Harmonic Analysis of the Soprano Clarinet

A thesis submitted in partial fulfillment of the requirement
for the degree of Bachelor of Science in
Physics from the College of William and Mary in Virginia,

by

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Abstract

Many variables play into why and how the timbre of the clarinet changes. This project focused on the range of the instrument and loudness. Each chromatic note of the clarinet was recorded, from E3 to C6, and the clarinet was split into low-register, middle-register, and high-register. I ran five trials to analyze general trends of the spectra using a software called SPEAR (SPEAR, n.d.). SPEAR showed that the low-register and middle-register notes did not have prominent second harmonics but the high-register did, indicating that the clarinet acts less like a closed-pipe in the higher range. I then focused on one trial and ran individual FFTs on each note in Audacity, and exported the data to MATLAB. The low-register notes all included stronger odd harmonics than even harmonics, however, some notes in the middle-register exhibited a strong fourth harmonic. In the high register, there were many more even harmonics that were stronger than the odd harmonics, indicating the the clarinet was acting less like a closed-pipe. Noise was reduced in several ways. Firstly, I just subtracted the FFT of the background noise in the room from the clarinet spectra, which reduced the low-frequency noise. Next, I tried subtracting the spectra of the attack (very beginning of the sound envelope) right before the note was heard, which reduced both the low and high frequency noise. Furthermore, I decided to subtract two spectra from each other, which eliminated all of the noise that was shared between the two spectra. This reduction of noise was so accurate that the strength of the harmonics in the high register of the clarinet were reduced, showing that the general trend in this range was that the first harmonic was the strongest, and each harmonic afterwards was decreasing linearly in strength. I ran additional tests using loudness as a variable, which showed that the relative strength of the even harmonics became stronger in decibel level when loudness increased.

Chapter 1

Introduction

1.1 Motivation

I have been a musician from the time I was very young. My focus on reed instruments began when I was 11 when I started learning the saxophone. However, my focus shifted to clarinet three years later, which has become my primary instrument today. Once in college, I met music professors who saw my talent, drive, and passion for music composition. For the last three years, music composition has become my main passion and is what I want to do with my life. In the fall of 2017, I will begin my masters at The University of Chicago studying music composition. At William and Mary, I have finished an honors thesis in music composition entitled "A Spectralist Approach to the Vibrations of the Universe." This thesis utilizes the Compton wavelengths formula to calculate the frequencies of subatomic particles (using their rest mass) and, after scaling them down many, many octaves, uses these as the harmonic language of the piece. The thesis is also inspired by string theory, in which every particle is imagined as a standing wave. In fact, most of my music is inspired by physics, as I have always had an attraction to the field. As eluded in my music thesis title, spectralism is a genre of contemporary classical music that I am incredibly attracted to.

My fascination with spectral music is likely due to my studies in physics, as "spectral music offers a formal organization and sonic material that comes directly from the physics of sound, as discovered through science and microphonic access," (Grisey, 2009). Spectral music involves capturing a sound with a microphone, which is often the sound of a musical instrument (but can be really any sound in nature), and analyzing its sound spectrum. The spectrum can be determined by a Fast Fourier Transform, which will tell you which pitches are loudest in the sound. Once these pitches are found, they can be utilized in a composition. I find the spectra of musical instruments to be particularly interesting, because their physics can be clearly defined.

1.2 Goal of this Research

As both a composer and clarinetist, I am extremely interested in the harmonic analysis of the clarinet; therefore, I want to dive into the way in which this instrument is bound to the laws of physics. I will explore how the spectra of the clarinet behave over the range of the instrument. I will also analyze background noise, noise within the instrument. Additionally, I am interested in how the musician may change the strength of the harmonics, known as the tone colour of the sound, which I will explore using loudness as a variable.

Most research I have found discussing clarinet acoustics gives over-simplified results of the harmonics present. I have also have not found studies involving the various range of the instrument. This research project gives me not only another tool for composition, but will add another piece of scholarly work into the field of acoustics. I hope to always be merging the arts and the sciences together throughout my work, and to always be inspired by physics and the world around me.

Chapter 2

Theory

The clarinet is characterized primarily by its unique tone colour. This tone colour is attributed to the the relative strengths of the harmonics that are heard, and with the clarinet, the odd harmonics are what dominate. The reasoning for this is because the clarinet acts mainly in accordance with a closed tube instead of an open tube. While this is oversimplified, the difference can be seen below:

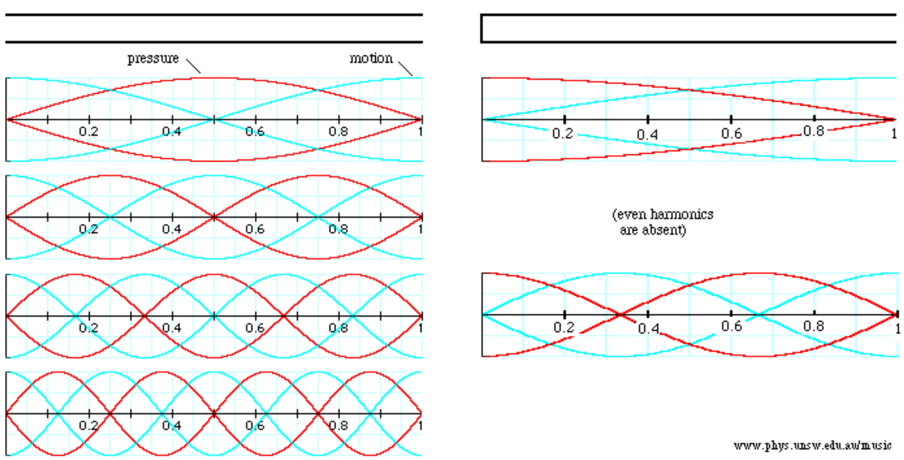

Figure 2.1: Open pipe (left) versus closed pipe (right) (Wolfe).

On the left an open tube is pictured, which is how wave propagation in a flute would operate. On the right is the closed tube. However, realistically, by how much are the even harmonics eliminated in a clarinet? Is this domination of the odd harmonics constant throughout the range of the instrument? Previous research, such as that done by Dickens and Scavone, provides impedance as a function of frequency for only specific captured moments of sound, and is thus harder to show trends over the range of the instrument (Scavone). It is my goal in this research to provide comparisons in the harmonic spectra of the clarinet in its different ranges, which seems to be lacking in the literature. For context, we can see from Dickens the pitch D 5 played on both a flute and a clarinet.

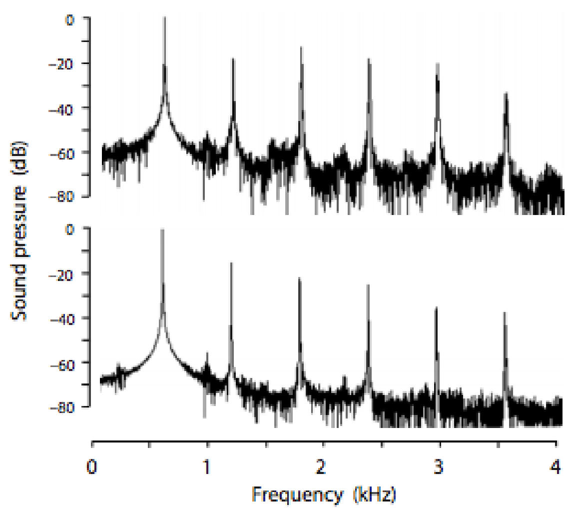

Figure 2.2: D5 spectra for a flute (top) and a clarinet (bottom) (Dickens, 2007).

From this image, it is shown that the clarinet spectrum for D5 is not that much different than that of the flute. This is an indication that the harmonic analysis of the clarinet cannot be oversimplified and generalized throughout the entire range. Why does the clarinet sometimes function like an open tube, and where in the range of the instrument?

2.1 Range

The clarinet functions effectively in three ranges: from E 3 to F 4, the throat tones (G4 to Bb 4), and from B 4 to C 6. The fingerings for B 4 to C 6 are exactly the same as E 3 to

F 4, except that a register key is pressed. The effect this has the wave propagation in the instrument can be shown below:

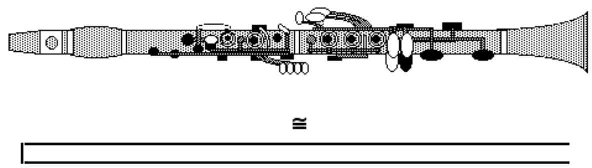

Figure 2.3: Approximation of the Bb Clarinet as a cylindrical pipe open on one side (Wolfe).

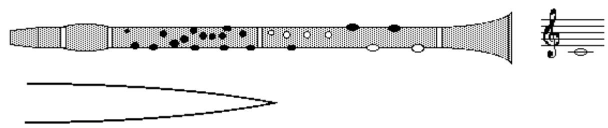

Figure 2.4: Wave equation for C4, in the lower range of the instrument in which the register key is not pressed (Wolfe).

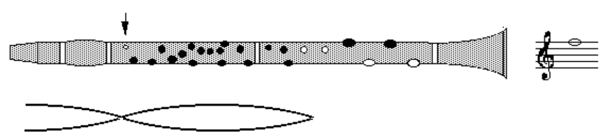

Figure 2.5: Wave equation for F5, in the upper range of the instrument in which the register key is pressed (Wolfe).

It can be seen by Wolfe that by adding the register key, a node is added in the wave. However, generally speaking, by fingering a note on the instrument, you are shortening the length and affecting the pitch; I am interested in how the harmonic spectra and wave propagation may change throughout the range of the instrument through this shortening and lengthening process.

Chapter 3

Experimental Technique

For experimentation, I used my own soprano clarinet model, which is a Buffet-Crampon R13 with Stained African blackwood and a poly-cylindrical bore tuned to 440 Hz. An image of the experimental setup is shown below.

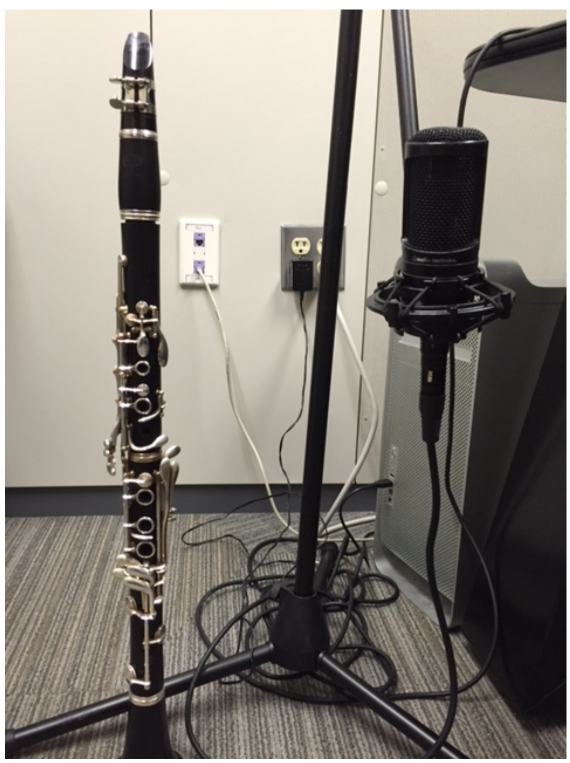

Figure 3.1: Buffet R13 Soprano Clarinet with Microphone.

This project analyzes the (mostly) complete spectra of the soprano Bb clarinet, from the bottom of its range, E 3, to near the top of its range, C 6. The reason for not going higher than C 6 is that C 6 is the highest fingered note that functions as a "mirroring" of the lower range. Higher than C6 is the altissimo range. Sound was recorded using a microphone and the computer program Audacity (Audacity, n.d.). The microphone was placed about 6 inches away from the bottom of the clarinet, where the open end of the instrument is located. For analyzing sound spectra, I first used an open source software called SPEAR (sinusoidal partial editing analysis and resynthesis). SPEAR is unique in that it shows results as frequency as a function of time instead of impedance versus frequency graphs. This tool will be important for showing general trends along the range of the instrument.

I proceeded to then focus on one complete recording of the clarinet over its entire range. With one full trial in Audacity, I trimmed 1 ± 0.005 seconds off the beginning and end of each pitch (sound envelope). I then measured the length of each sound envelope with error of ± 0.01 seconds. Following this, I took an FFT over each sound envelope, avoiding the clipped ends. The FFT was taken using the Hanning window function with a size of 4096. The data for each sound envelope was then exported and uploaded into MATLAB where I could study the sound spectrum for each pitch more in depth.

Chapter 4

Results and Analysis

I ran five trials, playing the chromatic scale of the clarinet from E 3 to C 6. Each note of the chromatic scale functions as the fundamental frequency. For trials one and two, I tuned the whole clarinet to A 440, played each note separately, sustained the pitches for several seconds, and tuned each note individually. No pitch was more than 10 cents off. Cents describes a tuning system in which between each chromatic note is 100 cents. For trial three, I ignored tuning the clarinet (and pushed in all of the components all the way), and again played each note separately and sustained each pitch for several seconds. For trials four and five, I re-tuned the clarinet and slurred each pitch of the chromatic scale (no spacing between each pitch/continuous breath).

4.1 Range Analysis of Spectra in SPEAR

SPEAR is a software that loads a sound file and performs an fast-fourier transform. Each graph shows from left to right the chromatic scale from E3 to C6. For each file, I set the frequency resolution to 500 Hz, which corresponds to an FFT size of 1024. The figure below shows what the Trial 1 looks like after this process.

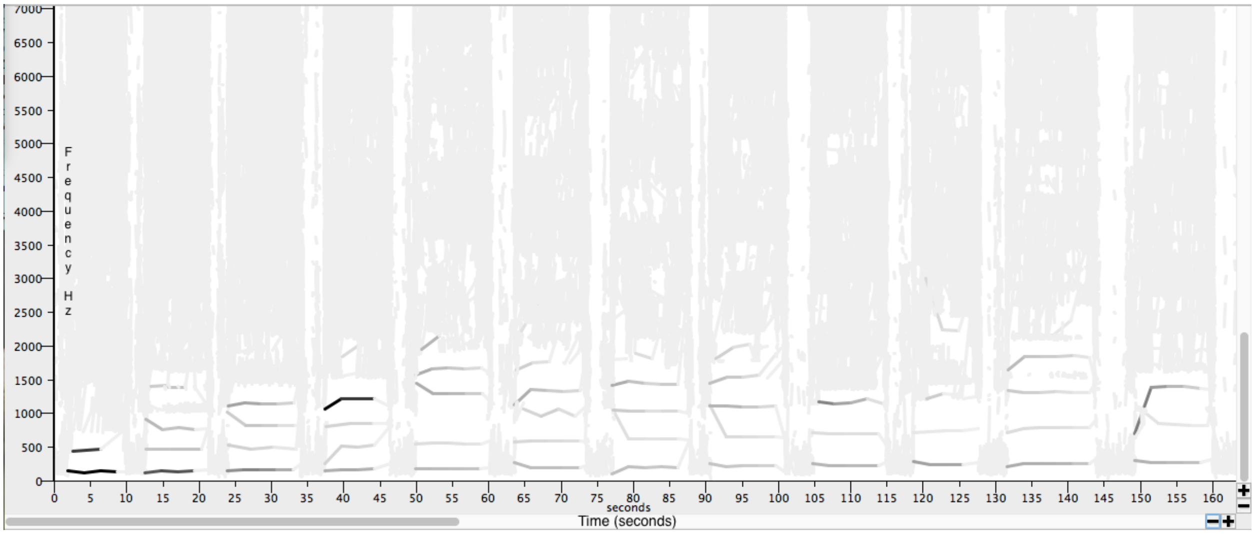

Figure 4.1: Trial 1 SPEAR file after the FFT.

To “clean up” the file, I then selected and deleted every partial that was less than 1 second, and generally selected partials with an amplitude less than -50 dB. The resulting file is shown below.

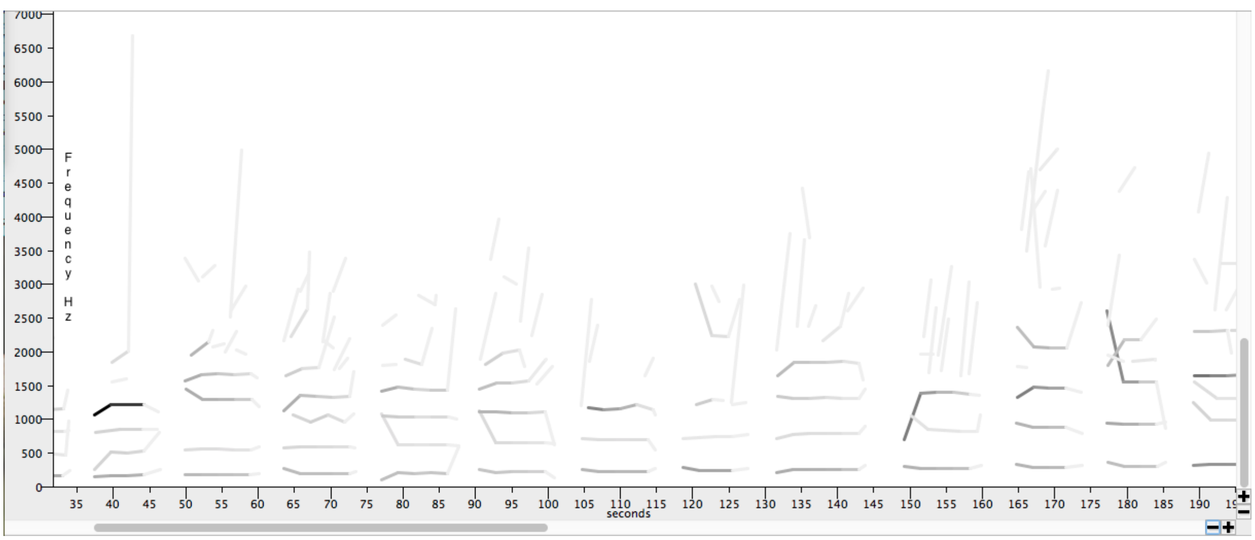

Figure 4.2: Trial 1 SPEAR file after the “cleaning up”.

Following this step, I remove the attack and decay of each pitch, and manually remove the remaining partials that are not constant, likely wavering due to slight changes in the embouchure.

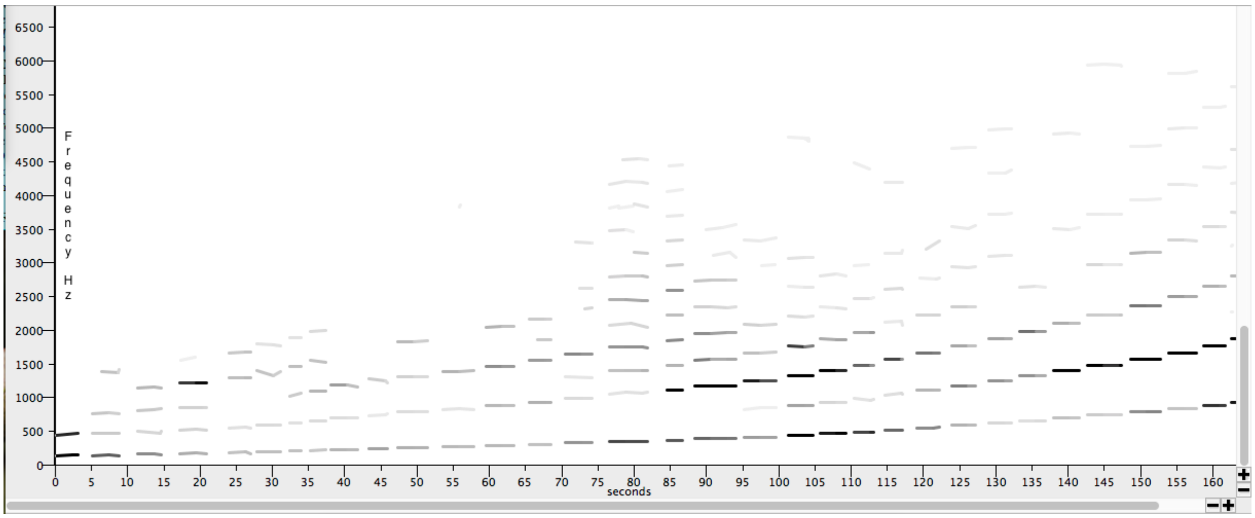

Figure 4.3: Trial 1 SPEAR file after further removing attacks and decays.

The final edited frequency versus time graphs for Trials 2 through 5 are shown below.

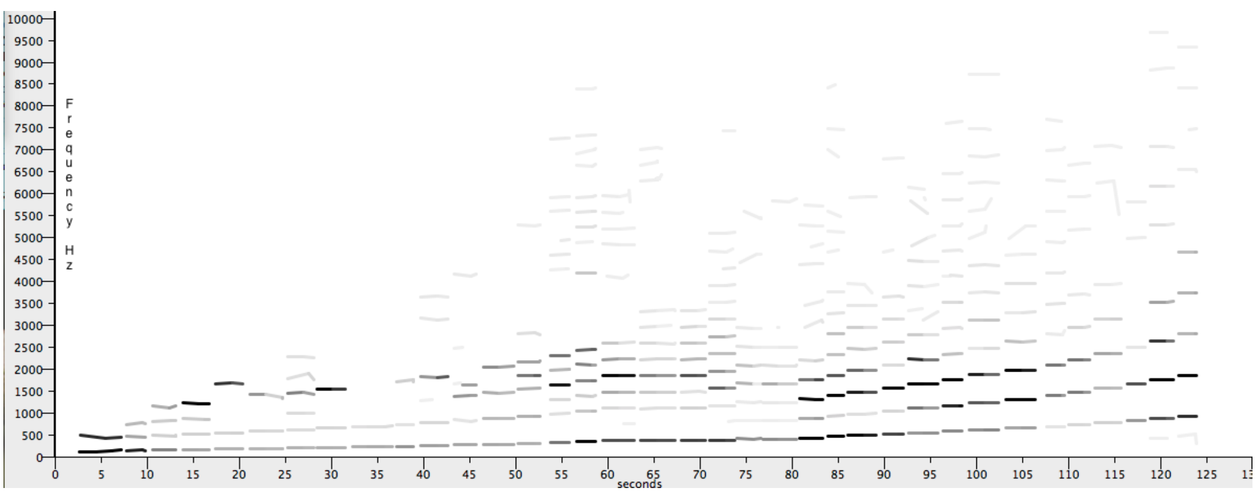

Figure 4.4: Trial 2 frequency versus time graph. The clarinet was tuned to A 440, each pitch was tuned, and the pitches were separated.

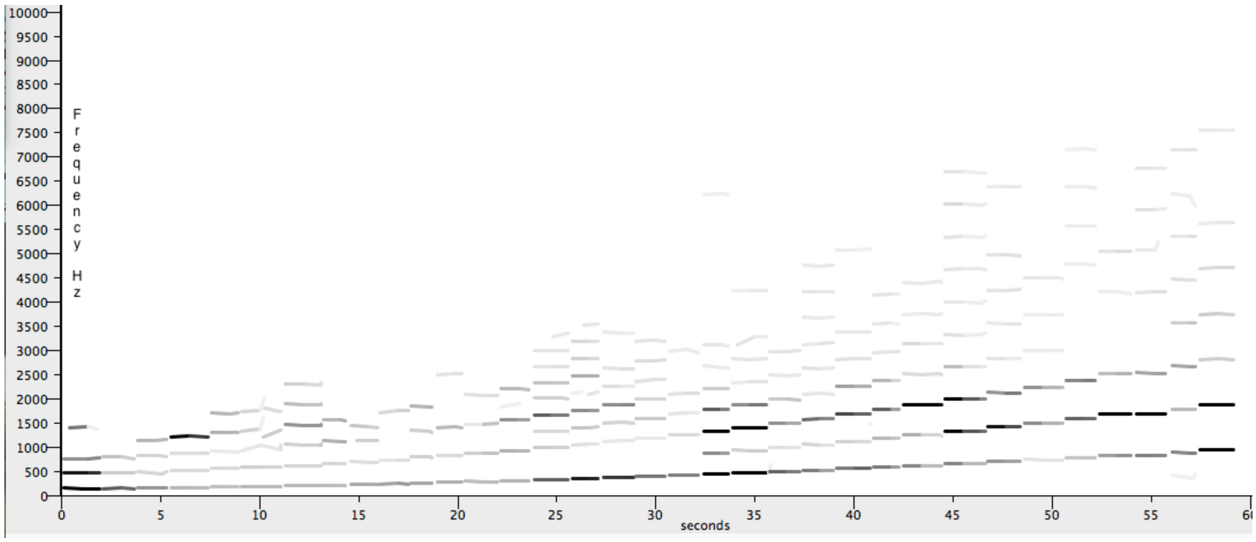

Figure 4.5: Trial 3 frequency versus time graph. The clarinet was “de-tuned,” meaning that the the barrel and joints of the instrument were pushed all the way in. The pitches were separated.

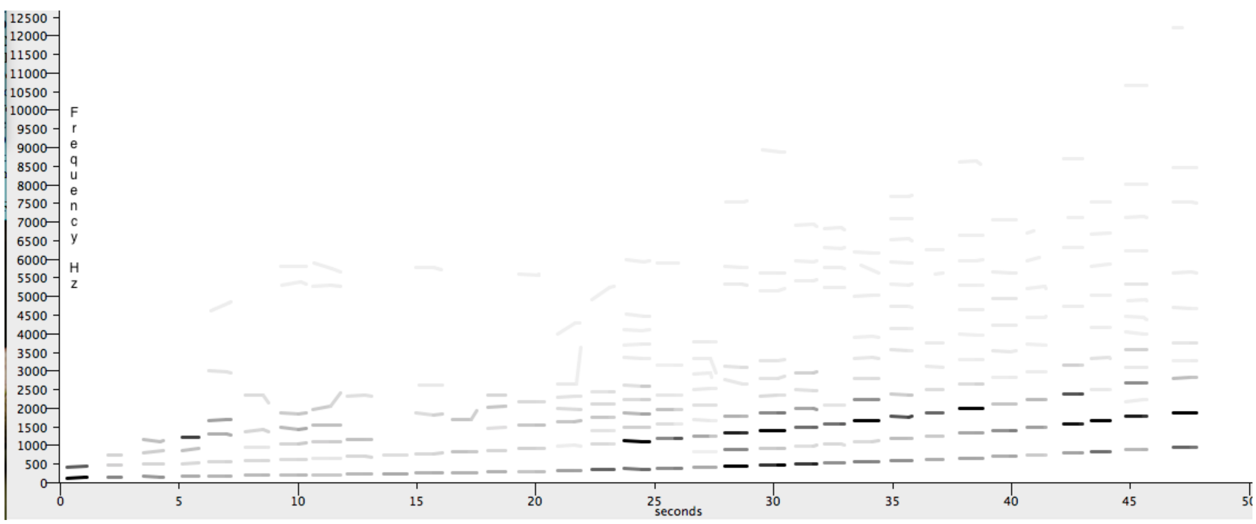

Figure 4.6: Trial 4 frequency versus time graph.The clarinet was tuned and the chromatic scale was slurred.

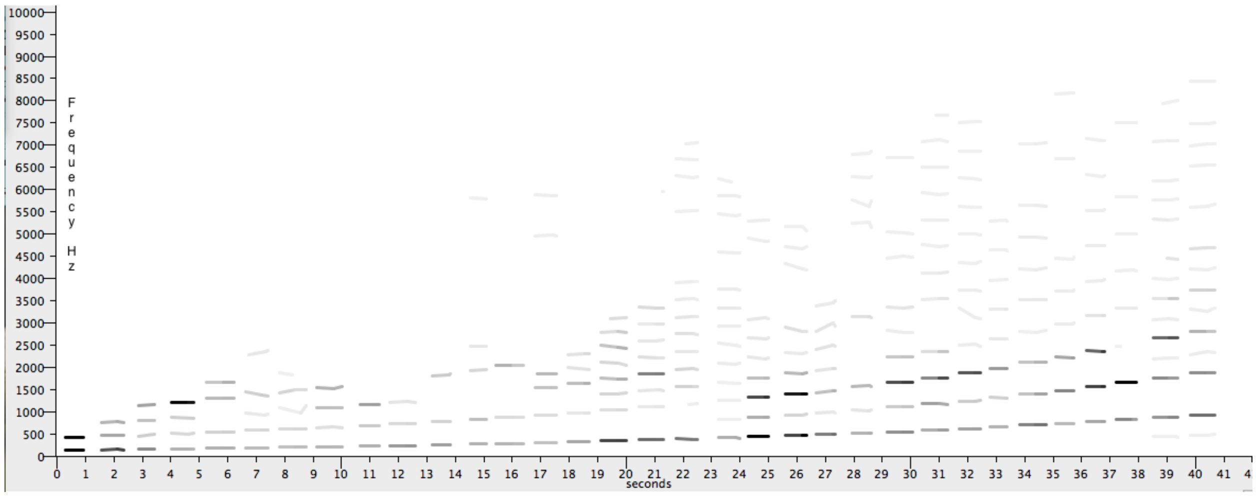

Figure 4.7: Trial 5 frequency versus time graph. The clarinet was tuned and the chromatic scale was slurred.

Several observations in the spectra can be seen from these graphs. Firstly, the lowest note of the instrument has only two extremely prominent harmonics. These are the first and the third harmonics, because the second partial shown is 3 times the frequency of the fundamental. Additionally, what I will label as the richness of the sound, or, the clear visibility of definite partials, increases as the fundamental frequency increases. Most notably, a partial is added in when the fundamental frequency reaches Bb 4 (the first pitch with the register key added) in what appears to be between the first and third partials. This partial is the 2nd harmonic, because it is twice the frequency of the fundamental. This result is extremely important in distinguishing the timbre of the high-register of the clarinet from the lower and middle registers. When adding this register key, the 2nd harmonic becomes very prominent, and the clarinet loses some of its distinct characteristic of acting as a closed tube. However, as seen by the darkness of the lines, the first and third harmonics remain farily prominent throughout the entire range of the instrument.

4.2 FOCUS: Trial 3

The following results were explored using only Trial 3. This trial was chosen specifically because all of the joints of the instrument were pushed together, eliminating the potential variable that length adjustment could have on the sound spectra. As stated in the procedure, Audacity was used as a method of recording sound and running the FFT on each sound envelope. An FFT size was set to 4096, meaning that each FFT had 2047 data points, comprised of 2 coordinates (frequency and decibel level). This data was exported from Audacity and uploaded into Matlab where I analyzed the results.

4.3 Techniques for Eliminating Noise

When first trying to eliminate background noise from the experiment, I decided to focus on the environment surrounding the clarinet.Within the recorded audio, a small segment without the clarinet was selected, and a FFT was run on this envelope. Since this FFT also had a segment size of 4096, it could be subtracted from the FFT of any note, and what should be left is just the harmonic spectra of the clarinet. The FFT of the background noise showed a large amount of sound in the low frequency range, which is likely attributed to the electronic hum of 60 Hz. The tiny spike at the end of the FFT is likely due to any high pitched frequency hums that could have been occurring in the room. As shown below, when subtracting this FFT from a sample pitch of G3, the spectrum of the note is fairly level at 0 except where the spikes in the harmonics are. However, the frequency range where the harmonics are present still includes an elevated decibel level. Additionally, the pitch D5 was tested (G3 fingering plus the register key) to see if range was affected by this process. Similar results were obtained.

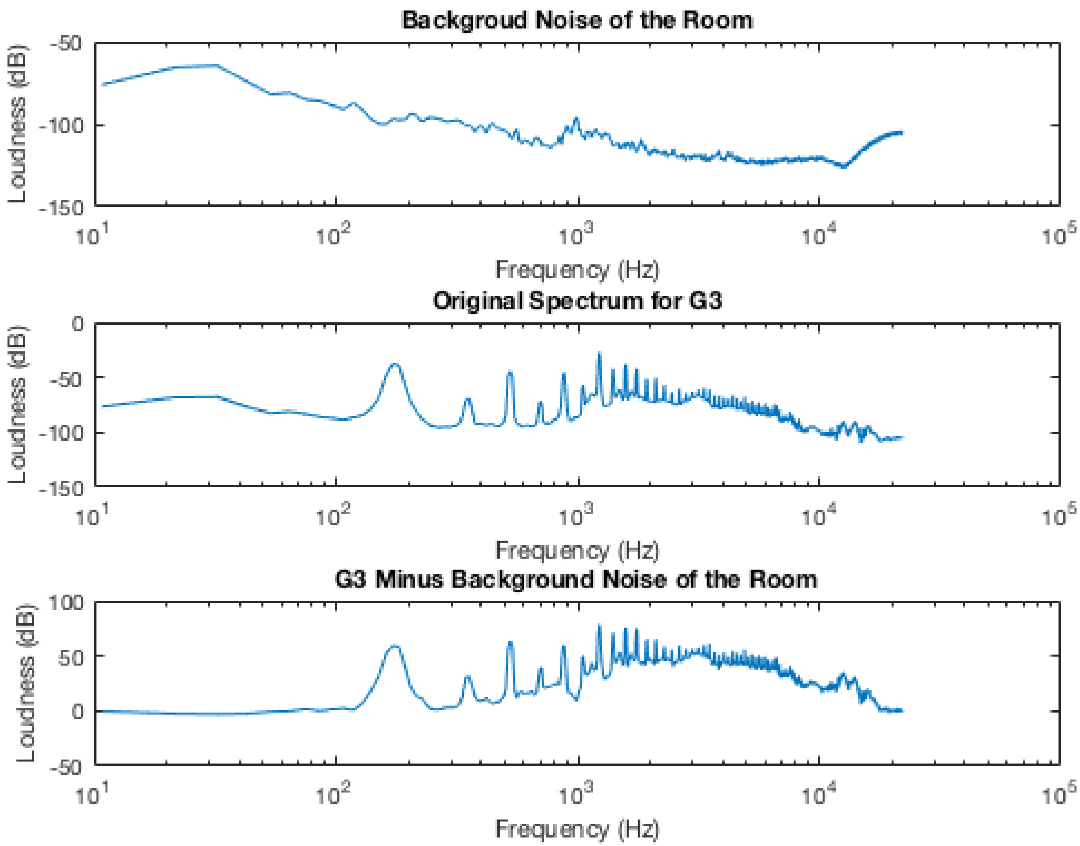

Figure 4.8: Subtracting background noise off of the pitch G3.

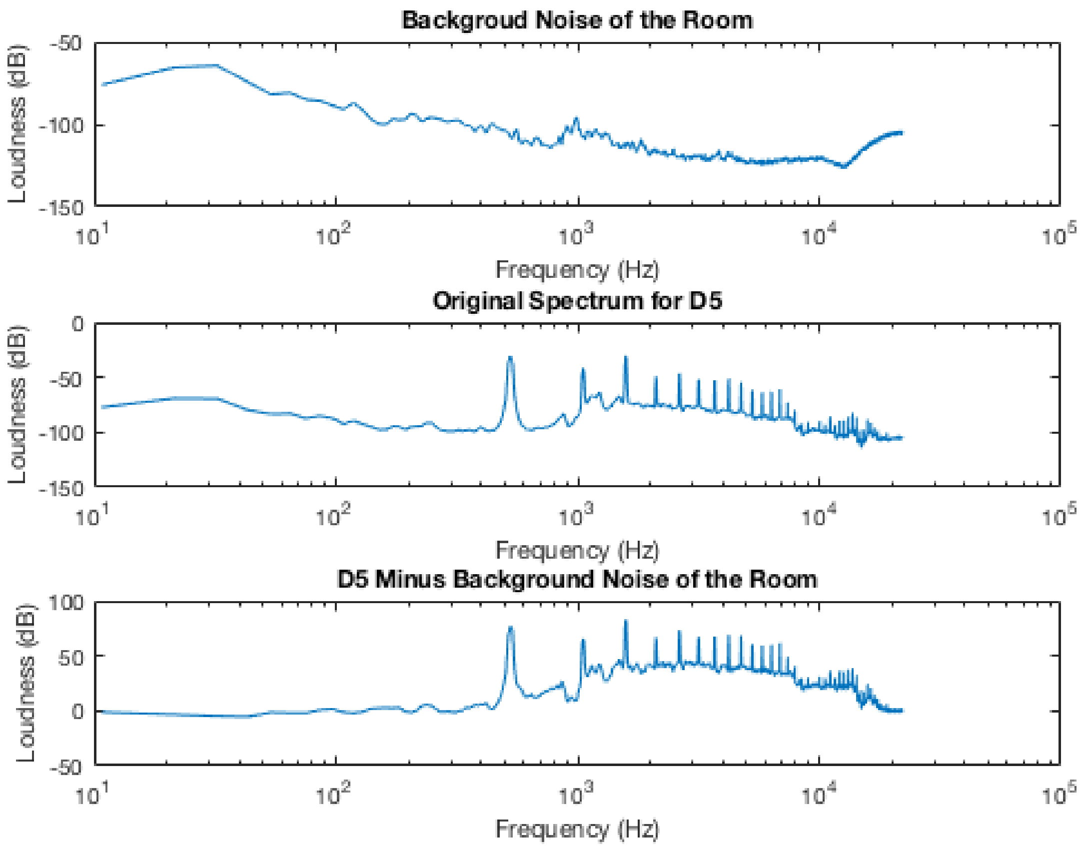

Figure 4.9: Subtracting background noise off of the pitch D5.

In order to further correct for noise, I decided to focus on noise within the clarinet when it is being played. To counter this noise, I selected a segment of the Trial 3 audio right before the designated note was played. By doing this, I was selecting the attack of the note, from where only background noise was happening, to the sound of air entering through the instrument and the very beginning of detectable sound. An FFT of size 4096 was then produced, and subtracted from the FFT of the note that followed the attack. This was done twice, for G3 and D5 as done before. The results are shown below:

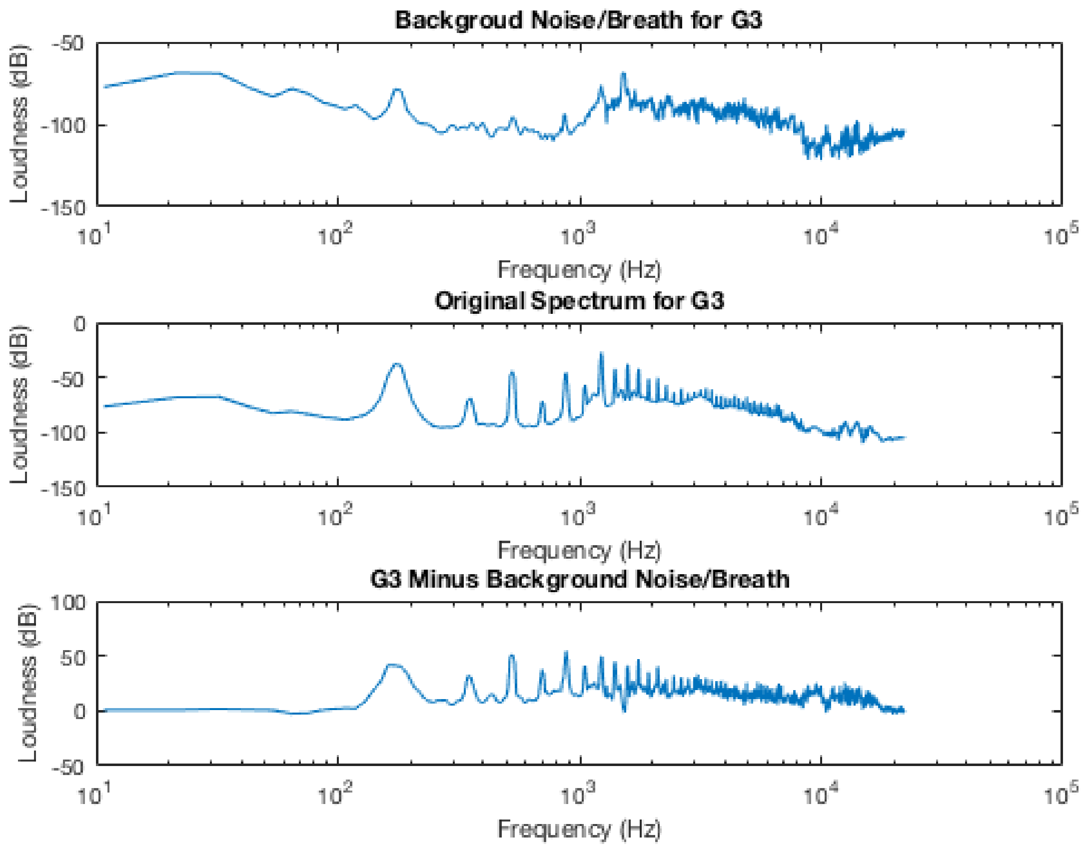

Figure 4.10: Subtracting the attack off of the pitch G3.

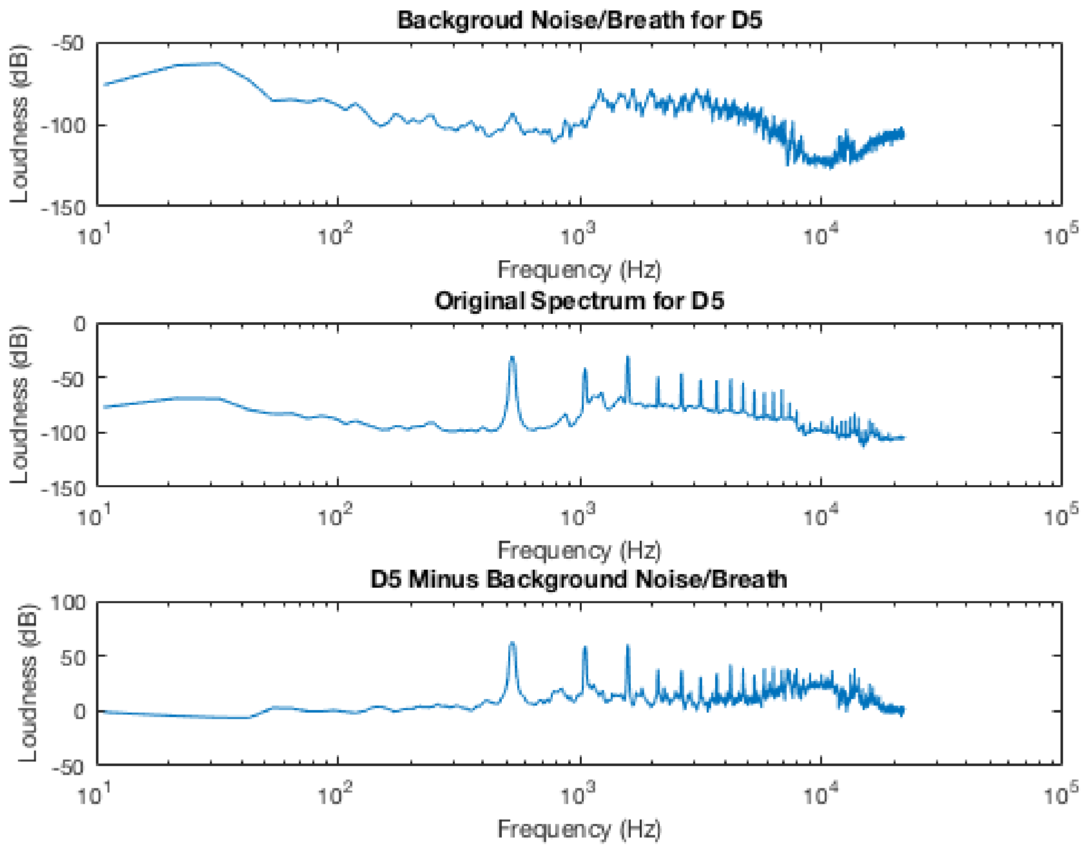

Figure 4.11: Subtracting the attack off of the pitch D5.

The results show that practically all noise was reduced from each spectrum, and that the decibel level went down to almost 0 after each harmonic spike. Therefore, to accurately portray the spectra of a given musical instrument, it is critical to subtract as much noise from the environment and instrument as possible. This will allow for only the harmonic content of the sound to be portrayed.

Cross-spectra analysis is perhaps the most illuminating technique for analyzing sound spectra. I have provided two examples of cross-spectra analysis - one in the low range of the instrument and one in the high range. In each range, two pitches were chosen that are a tritone apart, as pitches of this interval have minimal overlapping harmonics. In the low range, I chose to analyze A#3 with E4, and in the high range, I chose F5 and B5. These are shown below:

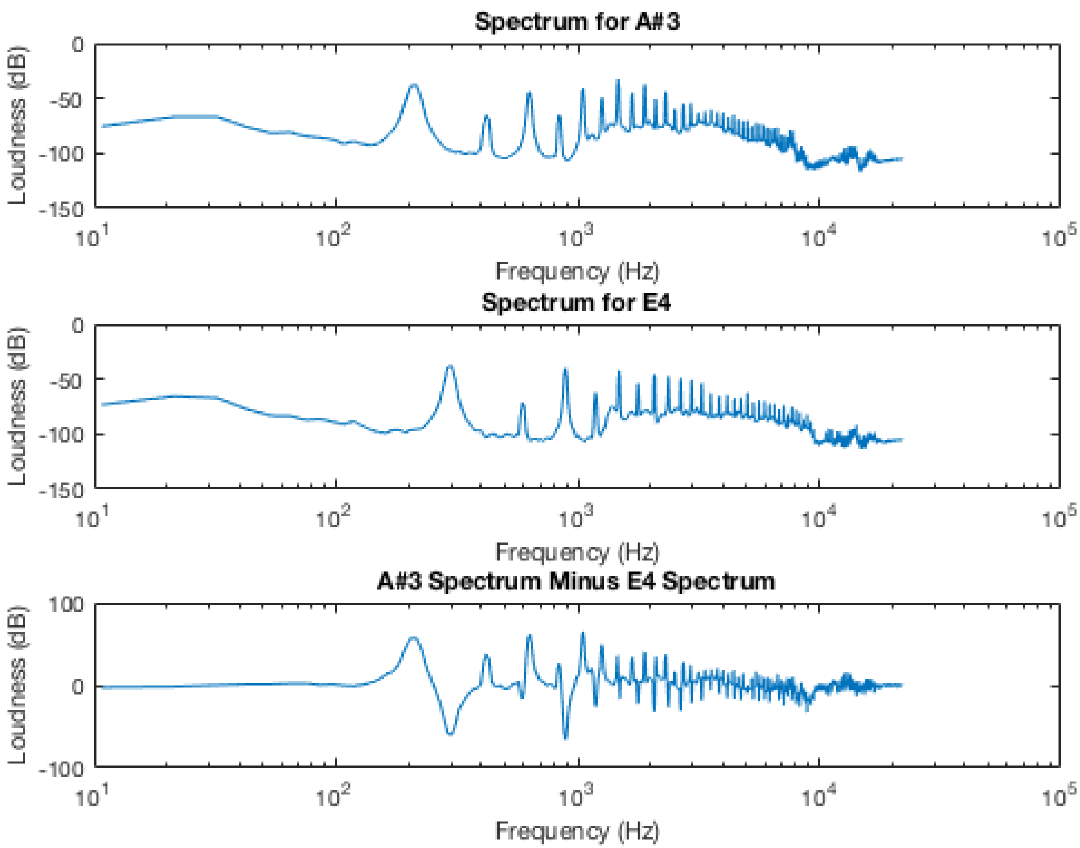

Figure 4.12: Subtracting E3 spectra from A#3 spectra for complete noise reduction.

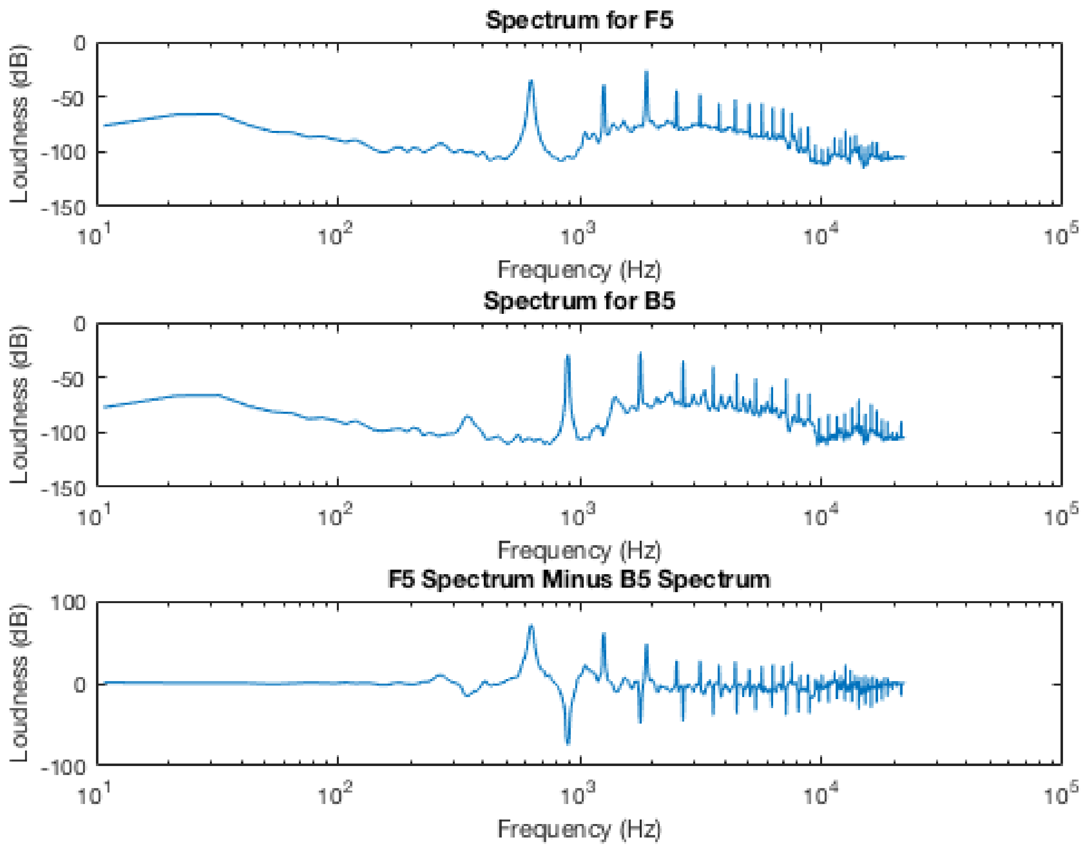

Figure 4.13: Subtracting B5 spectra from F5 spectra for complete noise reduction.

By subtracting one spectrum from the other, all of the the frequency content that is contained in both spectra are eliminated. This shared content is the background environment noise and non-pitched noise within the instrument that occurs when being played. What is left is very close to the pure harmonics content, with the spectrum of one note pointing up and the subtracted spectrum of the other note pointing down.

This technique is particularly illuminating. Individually, it is shown that the first partial for both F5 and B5 are not the strongest of each series. However, when crossing the two, noise is eliminated, and the partials are lowered drastically. Now the relative strengths have changed, and the first partials of each spectrum are the strongest, and the rest decrease uniformly in strength.

4.4 Range Analysis of Spectra in MATLAB

All of the spectra studied in each register of the clarinet had the general background noise subtracted from the Y-Axis, but not the noise from the attacks. For the low-register of the instrument, I selected three notes: the lowest note on the instrument with all fingers pressed (E3), as well as G#3 and B3, chosen semi-arbitrarily. I wanted to choose three notes that were fairly spaced out over the low-register range, but had varied enough fingerings The spectra for each of these notes are shown below. Additionally, I have included a table that includes the numerical value for the strength of the first 6 harmonics. This table includes ratios of each odd harmonic, n, to the even harmonic directly above it, n + 1. (Ratios of the first to the second harmonic, third to the fourth harmonic, and fifth the the sixth harmonic).

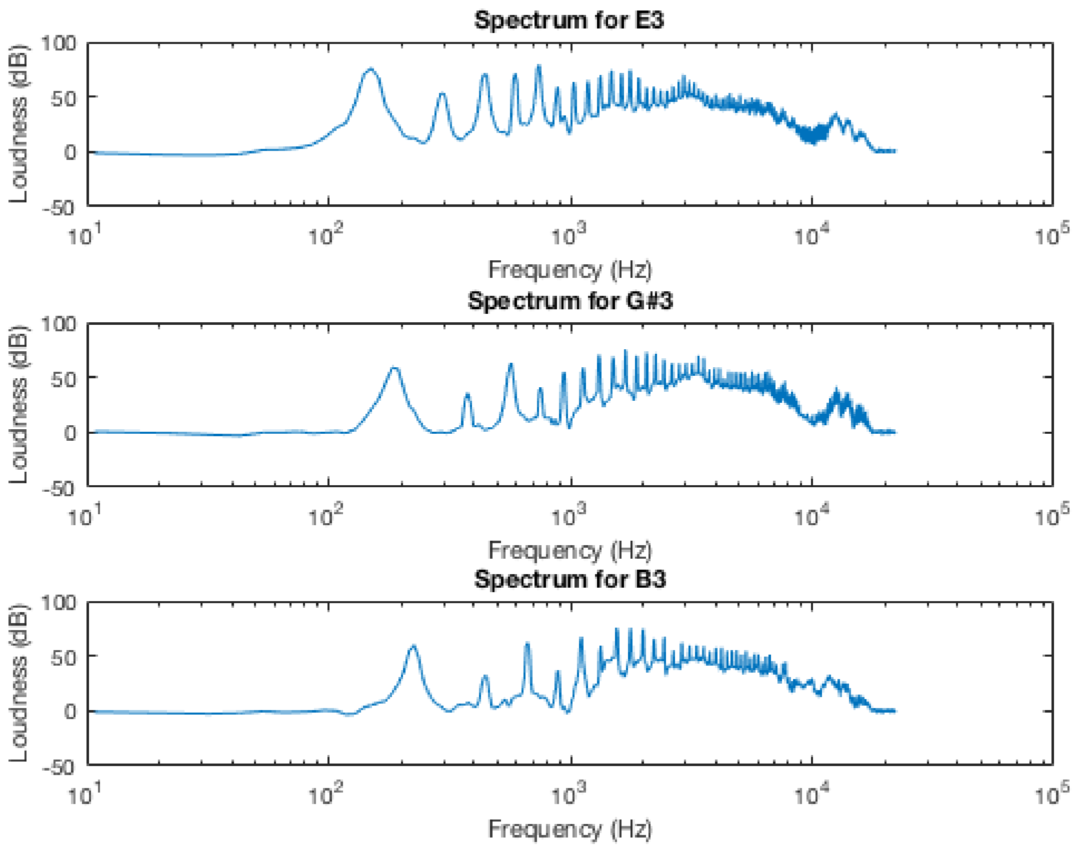

Figure 4.14: Low Range Spectra.

Harmonic	E3	G#3	B3
1	76.10	58.96	60.20
2	53.21	36.13	32.09
Ratio	1.43	1.63	1.88
3	70.98	63.36	62.51
4	71.09	41.13	36.33
Ratio	1.00	1.54	1.72
5	79.23	55.18	67.30
6	58.96	59.24	59.57
Ratio	1.34	0.93	1.12

Table 4.1: Strengths of odd and even harmonics in the low range.

What is particularly interesting to analyze are the ratios between each odd harmonic, n, to the even harmonic, n + 1. This shows by how much larger (or sometimes lower) the odd harmonic is to the even harmonic directly above to it in the harmonic series. Because most previous studies say that the clarinet functions as a closed pipe with odd harmonic dominating, we would hope to see ratios larger than 1, indicating that the odd harmonics are always stronger than the even harmonics. In the low register, each ratio is indeed greater than or equal to 1. Most drastic are the difference between the first harmonic and the second harmonic for each note, which tells us that the fundamental pitch is strong and the first even harmonic is not very strong at all, which is what we expect.

Three notes in the middle register of the instrument were chosen for in depth spectral analysis. F#4 was chosen because it is the first note that removes the left hand thumb. G4 was chosen because no fingers are pressed on the instrument (completely open). Lastly, A#4 was chosen because it is the first note with the register key pressed. Below are the spectra of these three notes, as well as a table including the strength (in dB) of each harmonic.

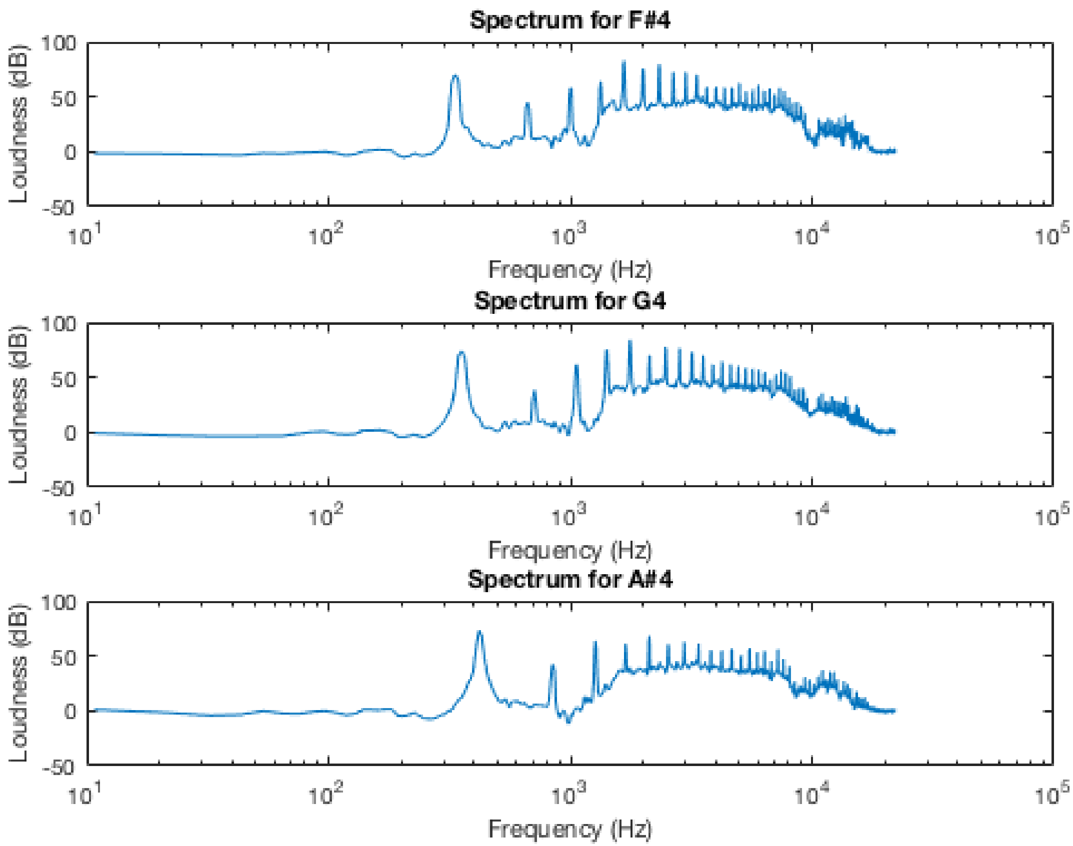

Figure 4.15: Middle Range Spectra.

Harmonic	F#4 (dB)	G4 (dB)	A#4 (dB)
1	69.91	73.92	73.36
2	44.83	38.54	42.35
Ratio	1.56	1.92	1.73
3	58.17	61.98	63.65
4	63.90	73.80	61.34
Ratio	0.91	0.83	1.04
5	82.96	77.72	68.40
6	75.64	76.73	61.56
Ratio	1.10	1.20	1.13

Table 4.2: Strengths of odd and even harmonics in the middle range.

Most of the ratios between harmonics are greater than one, which is what we would expect. However, For F#4 and G4, the fourth harmonic is higher than the third harmonic. This could likely be due to a node opening where the thumb usually is placed, which is about 1/4 the way down the instrument. When a node is touched 1/4 the way on a string, the fourth harmonic is prominently activated, which is what seems like is happening on the clarinet. However, between 10^3 and 10^4 there is heightened noise, which is noise occurring within the instrument since this was not subtracted from the spectrum. If this noise was accounted for, likely the fourth harmonics would not be so strong.

Three pitches were chosen for analyzing the high register of the clarinet. B4 was chosen because this is the first note that includes the register key and has all of the keys depressed (equivalent of E3 but with the register key). G#5 was chosen semi arbitrarily, and C6 was chosen as this is the highest note which fingering is reflective of a lower register pitch with the register key. Above C6 is the altissimo range.

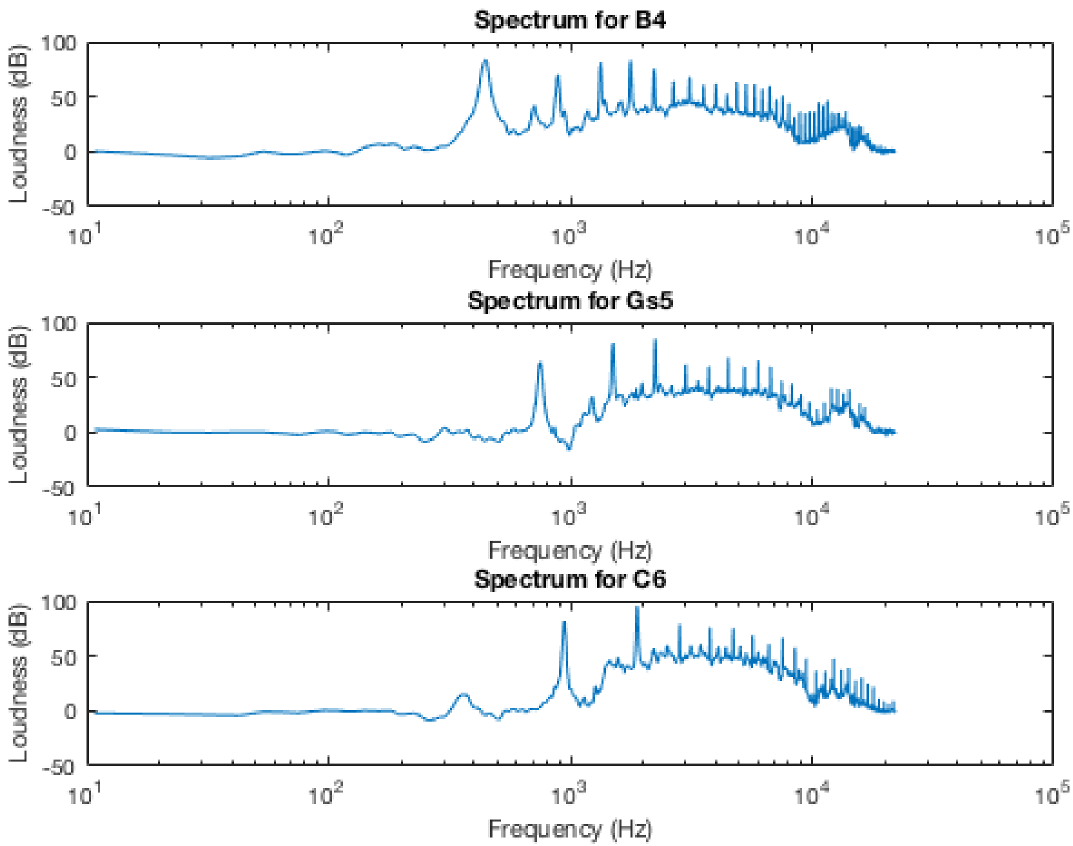

Figure 4.16: High Range Spectra.

Harmonic	B4 (dB)	G#5 (dB)	C6 (dB)
1	83.15	64.09	81.68
2	69.06	81.09	95.73
Ratio	1.20	0.76	0.85
3	81.51	85.07	78.85
4	83.16	85.07	78.85
Ratio	0.98	1.37	1.04
5	74.92	60.22	75.03
6	64.08	68.26	68.65
Ratio	1.16	0.88	1.09

Table 4.3: Strengths of odd and even harmonics in the high range.

In the highest range of the instrument, the second harmonics appear to be higher than the first harmonic. Additionally, several other even harmonics were higher than expected, and stronger than nearby odd harmonics. However, this could be attributed to noise within the instrument as well, as only background noise was subtracted from this data. However, as seen with the cross-spectral analysis done above, a more realistic trend is that the first harmonic is the strongest with each following harmonic uniformly lowered in strength.

4.5 Tests for Spectral Manipulation - Loudness

Directions for changing tone colour of the instrument is seen in classical music, as composers may want to portray certain effects or moods within their pieces. How is it that the instrument is changing its timbre, and what is the musician doing to do this? Changing timbre is attributed to a change in the relative strengths of the harmonics. Most importantly, I am interested in seeing if it is possible to increase or decrease the presence of the even harmonics within the clarinet. There are many ways that a musician may be able do this, including the position of tongue in the oral cavity, tightness of mouth, alternate fingerings, and reed softness. However, the scope of this project only included testing one variable for tone colour/spectra manipulation, which is loudness. This was tested on a low-range pitch (C4) and a high range pitch (G5), which is C4 with the register key pressed. The data for C4 is shown below.

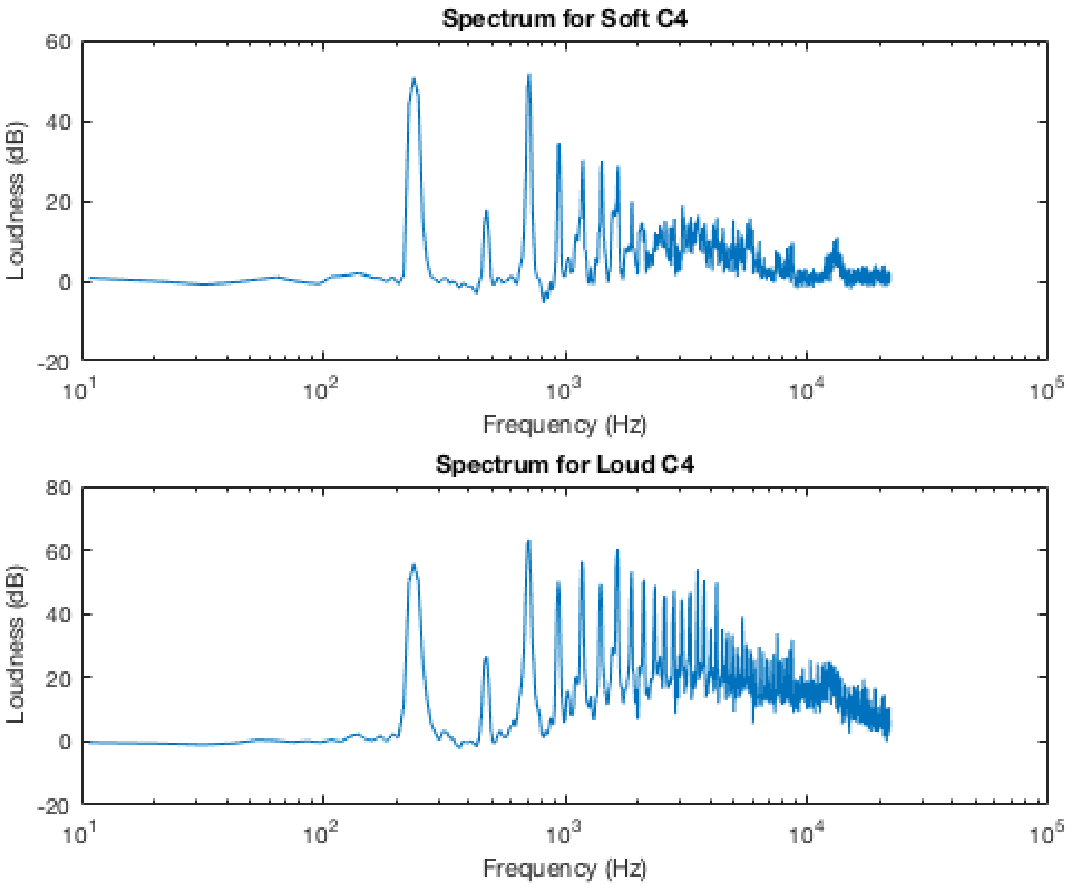

Figure 4.17: Soft versus Loud Spectra for C4.

Harmonic	C4 Soft (dB)	C4 Loud (dB)
1	50.68	55.68
2	17.82	26.76
Ratio	2.84	2.08
3	51.81	63.22
4	34.38	50.20
Ratio	1.51	1.26
5	30.20	56.48
6	30.03	48.99
Ratio	1.01	1.15

Table 4.4: Soft versus loud strengths of odd and even harmonics for C4.

This data, as specified above for low-range clarinet spectra, has a mostly increased intensity of the odd harmonics. When analyzing the C4 note played softly, this trend is seen, and most importantly, the ratio between the first and second harmonic is 2.84 (the first harmonic is 2.84 times the strength of the second harmonic), and the ratio between harmonic 3 and 4 is 1.51. However, when analyzing the C4 note played loudly, this 1 to 2 ratio is reduced to 2.08 and the 3 to 4 ratio is reduced to 1.26. The ratio for comparing harmonics 5 and 6 is actually slightly larger for when C4 is played loudly.

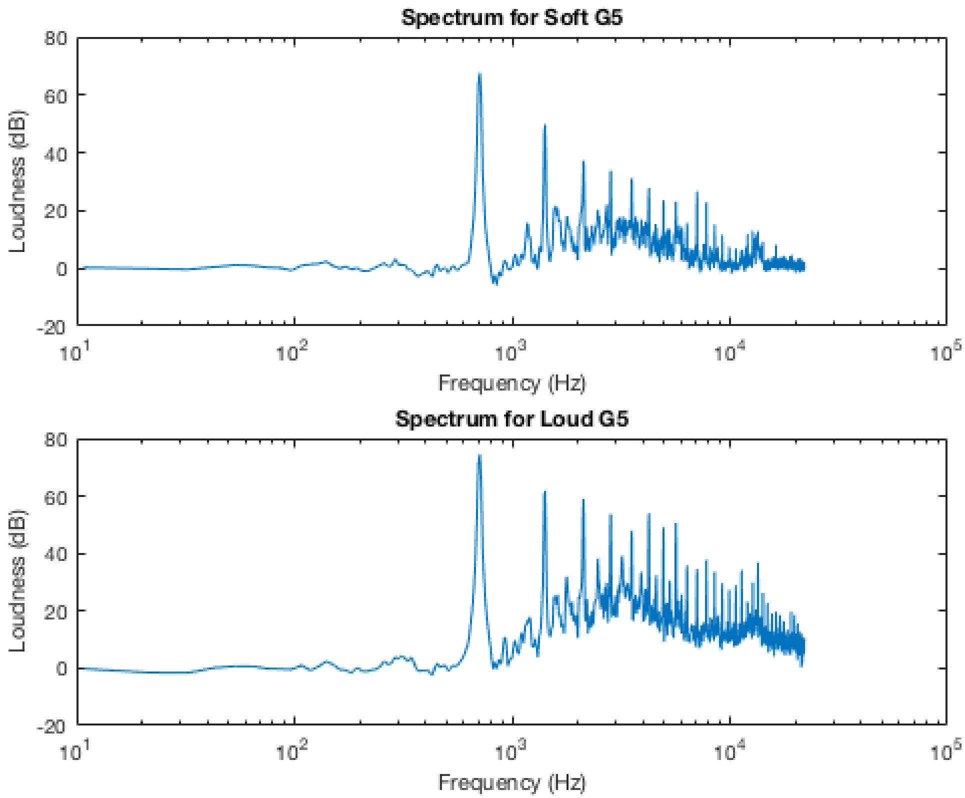

Figure 4.18: Soft versus Loud Spectra for G5.

Harmonic	G5 Soft (dB)	G5 Loud (dB)
1	67.74	74.44
2	49.79	61.90
Ratio	1.36	1.20
3	37.17	59.03
4	33.75	53.81
Ratio	1.10	1.10
5	31.14	47.93
6	27.85	53.92
Ratio	1.12	0.89

Table 4.5: Soft versus loud strengths of odd and even harmonics for G5.

As seen for the note G5, the general trend for high-range spectra as viewed above still holds, where the first 2 harmonics are the strongest and the rest uniformly decrease in decibel strength. However, for G5 played softly, the ratio between the harmonic 1 and harmonic 2 is 1.36, whereas this ratio for G5 played loudly is 1.20. This ratio for harmonic 3 and 4 is 1.10 for both. When comparing harmonics 5 and 6, while the ratio for the G5 soft is small, for when G5 is played loudly, the 6th harmonic is actually larger than the 5th harmonic. This data gives some slight indicated that playing louder increases the presence of the even harmonics, at least for the second harmonic.

From the data for both C4 and G5 one can suspect that increasing loudness does indeed increase the presence of the even harmonics. This is likely due to the increased air support; with more air flow, the oral cavity begins to act as more of an open tube rather than a closed tube, and the clarinet starts to behave slightly more like the harmonic spectra of a flute. However, since the upper range of the clarinet already had this tendency due to the opening of the register key, the high range spectra were less affected by this attempt at spectral manipulation.

Chapter 5

Conclusions

This project explored how the timbre of the clarinet changes over the range of the instrument. To explore this, each chromatic note of the clarinet was recorded, from E3 to C6. Higher than C6 is the altissimo range, which was not in the scope of this project. The clarinet was effectively split into three ranges: low-register, middle-register, and high-register. I designated the low-register from E3 to F4, as these notes include the thumb pressed down. Starting at F#4 and lasting until Bb4, the thumb is no longer pressed down, so I designated this as the middle-register. The high-register starts at B4 and goes until C6. Important to note is that Bb4 is the first note that includes the register key, and B4 to C6 acts as a "mirroring" of E3 to F4 but with the register key pressed. The register key jumps the pitches to an octave and a fifth higher than the low-register notes. First, I decided to run five trials in slightly different ways to analyze general trends of the spectra. This was done using an open-source software called SPEAR. The results from this showed that the low-register and middle-register notes did not have prominent second harmonics (in fact, they were not even visible when the sound files were "cleaned up"). However, right at Bb4, the top of the middle-register range, and throughout to C6, the second harmonic became more intense. This indicates that the clarinet is acting less as a closed-pipe in the higher range.

After studying the SPEAR files, I decided to focus on Trial 3 where the joints of the clarinet were pushed together, and I ran individual FFTs on each note of the clarinet in Audacity. The data from these FFTs were then exported into MATLAB where I could study them more in depth. The low-register notes all included stronger odd harmonics than even harmonics, which is what was expected. However, in the middle-register, some notes exhibited a strong fourth harmonic. This was attributed to the opening (node) that was present when removing the thumb. Lastly, in the high register, there were many more even harmonics that were stronger than the odd harmonics, again indicating the the clarinet was acting less like a closed-pipe.

Noise was particularly present in the middle and high register of the clarinet. I decided to combat this in several ways. Firstly, I just subtracted the FFT of the background noise in the room from the clarinet spectra. This reduced to low-frequency noise, but not the higher-frequency noise. Therefore, I decided to subtract a spectra of the attack right before the note was heard for two pitches. This proved to reduce both the low and high frequency noise, indicating that a lot of the noise present was occurring in the instrument itself.

To further show this, I decided to subtract two spectra from each other, which would eliminate all of the frequencies that were shared between the two spectra. If two spectra were chosen wisely so that they had little to none overlapping harmonics, then what we would expect to see is complete noise reduction. This is in fact what was shown. What is particularly illuminating is that the reduction of noise in the higher register actually reduced some of the strength of the even harmonics, showing that what was actually happening in this range is that the first harmonic was the strongest, and each harmonic afterwards was decreasing linearly in strength.

Lastly, spectra manipulation was tested by using loudness as a variable. What this showed was that loudness did have an effect on the presence of the even harmonics. Particularly, the ratios between the odd and even harmonics decreased when loudness increased, indicating that the even harmonics became stronger in decibel level as compared to the odd harmonics.

5.1 Future Plans

There are a million and one things that could change the harmonic spectra of the clarinet. This project only focused on a couple variables - the range of the instrument (main focus) and loudness. Extra variables that may be explored are the following: position of tongue in the oral cavity, tightness of mouth, length adjustments of the instrument, alternate fingerings, altissimo range, and reed softness. A catalogue of spectra, for each note, should exist in the public domain. While my experiment did just that, for higher reliability, more trials should be taken (on various clarinet models as well) and an average spectrum should be taken. Even further, this could be done for every musical instrument. With this information, we would know very exactly and precisely how musical instruments operate, and for the contemporary composer, this opens a beautiful new toolbox.

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