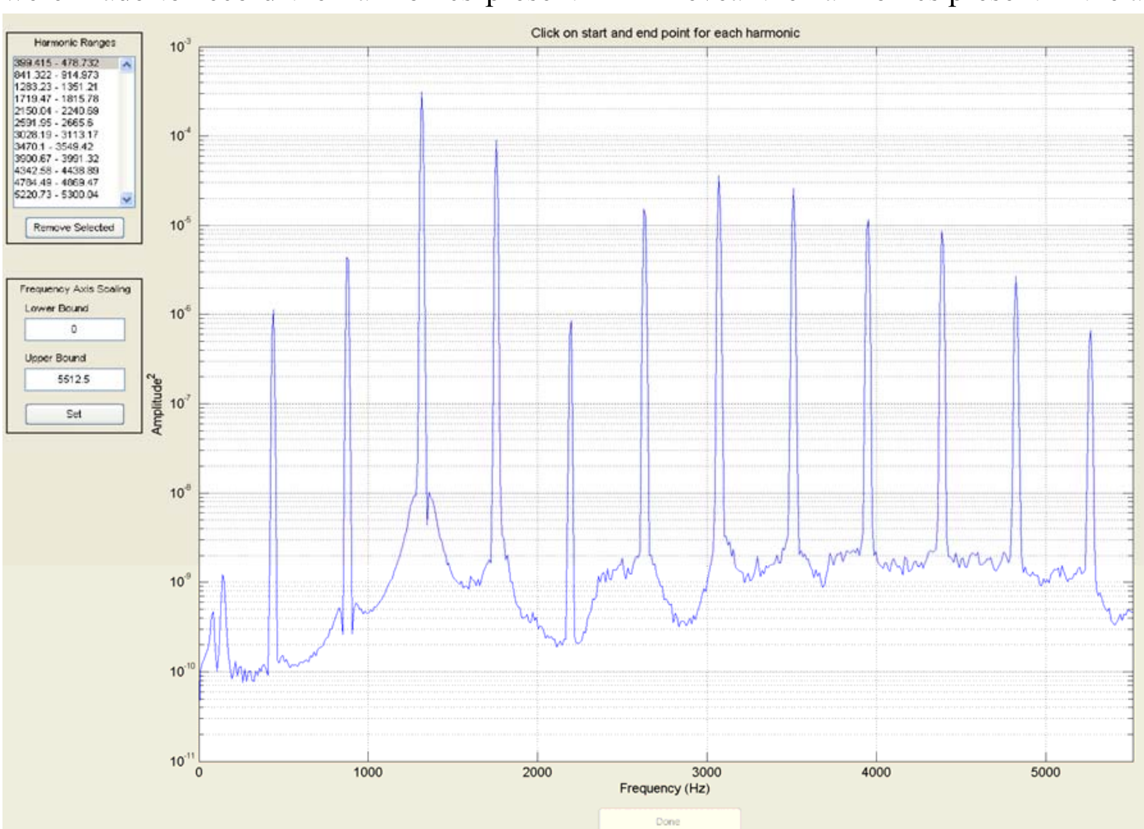


Figure 7. The harmonics signature found for A4 on a plastic oboe.

output of the oboe. A formant, or resonance region where harmonics are emphasized regardless of the fundamental,[4] appeared between 1200 Hz and 1600 Hz for all of the notes tested.

A second, minor formant appeared at about 2500 Hz. A comparison of the harmonic "signature" produced on both oboes for the note A4 shows that though there are noticeable differences overall such as the larger amplitudes of the higher harmonics present in the wooden oboe, both of the major formants are nearly identical.

Further comparisons between the different notes and the different oboes yielded various interesting patterns. For, example, a comparison of all the notes tested on both of the oboes showed a peak that seemed to have a maximum at 0 Hz. This narrow peak was present in all of the notes tested except for A4. A comparison of F4 and its alternate fingering, forked F4, was done as well as one of F4 at soft, normal, and loud volumes (figures10 and 11).

The inharmonicity of an instrument is a measure of how far the observed harmonics are from being integer multiples of the fundamental.[4] A comparison of the inharmonicity of the harmonics in A4 between the two oboes showed that the harmonics present in a Lorée wooden oboe are the least inharmonic. Though the differences between the two are very small, they may be a contributing factor as to why many people believe wooden oboes are better, i.e. have superior sound quality, than plastic ones.

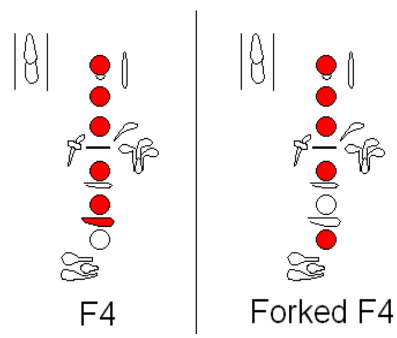


Figure 8. Fingerings for F4 and forked F4 on the oboe.

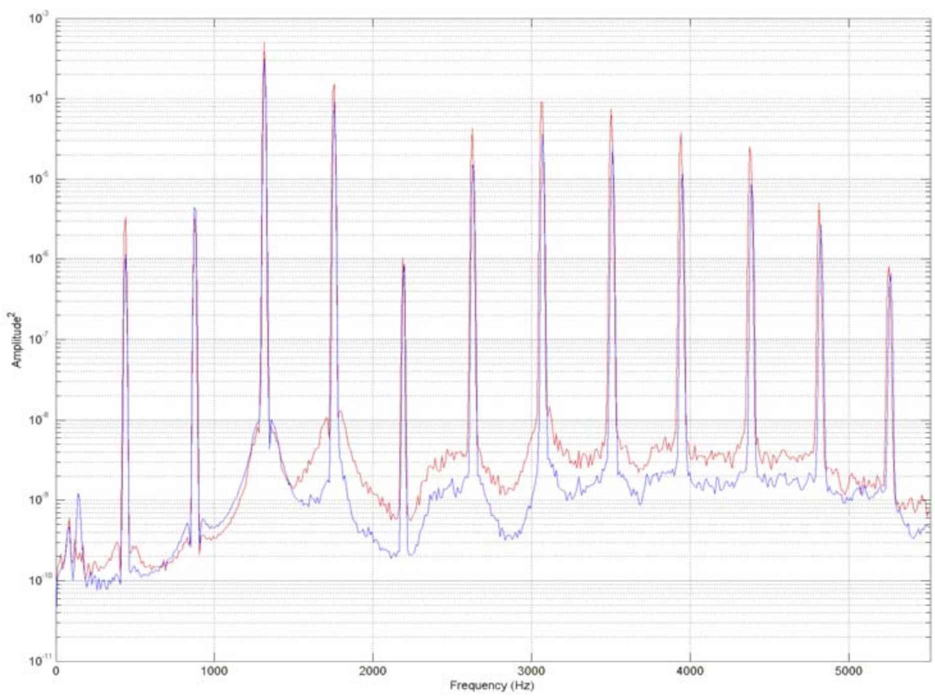
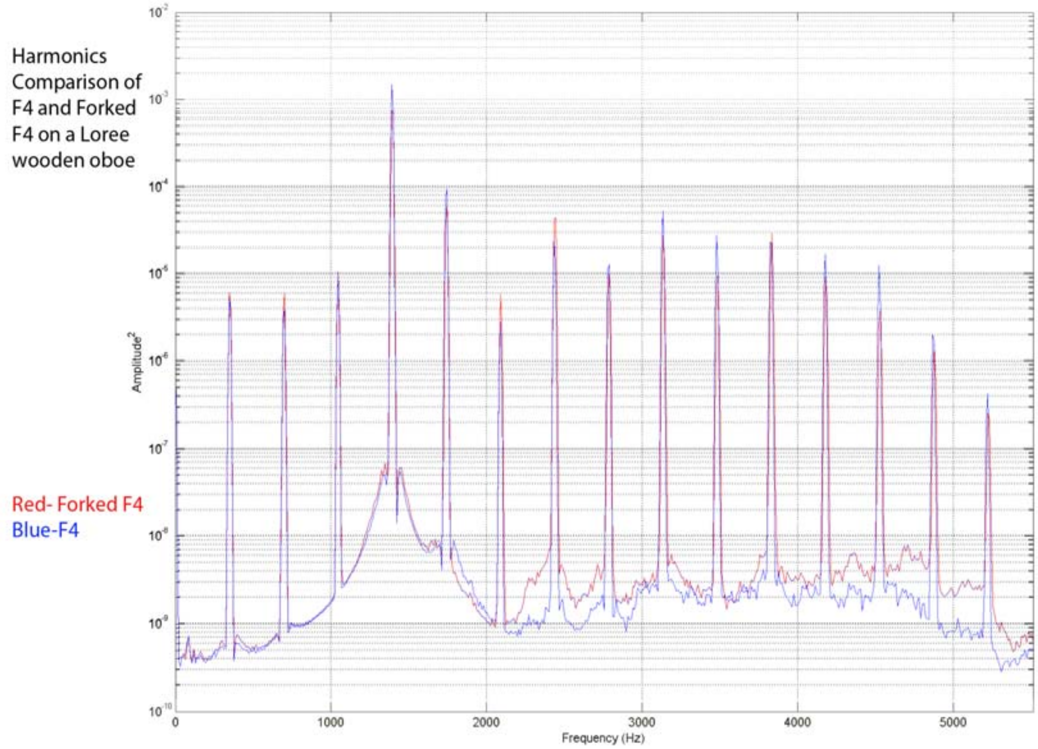
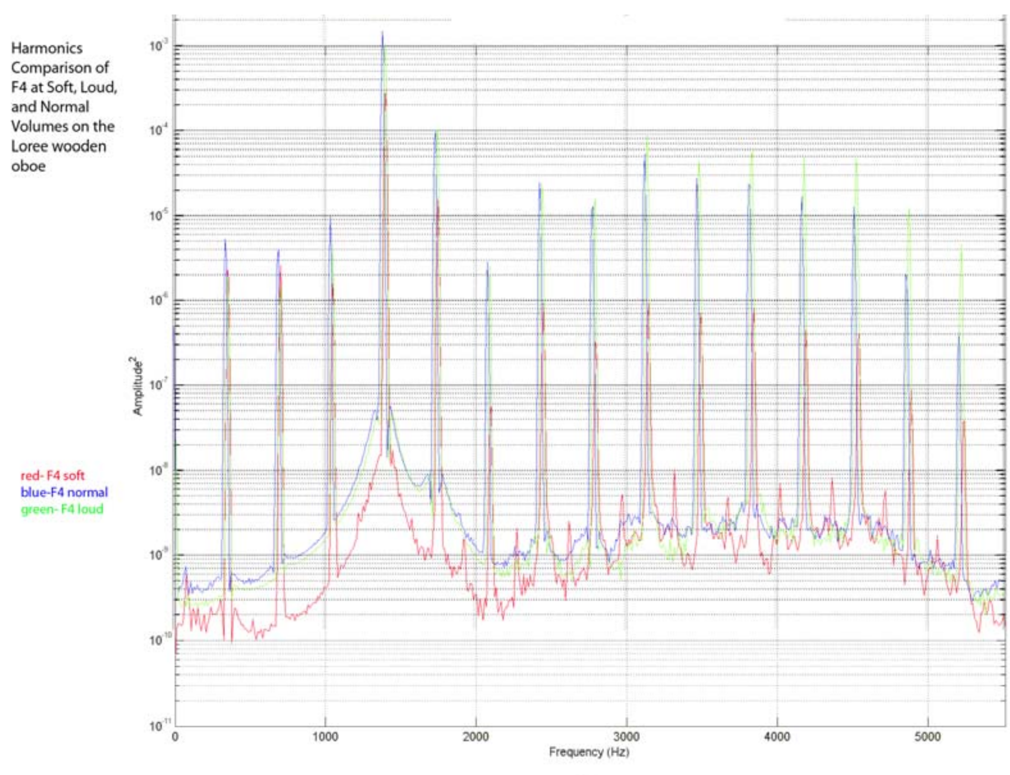
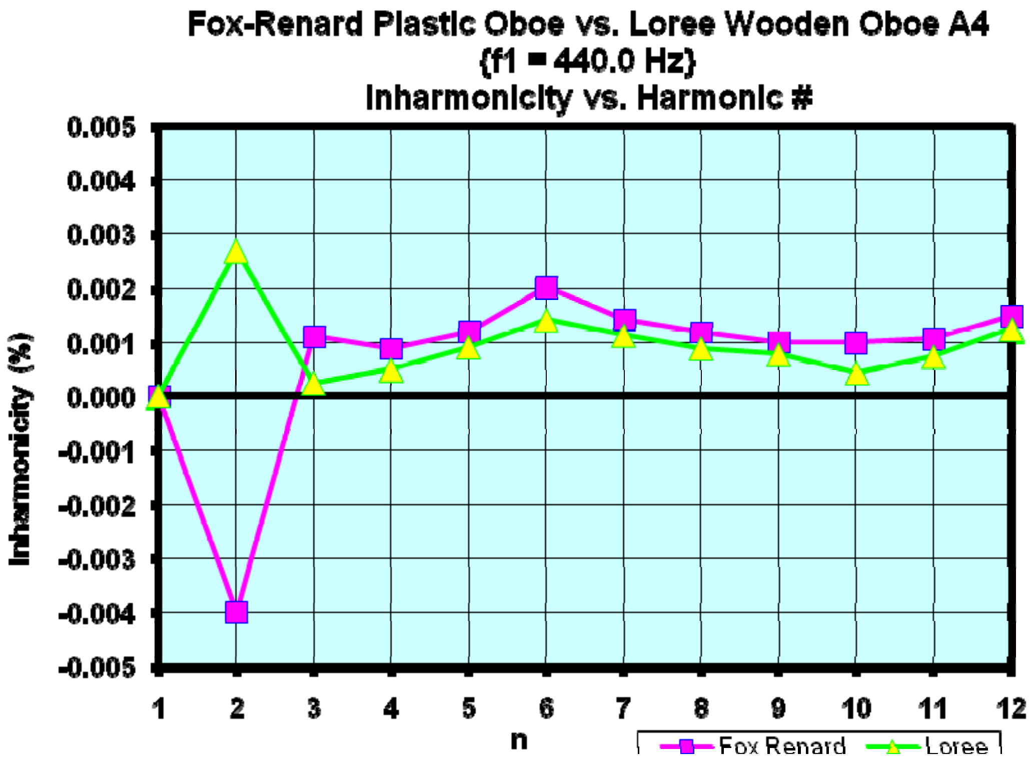


Figure 9. Comparison of the harmonics present in A4 from the Lorèe wooden oboe (red) and the Fox Renard plastic oboe (blue).

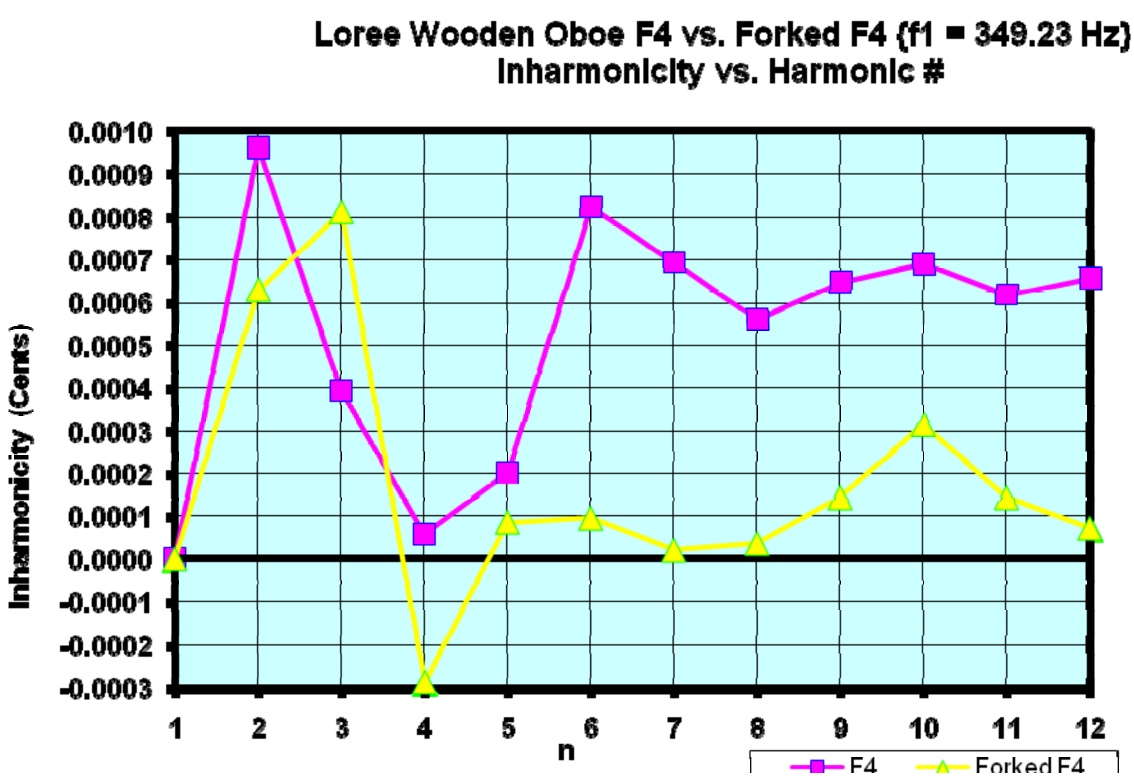


Figures 10 and 11. Comparisons of the harmonics in forked F4 and F4 (above) as well as those in F4 at soft, normal, and loud volumes (below), all on the Lorèe wooden oboe.





Figures 12 and 13. Comparisons of the inharmonicity of a plastic oboe and a wooden oboe playing A4 (above) and of F4 and forked F4 (below).



B. Data Corrections and Calibrations

The raw pressure and particle velocity data obtained using the piezoelectric transducer method experienced frequency-dependent phase changes by the microphone and preamplifier circuitry. These changes rotated the real and imaginary parts of the data and needed to be corrected so that the true real and imaginary parts could be determined. The mic phase corrections were established using a standing wave tube -- driven with a piezoelectric transducer -- with the mics in question outside of the tube, next to the transducer. The phase correction angle, $\varphi_c(f)$ degrees, was found from the raw phase data using a rotation matrix in the complex plane where, for $\varphi_c > 0$,

$$\begin{bmatrix} X_{corr}(f) \\ Y_{corr}(f) \end{bmatrix} = \begin{bmatrix} \cos[\varphi_c(f)] & -\sin[\varphi_c(f)] \\ \sin[\varphi_c(f)] & \cos[\varphi_c(f)] \end{bmatrix} \begin{bmatrix} X_{obs}(f) \\ Y_{obs}(f) \end{bmatrix} \quad (11)$$

and for $\varphi_c < 0$,

$$\begin{bmatrix} X_{corr}(f) \\ Y_{corr}(f) \end{bmatrix} = \begin{bmatrix} \cos[\varphi_c(f)] & \sin[\varphi_c(f)] \\ -\sin[\varphi_c(f)] & \cos[\varphi_c(f)] \end{bmatrix} \begin{bmatrix} X_{obs}(f) \\ Y_{obs}(f) \end{bmatrix} \quad (12).$$

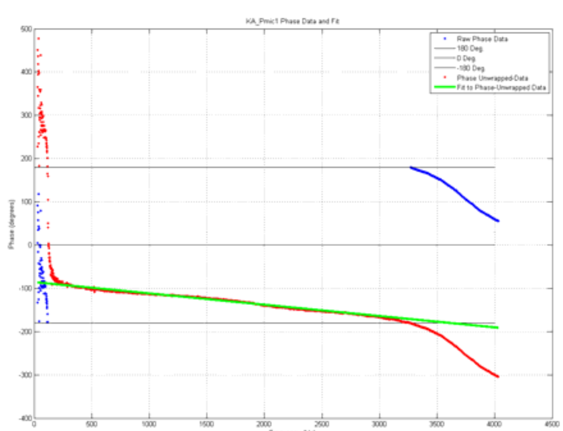


Figure 14. Graph of the Pmic 1 calibration fit. Blue is the original wrapped data, red is the unwrapped data, and green is the straight line fit.

The terms X_{corr} and Y_{corr} are the phase corrected real and imaginary components, respectively, while X_{obs} and Y_{obs} are the corresponding measured components. Once the data from the standing wave tube was compiled, a few trends became apparent. Scattered data occurred at low frequency due to acoustical interactions of the area surrounding the piezoelectric transducer. This was tested to ensure it wasn't an artifact of the mics by switching the outside mics with those inside the standing wave tube. A comparison of the data showed that the low frequency behavior of the phase was due to the external geometry of the piezo-driver end of the standing wave tube, not the mics themselves. At high frequency, about 3200 Hz, resonance in the piezo transducer

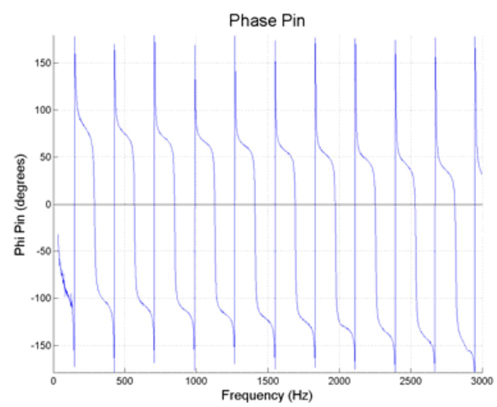
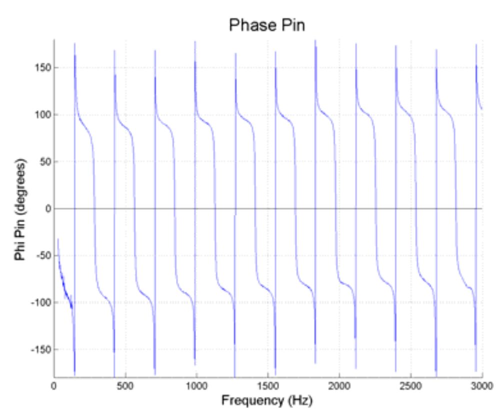


Figure 15 and 16. Pressure in (Pin) phase uncalibrated (top) and calibrated (bottom).



created a radical curve down. A polynomial fit overcompensated for these trends so a straight line fit was used as it corrected for just the mic shifts and none of the extra effects of the standing wave tube and piezo-driver. On average, the phase slope for the pressure mics was about -0.025 and the slope for the particle velocity mics was about -0.008.

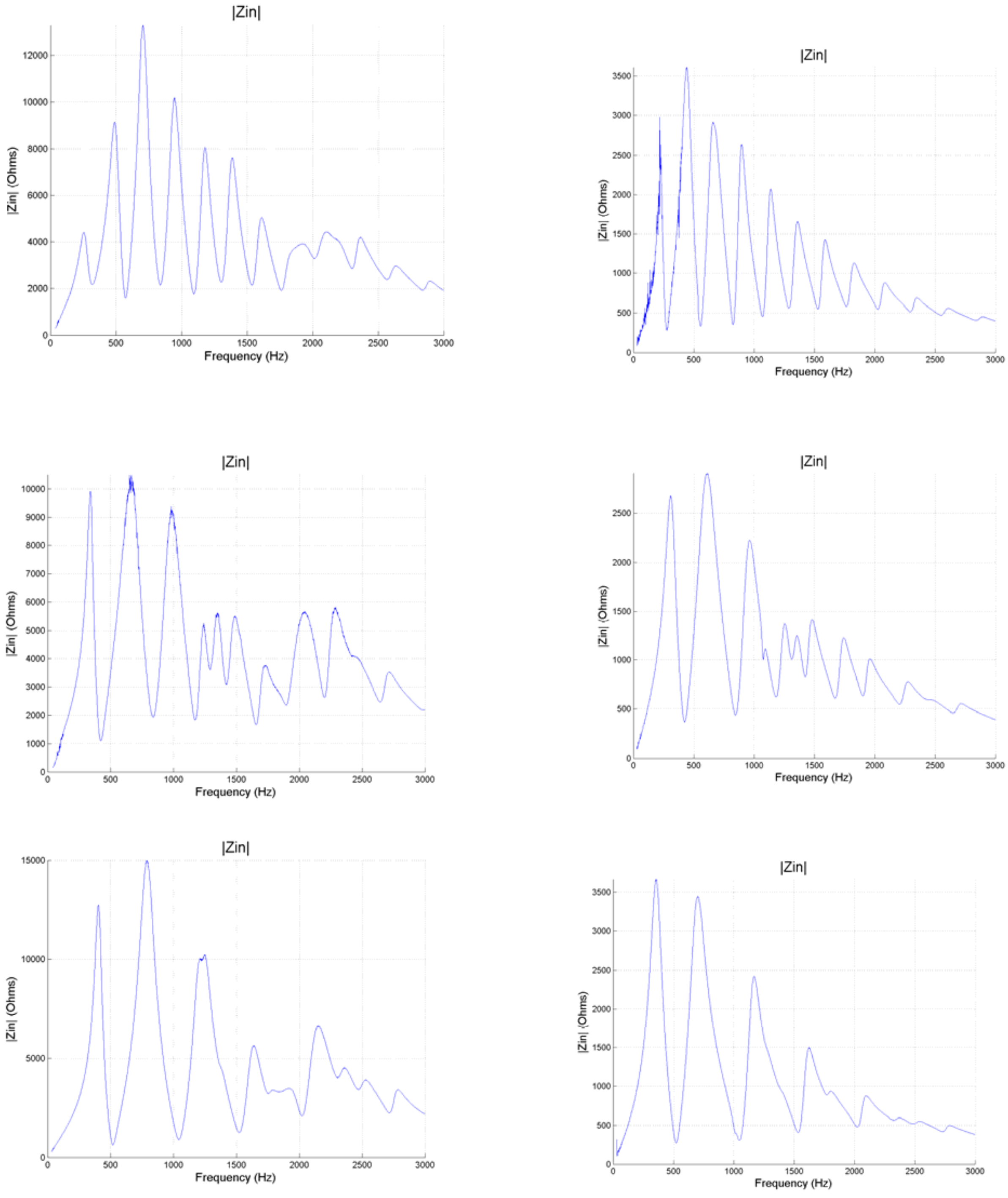
The absolute microphone sensitivities were determined for input into the impedance analysis program. This was done using an Extech Sound Level Calibrator (SLC) model 407766 and an Extech Sound Pressure Level (SPL) Meter model 407768. After verifying that the sound level in the SLC was 94 dB using the SPL meter, the pressure mics were placed into a custom built cap that created an airtight seal around the top of the SLC. The resultant voltage amplitude was measured using a multimeter. The particle velocity mic sensitivities were measured in a similar method. The mic was placed in the SLC, without the special cap, and the voltage change was measured with the multimeter. On average, the pressure mic sensitivities were about 280 mV(rms)/ Pa(rms) and the particle velocity mic sensitivities were about 80 mV(rms)/ Pa*(rms) where 1 Pa* is 2.4 mm/second.

C. Impedance Analysis

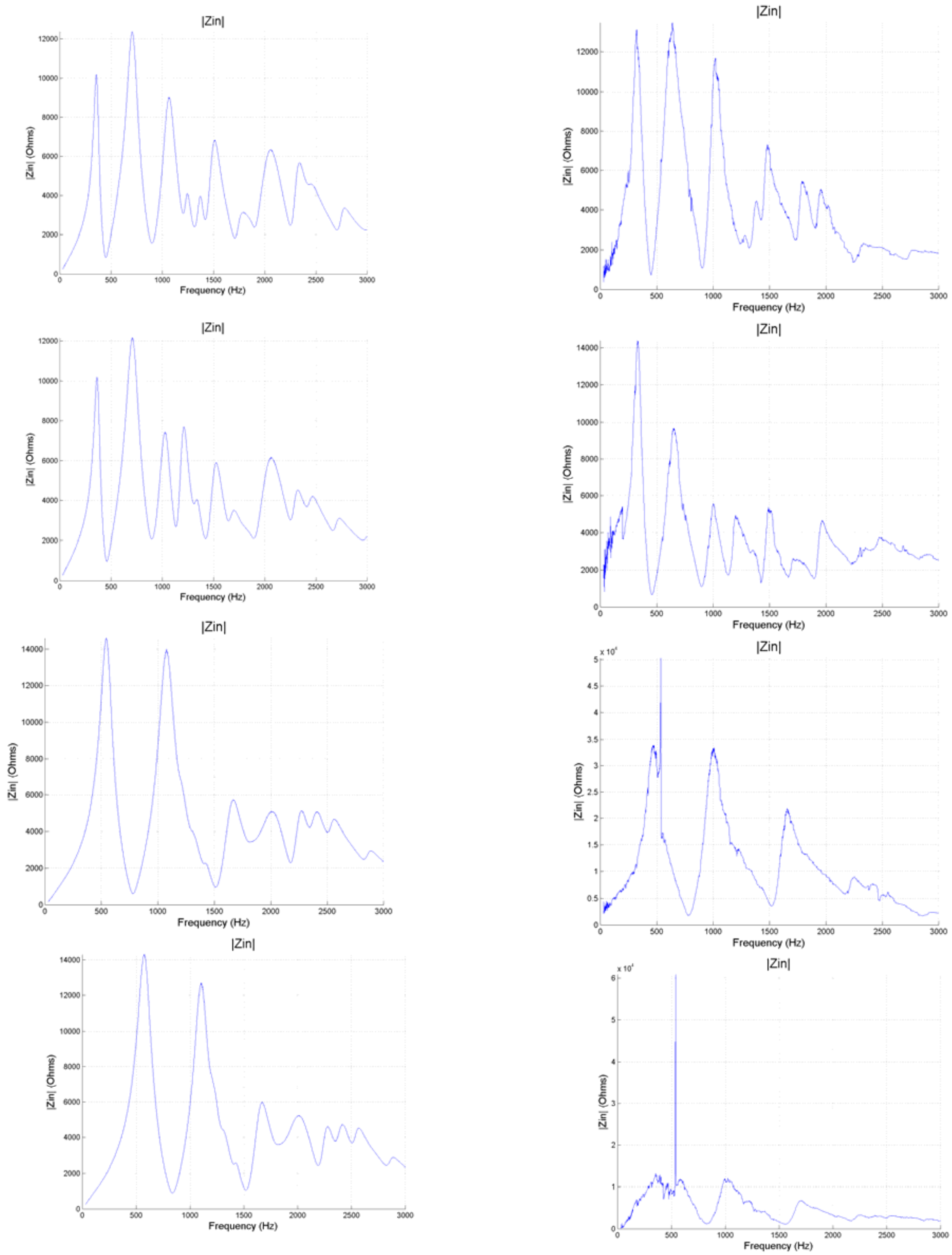
Results of the impedance analysis program resulted in multiple graphs that reported all the real and imaginary parts of the input and output pressure and particle velocity as well as the impedance and the sound intensity levels with their magnitudes and phases. The real result of running all these tests comes from comparing the data from the wooden oboe to that of the plastic oboe and also to the measurements from other instruments.

When comparing the data from the wooden oboe to that of the plastic oboe, one thing is immediately clear: there is a greater amount of noise present in the data from the plastic oboe. This is likely due to the fact that the tests for each oboe were completed in two different boxes at opposite ends of the room. An aural survey of the two locations reveals more 1/*f* noise from the ventilation system present in the back of the room, where the plastic oboe tests were completed, than in the front of the room, where the wooden oboe tests were run. It is also possible that the noise is a consequence of the material used to make the oboe, in this case plastic resin. Natural occurrences such as summer thunderstorms and not-so-natural occurrences such as the remodeling in the building that was going on two floors down could also have been factors.

Two other trends that immediately become apparent are that the wooden oboe impedances have higher impedance levels at high frequencies but often lower levels on the fundamental frequency of each note. Higher impedance levels mean that at that frequency, more pressure waves are bouncing back to the top of the instrument. More pressure waves at the mouthpiece results in the lips locking in on that frequency, making it easier to play. High impedance levels in the higher frequencies means the higher harmonics have a greater impact on the sound output resulting in a more complex sound. This trend in the wooden oboe becomes even more apparent in the upper notes. The low impedance levels mean it is harder for the lips to vibrate at that frequency. Low levels on the fundamental, such as in the notes B-flat 3 and E4, mean that the note in general is more difficult to play. Compared to the plastic oboe, the wooden oboe is typically more difficult to play. This could be due to the more dramatic conical shape of its bore or a characteristic of the wood. Side-by-side views of the impedance graphs for both oboes are on the following pages.



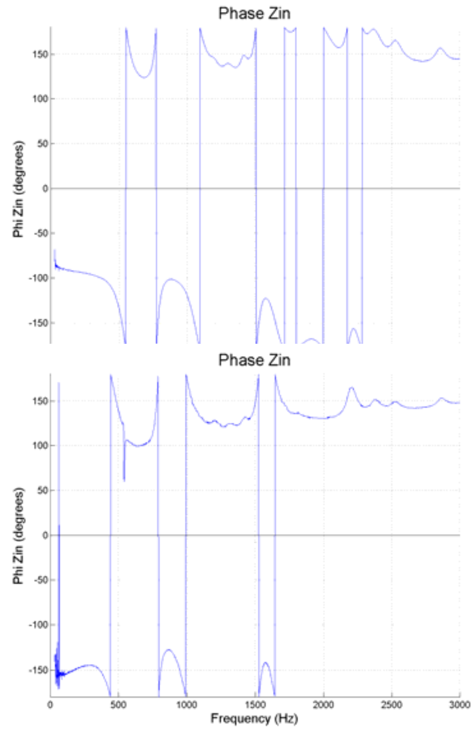
Figures 17 through 22. Graphs of the impedance in (Zin) magnitude for several notes for the Lorèe wooden oboe (left column) and the Fox Renard plastic oboe (right column). Starting at the top, the notes are Bb3, E4, and G4.



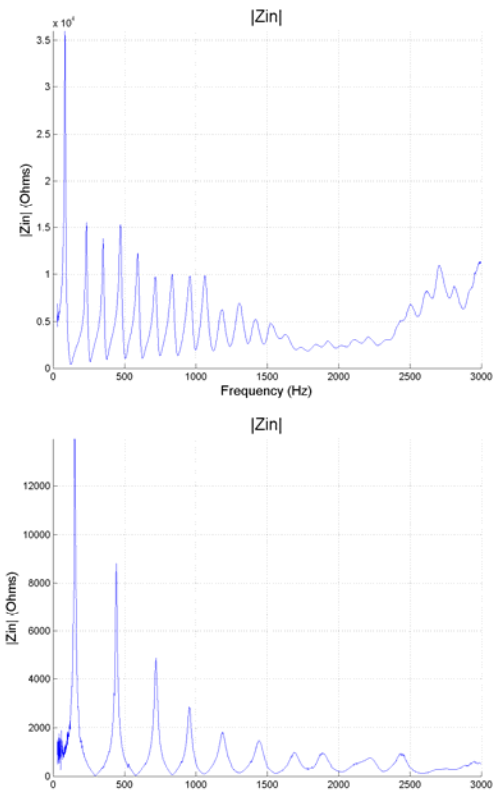
Figures 23 through 30. Graphs of the input impedance (Zin) magnitude for several notes for the Lorèe wooden oboe (left column) and the Fox Renard plastic oboe (right column). Starting at the top, the notes are F4, forked F4, C5, and C6.

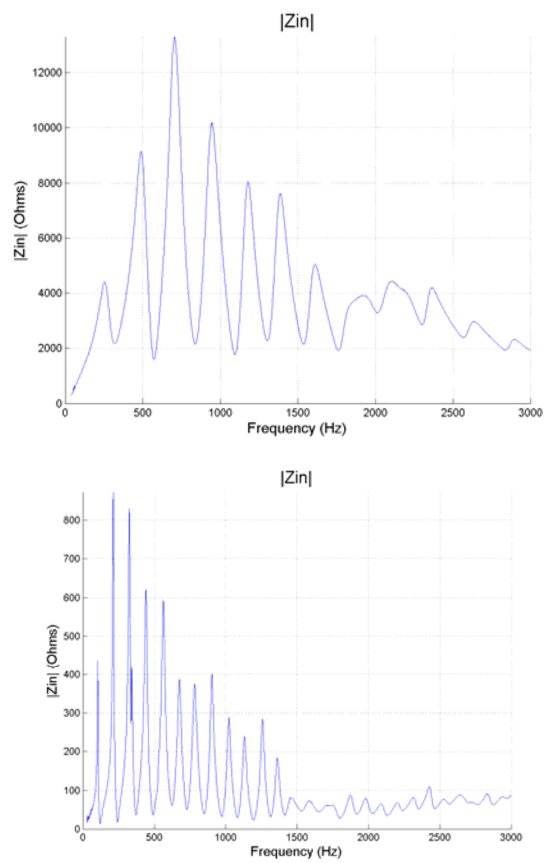
Similar impedance measurements have been produced for several other instruments including clarinet, trumpet, and tenor saxophone. Comparisons of these graphs and those of the oboe show a harmonics trend that is possibly a characteristic of bore shape. The trumpet and clarinet, two instruments with fairly cylindrical bores and flared out bells, displayed strong fundamentals relative to the other harmonics. The oboe and saxophone, with their conical bores, displayed weak fundamentals and stronger second and third harmonics.

The unique part of this experiment was the phase information that was found. Analysis of this information shows the phase changes of the harmonics and how there are slight differences between the two oboes.



Figures 31 and 32. Input impedance (Zin) phase changes for C5 on the Lorèe wooden oboe (top) and the Fox Renard plastic oboe (bottom).





Figures 33 through 36. Input impedance (Zin) magnitudes for trumpet (top left), clarinet (bottom left), oboe (top right), and saxophone (bottom right).

V. Conclusions

This study has exposed several unique aspects of the oboe and the sounds produced when it is played. The impedance spectra were successfully found and allowed a look at the complex interactions occurring in a conical bore. They also provided several physical reasons for why certain notes are harder to play. However, why these interactions occur is still relatively unknown. A comparison of input impedance to output impedance has the potential to show more about these interactions, but only the output impedance for Bb3 proved helpful in this regard. A large impedance mismatch between the mouthpiece and bell suppresses the fundamental and makes the note difficult to play. The other output impedance spectra proved hard to read and need to be studied more to fully understand their effects. The data found in this study has also opened the door to phenomena such as the many differences between wood and plastic as a medium that can be explored in the future.

VI. Future Work

This study mainly focused on the instrument body so further study of the different bore styles would build upon this information. It would also be beneficial to further separate the mechanical aspects of the instrument from the interactions that occur when it is played by a musician. A new excitation method that stimulates the reed would provide more accurate measurements of the harmonic interactions inside the bore. The development of smaller microphones would enable measurements to be made all the way up the instrument bore without creating disturbances in the sound waves. Small enough mics would make it possible to take measurements within the reed itself. Exploring the complex vibrations and air current interactions that go on through the reed assembly would offer more insight into how the complete instrument interacts with sound waves.

On more of a biological side, it would be of interest to do a physiological exploration of a musician's glottis, vocal tract, and mouth cavity to determine how any vibrations or pressure changes in these regions affect harmonic content.

VII. Acknowledgments

The author would like to thank her advisor Prof. Steve Errede for his help and guidance and her colleagues Marguerite Brown and Brendan Sullivan for their assistance in various stages of the project. Many thanks also go to the National Science Foundation for their financial support through grant PHY-0243675 and the University of Illinois at Urbana-Champaign for the use of their facilities.

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