FAST FOURIER TRANSFORM ANALYSIS

OF OBOES, OBOE REEDS AND OBOISTS:

WHAT MATTERS MOST TO TIMBRE?

By:

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Table of Contents

Table of Figures

Chapter 1

Introduction

1.1 Motivation

Opinions vary among oboists as to what particular aspect of their instrument, the oboe (see Figure 1), most enhances the sound it produces.

Figure 1 Oboe with full key system [1]

Because of the wide range of options available to oboists, many disagree about which makes the most difference to tone. Professional oboists insist on playing on wooden oboes, with homemade reeds. Because wooden oboes are susceptible to cracking, beginner oboists often use plastic or half plastic/half wooden instruments. Beginner and intermediate oboists also often play on manufactured reeds. These elements make up a "system," which includes the oboe, the oboist and the reed.

The original motivation for this project was to determine which aspect of the oboe "system" made the most difference to the quality of the tone produced. Initially the project focused solely on the composition of the oboe, and what difference it may have made to the acoustic spectrum. This was to eliminate as much variation from the oboist and the reed as possible. It has previously been established that the vibrations of oboe reeds are quite complex and involve Bernoulli forces and jet formation in the reed channel [2]. Human variation in embouchure[1] is difficult to measure and quantify, and there have been some attempts to experimentally measure and numerically model the non-linear characteristics of a double-reed [3, 4]. The focus of my work is not to attempt to explain how the sound is produced by the reed, but to examine the sound and look for differences in its harmonic content as each aspect of the oboe system was changed in turn. To make this analysis as straightforward as possible, I will examine in each of the experiments described in this thesis, the sound produced when a single note, A_4 (440 Hz), is played on the oboe.

The preliminary results obtained from the composition of the oboe indicated that further research would be needed into how the tone quality changes as oboist, oboe composition, and reed are changed in turn. Three other portions of the project were added to observe these differences: a driven oboe experiment, variation of oboes, and variation of reeds. Each portion of the project was aimed at holding constant some aspect of the oboe system. The driven oboe experiment attempted to eliminate variation from oboists by replacing the oboist with a steady flow of air through a tube. In the oboe variation portion of the project four oboists played on a wooden and a plastic oboe with their personal reed. In the

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[1] Embouchure is the mouth and lip position of a musician.

reed variation portion of the project the oboist, the reed and the oboe were controlled: the oboists played with reeds provided for them on a wooden and a plastic oboe. The same wooden and plastic oboes were used in the driven oboe, the reed variation and the oboe variation parts of the project. Finally, the notes played by each oboist of their own reed and instrument were compared to that of a professional oboist, to help distinguish what harmonic characteristics are shown by a professional oboist. This is not compared to the other results because certain aspects of that experiment could not be controlled.

1.2 Waves

There are many types of waves; however we are primarily interested in sound waves. Sound waves in air consist of the propagation of periodic pressure differences. Sound is a longitudinal wave, as shown in Figure 2, which means the displacement of the medium is in the direction of propagation. Sound propagates through air by the vibration and oscillation of the air molecules. In the case of the oboe, the reed vibrates and propagates the oscillations through the oboe and then through the air. The human ear then responds to these pressure differences.

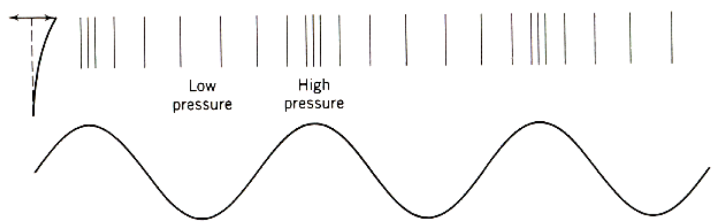

Figure 2 Variations in low and high pressure that correspond to a wave in air [5]

When a note is played on any musical instrument, the frequency of the resulting sound wave contains not just the frequency of the note played, but also harmonics of that frequency, where a harmonic is an integer multiple of the fundamental frequency or pitch. Musical notes are arranged into octaves, such that power of two harmonics of a given note correspond to the successive octaves. By analyzing the sound it is possible to determine which frequencies, and thereby which harmonics are present in the note. The amplitudes of the harmonics determine the quality of the sound produced, and differ from instrument to instrument. A tuning fork typically only has one frequency present, whereas a violin, piano or oboe have many harmonics present. Because instruments are not completely perfect it is not unusual for the higher harmonics to be slightly out of tune. This variation is usually not by more than 10 Hz for the frequencies relevant for this experiment. Some of the much higher harmonics could be as out of tune as 60 Hz higher or lower than the value of the harmonic, however these harmonics are not the focus of this study.

Fourier decomposition of a sound allows analysis of the frequencies it contains. In this work, we used Fourier analysis to observe the amplitudes. This made it possible to view the amplitude at all frequencies from 5 Hz to 21829 Hz. Human hearing ranges from about 20 Hz to 20 kHz. By comparing the differences in the amplitude of these harmonics it was possible to analyze trends between the oboists, oboes and reeds.

1.3 Oboes

1.3.1 Oboe Reeds

An oboe is a woodwind instrument driven by a double reed. The double reed consists of two pieces of thin bamboo cane that are bound on a piece of metal surrounded at the base with cork (see Figure 3). Manufactured oboe reeds are classified by their stiffness; “soft”, “medium soft”, “medium”, “medium hard” and “hard”. “Soft” reeds are thinnest at the tip and the reed is able to vibrate more freely whereas “hard” reeds are thicker near the tip making it more difficult for the reed to vibrate. Most reeds are made of bamboo cane that is machined until it is of a suitable thickness. However, some manufactures make plastic reeds for beginning oboists which vibrate even more easily than cane reeds. Plastic reeds are considered to produce far inferior tone quality than the cane reeds and therefore are only used by oboists who have just begun playing. Some oboists who have not learned how to construct their own reeds will purchase manufactured reeds and then shape the reed to their liking by scraping down bamboo on specific parts of the cane to make the reed harder or softer.

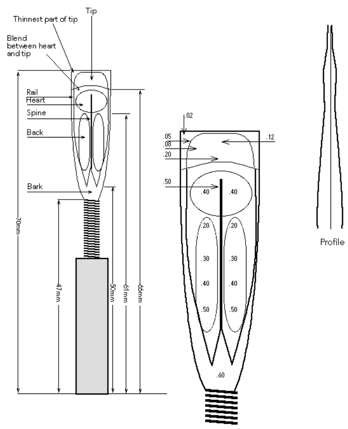

Figure 3 Oboe reed [6]

The reed is inserted into the top of the instrument. By moving air through the reed, air is moved through the bore of the oboe. The bore is made of three joints, the upper joint, the lower joint and the bell (Figure 4). The bore of the oboe is conical and terminates in a flared bell. Sounds in the oboe are produced by creating a standing wave inside the bore. By lifting various keys on the oboe the air column is changed producing different notes ranging from $B_3{}^\flat$ (approximately 233 Hz) to G_6 (approximately 1396 Hz). These key holes are able to change the wavelength of the standing wave, thus altering the fundamental frequency produced by the instrument.

1.3.2 Oboe Compositions

The primary difference in the quality of oboes from the same brand comes from what the oboes are made of. Plastic oboes, which are the most resilient and the least expensive, can be played for many years. They do not crack as easily as wooden oboes and are considered an excellent choice for student players. However plastic oboes are considered to have inferior tone quality as compared to wooden oboes. Wooden oboes are made of grenadilla, the wood from the African Blackwood, grown in southern Africa. Grenadilla wood, so dense that it sinks in water, is used to make many other woodwind instruments. The major drawback of a wooden instrument is that the wood cracks from variations in temperature and humidity; if a crack becomes severe enough the instrument can become unplayable. The part of wooden oboes most susceptible to cracking is the upper joint (Figure 4). In an attempt to solve this problem, oboe manufacturers began producing an intermediate level oboe in which the upper joint is made of plastic and the lower joint and bell are made of

Figure 4 Oboe joint diagram [7]

wood. Some manufacturers [8] believe that the upper joint has very little influence on the tone and by replacing it with plastic it makes little difference to the tone of the oboe itself. However professional oboists still prefer wooden instruments to the alternatives.

Many oboists believe there to be a distinct tone difference between plastic and wooden instruments; wooden instruments are considered to have a rich warm tone while many plastic instruments are believed to have a harsher more focused sound. While the frequency of the note played is always present, other frequencies are also excited. These frequencies are harmonics of the original note. While these frequencies are present in the note played, to the human ear the fundamental frequency is dominant. The unique sound of each instrument depends on the harmonics present & their relevant amplitudes.

1.4 Summary

To examine these aspects of the oboe system most effectively five separate experiments were designed in an attempt to control the maximum number of variables. In all these experiments, the note A_4, of frequency 440 Hz, was played. Chapter 3 discusses the first experiment, the driven oboe, which attempted to eliminate variation from the oboist. Chapter 4 examines the sound produced by oboes manufactured by Fox Oboe Company, and made of plastic, wood and half-plastic/half-wood and played by a single oboist. Chapter 5 covers the oboe variation experiment; this measured differences in the acoustic spectra created by different oboists playing on personal reeds. Chapter 6 discusses the impact of reed variation, when the same set of oboists is provided with three types of reeds. Chapter 7 has the fewest controlled variables, but allows examination of the note of a professional oboist compared to the amateur oboists used in the previous portions of the experiment. The results of these separate experiments are synthesized and examined in the conclusion, Chapter 8.

Chapter 2

Fourier Analysis and Fast Fourier Transforms

2.1 Fourier Analysis

Fourier Analysis uses the sum of an infinite series of sine and cosine functions to express a complicated waveform. For a given waveform defined on an interval (-π, π) it is possible to find the frequencies present in the wave form and the amplitude at those frequencies. The waveform can be expressed as a summation:

$$g(t) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty}(a_n \cos 2\pi f_n t + b_n \sin 2\pi f_n t) \tag{1}$$

The amplitudes at each frequency $f_n = nf$, where f is the fundamental frequency, are given by:

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} g(t)\cos(n\pi f t)\,dt$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} g(t)\sin(n\pi f t)\,dt \tag{2}$$

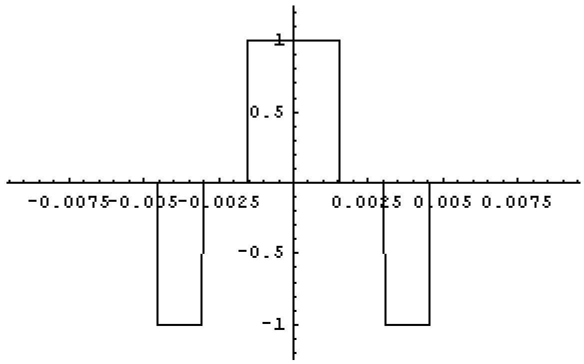

Figure 5 Piecewise function plotted as amplitude on the x-axis and time on the y-axis

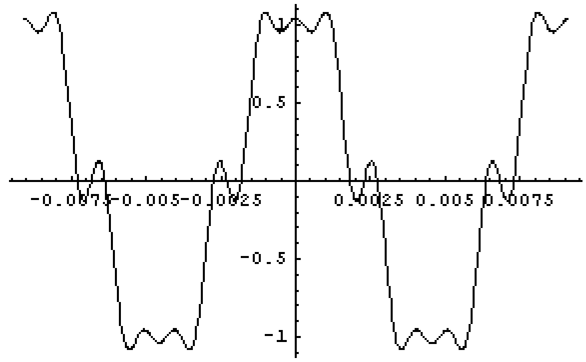

Figure 6 Fourier analysis estimation of the piecewise function in Figure 5 obtained by adding the waves shown in figures 7-9.

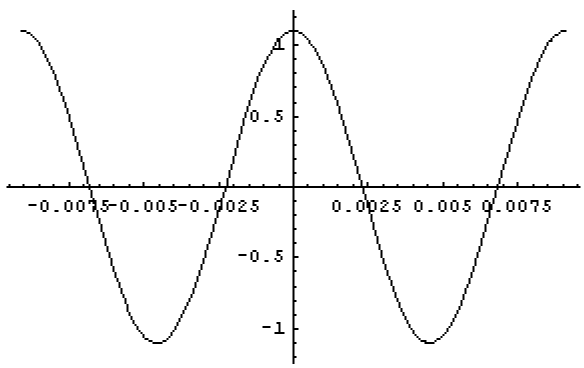

Figure 7 Component of Figure 6 with frequency 220 Hz

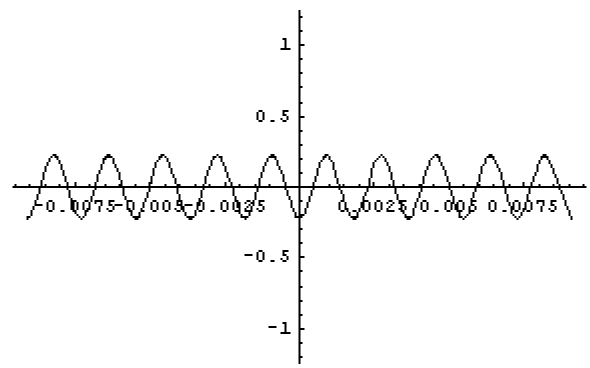

Figure 8 Component of Figure 6 with frequency 1100 Hz

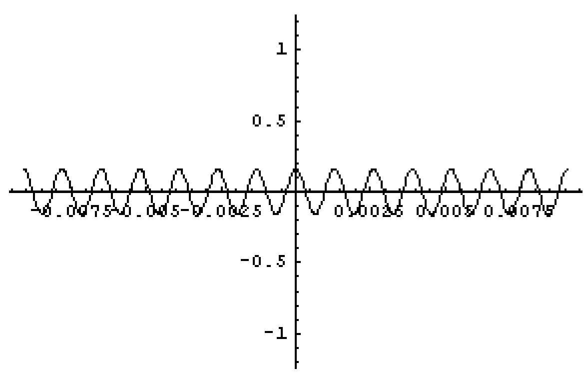

Figure 9 Component of Figure 6 with frequency 1540 Hz

which come from the orthoganality of the sine and cosine functions. As an example, I show the Fourier decomposition of a piecewise function, shown in Figure 5, as the summation of a finite series of sine and cosine waves (Figure 6). This Fourier series is then composed of cosine waves of various amplitudes and frequencies (shown in Figures 7, 8 and 9).

2.2 Discrete Fourier Transforms

For analyzing waveforms of finite length, a discrete Fourier transform (DFT) [9] can be used. A DFT takes small samples (Δ) of a function h(t) in the time domain and for those sampled points finds the frequency which is related to the sampling rate (1/Δ) for N sampled values by:

$$f_n \equiv \frac{n}{N\Delta} \quad \text{where } n = \frac{-N}{2}, \ldots \frac{N}{2} \qquad \textbf{(3)}$$

However, sampling gives a finite limit to the number of frequencies measured in a given function. The Nyquist critical frequency is related to the sampling rate by:

$$f_c = \frac{1}{2\Delta} \qquad \textbf{(4)}$$

As a result of the sampling rate's relationship to the frequency of the function, aliasing can occur as seen in Figure 10. This means that the frequencies that lie outside of the Nyquist critical frequency are moved within the range of $-f_c < f < f_c$. This results in

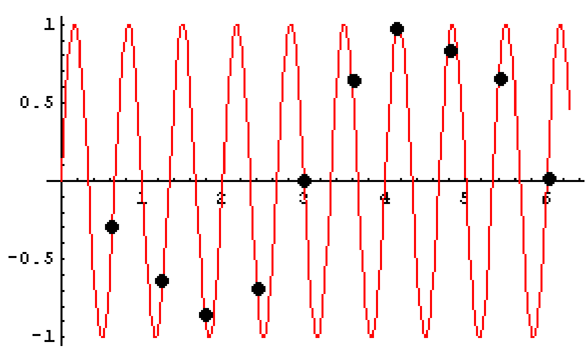

Figure 10 Aliasing with too small of a sample size results in a lower frequency being found.

signals with a higher frequency being sampled at such intervals that a signal with a lower frequency, which may not even be present in the original signal, is generated. In this particular case the sampling rate was 44100 Hz. Thus we know that the Nyquist critical frequency will be 22050 Hz, which is well outside the expected range of an oboe frequency spectrum and human hearing (human hearing ranges from approximately 20 to 20,000 Hz) thus it is unlikely that aliasing will be a factor.

If we considered a Fourier transform of N samples then $k = 0, 1, 2 \ldots, N - 1$, $t_k = k\Delta$ and $g_k \equiv g(t_k)$. Assuming that N is even then the final discrete Fourier transform is given by:

$$G_n = \sum_{k=0}^{N-1} g_k e^{i2\pi f_n t_k} \tag{5}$$

2.3 Fast Fourier Transforms and SpectraPLUS

Fast Fourier transforms utilize various numerical algorithms to reduce the time spent on calculating the discrete Fourier transform (DFT). Such an algorithm was first developed by Gauss in 1805 but this work was never widely recognized. The algorithm was redeveloped independently by J.W. Cooley and J.W. Tukey in 1965 [10, 11]. This shows that a discrete Fourier transform of length N as a sum of two transforms of lengths N/2. Each of these are subdivided into two, and by continuing this procedure the entire transform can be constructed by performing a much smaller number of computations. However, this method requires that the function be reassembled in a particular order. If during the decomposition each function is given a denotation based on zeroes and ones than by using bit-reversed order the function will sum in the proper order.

SpectraPLUS [12] uses the FFT to decompose the original waveform into a spectrum of frequencies and amplitudes. Using as its input a recorded sound in the form of a .wav file, it is able to output a time series of the function as well as a frequency spectrum (Figure 11).

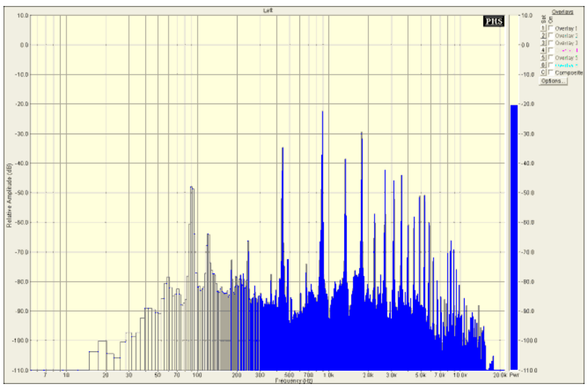

Figure 11 Spectrum output for plastic Oboe 1 A (440 Hz)

In all the experiments described here, I recorded the sound of the oboe playing A_4 (440 Hz) for each of the six oboes. None of the sound recordings consist of a pure tone, meaning that not only was 440 Hz present but also nearby frequencies and harmonics. This made it necessary to not only look at the amplitude of each oboe at 440 Hz but also at neighboring frequencies. To determine this range I chose a range of 40 Hz below the expected frequency and 40 Hz above the expected frequency. Using this same method I also examined the harmonics of 440 Hz to determine if there were differences in the amplitudes there.

SpectraPLUS uses a reference dB level to measure all amplitudes of sound files. Because of this all amplitude measurements are in –dB, meaning that they are of lower amplitude than the reference frequency. The more negative the amplitude, the less it is.

Because the oboe is so sensitive to minor fluctuations of the embouchure of the player it was necessary to average the sampled fast Fourier transforms. If I had looked solely at the FFT from a single sample it would have had small discrepancies that may not have indicated the actual trend of the specific oboe, but merely of that time sample. SpectraPlus allowed the averaging of outputs continuously. It was then possible to export the amplitude and frequency of these outputs as an Excel file. I also normalized the amplitudes of the waveforms in the oboe variation, reed variation and professional oboe experiments. This was done by dividing them by the overall power of the file. Each file was 1.94 seconds in duration in order to ensure that the Fourier spectrums would not vary as a result of the overall length of the file.

Chapter 3

Driven Oboe

3.1 Experimental Setup

As mentioned earlier, many factors pertaining to an individual musician, such as embouchure and breath speed, might affect the tone quality of an instrument. The goal of the driven oboe experiment was to eliminate such variation that might be caused by the oboist. To do this, an air tube was used to provide a controlled flow of air into the reed and oboe and a microphone was used to record the sound. Because it was impossible to mimic the pressure differences created by the human mouth it was necessary to have a faster air stream than an oboist might use to produce a tone on an oboe. The air source was a large air pump in the basement of the building the experiment was performed in. The pump only operated when pressure in the air tank fell below a specific level, which allowed for a steady flow of air at about 7.497 m/s. All of the velocities measured were within .5 m/s of the average. A human oboist was measured with an average air velocity of 4.495 m/s, with all velocities measured within 1.5 m/s of the average. This air velocity discrepancy caused the oboe to play very loudly and over saturate the microphone. To remedy this, a box lined with acoustic foam was used, which not only helped to dampen the sound of the oboe, but also helped eliminate background noise (see Figure 12). Two oboes were used in the experiment, one plastic oboe and one wooden oboe. The plastic oboe was manufactured by Fox Oboe Company and the wooden oboe was manufactured by Selmer. Three different reeds: one plastic and the other two soft and medium cane reeds were used to play each oboe.

The oboes were all recorded playing A_4 (approximately 440 Hz). This particular note was selected because it is the note that orchestras tune to. Because of this each oboe, oboist and reed must be capable of playing 440 Hz in tune. A tuner was used to ensure that the oboes were playing in tune. To adjust the tuning an oboist typically adjusts his or her embouchure. Because there was no oboist in this experiment, the oboe was tuned by manipulating the air tube and adjusting the pressure of a clamp on the end into which the reed was inserted. This made it possible to adjust the pressure on the reed, and to adjust the tuning marginally. The oboes were all recorded playing for more than 5 seconds and a clip of 1.94 seconds was taken from each of these recordings and input into SpectraPLUS. The results of the spectrum obtained from the wooden and plastic oboes are compared in Figures 13, 14 and 15, where what changes from one figure to the next is the type of reed used. In each figure the spectrum in red refers to the wood oboe and that in blue refers to the plastic oboe.

Figure 12 Experimental setup for driven oboe experiment. The box lined with acoustic foam is on the right, and the zoomed portion of the photo shows the plastic reed inserted into the air tube.

3.2 Results: Full Spectrum

3.2.1 Results: Soft Reed

By simply listening to the wooden and the plastic oboe (Track 1 and 2) it is clear the plastic oboe has a much harsher tone. The plastic oboe almost sounds out of tune, but is tuned to the same frequency as the wooden oboe. The full spectrum graphs show that the plastic oboe has higher amplitude at the higher harmonics than the wooden oboe. In the soft reed, Figure 13, this amplitude difference can be observed at the third (1320 Hz) to the thirteenth (5720 Hz) harmonics. There are also some harmonics that the plastic oboe excited that the wooden oboe did not excite at all. This can be seen at the harmonics that occur at 7480 Hz, 7920 Hz, 8880 Hz, 9680 Hz, 10120 Hz and 11440 Hz. These frequencies all correspond to harmonics of 440 Hz. Because the harmonics were slightly out of tune, these peaks actually occurred at 7469 Hz, 7897 Hz, 8874Hz, 9658 Hz, 10086 Hz and 11413 Hz. It is possible that the higher amplitudes at the

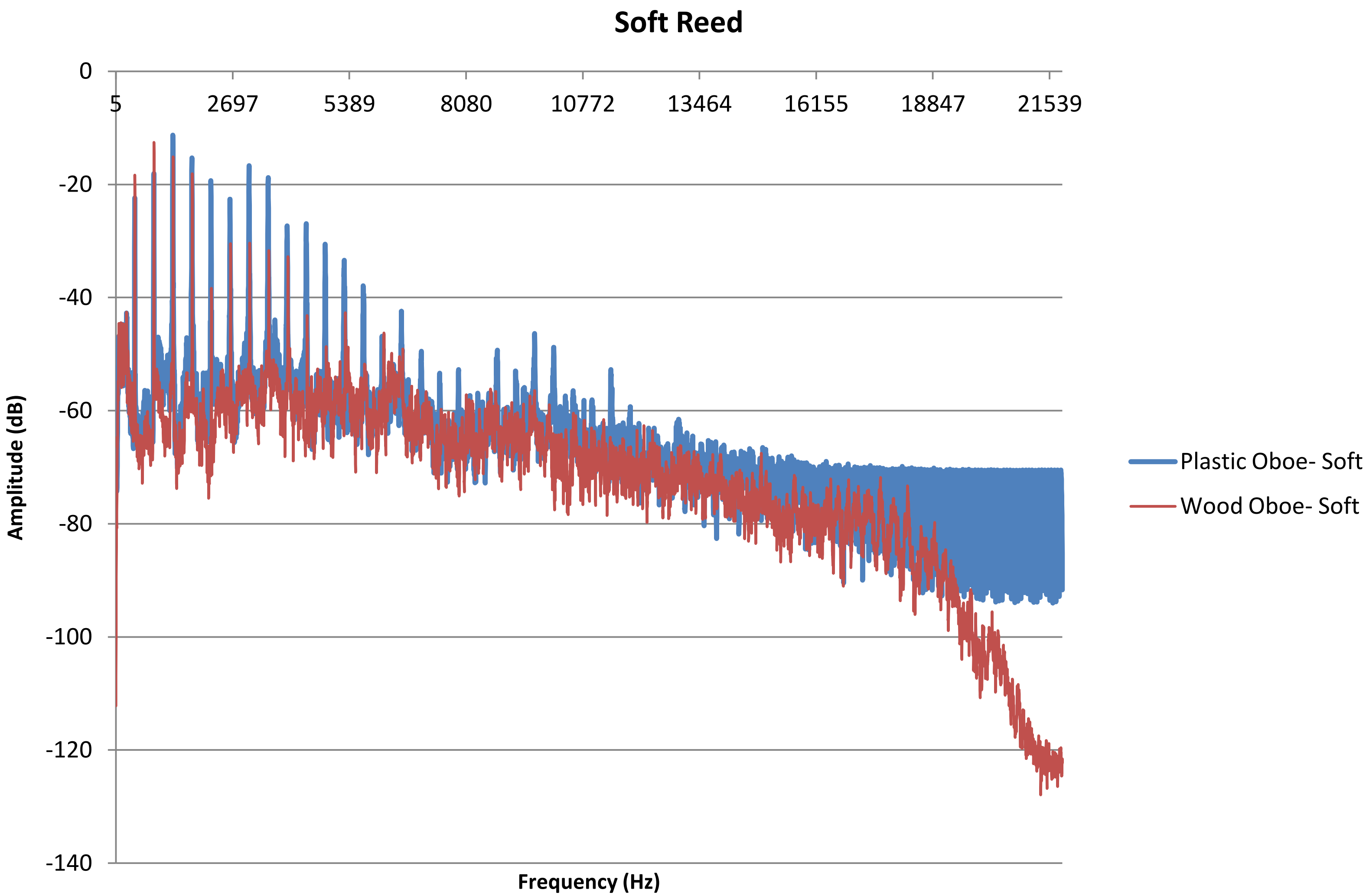

Figure 13 Spectrum of an oboe played by a driven soft reed

upper harmonics and the extra harmonics account for the harsher sound of the plastic oboe.

In both the wood and plastic oboes the fundamental frequency is not the highest amplitude frequency present in the spectrum. The second harmonic, 880 Hz of greater amplitude with an amplitude of -12 dB in the wood oboe and an amplitude of -18 dB in the plastic oboe. The third harmonic is of the highest amplitude of any frequency in the spectrum with amplitude of -15 dB on the wood oboe and -11 on the plastic oboe.

When the plastic oboe was played using a soft reed an oscillation of amplitues occurred over 16 kHz with amplitude of about 10 dB (see Figure 13). The cause of this oscillation is unknown; however when the sound file was passed through a low-pass filter at 16 kHz there was no noticeable tone difference. The oscillation in the plastic oboe mostly took place at frequencies beyond the audible spectrum. In contrast to the oscillation shown by the plastic oboe, the wooden oboe showed a sharp drop off in the amplitudes in the spectrum over 16 kHz.

3.2.2 Results: Medium Reed

There is an audible difference between the wooden and the plastic oboes (Tracks 3 and 4) once again. The spectra, Figure 14, for the wooden and plastic oboes played by the medium reed showed many similarities to the soft reed. The plastic oboe showed higher amplitudes at the higher harmonics than the wooden oboe. These amplitude differences were from the fifth (2200 Hz) to the seventeenth (7480 Hz) harmonics. The plastic oboe excited some harmonics that

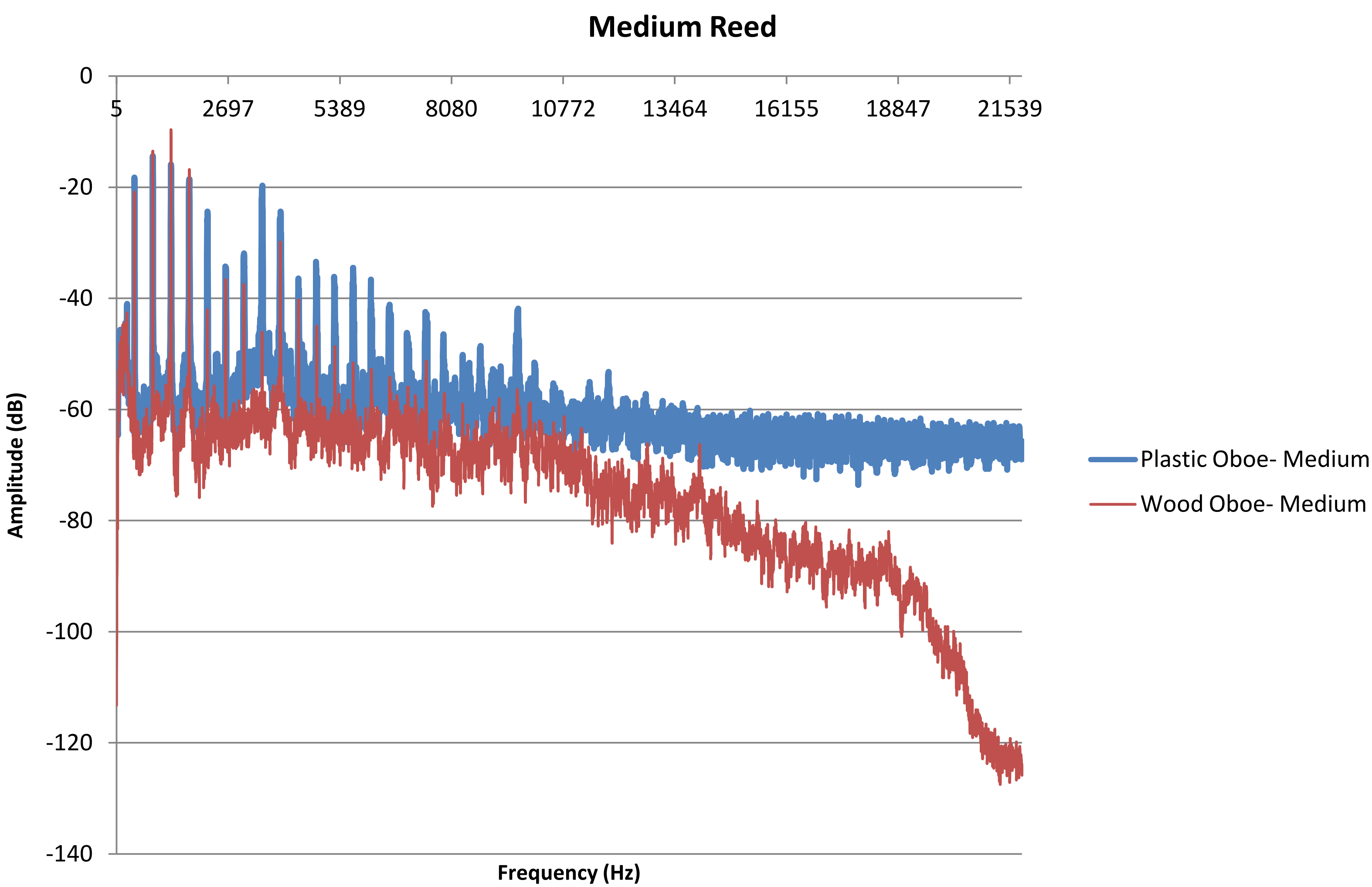

Figure 14 Spectrum of an oboe played by a driven medium reed

the wooden oboe did not excite, however not as many harmonics as with the soft reed. The medium reed excited frequencies near primarily 9680 Hz on the plastic oboe but not on the wooden. This peak actually occurred at 9673 Hz. While there are several other minor peaks in the plastic oboe's spectrum, none show a drastic difference to the wooden oboe. There was a change in the overall amplitude between the plastic and the wooden oboes, but this amplitude difference was only 5 dB. The medium reed also showed similar oscillations over 16 kHz, these oscillations are of much lower amplitude than those seen with the soft reed. This indicates that the oscillations may be related to the reed strength. The medium reed also had higher amplitude at the third harmonic than the first harmonic. The third harmonic had amplitude of -9 dB in the wood oboe and -15 dB in the plastic oboe.

3.2.3 Results: Plastic Reed

There are still audible differences between the plastic and the wooden oboe (Tracks 5 and 6). The plastic reed showed many differences to the spectra obtained using cane reeds (see Figure 15). The amplitudes of the entire spectra played by the plastic reed showed more similarities to each other than with the previous cane reeds, however differences are still apparent. Once again the plastic oboe showed higher amplitudes at higher harmonics than the wooden oboe. There are fewer harmonics which show greater amplitudes when played with the plastic reed than with either of the cane reeds. Only at 2200 Hz, 3060 Hz, 3520 Hz, and 5280 Hz are there significant amplitude differences. However, unlike

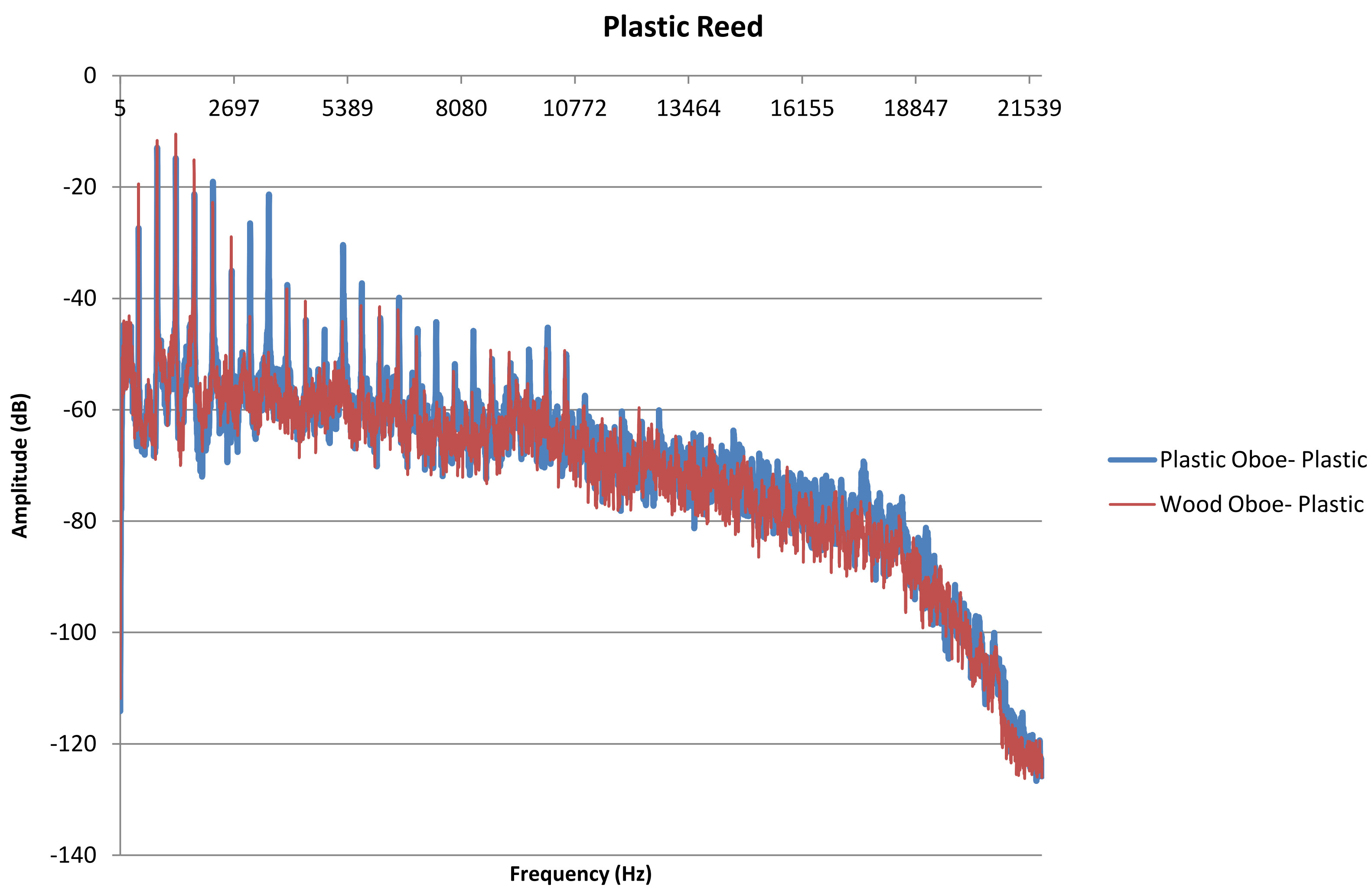

Figure 15 Spectrum of an oboe played by a driven plastic reed

with the cane reeds, the plastic oboe has no oscillations present over 16 kHz. This indicates that the oscillations that were present in the spectra for the cane reeds might be particular to the type of reed that was used. Instead, the plastic oboe showed a drop off similar to the wooden oboe. Once again the third harmonic showed the highest amplitude of any frequency in the spectrum. The amplitude at 1320 Hz was -10 dB in the wood oboe and -14 dB in the plastic oboe.

3.3 Results: Harmonics

In Figure 16, I have plotted only the values at 440 Hz and higher harmonics. By plotting only the amplitudes at the harmonics it is possible to observe a systematic difference in the amplitudes of the higher harmonics between the plastic and the wooden oboe. From this plot, it is clear that there are few correlations between the reeds. It seems that the oboes, regardless of the reed used emphasize some of the same harmonics and ignore others. All of the oboes show greater amplitudes at the second harmonic (880 Hz). The wooden oboes showed a distinct drop off in harmonic amplitude at the fifth harmonic (2200 Hz). The plastic oboes all emphasized the eighth harmonic (3520 Hz), and showed a decrease in amplitude at the sixth harmonic (2640 Hz). It is clear from this plot that in none of the trials is the highest amplitude frequency the first harmonic. This is peculiar since this is the frequency that was played, tuned and heard in all of the experiments.

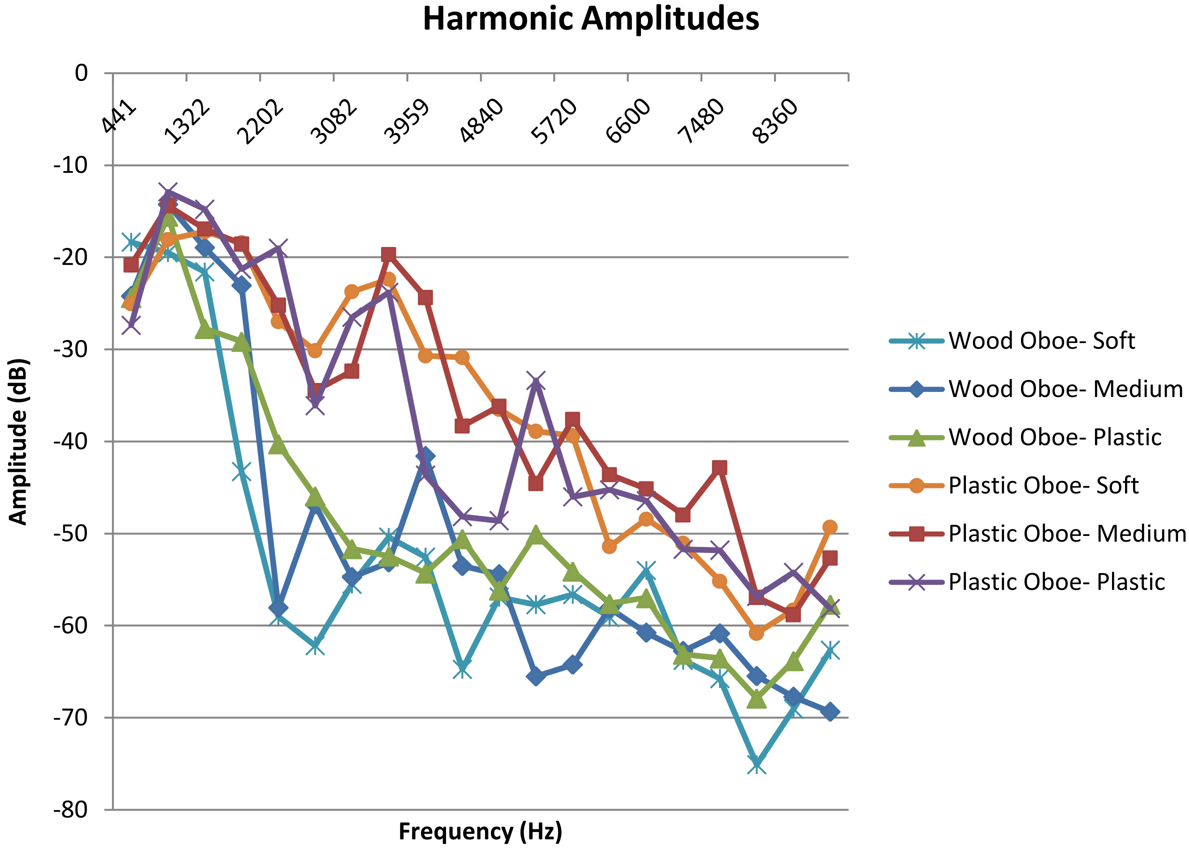

Figure 16 Amplitude vs. frequency plot of harmonics for a driven oboe

Chapter 4

Fox Oboes

4.1 Experiment

The main objective of this part of the experiment was to determine if there was a difference in the acoustic spectra when oboes of different compositions were played. In an attempt to control the number of variables, I used the same reed and the same oboist (myself). Six oboes were used: two wooden, two plastic and two half wooden/half plastic. All of the oboes were produced by the Fox Oboe Company in South Whitley, Indiana. The oboes had the same key configuration, and the only noticeable difference was the material that the oboe was made of. Oboes 1 and 2 were made of plastic; oboes 3 and 4 were made of half-plastic, half-wood, and oboes 5 and 6 were made entirely of wood.

4.2 Results: Full Spectrum

While there are audible differences between oboes of both the same and varying compositions, these variations are not consistent (Tracks 7 through 12).

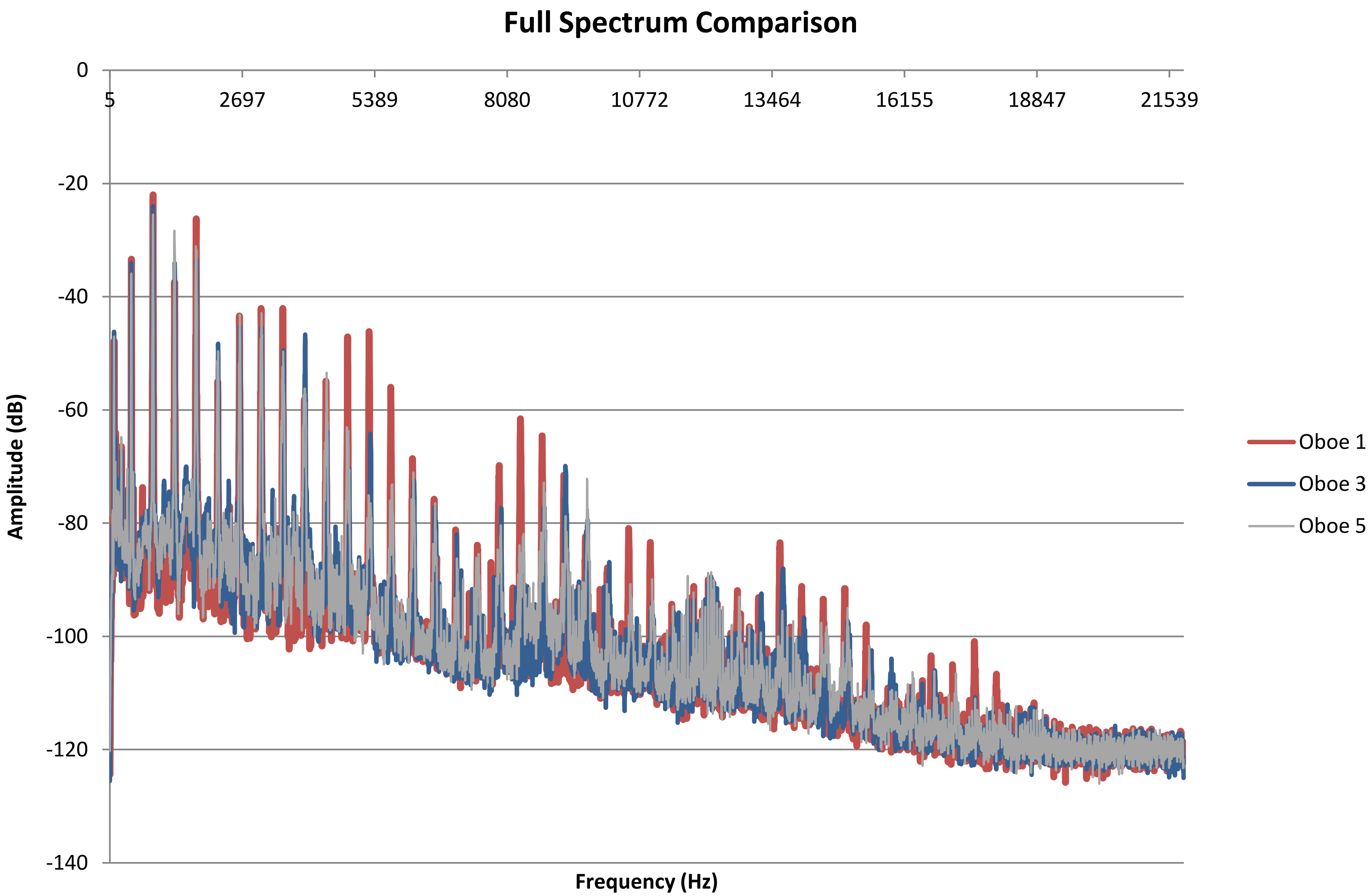

Figure 17 Spectrum for Fox oboes 1, 3, and 5. Oboe 1 is made of plastic, oboe 3 is half-plastic/half-wooden and oboe 5 is made of wood.

There are few differences in the spectra of oboes of the same compositions. Because there were few differences between oboes of the same composition, only one oboe of each composition was compared in Figure 17. Oboe 1, a plastic oboe, is displayed in red; oboe 3, a half-wooden/half-plastic oboe, is displayed blue, and oboe 5, a wooden oboe, is displayed in grey. The plastic oboe shows higher amplitudes in some of the harmonics. These differences occur near the harmonics at 1760 Hz, 3520 Hz, 4840 Hz, 5280 Hz, 5720 Hz, 7920 Hz, 8360 Hz, and 8880 Hz. The actual frequencies observed were 1760 Hz, 3515 Hz, 4832 Hz, 5270 Hz, 5712 Hz, 7908 Hz, 8344 Hz, and 8826 Hz.

The Fox oboes spectra have several differences from the driven oboe spectra. The driven oboe experiment only showed harmonics up to 11440 Hz. The Fox oboes showed consistent harmonics up to 18040 Hz as seen in Figure 17. A wide peak, centered about 12 kHz also appeared in this portion of the experiment which was not present in the driven oboe experiment. The peak is a little less than 1 kHz in width, and with amplitude of approximately 25 dB. This wide peak is made of many smaller peaks at non harmonic frequencies. Because these variations appeared only in the Fox oboes, it indicates that the variations may have been caused by the oboist.

4.3 Results: Harmonics Comparison

Figure 18 shows that there were fewer differences in the amplitudes at particular harmonics in the Fox oboes than there were in the driven oboes. All of the oboes showed a significant increase in amplitude at 880 Hz and at 2200 Hz. It is more evident in these notes that the first harmonic is not of the highest amplitude. As in the driven oboe experiment, it appears that 880 Hz is consistently of the highest amplitude. There is not a large difference in the amplitudes of the plastic and wooden oboes; however the plastic oboes have the highest amplitude of the oboes played. The wooden oboes had a more gradual decrease in the amplitudes of the frequencies between 2640 Hz and 6600 Hz.

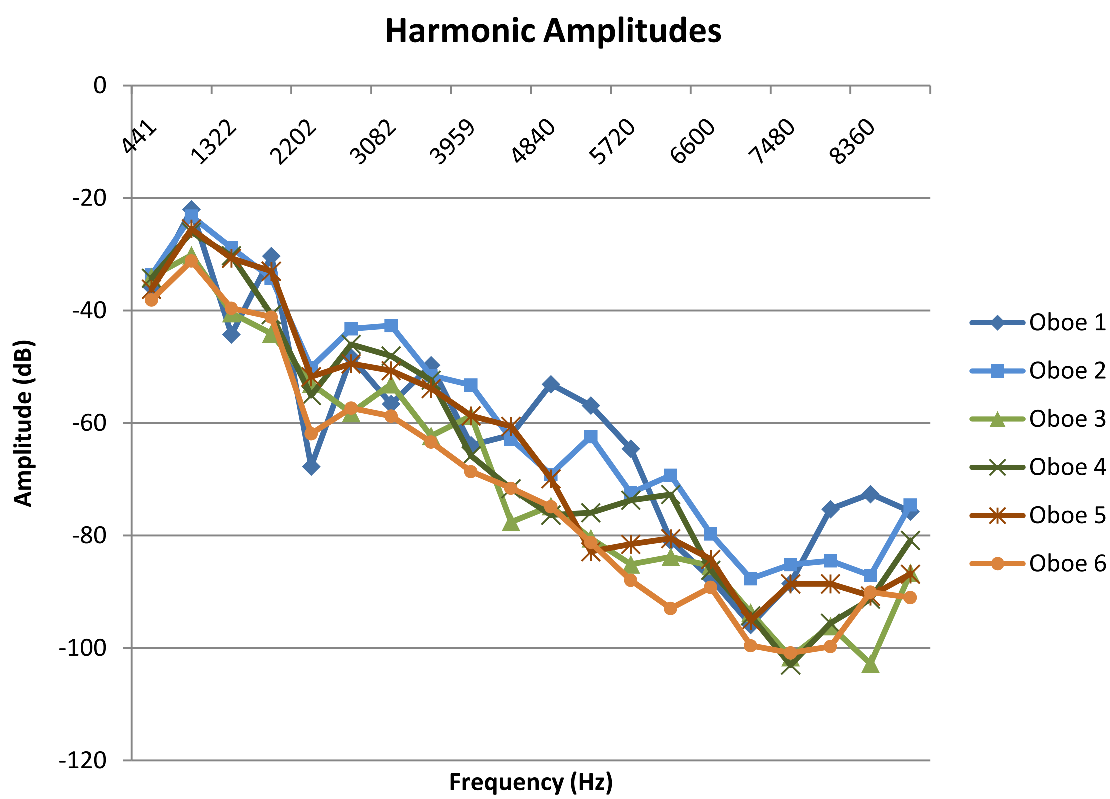

Figure 18 Amplitudes at harmonics for Fox Oboes

4.4 Results: Width of Harmonics

It is hard to determine from the full spectrum what is occurring at the frequencies immediately around the harmonics. To observe these frequencies a

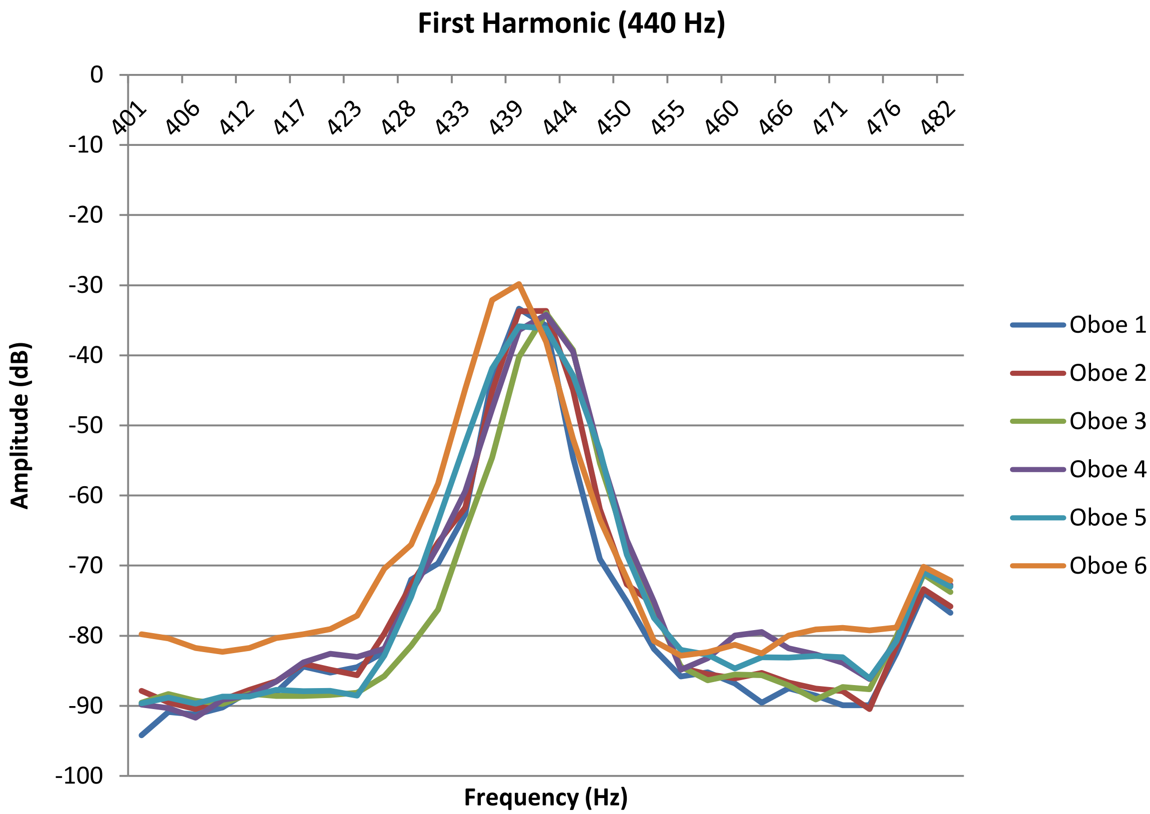

Figure 19 Amplitudes at 440 Hz and surrounding frequencies for Fox oboes

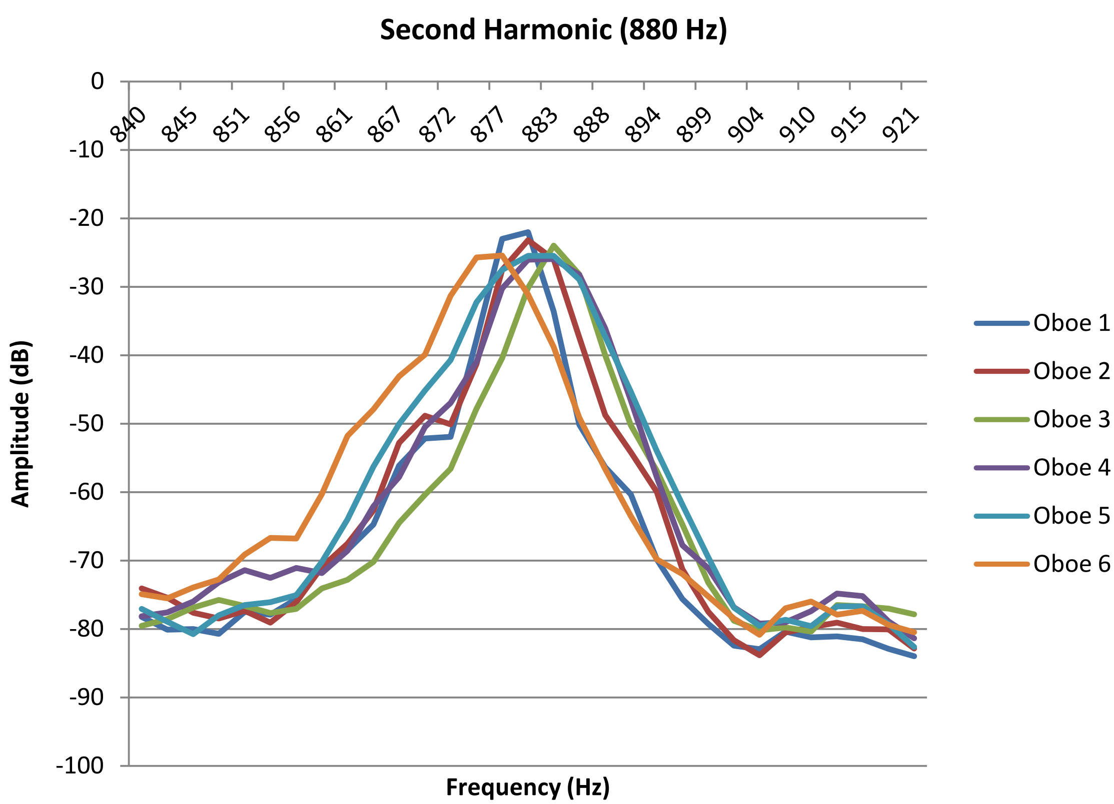

Figure 20 Amplitudes at 880 Hz and surrounding frequencies Fox oboes

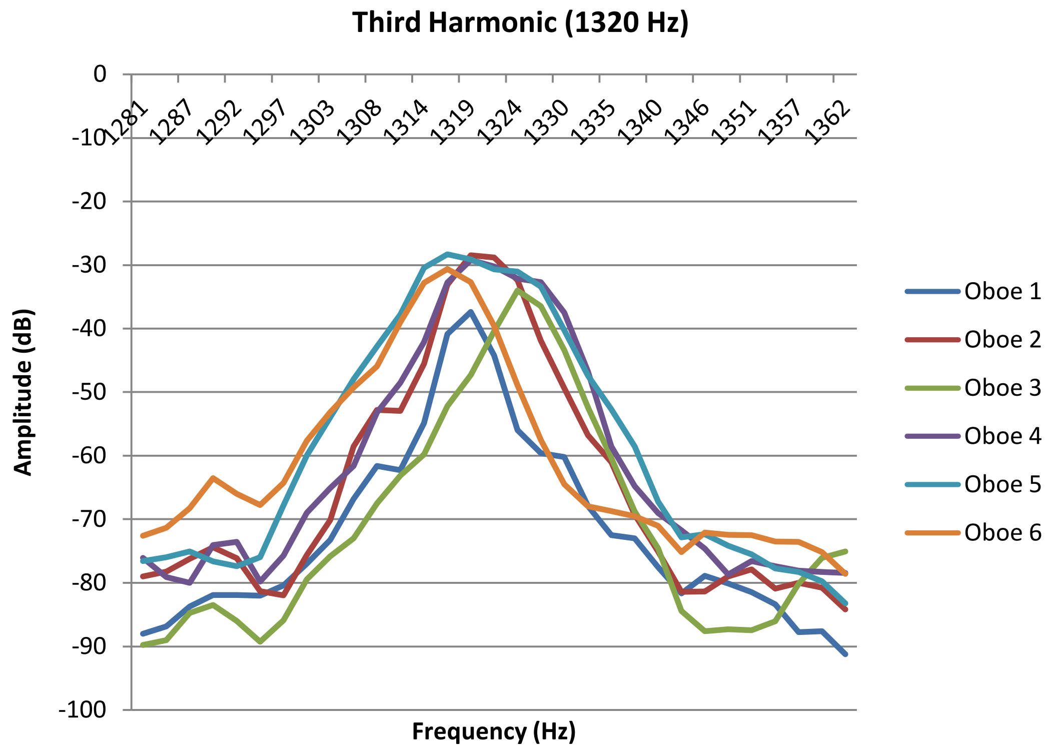

Figure 21 Amplitudes at 1320 Hz and surrounding frequencies for Fox oboes

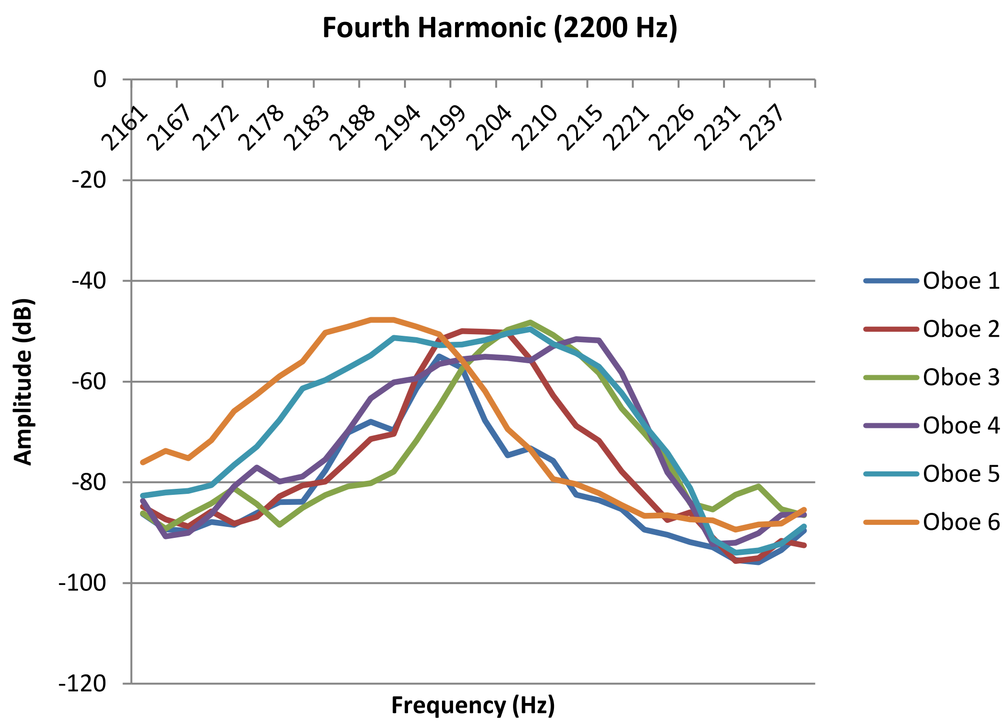

Figure 22 Amplitudes at 2200 Hz and surrounding frequencies for Fox oboes

small section of the full spectrum was graphed. By observing frequencies that fall within the range of 40 Hz below a harmonic and 40 Hz above a harmonic it is possible to observe more variations in the oboes. Figure 19 shows that at 440 Hz there were very few differences between any of the oboes. Oboe 6, in orange, appeared to be slightly out of tune at 440 Hz. However, all six oboes were very similar in their amplitudes around 440 Hz, which is expected as it is the frequency played and the frequency which was tuned.

At the second harmonic, 880 Hz (Figure 20), differences between the oboes begin to become more apparent. Oboes 5 and 6, the wooden oboes, begin to show higher amplitudes at the frequencies surrounding the harmonics. This difference becomes more obvious at the third harmonic. While oboe 6 is shifted slightly it is clear that oboe 5 has the highest amplitude at the frequencies surrounding the harmonic. This difference continues through the higher harmonics, but becomes more difficult to see because the harmonics begin drifting out of tune. In Figures 21 and 22, it is clear that the wooden oboes have the highest amplitudes at the surrounding frequencies. However, this also shows that some of the harmonics are drifting out of tune. Despite the tuning problem, it appears that the wooden oboes appear to include more frequencies surrounding the harmonic than the plastic or half-plastic/half-wooden oboes.

Chapter 5

Oboe Variation

5.1 Experiment

In the next portion of my experiment I attempted to observe differences between oboists playing on their own reed and two different oboes. The oboes used in this portion of the experiment were the same plastic and wooden oboe used in the driven oboe experiment. Four different oboists played a note on a wooden oboe and a plastic oboe with their own reeds. Oboist 1 has been playing for 3 years and her reed was made by a professional oboist. Oboist 2 has been playing for 9 years and her reed was manufactured. Oboist 3 had played for 9 years but had not played in 7 years and was playing on a manufactured reed with personal variations. Oboist 4 has been playing for 11 years and was playing on a manufactured reed with personal variations. Oboists 1, 2 and 4 all play currently with the Mount Holyoke College Orchestra.

In the previous experiments it was not necessary to worry about the amplitude of the sound files compared to each other. In the driven oboe experiment the air flow rate was constant throughout, thus the volume of the sound file was even throughout. The Fox oboe experiment had only one oboist playing, and making a conscious effort to have as little embouchure variation as possible between notes. However in this experiment the goal was to look at the variation between oboists. Because each oboist played the note at a different volume it was necessary to normalize the sound files. This was done by dividing the amplitude at each frequency by the total power of the clip, thus eliminating variation in the notes due to the overall amplitude of the note played.

5.2 Results: Full Spectrum

In this part of the project it is unclear whether or not the oboe's composition had any effect on the harmonic content of the note. By listening to the recordings of the individual oboists it is clear that there is a distinct variation between oboists (Tracks 13-20). However, it is much more difficult to hear the difference between the plastic and wooden oboes played by the same oboist. Oboist 1, whose spectra is shown in Figure 23 shows higher amplitudes with the plastic oboe at 2651 Hz, 3087 Hz, 3534 Hz, 4417 Hz, and 5747 Hz. These frequencies correspond approximately to the sixth, seventh, eighth, tenth and thirteenth harmonics. The plastic oboe showed peaks at 7066 Hz, and 7948 Hz. These correspond to the sixteenth and eighteenth. Oboist 1's spectrum also shows

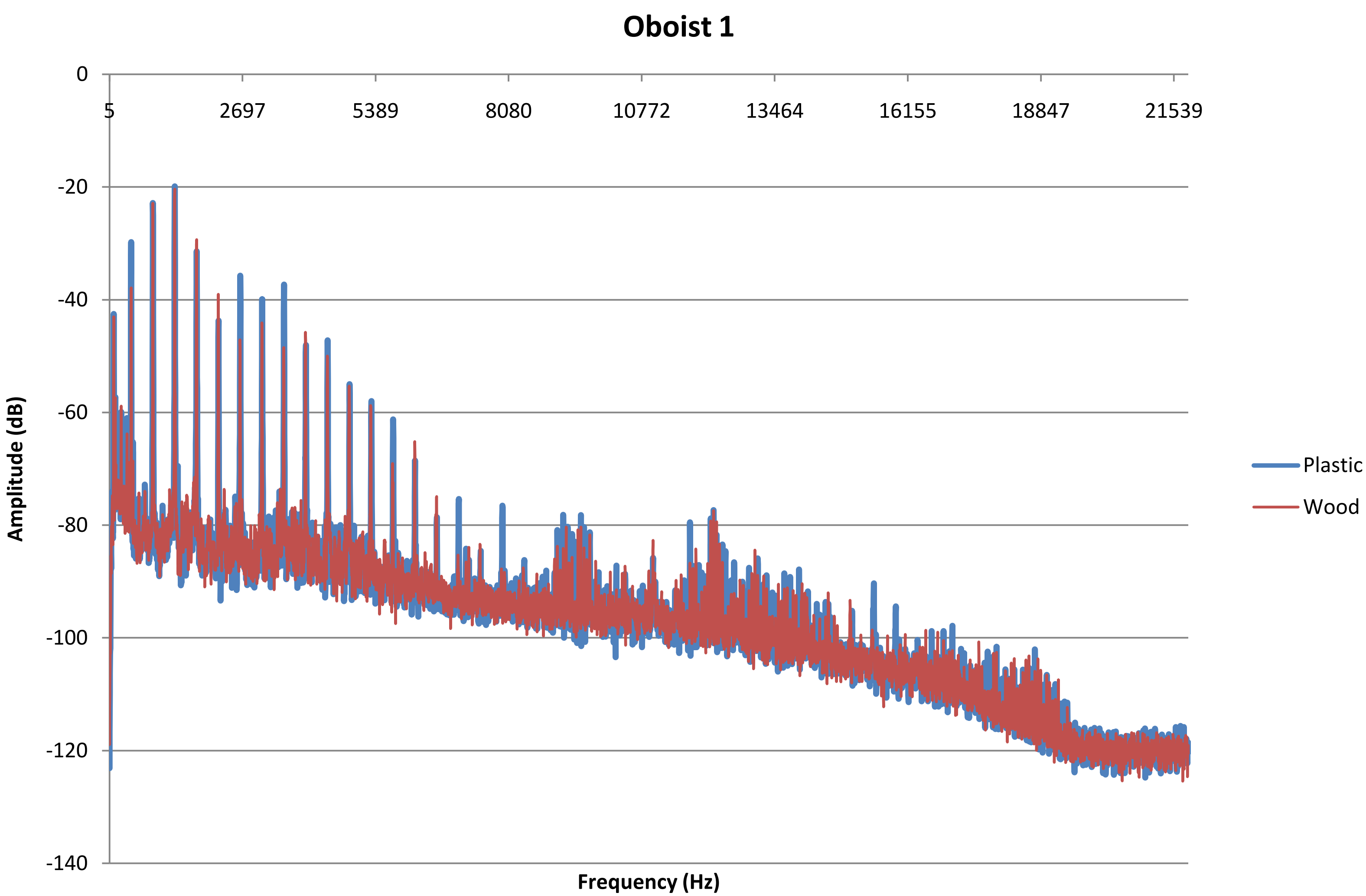

Figure 23 Spectrum of oboist 1 for wood and plastic oboes

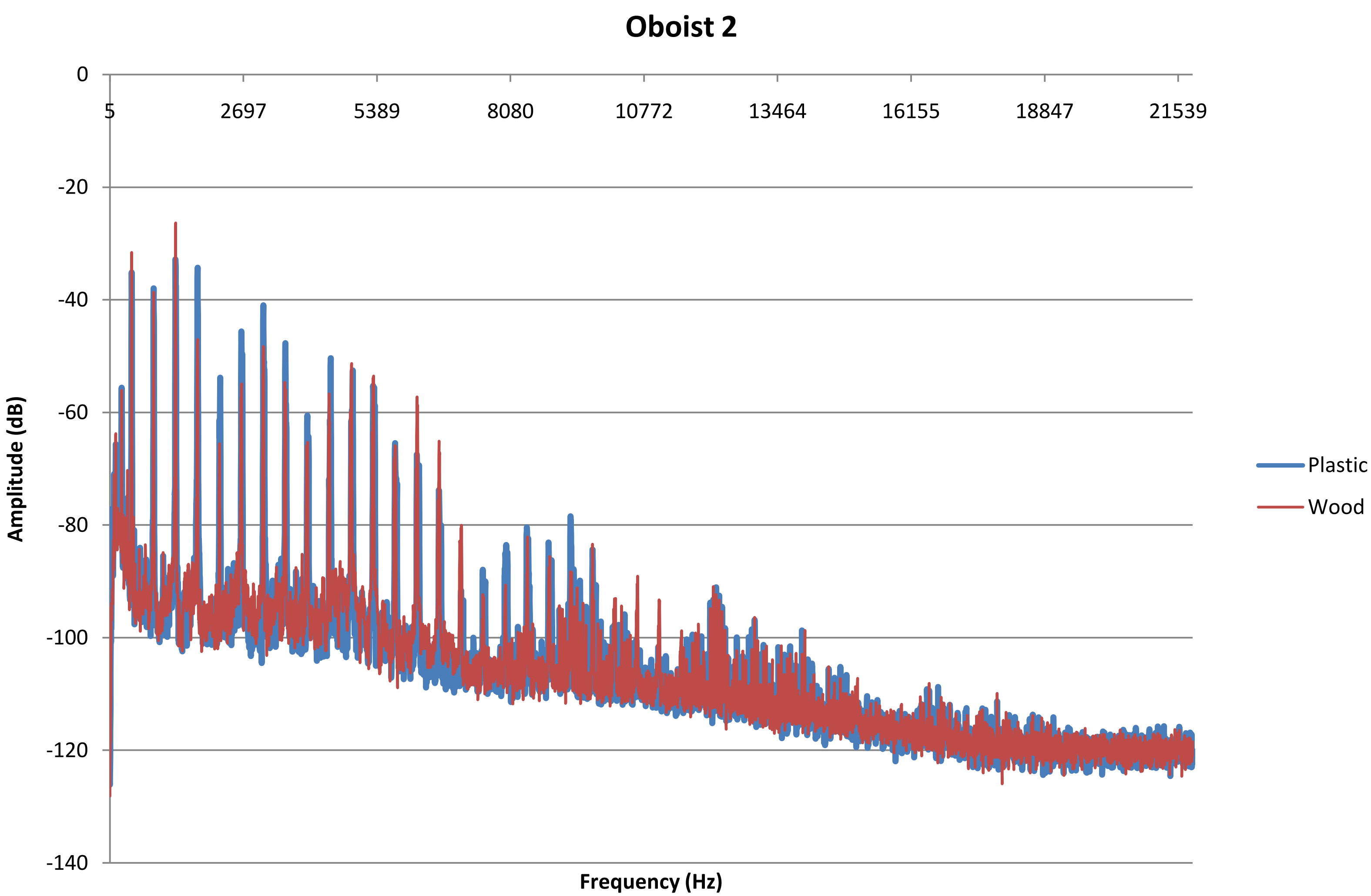

Figure 24 Spectrum of oboist 2 for wood and plastic

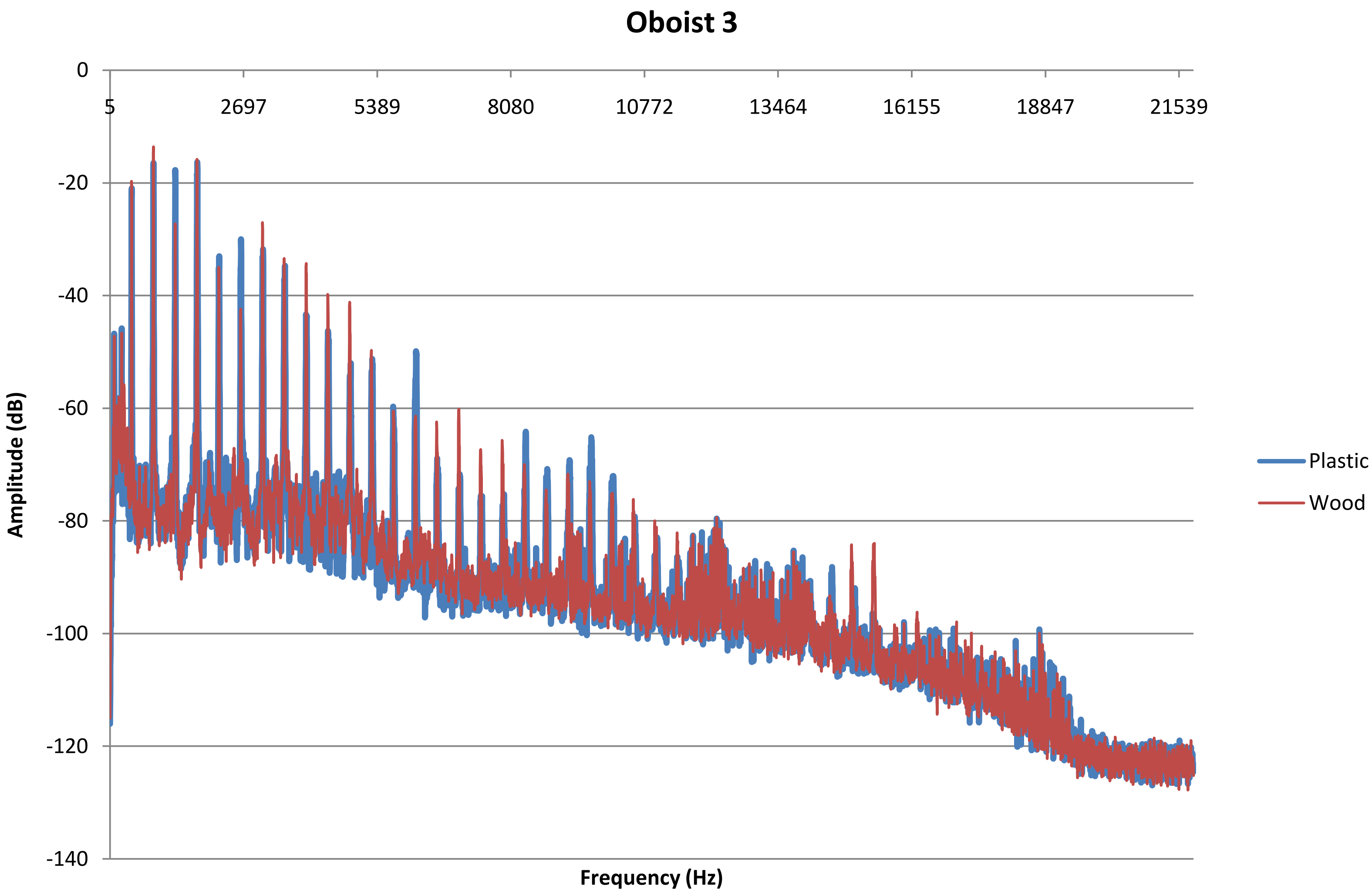

Figure 25 Spectrum of oboist 3 for wood and plastic oboes

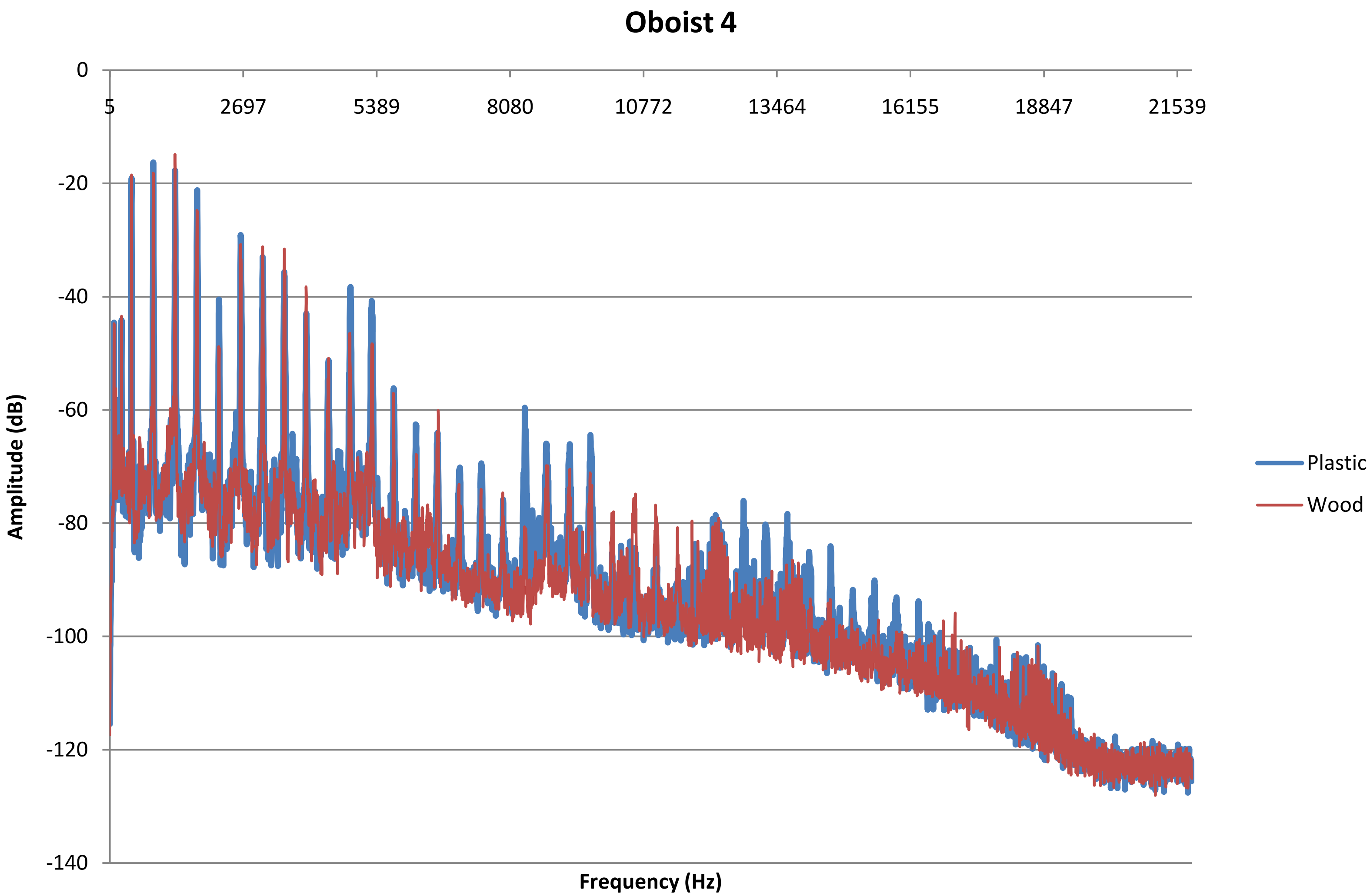

Figure 26 Spectrum of oboist 4 for wood and plastic oboes

peaks at 11749 Hz and 15466 Hz which do not correspond to a particular harmonic. Oboist 1 shows the highest amplitude in her spectrum at 1320 Hz, where both plastic and wooden oboes have amplitude of -20 dB. The second harmonic, 880 Hz has a lower amplitude than 1320 Hz but is still of greater amplitude than 440 Hz. Oboist 1 is the least experienced of the oboists in this experiment, which might explain why there are high non-harmonic frequencies present in her note.

Oboist 2, Figure 24, shows higher amplitudes on the plastic oboe at 1768 Hz, 2226 Hz, 2654 Hz, 3098 Hz, 3540 Hz, 3981 Hz, 4452 Hz, 7518 Hz, 7992 Hz, and 9289 Hz. These frequencies correspond to approximately the fourth through tenth, seventeenth, eighteenth and twenty-first harmonics. Oboist 2's spectrum had no peaks that did not appear on both the wood and plastic oboes. The highest amplitude in the Oboist 2's spectrum is the third harmonic (1320 Hz). However 880 Hz is of lower amplitude than the first harmonic.

Oboist 3, Figure 25, has higher amplitudes on the plastic oboe at 1320 Hz, 2646 Hz, 6169 Hz, 8374 Hz, 8791 Hz, 9251 Hz and 9701 Hz. These frequencies correspond to the third, sixth, fourteenth, nineteenth, twentieth, twenty-first, and twenty second harmonics. In oboist 4's spectrum the second, third and fourth harmonics are all of relatively uniform amplitudes, around -18 dB.

When the plastic oboe was played by Oboist 4, Figure 26, 2202 Hz, 4850 Hz, 5281 Hz, 6175 Hz, 7044 Hz, 7485 Hz, 8376 Hz, 8804 Hz, 9275 Hz, and 9658 Hz were played at higher amplitudes than on the wooden oboe. These correspond fifth, eleventh, twelfth, fourteenth, sixteenth, seventeenth, and nineteenth through twenty-second harmonics. There were also additional frequencies beyond 9658 Hz that had higher amplitudes on the plastic oboe. None of the oboists had harmonics present in the plastic oboe that were not present in the wooden oboe. All of the oboists had a peak of approximately 10 dB and width of approximately 1 kHz, centered around 12 kHz. Oboist 4 has higher amplitude at the second harmonic and third harmonics as compared to the fundamental; however the two harmonics are of relatively uniform amplitude.

The different oboists also seem to be capable of exciting only up to a certain harmonic. Oboist 1 was able to excite harmonics up to 6624 Hz. There continues to be harmonic content after that point, however on the full spectrum it is clear that those peaks are sporadic. Oboist 2 could excite harmonics up to about 9000 Hz while oboists 3 and 4 had considerable harmonic content over 10 kHz.

5.3 Results: Harmonics Comparison

The differences between the oboists are most easily recognized by observing the amplitudes of the harmonics in Figure 27. The oboists independently show many similarities in amplitudes; however there is no clear correlation in the graph except among oboists. Oboist 2 has the highest amplitude at the higher harmonics. Oboist 1 also has high amplitudes at the higher harmonics, while Oboists 3 and 4 have much lower amplitudes.

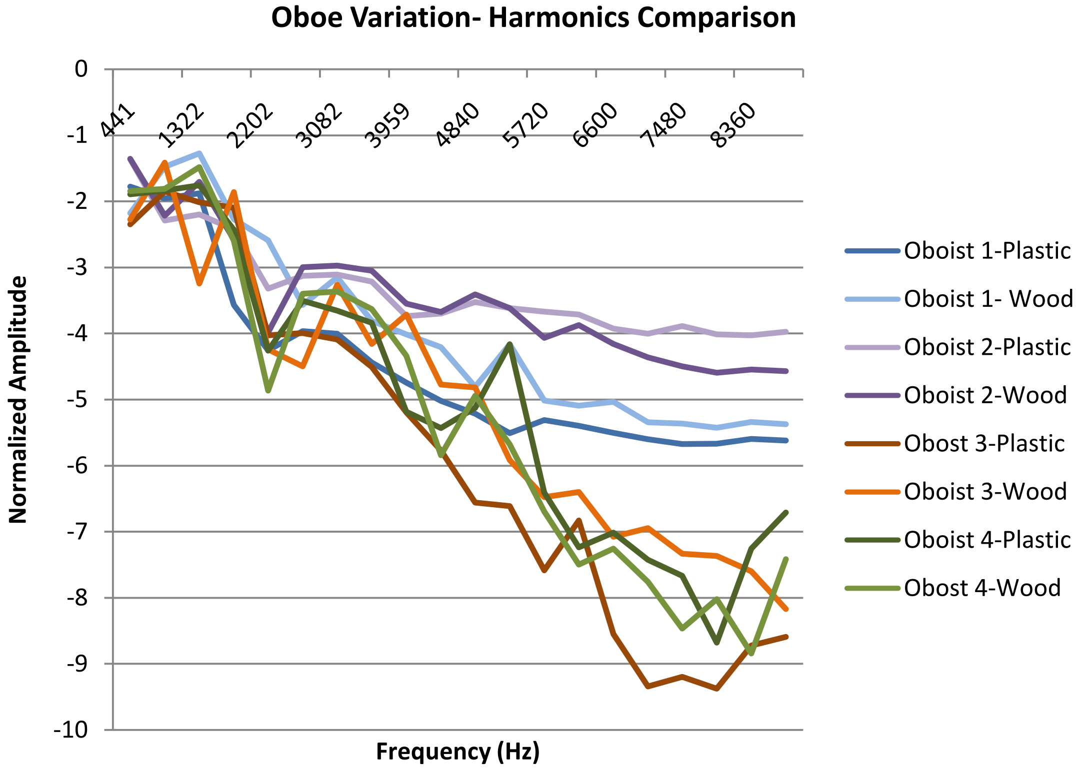

Figure 27 Amplitudes of harmonics for oboists on wood and plastic oboes

5.4 Results: Width of harmonics

Observing the amplitudes of the harmonics and their surrounding frequencies in Figure 28 shows clearly that there are major differences between the oboists. Oboist 2 has the greatest amplitude at 440 Hz, but also the greatest amplitude at the surrounding frequencies. The plastic oboe played by oboist 2 has marginally greater amplitude at surrounding frequencies however both appear to have the same amplitude at 440 Hz. Oboist 1 had lower amplitudes at the surrounding frequencies then oboist 2. Again there were few differences between the wooden and the plastic oboes. Oboists 3 and 4 had very similar amplitudes at 440 Hz. However, oboist 3 had marginally higher amplitudes at surrounding

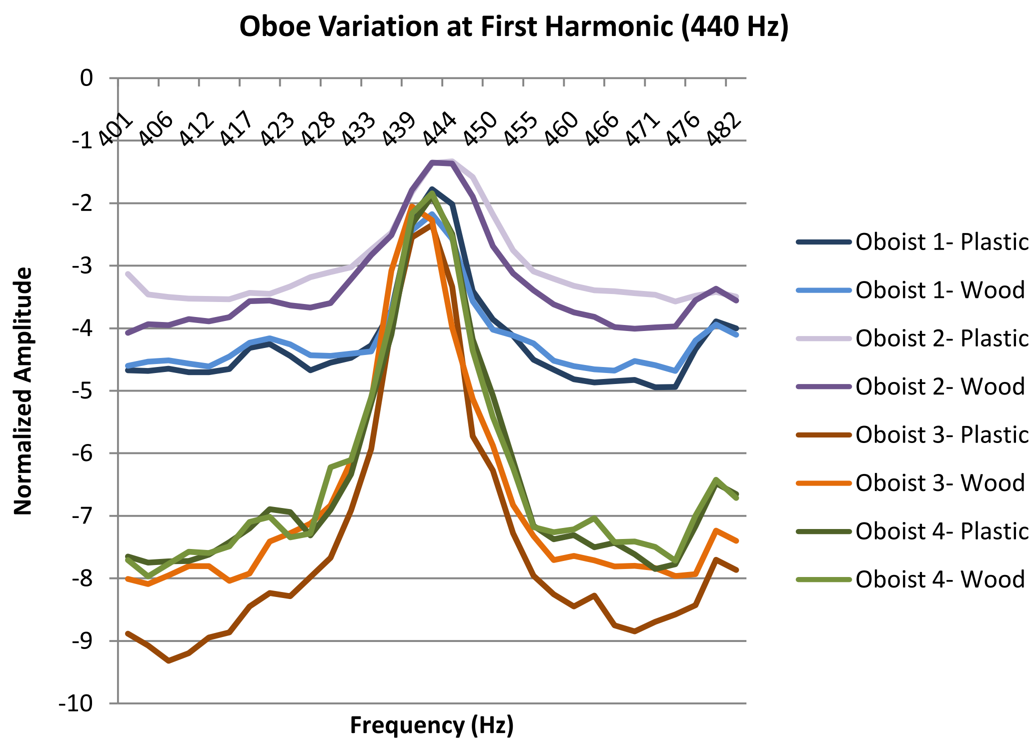

Figure 28 Amplitudes at frequencies surrounding 440 Hz for oboists on wood and plastic oboes

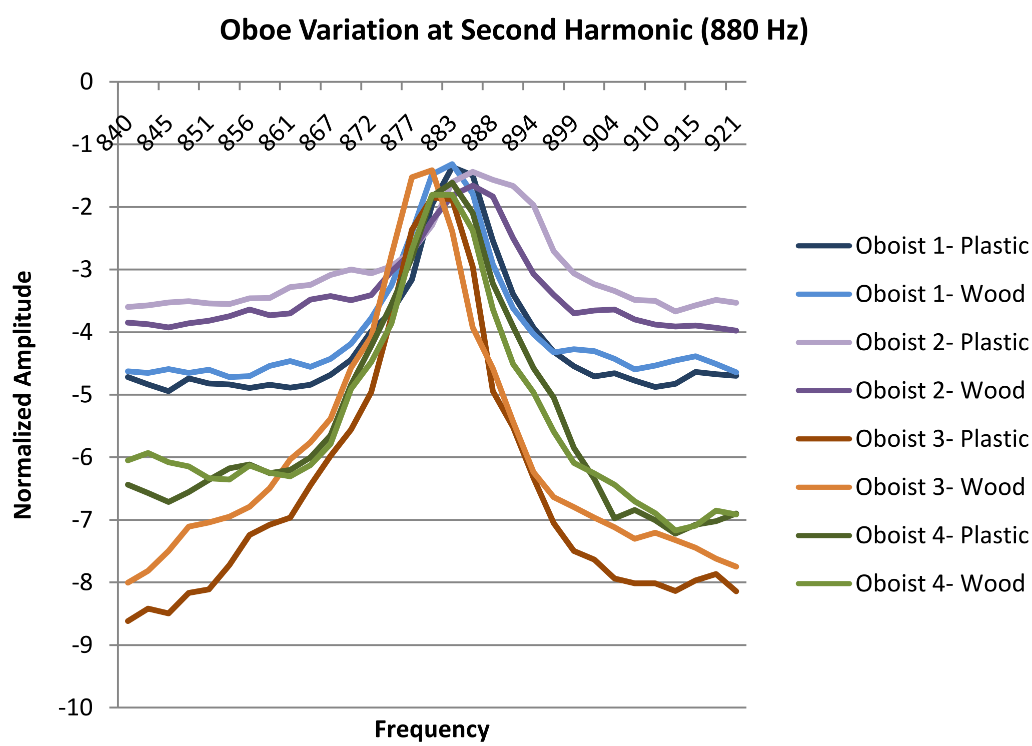

Figure 29 Amplitudes at frequencies surrounding 880 Hz for oboists on wood and plastic oboes

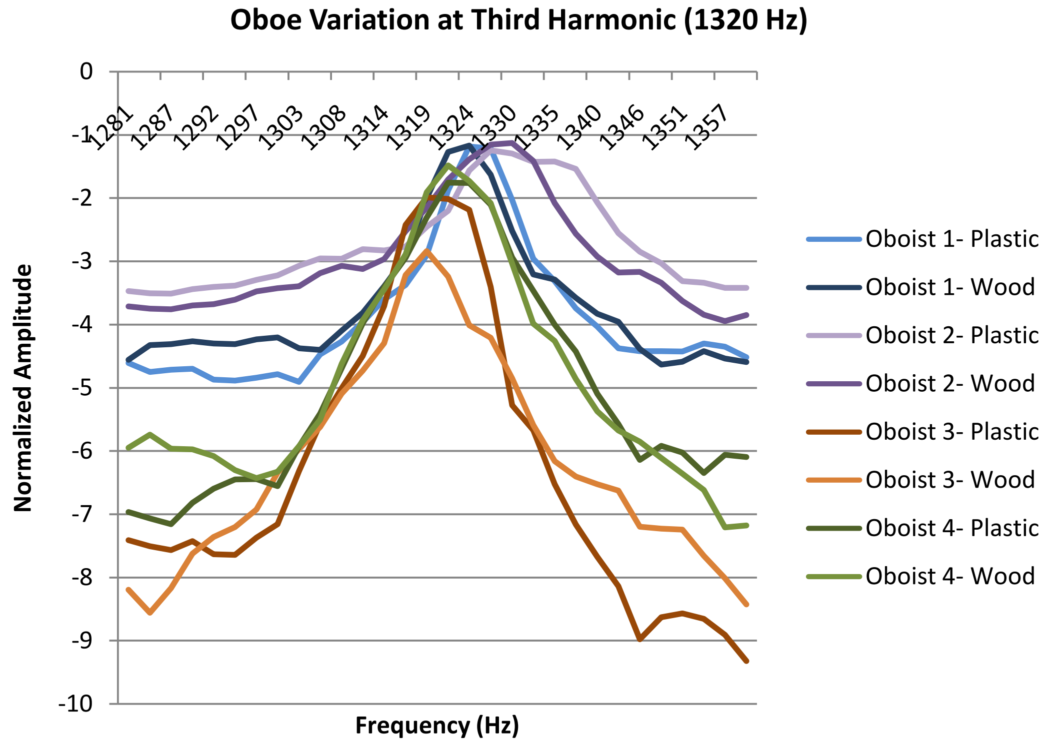

Figure 31 Amplitudes at frequencies surrounding 1320 Hz for oboists on wood and plastic oboes

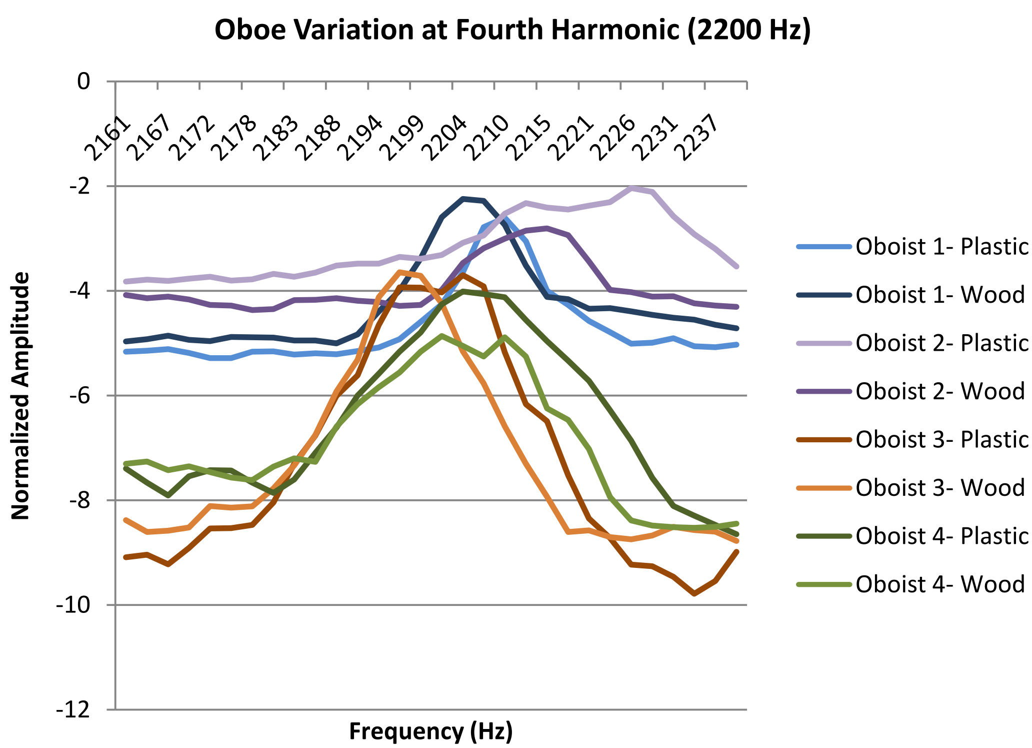

Figure 30 Amplitudes at frequencies surrounding 2200 Hz for oboists on wood and plastic oboes

frequencies, and oboist 4 had the lowest amplitudes at the surrounding frequencies.

The similarities between notes played by the same oboist continue up the spectrum. With the exception of Oboist 2 playing the plastic oboe there appear to be no cases where the amplitude at the surrounding frequencies of the harmonic for the wooden oboe exceeds those of the plastic oboe. However the peaks for all oboists broaden considerably after the fundamental harmonic. Despite this change, the amplitudes for the different oboists remain distinct.

Chapter 6

Reed Variation

6.1 Experiment

The reed variation portion of the project concentrated on the variation between different oboists playing on the same reeds. The oboists from the previous section were provided with the same plastic, soft and medium reeds used in the driven oboe experiment. The plastic and wooden oboes from the driven oboe and oboe variation portion of the project were also used. The reeds were dipped in alcohol between oboists to sterilize them. This should not have affected the integrity of the reed, and did not appear to. There are distinct differences in the sound files (Tracks 21-44). There is little variation to the ear between the plastic and wooden oboes; however the difference between the cane and plastic reeds is much more noticeable.

6.2 Results: Full Spectrum

The full spectrum results showed several interesting trends. The plastic oboe still shows higher amplitudes at some harmonics than the wooden oboe.

This is most noticeable in Figures 33, 36, 39 and 42. These spectra correspond to the notes played with a medium strength reed. The amplitudes at the frequencies surrounding the harmonics in the plastic reed trials, Figures 34, 37, 40 and 43 are greater than those played with cane reeds. This can be seen by a broadening of the peaks in the plastic reeds. This trait was clear for all of the oboists. It also appears that the number of harmonics each oboist is able to excite depends on the reed used. With the exception of oboist 1, the plastic reeds excited regular harmonics up to 17601 Hz. Oboist 1 only has harmonics up to 15049 Hz, after which the amplitude of the frequencies surrounding the harmonics exceeds the amplitude of the harmonics. The soft reeds, by comparison, excited harmonics sporadically up to the highest harmonic. In oboist 1, Figure 32, frequencies as high as 9082 Hz were excited with the soft reed. The frequencies higher than that do not appear to be uniform harmonics, and in some cases, the frequencies are not harmonics of 440 Hz. This suggests that the least experienced oboist, as in the oboe variation experiment, is not as in tune at the higher harmonics as the other oboists. Oboist 2's soft reed spectrum, Figure 35, shows harmonics as high as 19313 Hz, however not all the harmonics between 19313 Hz and 440 Hz are present. The harmonics that are present are of much lower amplitude than the plastic reed. Oboist 3's soft reed spectrum follows a similar pattern in Figure 38. Harmonics as high as the forty-third are present, however there are absent harmonics. Oboist 4, Figure 41, has regular harmonics as high as 15437 Hz, however they are of much lower amplitude than those in the plastic reed spectrum.

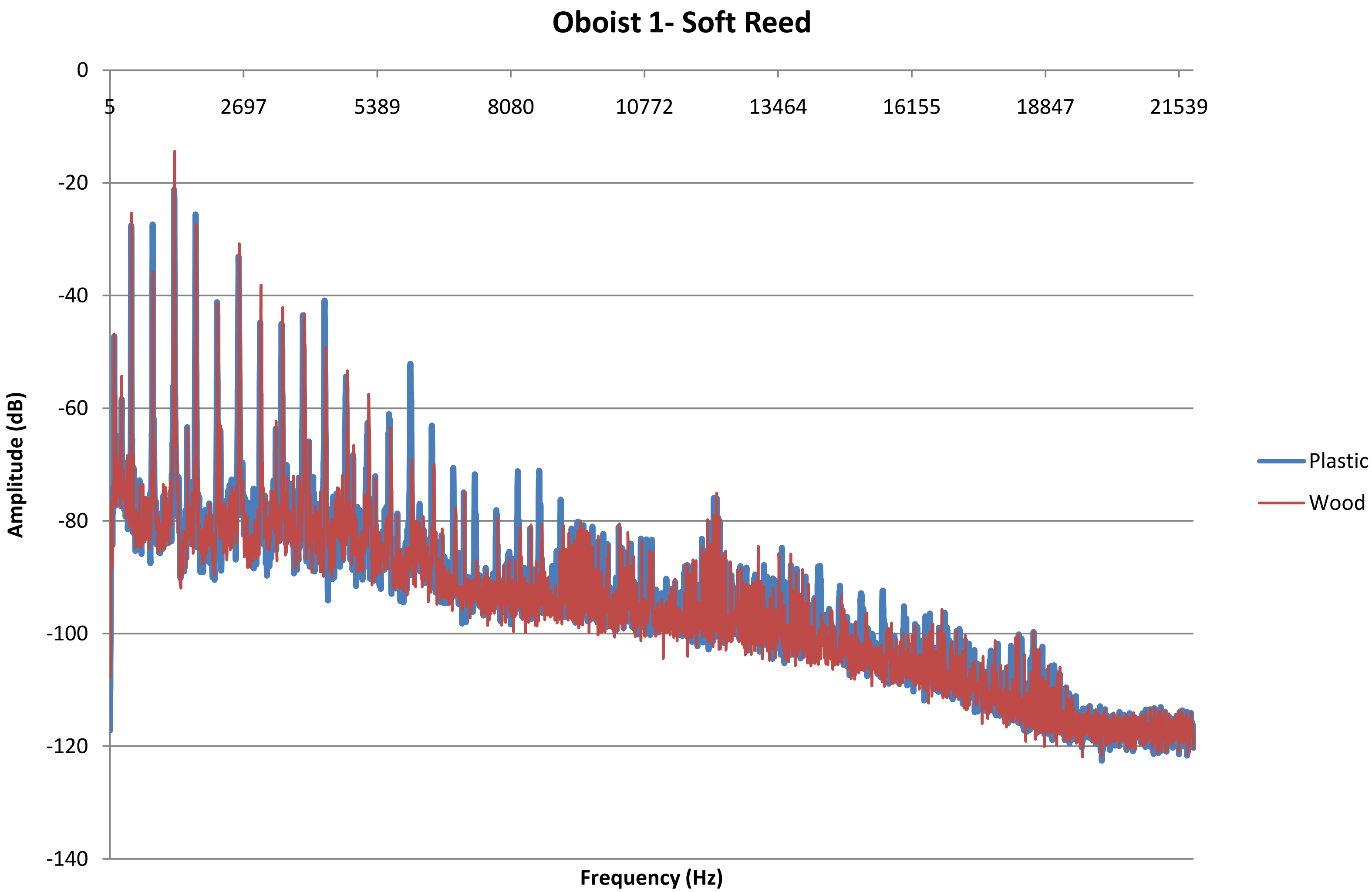

Figure 32 Spectrum for oboist 1 using a soft reed on wood and plastic oboes

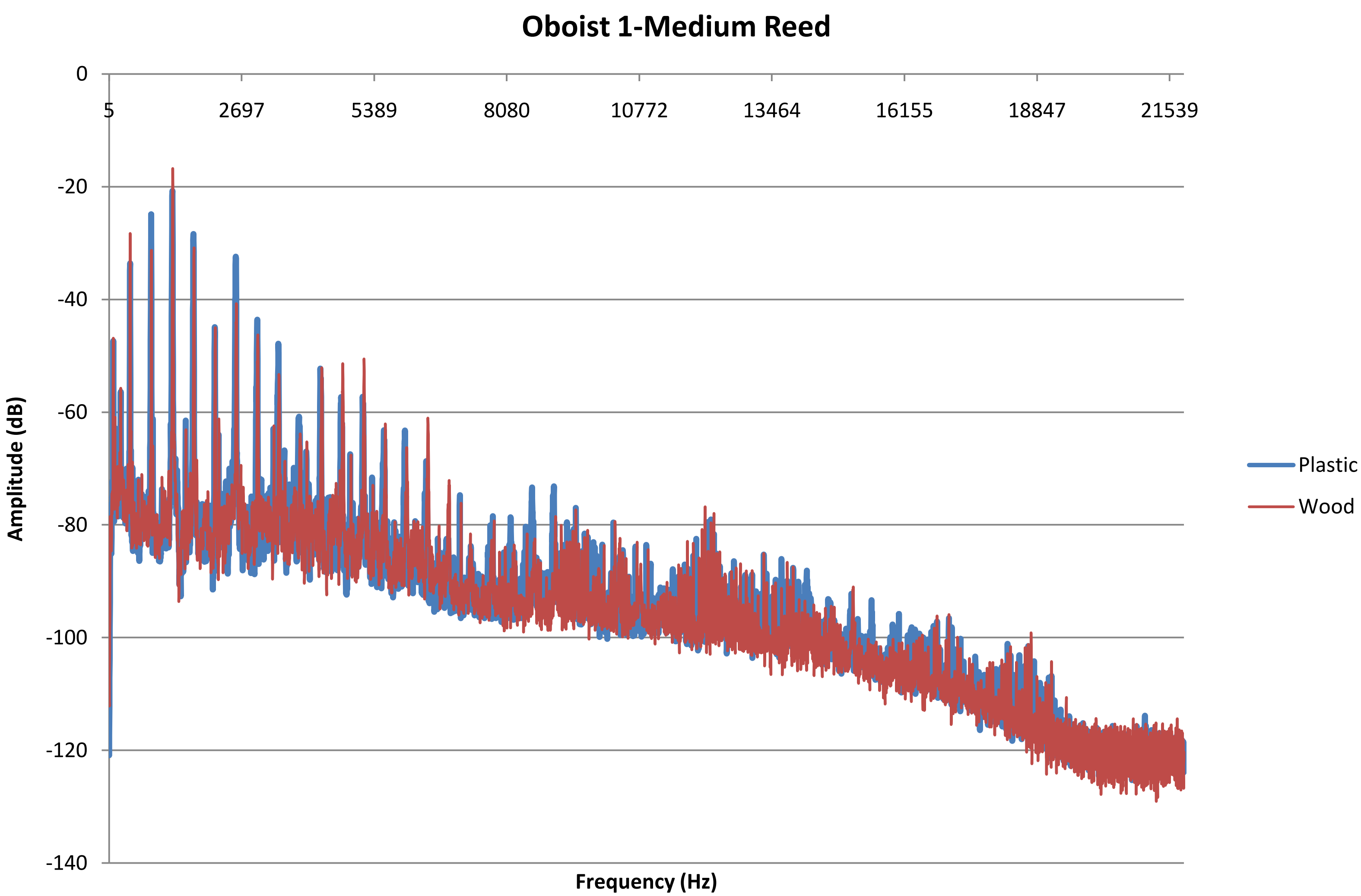

Figure 33 Spectrum for oboist 1 using a medium reed on wood and plastic oboes

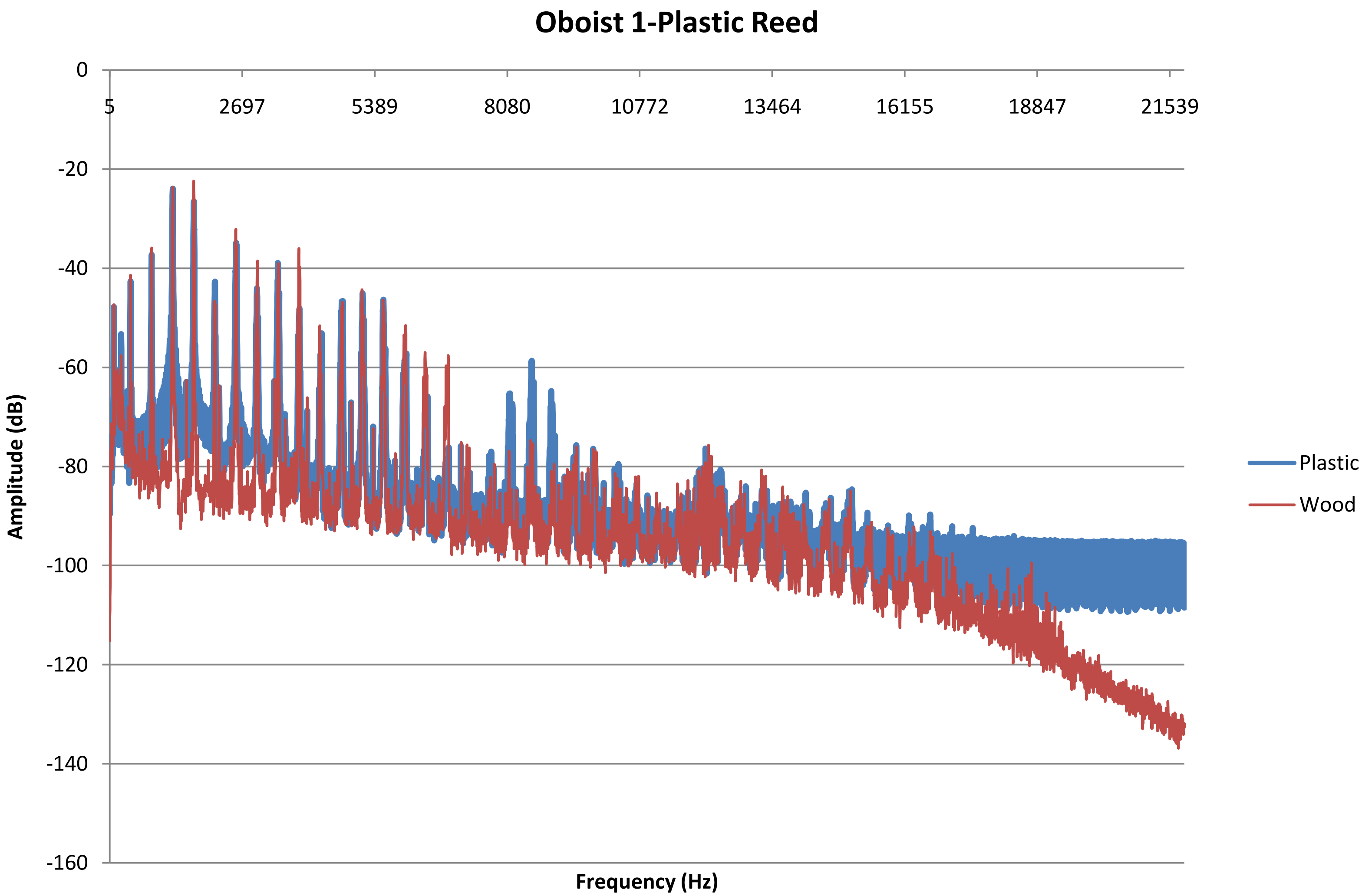

Figure 34 Spectrum for oboist 1 using a plastic reed on wood and plastic oboes

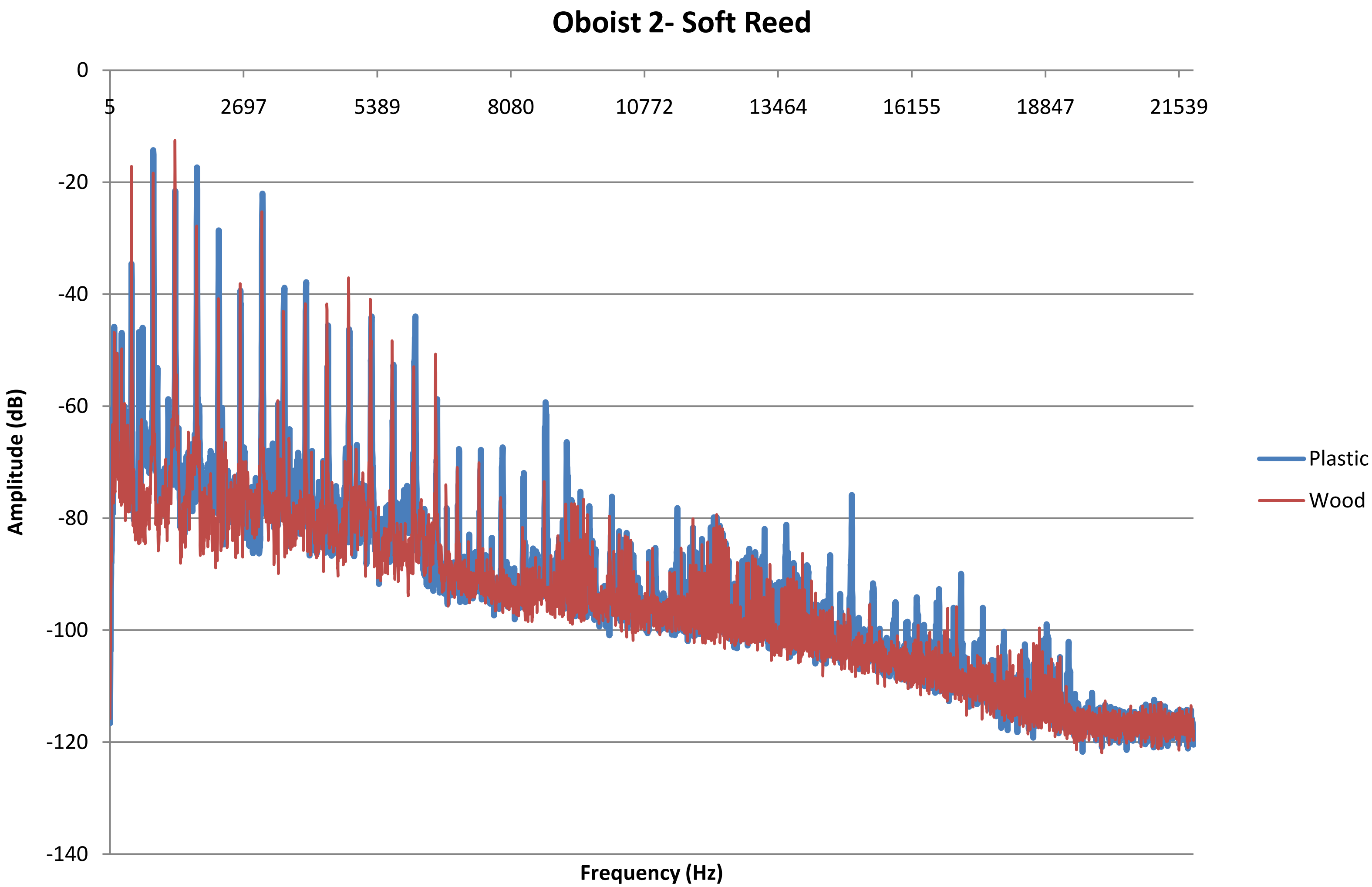

Figure 35 Spectrum for oboist 2 using a soft reed on wood and plastic oboes

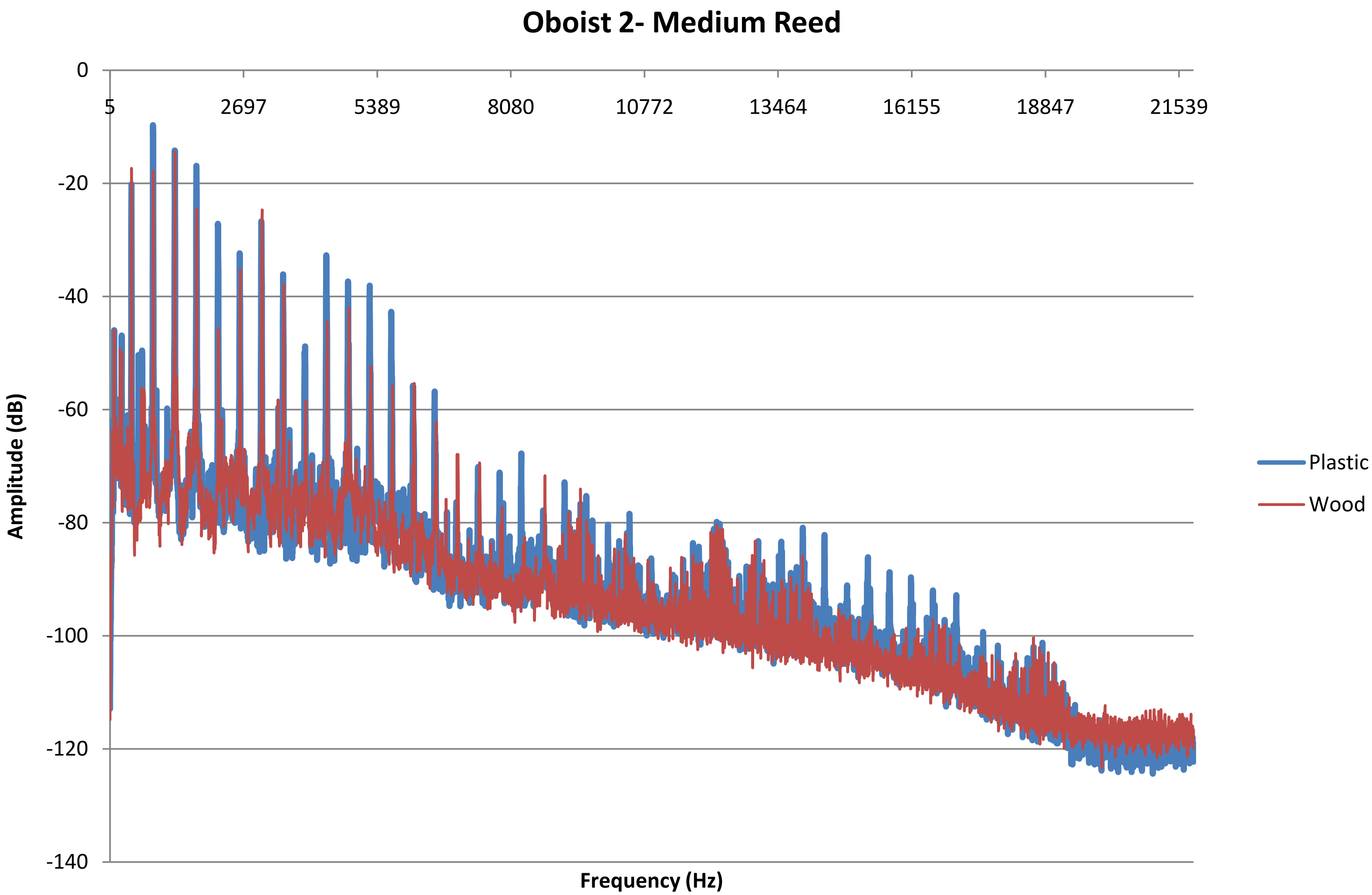

Figure 36 Spectrum for oboist 2 using a medium reed on wood and plastic oboes

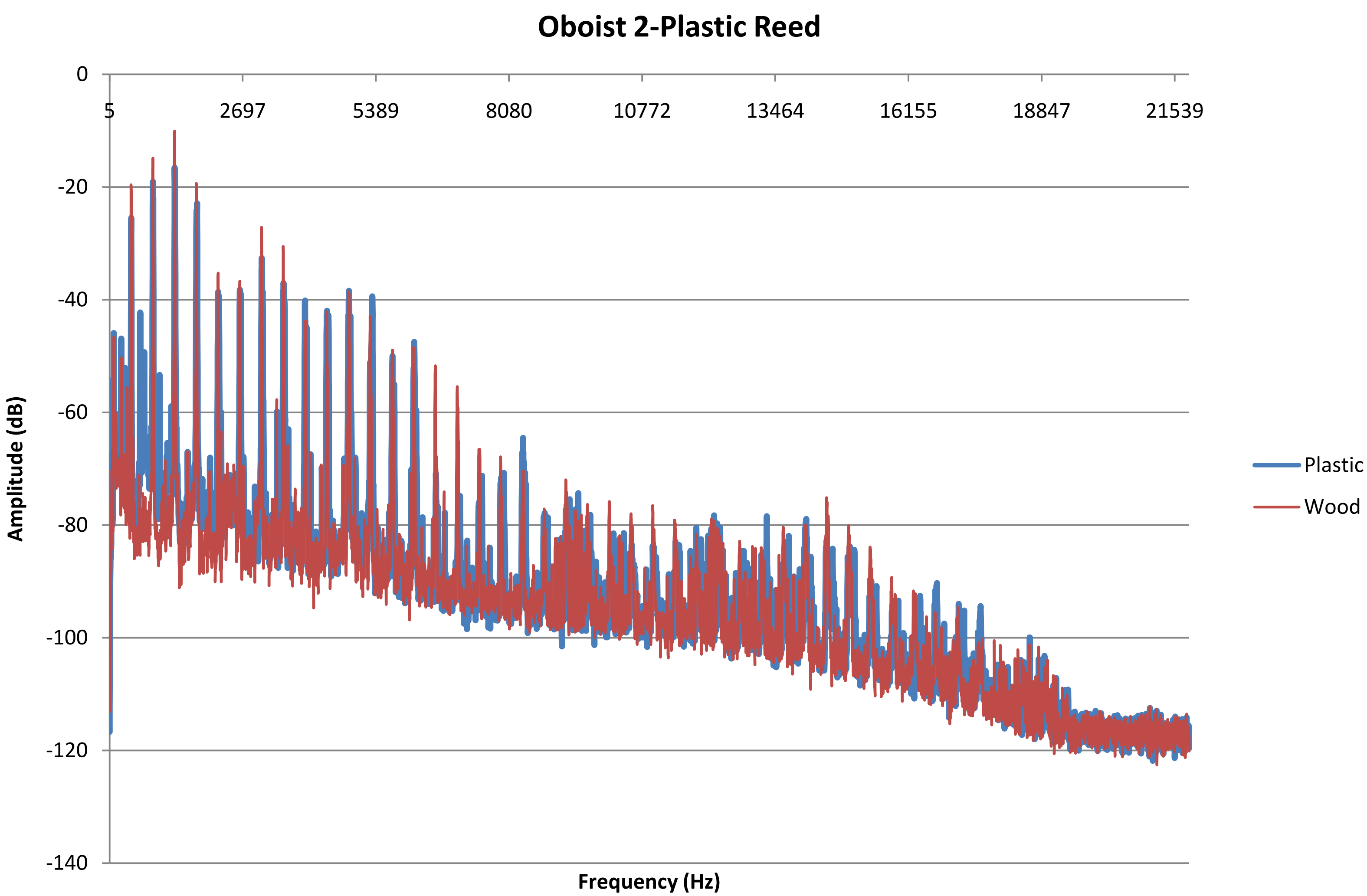

Figure 37 Spectrum for oboist 2 using a plastic reed on wood and plastic oboes

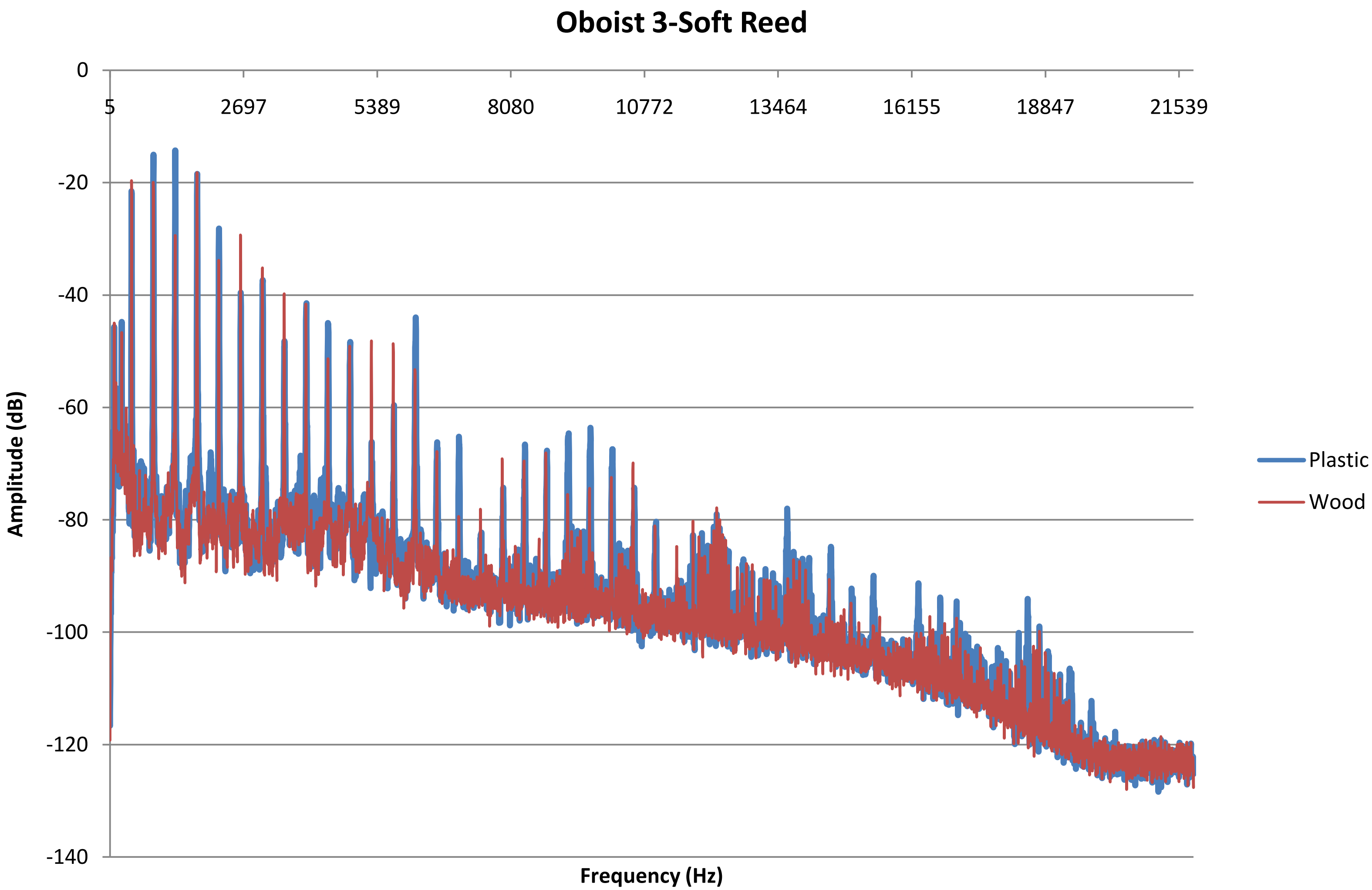

Figure 38 Spectrum for oboist 3 using a soft reed on wood and plastic oboes

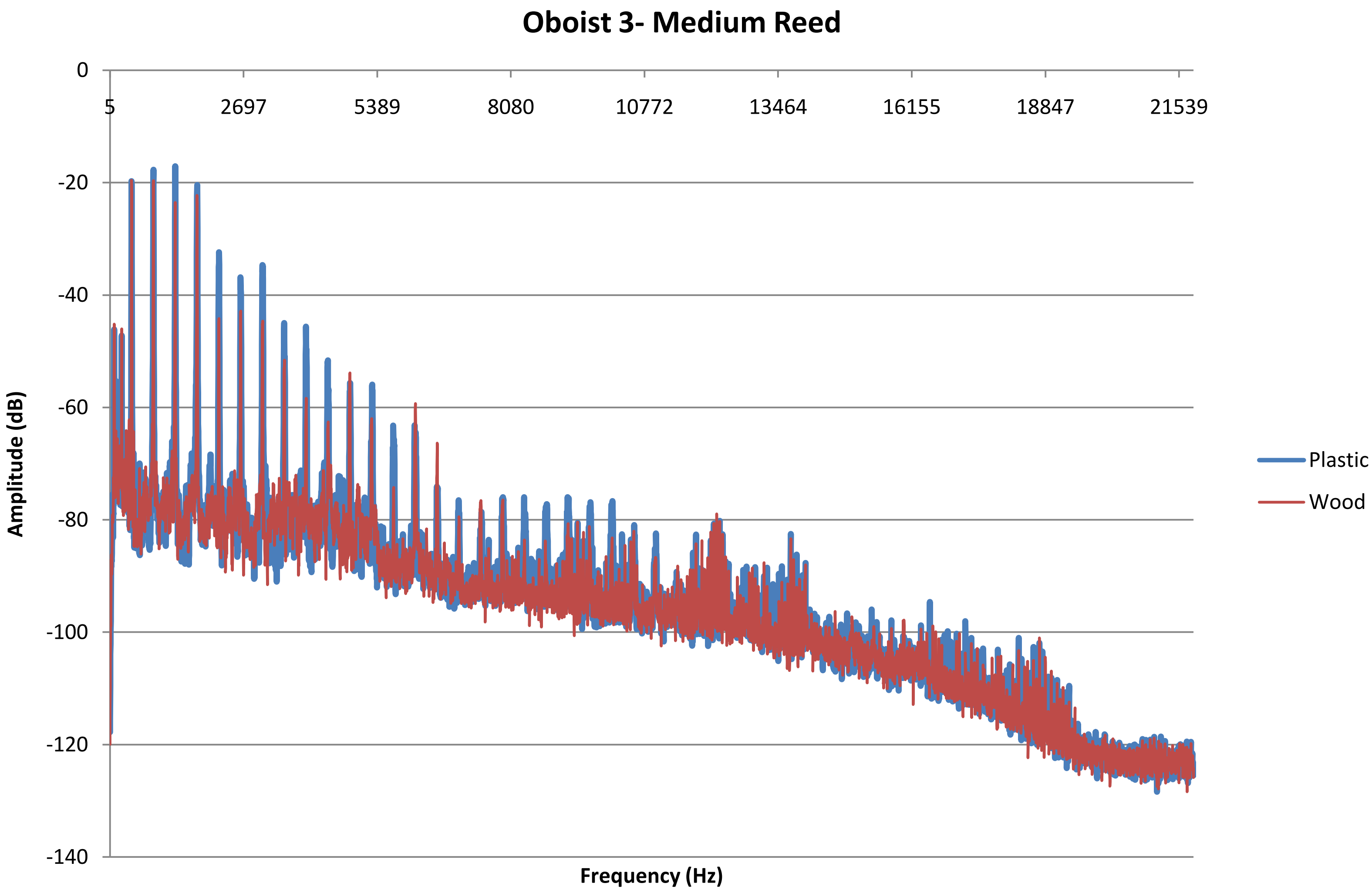

Figure 39 Spectrum for oboist 3 using a medium reed on wood and plastic oboes

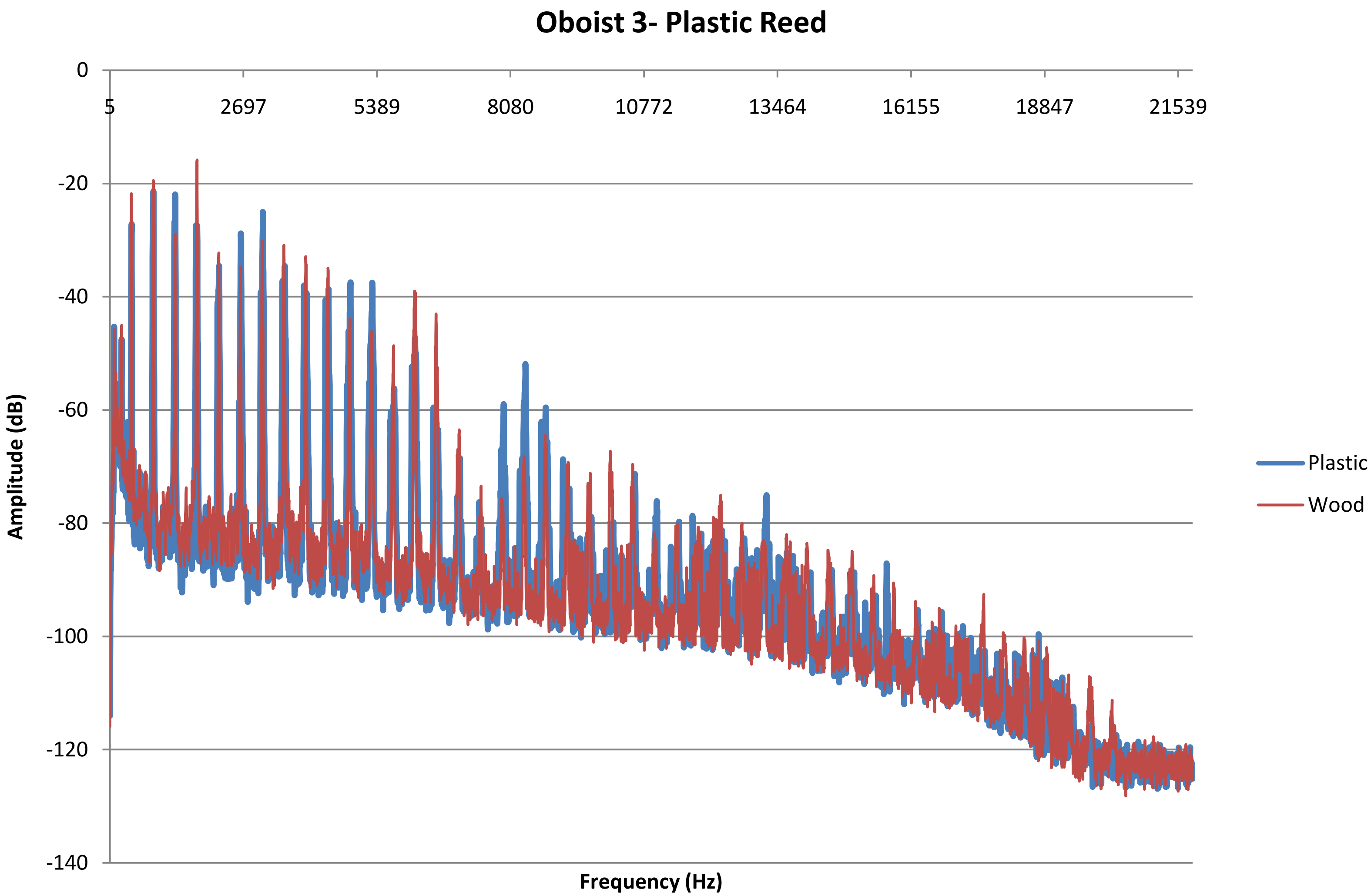

Figure 40 Spectrum for oboist 3 using a plastic reed on wood and plastic oboes

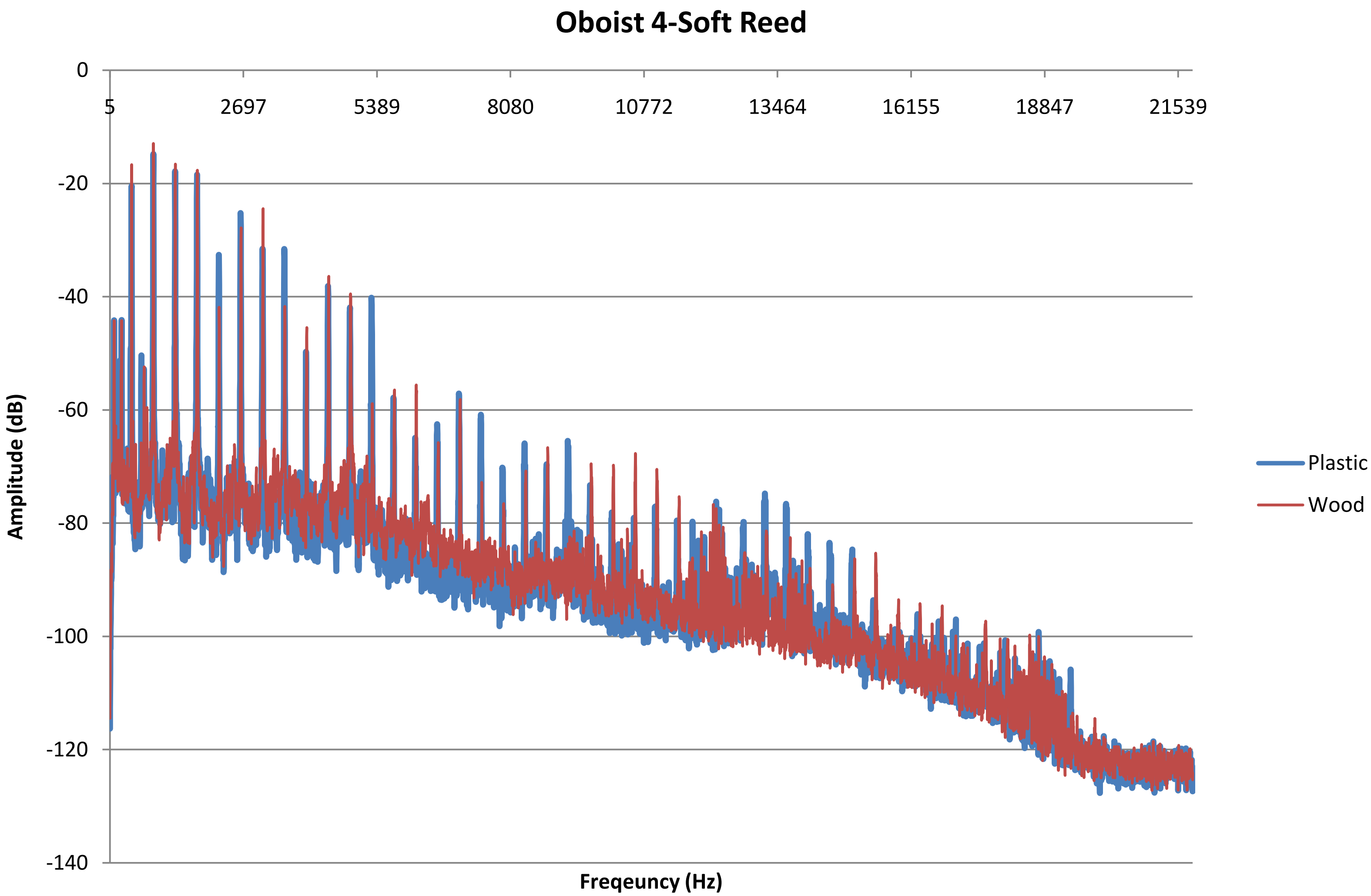

Figure 41 Spectrum for oboist 4 using a soft reed on wood and plastic oboes

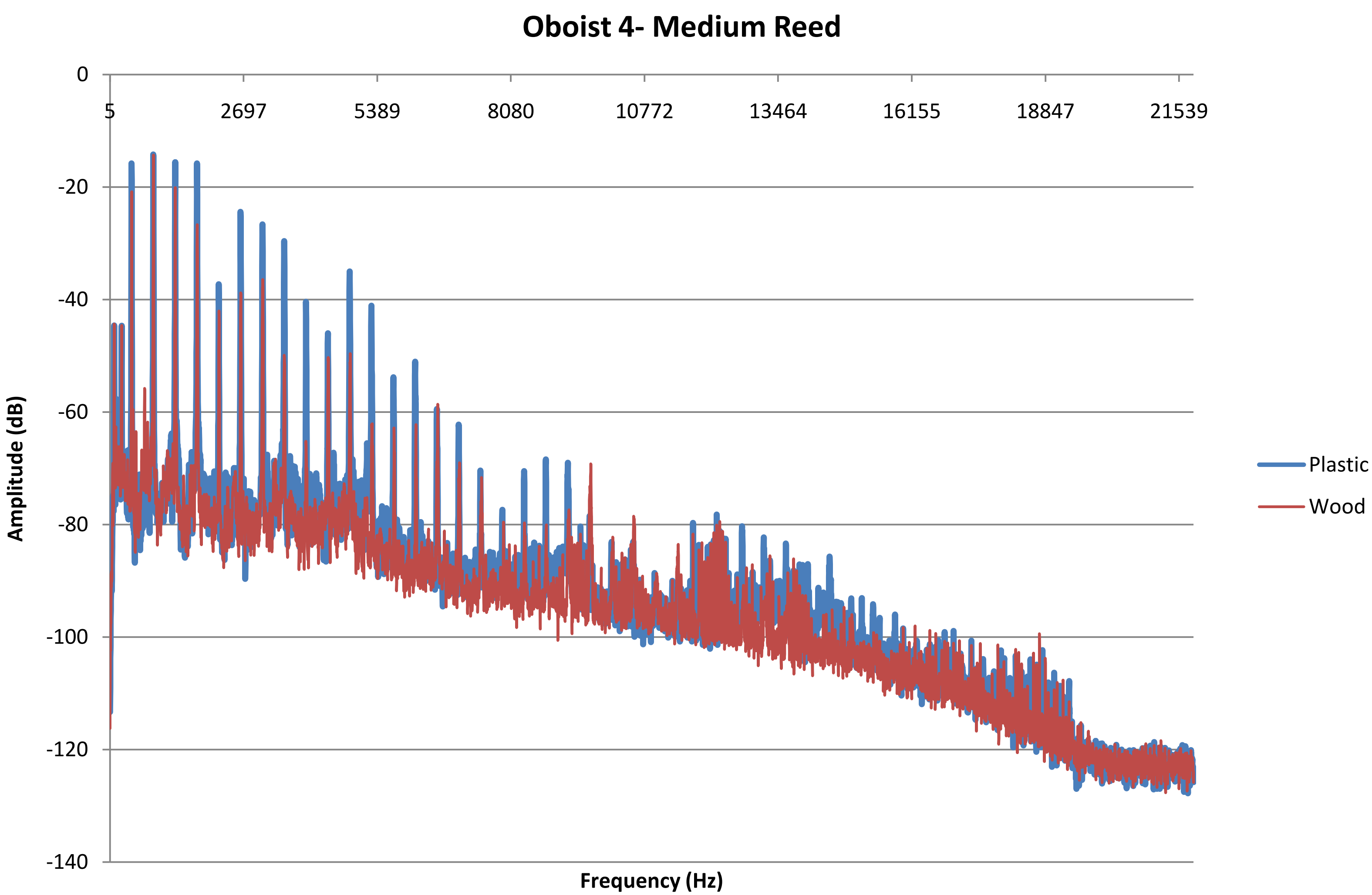

Figure 42 Spectrum for oboist 4 using a medium reed on wood and plastic oboes

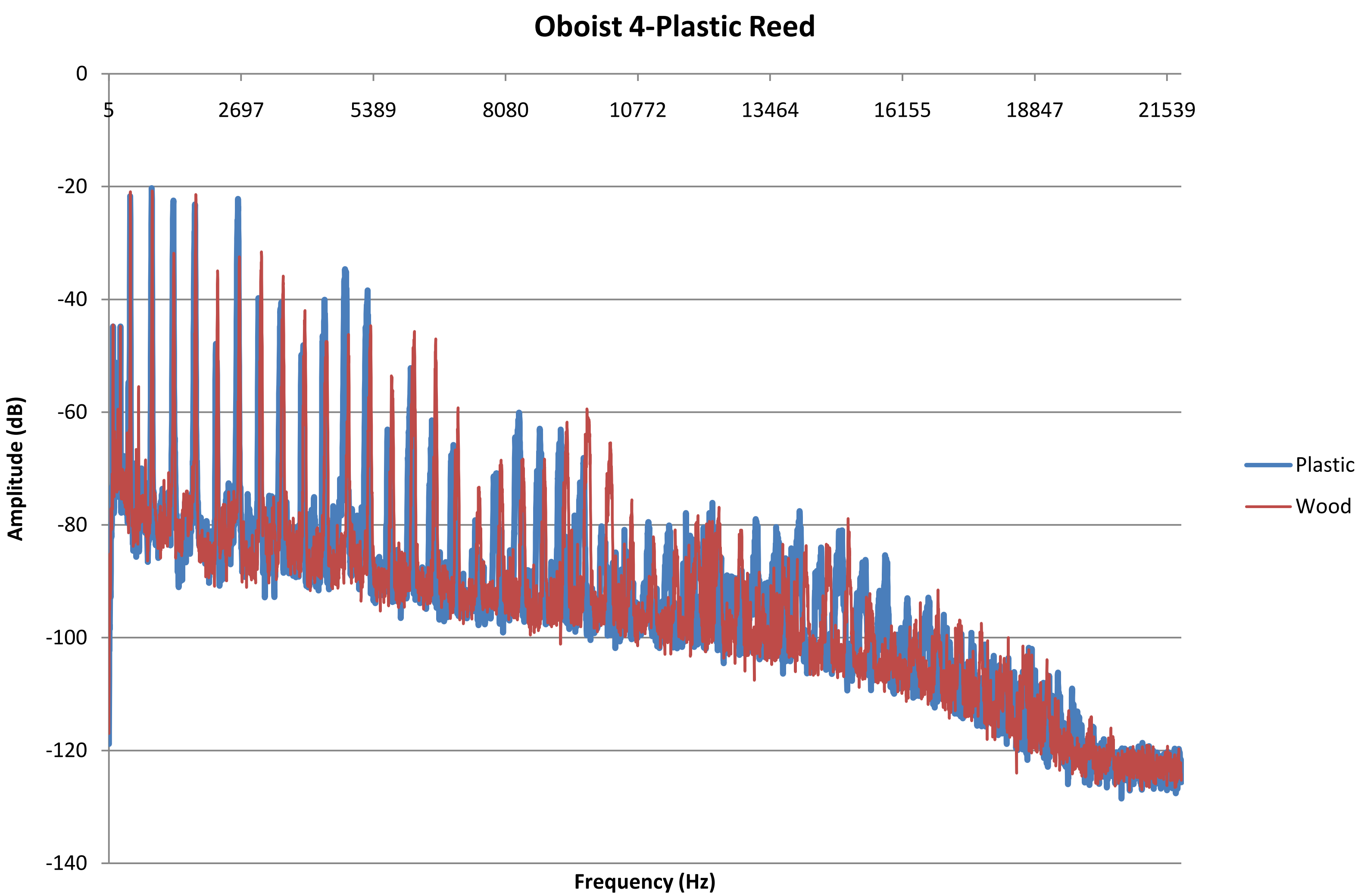

Figure 43 Spectrum for oboist 4 using a plastic reed on wood and plastic oboes

The oscillations which were present in the driven oboe experiment appear in this experiment, however at much higher frequencies. The oscillations occur in all the oboists notes, and begin at 20 kHz. This is the limit of the range of human hearing, so it is impossible that these oscillations affected the sound produced by the oboe. There is also a peak at 12 kHz with amplitude of approximately 10 dB and width of 1 kHz.

The amplitude of 440 Hz relative to the second and third harmonics seems to remain similar in each oboist, regardless of reed. Oboist 1's spectra consistently show 440 Hz of much lower amplitude than 880 Hz. The exceptions to this are the soft oboe spectra where the amplitudes of 440 Hz and 880 Hz are very similar. Despite these differences, the highest amplitude frequency in all of oboist 1's spectra is consistently 1320 Hz. Oboist 2 has 440 Hz at lower amplitude than 880 Hz, with the highest amplitude frequency at 1320 Hz. Again the soft reed spectra show a difference in these amplitudes; the third harmonic on the plastic oboe is of much lower amplitude than the first harmonic. Oboists 3 and 4 have very similar amplitudes at the first, second and third harmonics regardless of the reed used.

6.3 Results: Width of harmonics

The differences in the spectra of the oboists were not nearly as apparent as they were when the oboists were playing on their own reeds. When the oboes were played with a plastic reed the amplitudes at the frequencies surrounding 440 Hz seemed to be quite similar. In Figure 44, oboist 1 appears to be playing slightly out of tune. The amplitudes at surrounding frequencies for oboist 2 playing a wooden instrument are surprisingly different than any of the other curves.

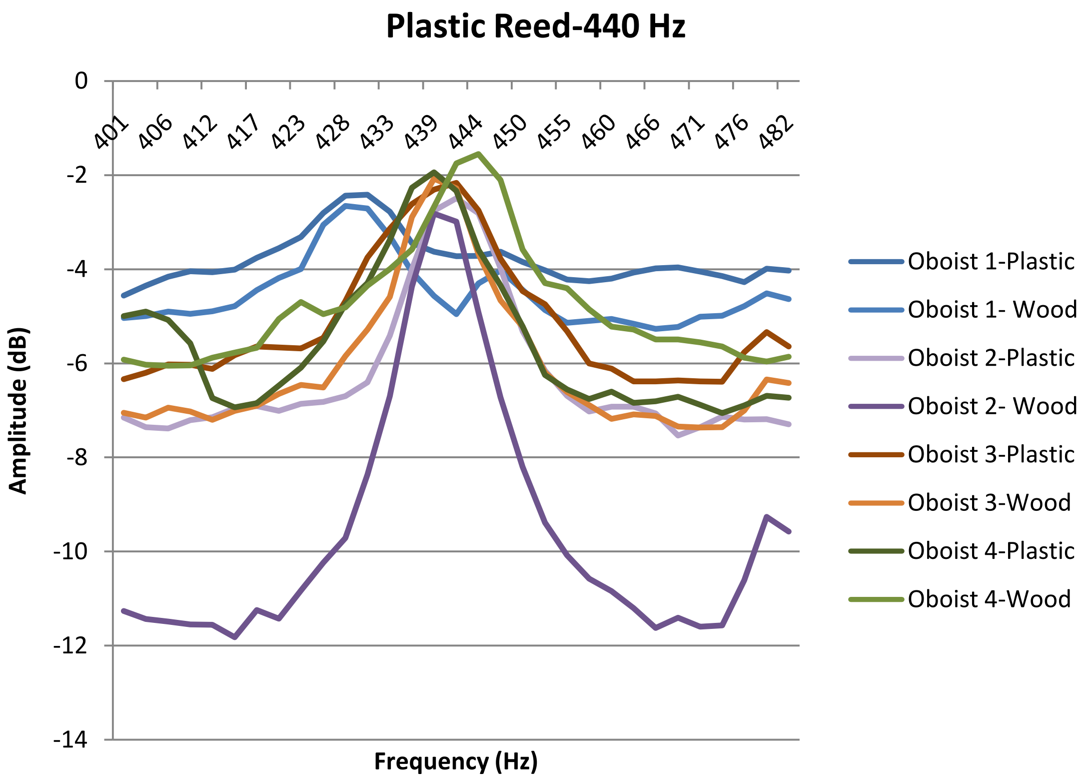

Figure 44 Amplitudes at frequencies surrounding 440 Hz for oboists using a plastic reed on wood and plastic instruments

For the soft reed, at the frequencies surrounding the first harmonic, there were more similarities between the oboists than the plastic reed, as seen in Figure 45. The amplitudes at 440 Hz appear to be approximately equal, and the amplitudes at the frequencies surrounding 440 Hz are also very similar, regardless of oboist. The amplitudes surrounding 440 Hz in comparison to those in the plastic reed are much smaller.

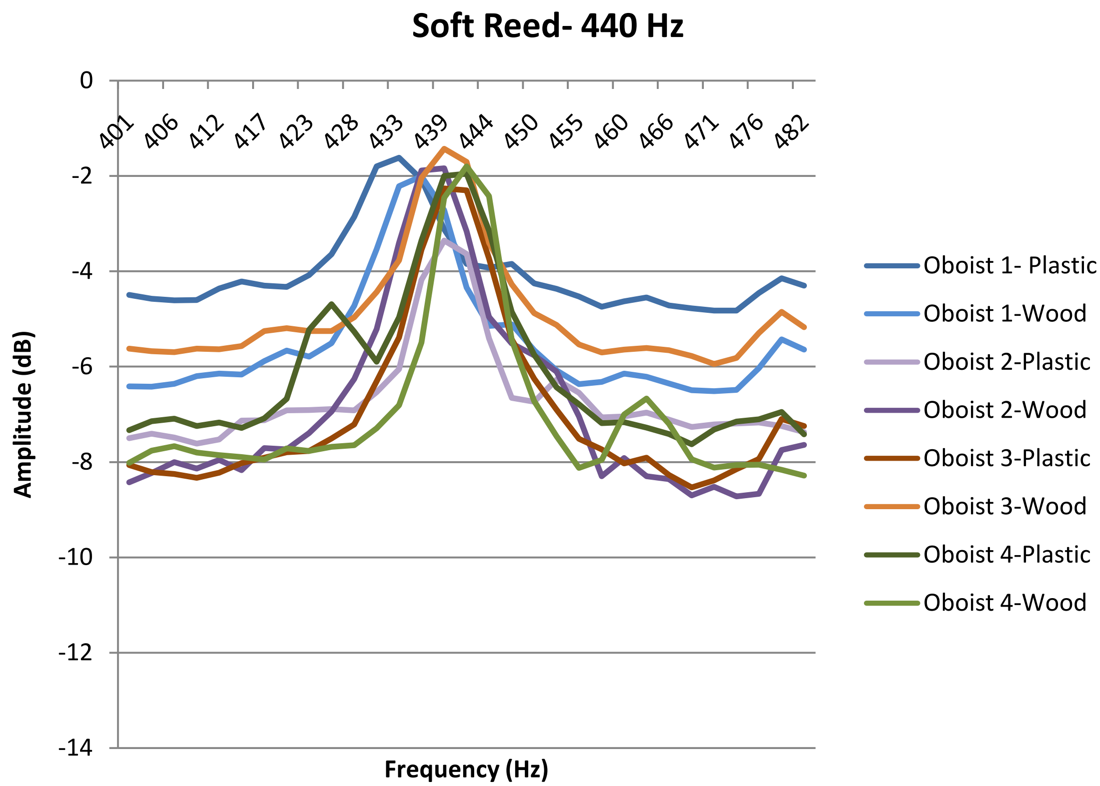

Figure 45 Amplitudes at frequencies surrounding 440 Hz for oboists using a soft reed on wood and plastic instruments

The most variation between amplitudes occurred when the oboists played on the medium reed (Figure 46). Overall there were many more differences in the amplitudes at the frequencies surrounding 440 Hz. Oboist 1 was once again marginally out of tune and oboist 2 had one curve which was very different from the others. There are still distinctly fewer similarities between oboists in this graph than when oboists selected their own reed.

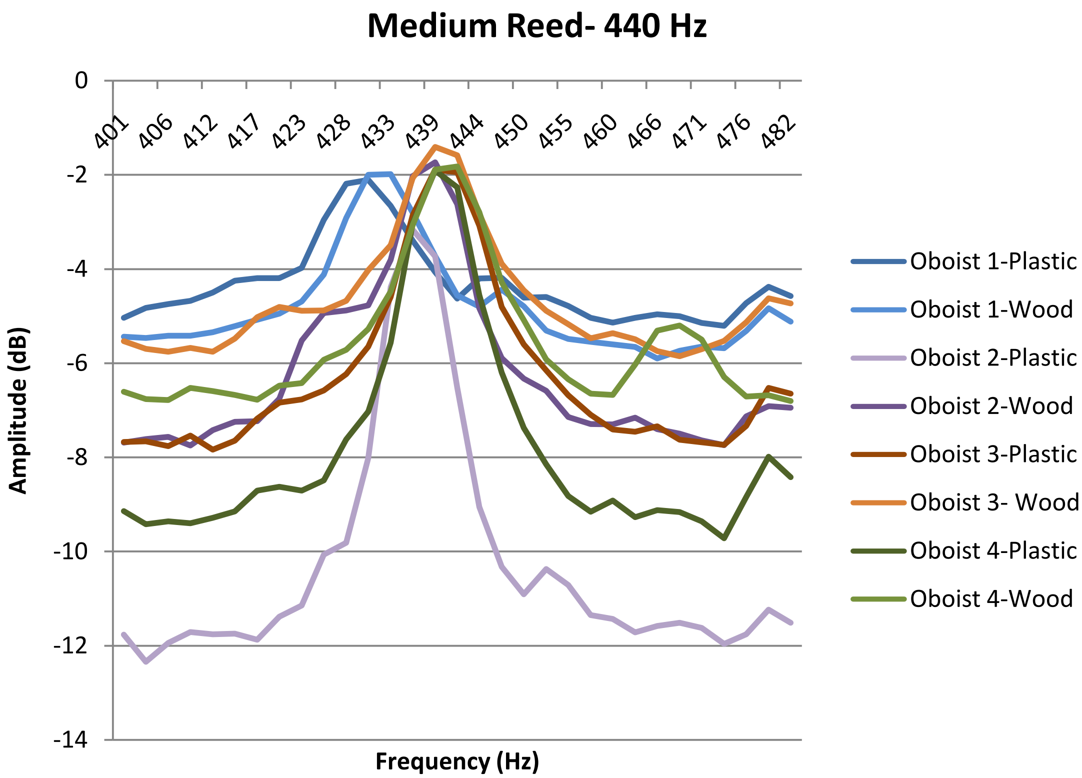

Figure 46 Amplitudes at frequencies surrounding 440 Hz for oboists using a medium reed on wood and plastic instruments

Chapter 7

Professional Oboist

7.1 Experiment

Because all of the oboists playing in the previous portions of the project were amateur, then a rough estimate of what harmonic composition makes up a "good" oboe note was necessary. A professional oboist provided a note from her own instrument on her own reed. Because the previous experiments relied on oboes or reeds provided for the oboists the best comparison were the oboists playing on their own reeds and their own oboes. While this has the most variation between oboists, the results are still important for determining which factors make a professional oboist and a professional oboe. Oboist 1 was playing on a Yamaha wooden instrument. Oboist 2 played on a plastic Renard oboe. Oboist 3 played on a wooden Selmer instrument and oboist 4 played on a plastic Fox oboe. The professional oboist was using a wooden Loreé instrument. Loreé is considered to be the best oboe manufacturer by most oboists. Yamaha, Renard, Selmer and Fox are all respected companies which target their oboes for student oboists. While these oboes are hardly of low quality, they are considered far inferior to a Loreé, simply based on brand name recognition.

7.2 Results: Full Spectrum

There are no noticeable differences in the sound of the oboe on the A_4 (440 Hz) compared; the notes, Tracks 45-49 sound nearly identical. There are distinct differences in the harmonic compositions of the professional oboist in comparison to the amateur oboists. The most noticeable difference in the spectrum is the amplitudes. The spectra have been normalized, however there are still great amplitude differences between the professional oboist and oboists 3 and 4 (Figures 49 and 50). The professional oboist also has far more clear and precise peaks at the harmonics and more uniform amplitudes at the frequencies between the harmonics. The most noticeable example of this is the higher amplitudes at the frequencies between 11 and 12 kHz. This peak in amplitudes is present in all of the amateur oboists and absent in the professional oboist. The professional oboist also shows a clean end of harmonic peaks whereas the amateur oboists have sporadic harmonic peaks in the higher harmonics. There is also a noticeable amplitude drop at 15 kHz in the professional oboist's note.

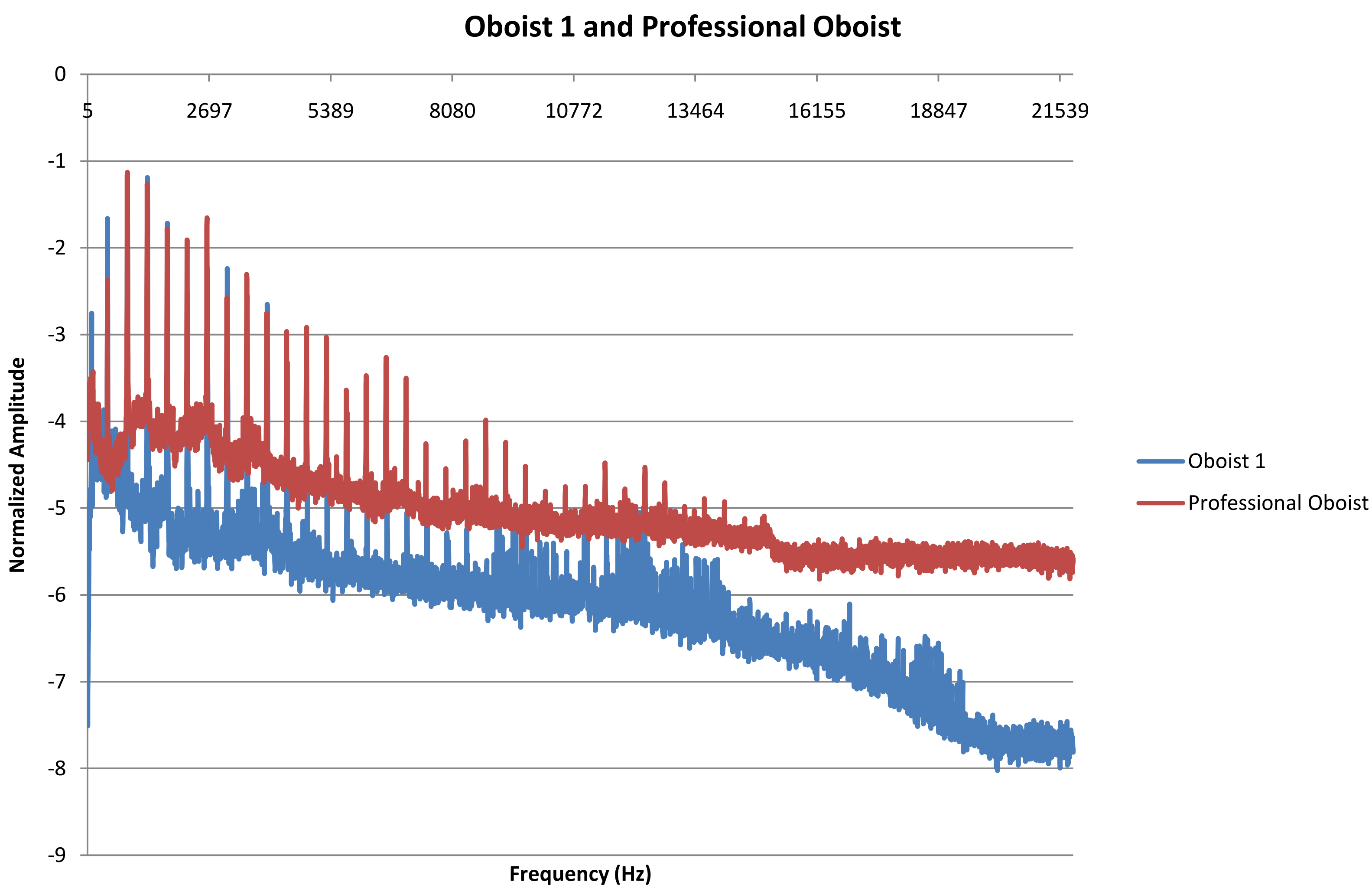

Figure 47 Spectrum for oboist 1 using her own reed and oboe compared to a professional oboist

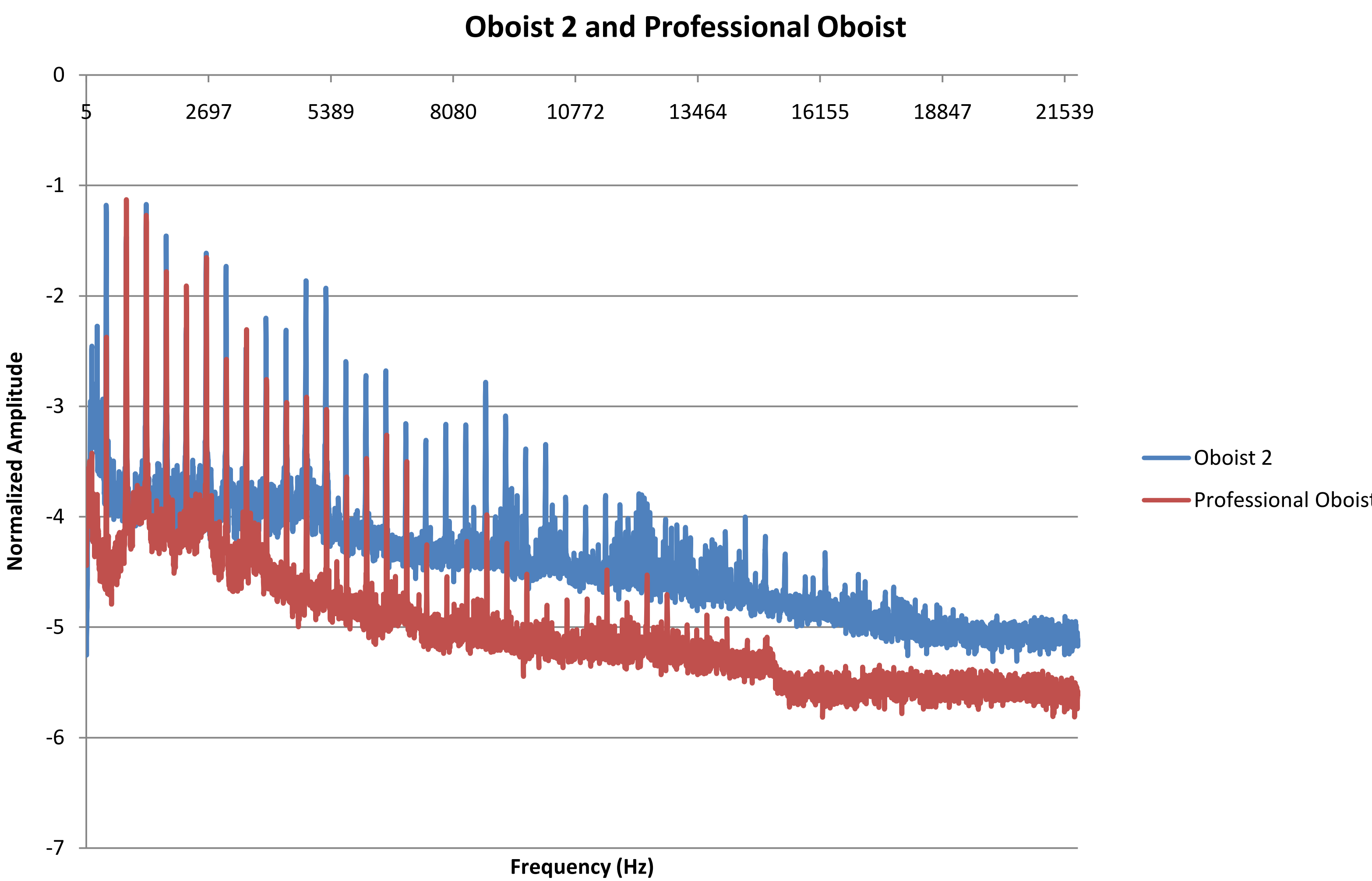

Figure 48 Spectrum for oboist 2 using her own reed and oboe compared to a professional oboist

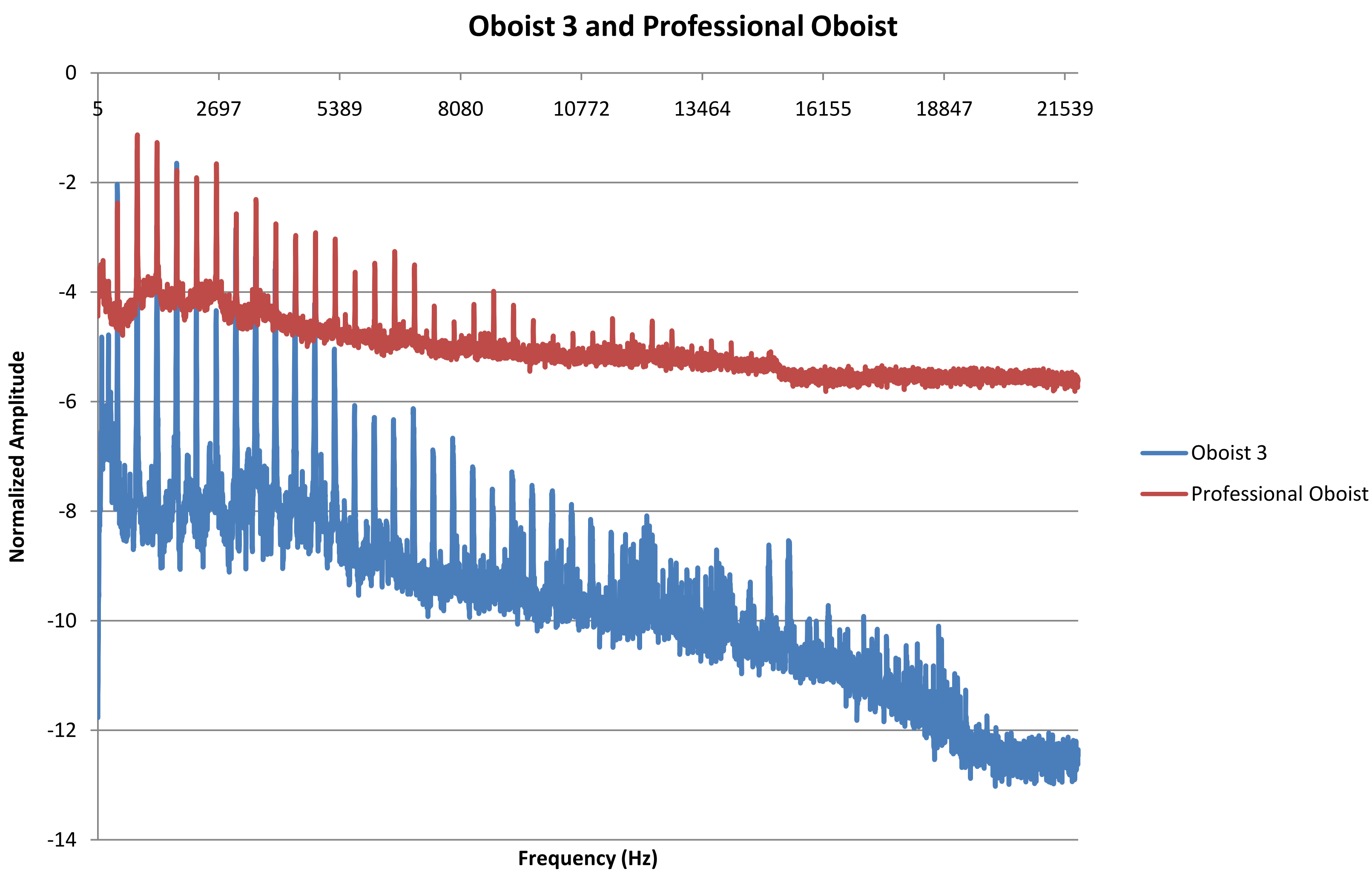

Figure 49 Spectrum for oboist 3 using her own reed and oboe compared to a professional oboist

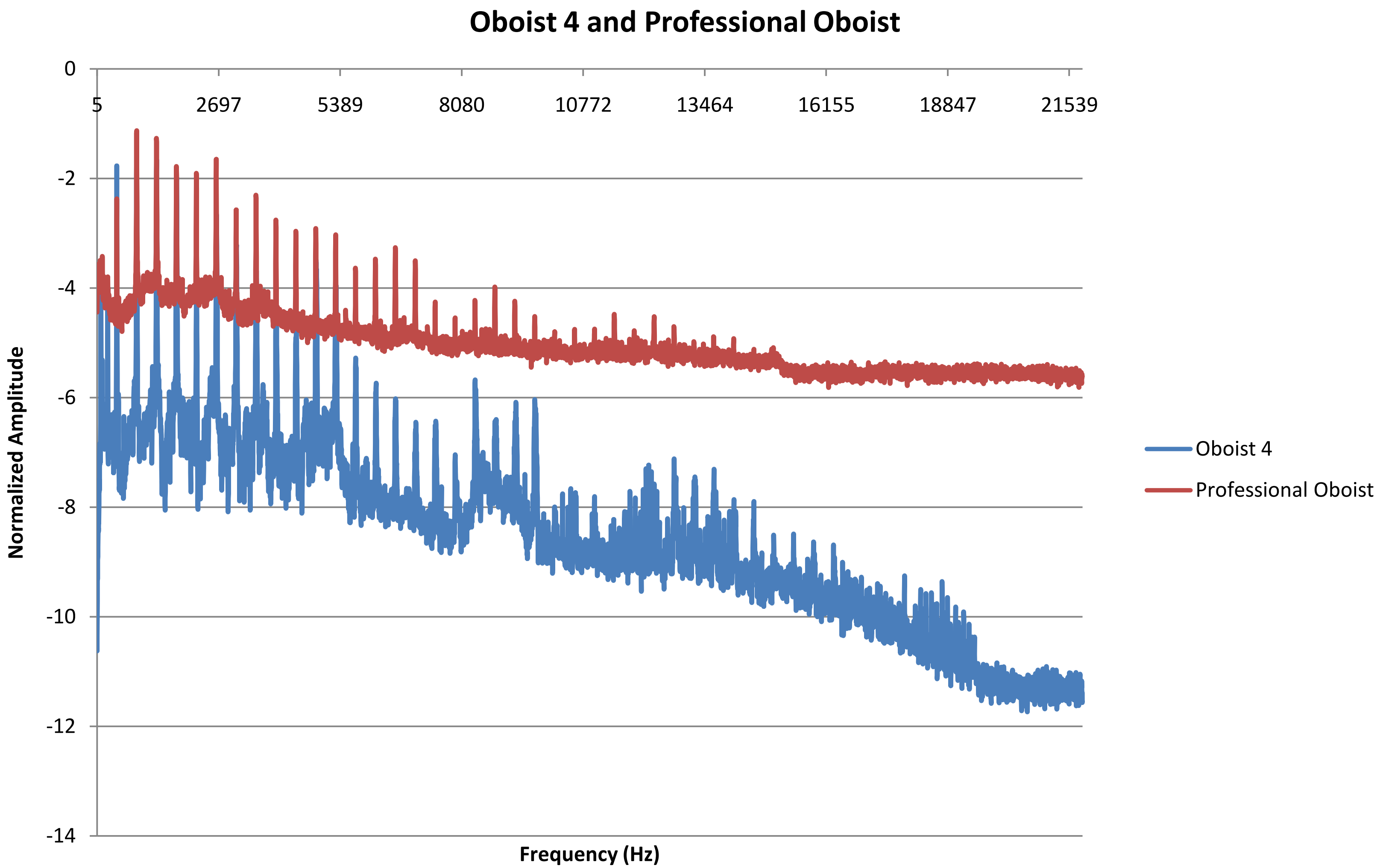

Figure 50 Spectrum for oboist 4 using her own reed and oboe compared to a professional oboist.

7.3 Results: Harmonics Comparison

There do not appear to be any distinct differences between the oboists in Figure 51, which shows the amplitudes at the harmonics. The professional oboist shows a far more regular decrease in the amplitudes at the harmonics than the amateur oboists. The professional oboist shows the largest difference in amplitude between 440 Hz and 880 Hz. The amateur oboists do not show the same difference in this experiment as they had in previous experiments. The first, second and third harmonics are all of comparable amplitudes.

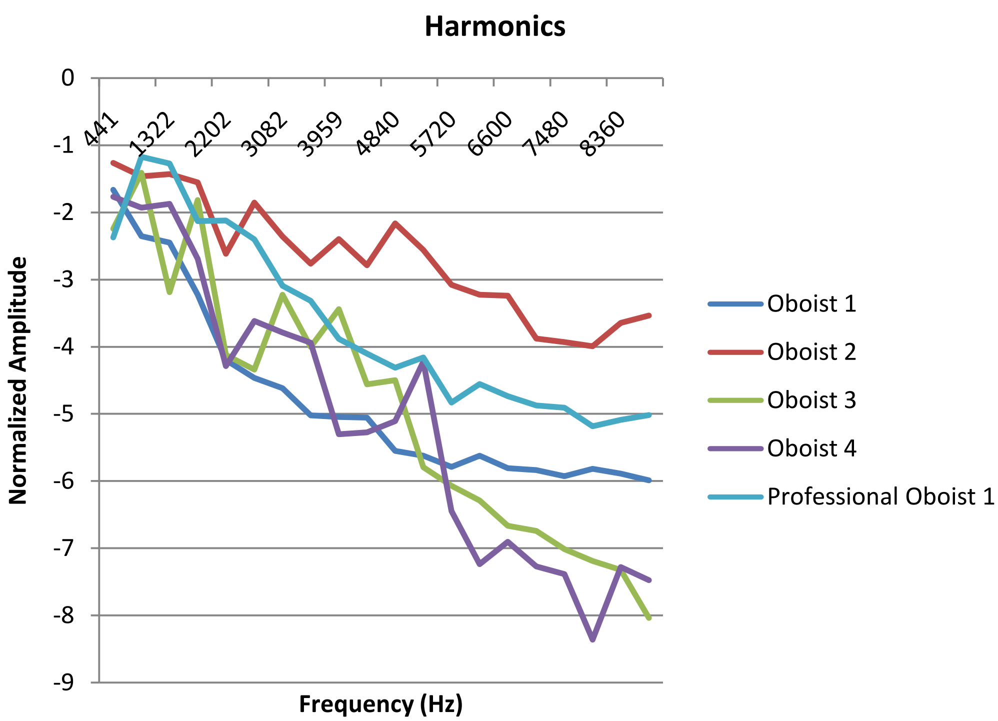

Figure 51 Comparison of harmonics for amateur oboists and professional oboist.

7.4 Results: Below 400 Hz

The most noticeable difference between the professional and amateur oboe notes are the amplitudes at frequencies less than 400 Hz (Figure 52). The

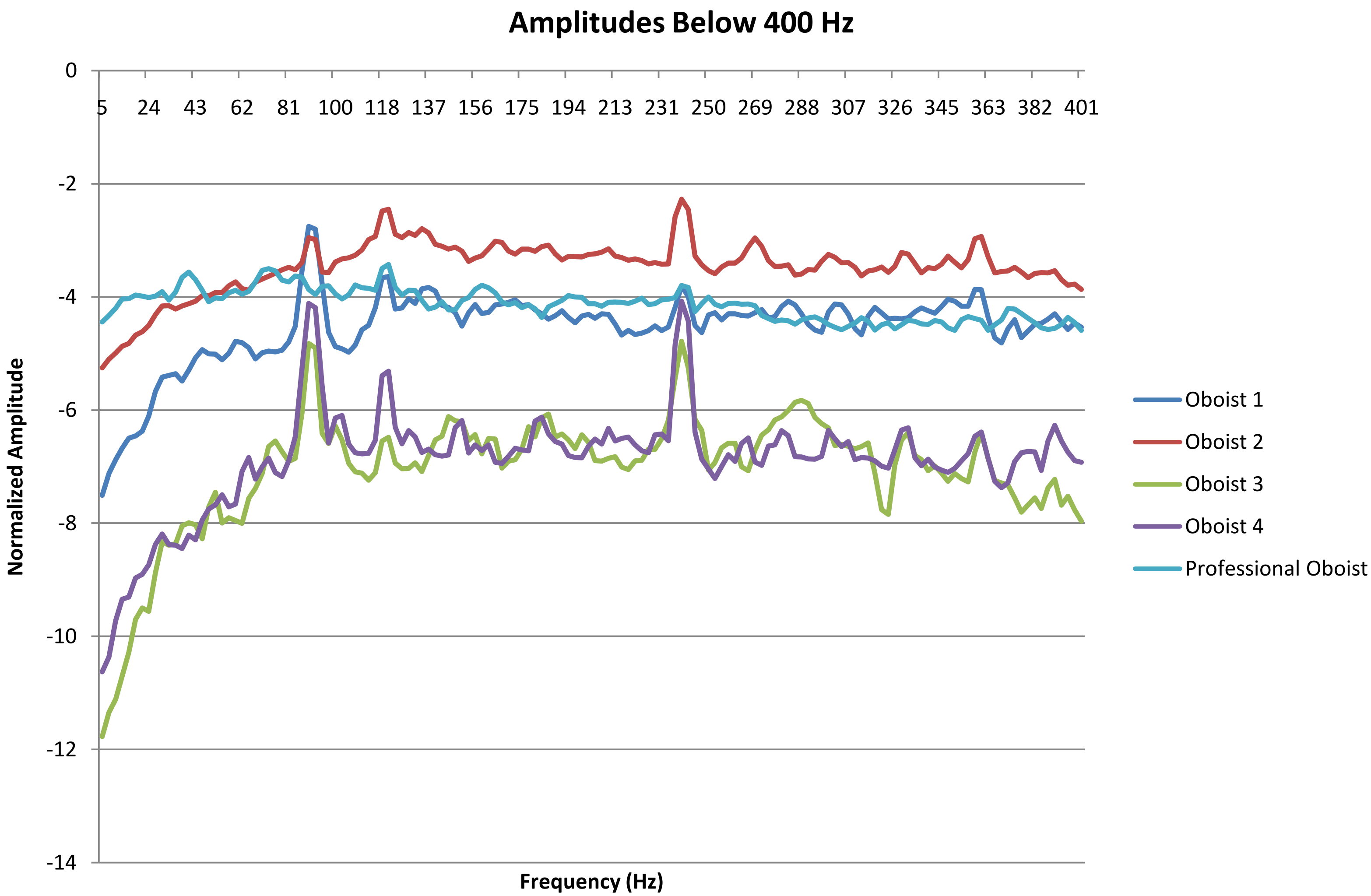

Figure 52 Amplitudes at frequencies below 440 Hz for oboists playing on personal reeds and oboes

professional oboist has no significant peaks at these frequencies. All but one of the amateur oboists have significant peaks at 88 Hz, which is a sub- harmonic of 440 Hz. However the amateur oboists also show peaks at 240 and 120 Hz. These frequencies are close to lower harmonics of 440 Hz. However, the lower harmonics of 440 Hz that would correspond to those frequencies are 220 Hz and 150 Hz. This indicates that these frequencies are separate from the harmonics of 440 Hz. While there are further harmonics of 120 and 240 Hz, the amplitude is small and the harmonics of 120 Hz die out after 480 Hz.

Chapter 8

Conclusion

The goal of this project was to determine which aspect of the oboe system influenced the harmonic content of the sound produced by an oboe the most. The factors varied were the reed composition, the oboe composition and the oboist. The experiment using an oboe excited by a fixed air source showed distinct differences in the effect the oboe composition had on the spectra. This experiment indicated that the oboe mattered more than the reed, since no obvious differences were visible in the reeds used. The Fox oboe experiments supported the observation that plastic oboes have higher amplitudes at higher harmonics than wooden oboes. However, this trend was not as apparent in the Fox oboes as with the driven oboe. This indicates that the oboist may have compensated for the harsher sound.

There was one major difference between the Fox oboe experiment and the driven oboe experiment. The Fox oboe full spectrum graphs showed many more harmonics than any of the driven oboes. The driven oboe graph seemed to stop showing any harmonic peaks over 10 kHz while the oboist was able to excite harmonics as high as 18 kHz. This may be because of the adjustments an individual oboist is able to make, but might also have been caused by the volume the driven oboe played at. The high volume and fixed air velocity might have overpowered some of the more subtle sounds of the oboe.

The reed variation portion supported some previous findings and expanded others. The results indicated that the plastic oboe does have higher amplitudes at higher harmonics. But it also supported that the difference in amplitude is not as large when the oboe is played by an oboist. The reeds showed more variation in this portion of the experiment than in the driven oboe. There were no conclusive findings in the driven oboe experiment concerning the reeds. In the reed variation portion of the project, the plastic reed showed greater amplitude at non-harmonic frequencies.

There were several characteristics that were unique to the spectra of the oboes when played by an oboist. In the oboe variation there were comparable amplitudes in the plastic instruments to those observed in the Fox oboes. This further indicates that there may be some compensation in the embouchure of the oboist to the plastic oboe sound. Also present in the Fox oboe, reed variation and oboe variation experiments was a peak of width 1 kHz centered around 12 kHz. This peak was not present in the professional oboist's note, which indicates that the peak may be related to the oboist or to lower quality oboes. Oboists in all of the experiments were able to excite far more harmonics than the driven oboe. However, each oboist seemed only able to excite up to a certain harmonic.

The inability to control pressure in the driven oboe experiment needs to be remedied. Because of the high velocity of the air flow the experiment destroyed the cane reeds. This made it impossible to continue to collect data, and indicates that too much stress was being put on the reed. This might have been caused by the tube not allowing the reed to vibrate freely as human lips might. We hope to repeat this experiment using a soft material at the opening to emulate the give of human lips. We will follow the setup suggested in experiments where the detailed behavior of the reeds was investigated. [13]

All of the spectra in this project were created from an A_4 (440 Hz) note played on all the oboes. For a more complete understanding of the acoustics of the oboe and to draw more general conclusions other notes would need to be tested. We plan to test one other note using the fixed air source experiment with the changes previously mentioned.

Overall, the conclusion appears to be one that would not be surprising to a musician: individual oboists, particularly when they are able to use a reed of their own selection, exert the greatest influence on the sound produced by their oboes. While the reed has a distinct influence on the acoustic spectrum, this difference does not appear when the oboe is played by a fixed air source. We have also found that there are quantifiable differences between the sounds produced by wooden and plastic oboes. There was less difference when the oboe was played by the oboist; indicating that the oboist can compensate for the tone quality difference. In particular, the least flexibility to adjust tone quality appears to belong to plastic oboes played with plastic reeds, which lends support to the musicians' aversion to use these.

CD Track Listing

1. Driven Oboe- Soft Reed- Plastic Oboe
2. Driven Oboe- Soft Reed- Wood Oboe
3. Driven Oboe- Medium Reed- Plastic Oboe
4. Driven Oboe- Medium Reed- Wood Oboe
5. Driven Oboe- Plastic Reed- Plastic Oboe
6. Driven Oboe- Plastic Reed- Wood Oboe
7. Fox Oboe 1- Plastic
8. Fox Oboe 2- Plastic
9. Fox Oboe 3- Half-Plastic/Half-Wood
10. Fox Oboe 4- Half-Plastic/Half-Wood
11. Fox Oboe 5- Wood
12. Fox Oboe 6- Wood
13. Oboe Variation- Oboist 1- Plastic
14. Oboe Variation- Oboist 1- Wood
15. Oboe Variation- Oboist 2- Plastic
16. Oboe Variation- Oboist 2- Wood
17. Oboe Variation- Oboist 3- Plastic
18. Oboe Variation- Oboist 3- Wood
19. Oboe Variation- Oboist 4- Plastic
20. Oboe Variation- Oboist 4- Wood
21. Reed Variation- Oboist 1- Medium Reed- Plastic Oboe
22. Reed Variation- Oboist 1- Medium Reed- Wood Oboe
23. Reed Variation- Oboist 1- Plastic Reed- Plastic Oboe
24. Reed Variation- Oboist 1- Plastic Reed- Wood Oboe
25. Reed Variation- Oboist 1- Soft Reed- Plastic Oboe
26. Reed Variation- Oboist 1- Soft Reed- Wood Oboe
27. Reed Variation- Oboist 2- Medium Reed- Plastic Oboe
28. Reed Variation- Oboist 2- Medium Reed- Wood Oboe
29. Reed Variation- Oboist 2- Plastic Reed- Plastic Oboe
30. Reed Variation- Oboist 2- Plastic Reed- Wood Oboe
31. Reed Variation- Oboist 2- Soft Reed- Plastic Oboe
32. Reed Variation- Oboist 2- Soft Reed- Wood Oboe

33. Reed Variation- Oboist 3- Medium Reed- Plastic Oboe
34. Reed Variation- Oboist 3- Medium Reed- Wood Oboe
35. Reed Variation- Oboist 3- Plastic Reed- Plastic Oboe
36. Reed Variation- Oboist 3- Plastic Reed- Wood Oboe
37. Reed Variation- Oboist 3- Soft Reed- Plastic Oboe
38. Reed Variation- Oboist 3- Soft Reed- Wood Oboe
39. Reed Variation- Oboist 4- Medium Reed- Plastic Oboe
40. Reed Variation- Oboist 4- Medium Reed- Wood Oboe
41. Reed Variation- Oboist 4- Plastic Reed- Plastic Oboe
42. Reed Variation- Oboist 4- Plastic Reed- Wood Oboe
43. Reed Variation- Oboist 4- Soft Reed- Plastic Oboe
44. Reed Variation- Oboist 3- Soft Reed- Wood Oboe
45. Oboist 1
46. Oboist 2
47. Oboist 3
48. Oboist 4
49. Professional Oboist

Appendix

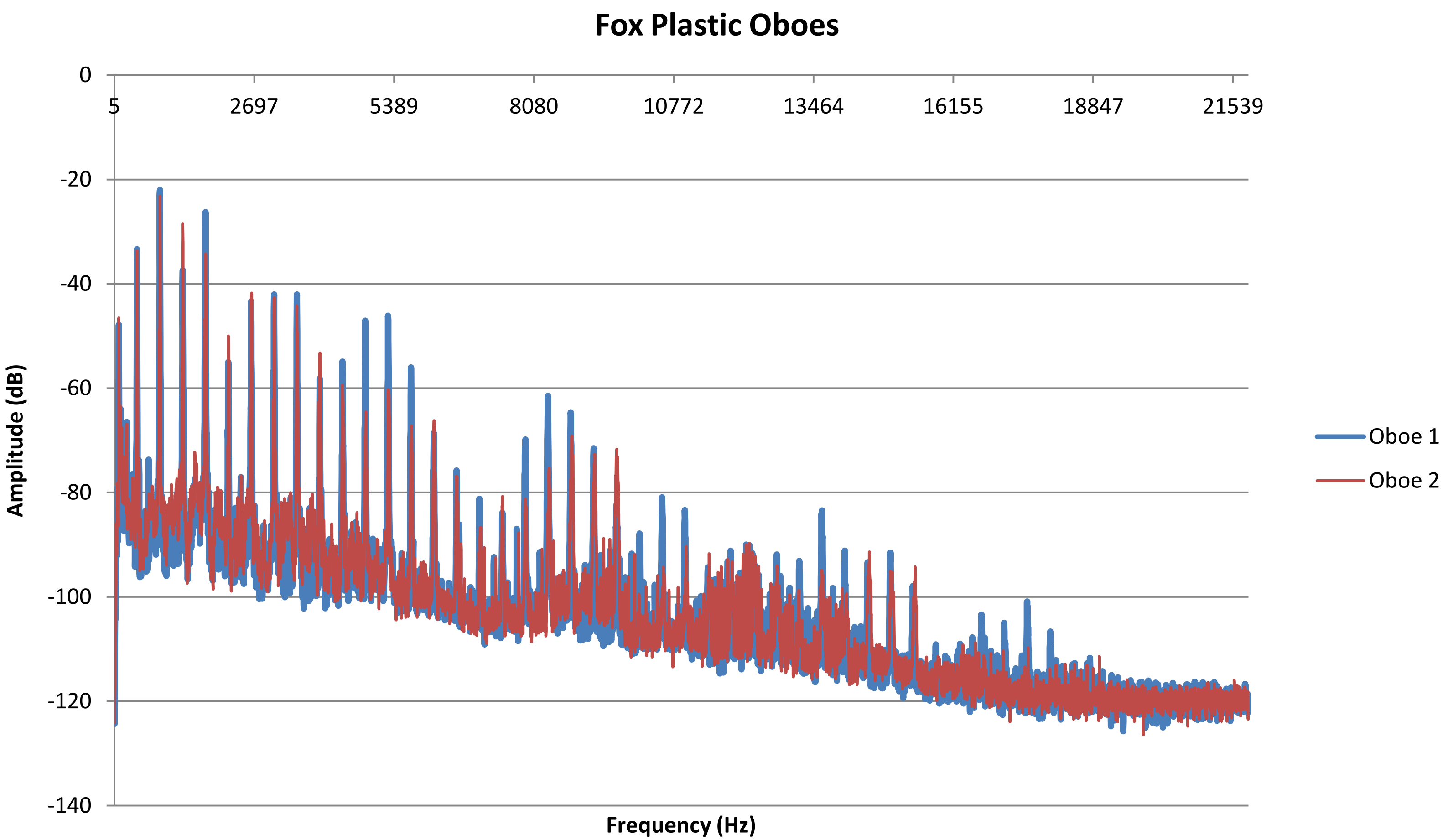

Figure 53 Spectrum of Fox plastic oboes

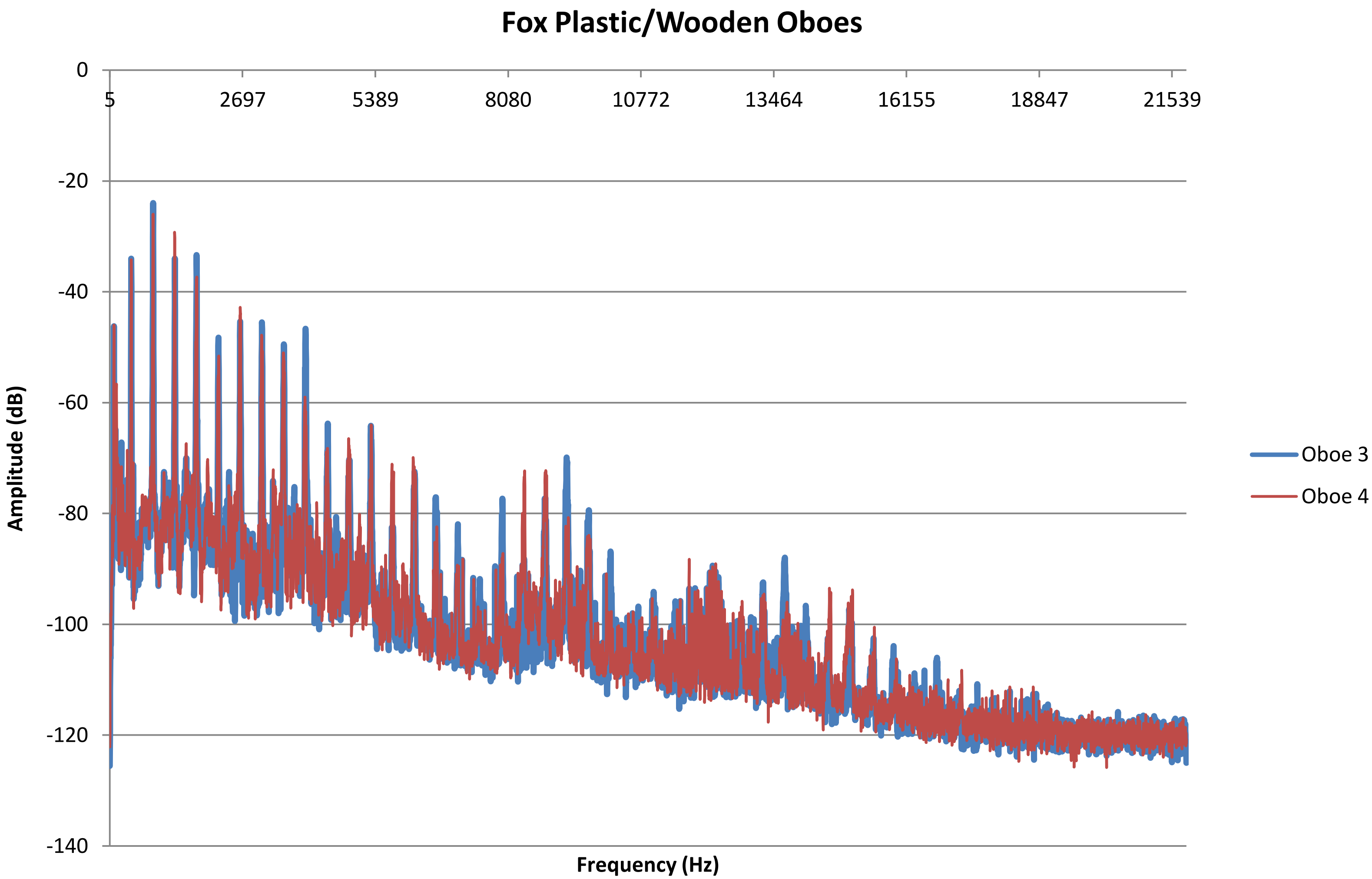

Figure 54 Spectrum of Fox half-plastic/half-wooden oboes

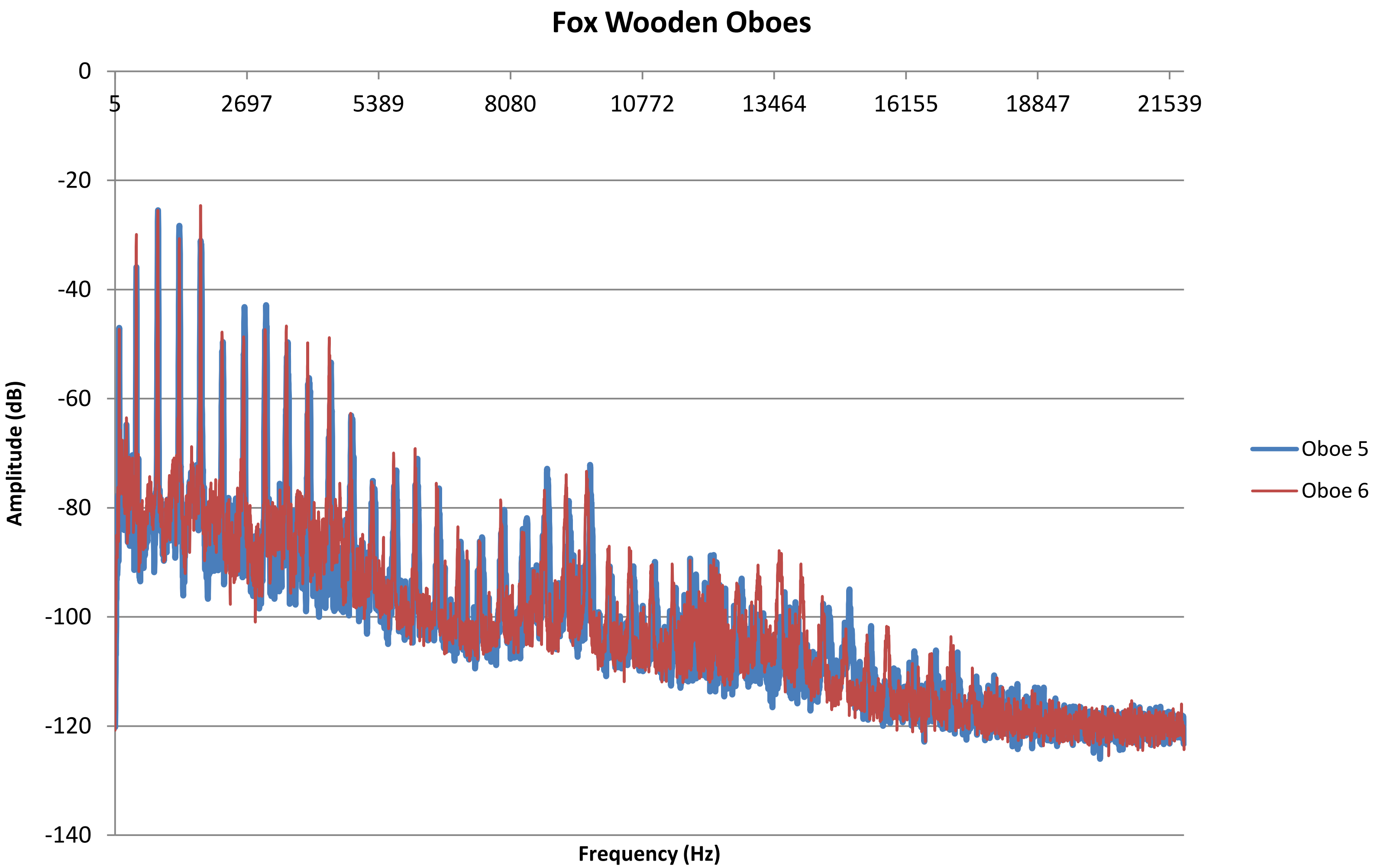

Figure 55 Spectrum of Fox wooden oboes

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[7] Figure 4 with additional information

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