Measuring and Countering the Effects of Temperature on the Sound of an E_b Alto Saxophone

Akash Agarwal
May 14th, 2015
2.671 Measurement and Instrumentation
Friday PM
Prof. Seering

Abstract

The effects of temperature, humidity and mouthpiece position on the output frequency of an alto saxophone were investigated in order to understand how a musician may compensate for various external conditions. Surface temperature sensors, a relative humidity sensor, a microphone and calipers were used to measure temperature of the instrument, internal bell humidity, output frequency and mouthpiece positioning, respectively. It was found that moving the mouthpiece 15 mm towards the neck of the instrument could effectively counter the 6.110 ± 0.19 Hz (2.624%) decrease in frequency induced by a temperature of 12.25*C being applied to the instrument. Further, it was found that although humidity affects output frequency, a 50% increase in relative humidity just yielded a 0.965 ± 0.19 Hz increase in frequency. However, the humidity results were inconclusive due to the inconsistency of the humidity sensor used.

1. Introduction

Knowing the effects of temperature on the pitch frequency of any instrument is valuable for any serious musician. The nature of this investigation was to examine such effects on a specific wind instrument, the E_b Alto Saxophone. Saxophones are seen in various contexts, including jazz bands, wind ensembles, pep bands at athletic contests and often in marching bands. As such, a saxophonist must cope with various temperature and humidity discrepancies over the course of his career. The sax will sound different depending on its surrounding area. For instance, the sound on one evening in a warm, grand concert hall will be unlike that when playing in the freezing cold bleachers of a northern athletic contest. The coldest recorded football game in 2009 for the Michigan Wolverines was 3.89*C[1]. As temperatures drop significantly, the output pitch of the instrument is affected. At this game, the pep band musicians would have to compensate for the extreme external conditions while performing, in order to serve as a supplement (and not a distraction) to the football team.

Surprisingly, even seemingly minor pitch discrepancies are detectable and unpleasant, especially in a large group where every musician is constantly listening to each other. Just one instrument varying from the rest can alter the overall sound of the band and performance of individuals within the section. To prevent such issues from arising, musicians tune their instruments before practicing and performing. While tuning, the main way for saxophonists to significantly alter the frequency of his/her output sound is by adjusting the mouthpiece on the cork of the instrument's neck, see Figure 1 below for an illustration of this process:

Figure 1: In the left image, the mouthpiece is pushed far onto the cork, which increases output frequency (sharpens pitch), while the right image demonstrates a mouthpiece position which would flatten pitch. Note the red line, the distance from mouthpiece base to the neck, is increased in the right side image.

The goal of this investigation was to examine how much the mouthpiece needed to be adjusted on the neck cork to counter the pitch variation caused by a change in humidity or temperature. In order to examine this question, the output sound frequency was measured while the instrument was warmed from an initial cold temperature. Surface temperature sensors were used to measure the temperature at two points on the instrument. Further, the frequency was examined while pulling the mouthpiece back from its deepest position on the neck. That is to say that the mouthpiece was pushed as far in as it could fit on the cork, and frequencies were then measured as the mouthpiece was incrementally pulled away from the sax neck. This position variation was used to determine the distance a saxophonist needed to move his mouthpiece to counter the effect of temperature. Humidity within the instrument was also examined to insure that the frequency discrepancies were caused primarily by the change in temperature. In order to insure that the musician did not affect the pitch while these parameters were being tested, a calibration exercise took place which determined that over 10 trials, the musician was able to hit the same note nine times. That is to say, in a sequence of 10 G's being played, a pitch range of 232.2-232.58 Hz was achieved for all but one trial. Therefore, the variations in pitch during the investigation had to have arisen from the variables being adjusted. Uncertainty propagation was used to determine the accuracy of the final results.

2. The Wave Physics of the Alto Saxophone

The behavior of an alto saxophone can be modeled as a closed air column with an internal, standing wave. This model enables a conceptual understanding of the instrument's behavior. The wavelength of the output sound is based on the length of this effective air column, which can be adjusted by closing or opening keys on the saxophone. Each key fingering represents a distinct note. The wavelength of the output sound is directly proportional to the length of the air column, as seen in Equation 1[2], where L is the length of the closed air column and λ is the wavelength of the output sound, both in meters. Note that this equation represents the first harmonic relationship of L and λ, for higher harmonics the multiplier of L (**bolded** for intelligibility) decreases in magnitude thus decreasing wavelength:

$$\lambda = (\mathbf{4}/\mathbf{1}) * L \tag{1}$$

Closing every key will create the longest possible air column (*L)*, and yield the lowest note the instrument can play, a low frequency output. This relationship between frequency and wavelength is illustrated in Equation 2[2], where *v* is the speed of sound in meters/second and *f* is the output frequency in Hertz:

$$v = f * \lambda \tag{2}$$

The air column created is relatively long when closing all keys, which yields a large λ (Equation 1). Since at constant temperature the velocity of sound is constant, the output frequency adjusts accordingly. Thus, a large wavelength correlates with low frequency output, or a low output sound. Conversely, if all the keys are left open then a high frequency output is generated as the length of the air column and thus λ are small.

The natural mechanism of the instrument is to adjust the frequency of the output sounds by changing λ. Differing fingerings on the instrument yield various λ values, which in turn change the output frequencies so that a range of notes and thus music can be attained. However, if λ (fingering of a note) remains constant, frequency can then be varied by adjusting the velocity of sound. In this investigation, the velocity of sound was adjusted by influencing the temperature of the air column, or the saxophone's temperature itself.

Since cold gas holds less energy than hot gas, when the sound wave in the air column interacts with the instrument's significantly cooled, inner surface, energy is lost and thus sound velocity is decreased. Therefore, decreasing the temperature of the instrument should flatten (decrease) the frequency of the final sound. One purpose of this research was to determine the extent to which a musician could reasonably expect to hear the instrument pitch change due to cold weather. This effect can be quantitatively understood in Equation 3[3], where T_c is the outside temperature in Celsius, and *v* is the velocity of sound in m/s:

$$v \approx 331.4 + 0.606Tc \tag{3}$$

While λ can be influenced by varying key openings, the characteristic length of the air column (and in turn, λ), can also be changed by adjusting the mouthpiece on the neck of the instrument. By pulling the mouthpiece farther out on the cork (right image, Figure 1), the characteristic air column length is increased and thus the output sound will be naturally lower in frequency, since λ is inherently increased based on Equation 1. This effect leads into the ultimate goal of the investigation, to determine the adjustment required of the mouthpiece on the neck cork to compensate for pitch variations brought upon by cold weather.

3. Measurement of Frequency based on Temperature, Humidity and Mouthpiece Positioning

To investigate the frequency response of an E_b alto saxophone based on the humidity, temperature and position of the mouthpiece, an experiment was performed to measure frequency of a single note given different values of each parameter mentioned. This procedure consisted of four major processes: The cooling of the saxophone, the adjustment of humidity within the horn, varying the mouthpiece position on the neck of the instrument and the actual measurement of frequency for each variable adjustment.

3.1 Mechanisms of Measurement Based on Temperature

To measure the frequency response of the instrument with temperature variation, two Vernier STS-BTA surface temperature sensors (STS) were adhered to the neck and bell of the instrument using Scotch tape. A Vernier MCA-BTA microphone was placed two inches from the opening of the bell. As for the instrument itself, a Selmer La Voix II alto saxophone was used for all measurements. The saxophone was placed outdoors in the naturally cold environment, 8 *C, for 15 minutes to experience significant cooling, and then (for all trials) two second whole notes were played as the instrument naturally warmed. These frequencies were plotted against the average of the two measured temperatures. This process was repeated for three separate notes, a low G (3 major keys closed), a high D (all major keys closed, D2) and a high G (first hole open, G2). A visualization of this setup can be seen from the red arrows in Figure 2[4]:

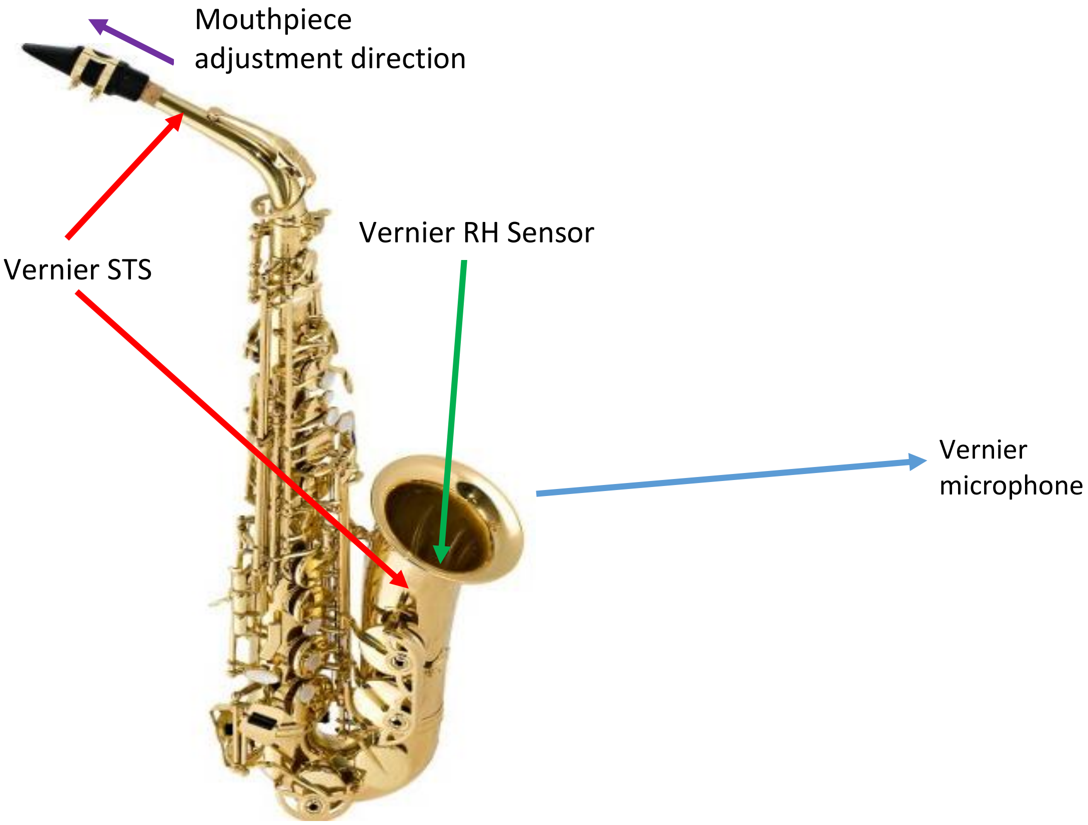

Figure 2: Alto saxophone with locations of various sensors used during experimenting highlighted by arrows

3.2 Mechanisms of Measurement Based on Humidity

For the frequency measurements based on humidity, a Vernier RH-DIN Relative Humidity Sensor (RH) was used with the same microphone to determine output frequency. The humidity sensor was placed in the bell of the instrument, 3 inches below the opening. In this way it measured the internal humidity of the instrument, adjusted by blowing warm, moist air from the lungs into the instrument. In order to insure that humidity was the only adjusted variable, a STS was adhered to the neck of the instrument and insured to be between 25-26*C for all trials. Although the Vernier RH determines humidity to four significant figures, only three significant figures were reported as the last digit varied so quickly that it was impossible to accurately track it. A visualization of this placement can be seen in Figure 2 above, from the green arrow. For humidity, only one note was tested.

3.3 Mechanisms of Measurement Based on Mouthpiece Position

The last variable which frequency was tested for was the position of the mouthpiece on the neck cork of the sax. The mouthpiece was pushed as deep as it would fit on the neck (5 mm from the beginning of the metal part of the neck), and then pulled off in increments of 5 mm while frequencies were recorded. The 5 mm increments were measured using measured using Mitutoyo Model CD-S6"CT calipers. Refer to the purple arrow on Figure 2 to understand the adjustment of the mouthpiece. Only a low G was tested in this investigation.

3.4 Overall Experimental Setup

Please refer to the block diagram in Figure 3 to see the method of connection to the computer for data collection:

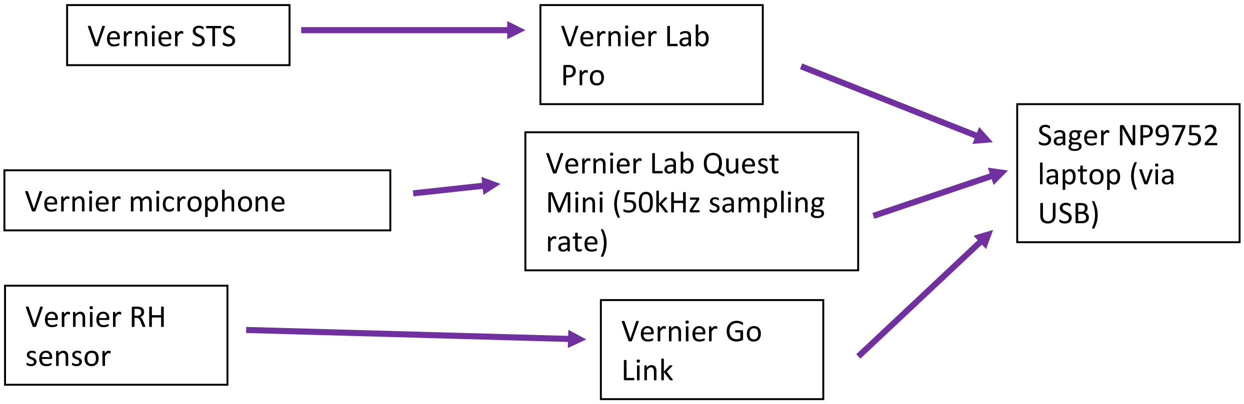

Figure 3: Sampled at 50kHz, diagram indicates sensor → computer setup

For all trials, the amplitude of the output sound was between 3.1-3.5 (arbitrary units) as measured in logger pro in order to insure that frequency variations were a cause of the adjusted variable as opposed to breathing differences of the musician. Frequency measurements were made using a fast Fourier transform on the output sound of the alto saxophone. This method of analysis generated a range for output frequency, and in this investigation the mean of the range was used with error bars to indicate the ± 0.19 Hz of uncertainty. Finally, uncertainty analysis was performed to determine the overall accuracy of this investigation.

4. Results and Discussion

The data show that decreases in temperature tend to flatten pitch, increases in humidity increase pitch, and increases in mouthpiece distance from the neck flattens pitch. For these measurements, the temperatures at the neck and horn of the saxophone were averaged to obtain an overall instrument temperature as the musician's breath heated up the instrument. Due to the difficulty to control the exact volume entering the instrument, the rate of warming up was outside of the scope of this research. As seen in Figure 4 below, it was found that for a low G, the frequency drop at 12.25*C from the maximum measured frequency was 6.110 ± 0.19 Hz, or a 2.624% decrease in frequency.

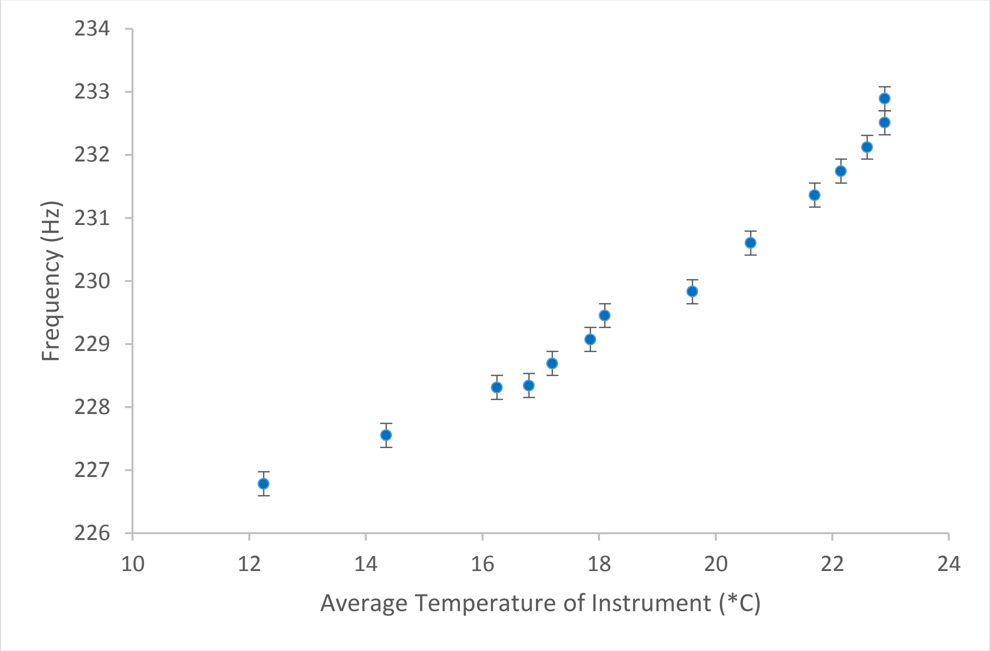

Figure 4: Frequency vs. the Average Temperature of the Saxophone for a low G

From Figures 5 below, it can be ascertained that for D2 at 12.25*C, the frequency drop from the maximum measured value was more significant in magnitude at 7.630 ± 0.19 Hz, as seen in Figure 5. However, this 2.172% frequency drop from the max is actually slightly less proportionally when compared to G. Further, the RH sensor tends to be unreliable and inconsistent with its readings. Due to the hardware issue, the results of the effect of humidity on pitch were inconclusive. Figure 6 below shows that G2 also experienced a significant frequency drop of 12.590 ± 0.19 Hz at 10.85*C, or a 2.704% decrease in frequency.

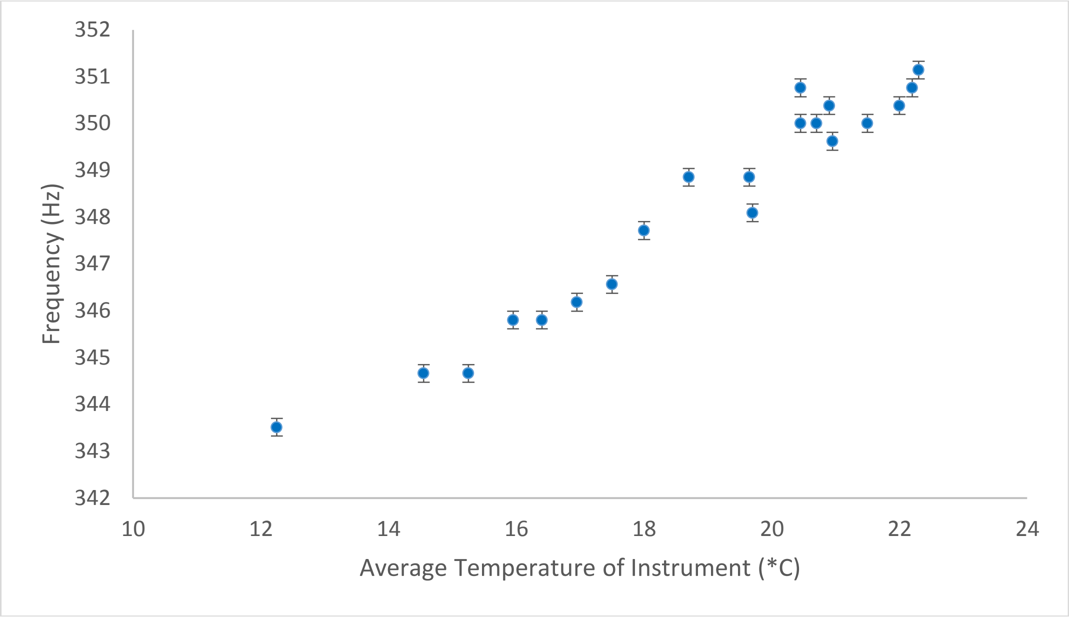

Figure 5: Output Frequency vs. the Average Temperature of the Saxophone for D2

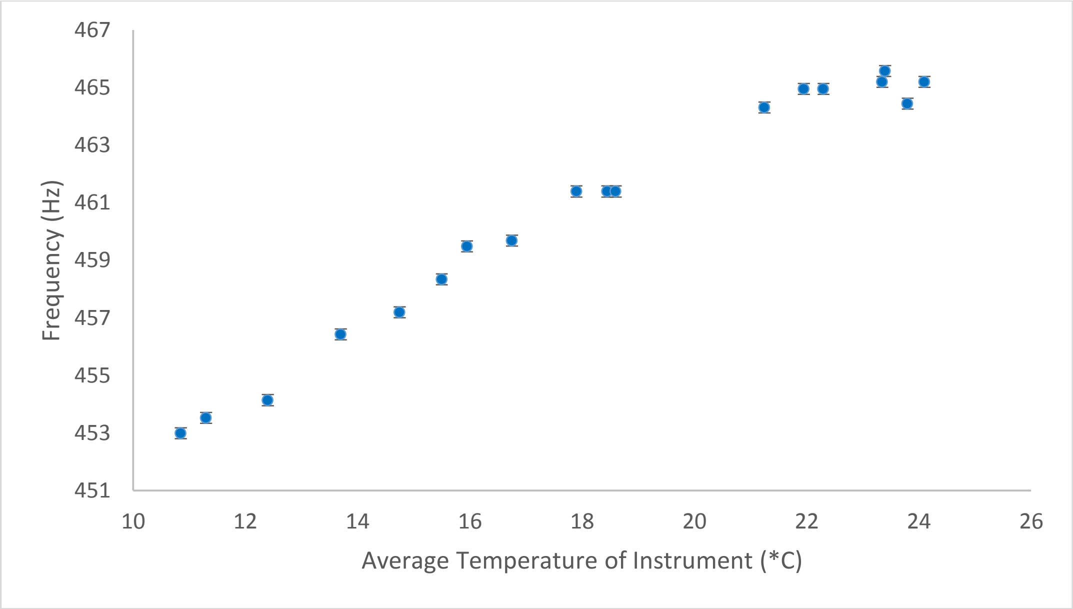

Figure 6: Output Frequency vs. the Average Temperature of the Saxophone for G2

The data indicate that cold temperatures cause the instrument to be flat, an observation which follows from Equation 2, as velocity of sound decreases due to the cold and wavelength remains constant (same note), frequency decreases. Keep in mind that as the instrument warmed up, the internal humidity also must have increased, so the increase in frequency cannot be solely attributed to temperature increase. That being said, given that a massive 50% increase in humidity, obtained through a focused humidity increase and unlikely to be brought upon naturally, only yielded a fractional (0.965 ± 0.19 Hz) frequency increase (Figure 8), it follows that the temperature variations were the main cause of frequency change for this experiment. For D2 and G2, the higher frequency notes, there seems to exist a range of temperatures, about 21-23*C where the output frequency is not impacted by temperature variation.

One important note regarding Figures 4-6 and the information obtained through these graphics, no trend lines were fit to the data. Although the data may seem logarithmic or polynomial in nature, it is impossible to generate a truly accurate trend without understanding the behavior of frequency as temperature is significantly *increased* passed 28*C. These effects were not examined in this investigation, due to the innate risk of completely denaturing a quality musical instrument. Therefore, any attempt to fit a trend to this data would be incomplete and inaccurate.

As can be seen in Figure 7, which is normalized based on each note's maximum frequency, temperature effects all three notes similarly, as decreases in temperature yield a decrease in output frequency.

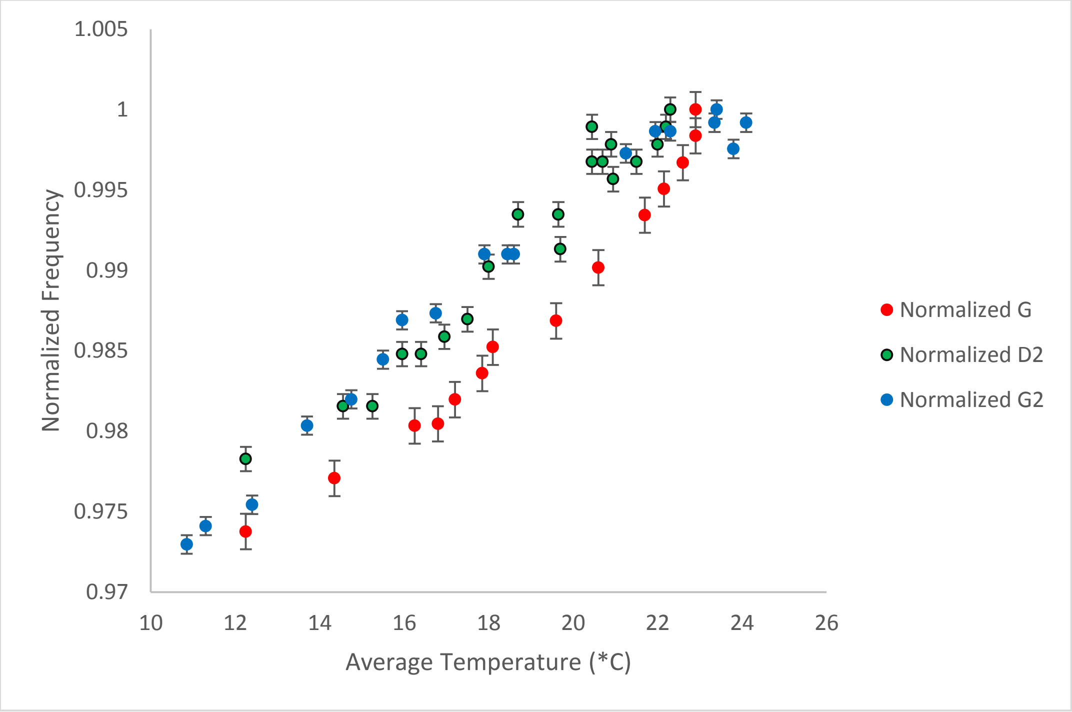

Figure 7: Frequency Normalized to Maximum Measured Frequency vs. Average Temperature of Instrument for G, D2 and G2

As related to humidity, the data show that a 50% increase in relative humidity would yield increase the frequency (on average) by 0.965 ± 0.19 Hz, or a 0.412% increase in frequency. There exists a correlation between humidity in the bell of the instrument and its output frequency; this change in frequency is proportional to 0.0193 ± 0.0078 multiplied by the change in relative humidity. Note that for this investigation, the humidity results were not seen as conclusive due to the inconsistency of the Relative Humidity sensor used. This relationship can be seen in Figure 8 below:

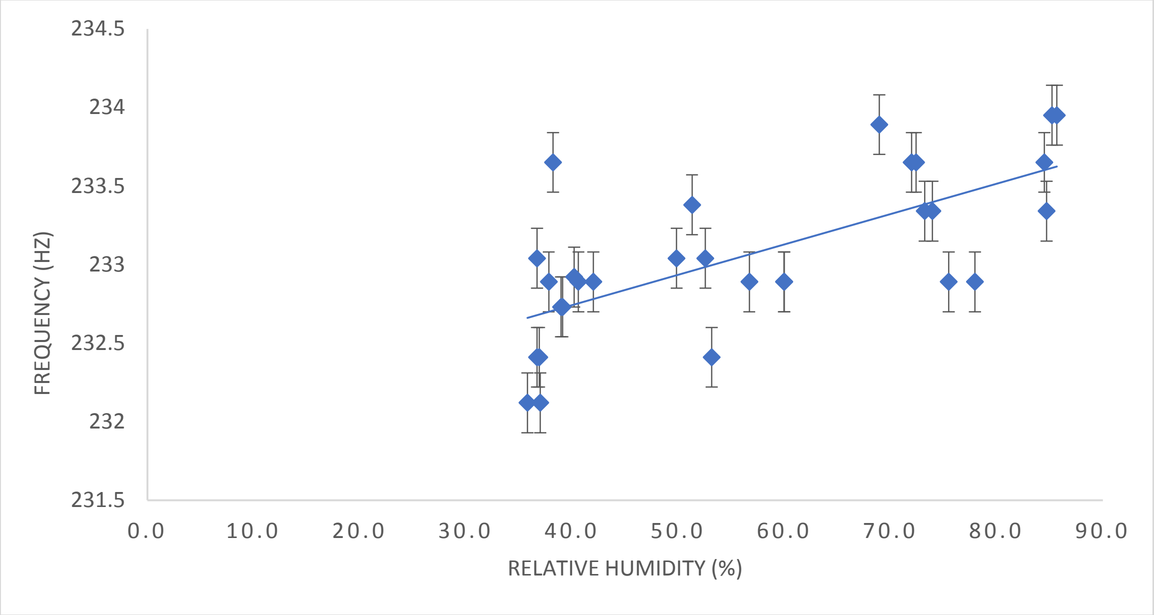

Figure 8: Output Frequency vs. Relative Humidity in the Bell of the Saxophone

Lastly, the effects of adjusting the mouthpiece on the neck of the instrument were examined for this investigation, in order to understand how to compensate for variations in humidity and temperature. It was found that a 20 mm shift of the mouthpiece from the neck could decrease the output frequency by 11.09 ± 0.19 Hz. Thus, simply shifting the mouthpiece could influence the pitch of the output sound by 4.707% for a low G. Physically, this effect can be understood by referring to Equation 1, as by moving the mouthpiece farther from the neck, the *L* of the effective air column and thus output wavelength are increased. Equation 2 details why output frequency drops as velocity of sound remains constant and wavelength is increased. Figure 8 shows the clear, linear relationship between distance from the neck of the sax and the pitch of the instrument:

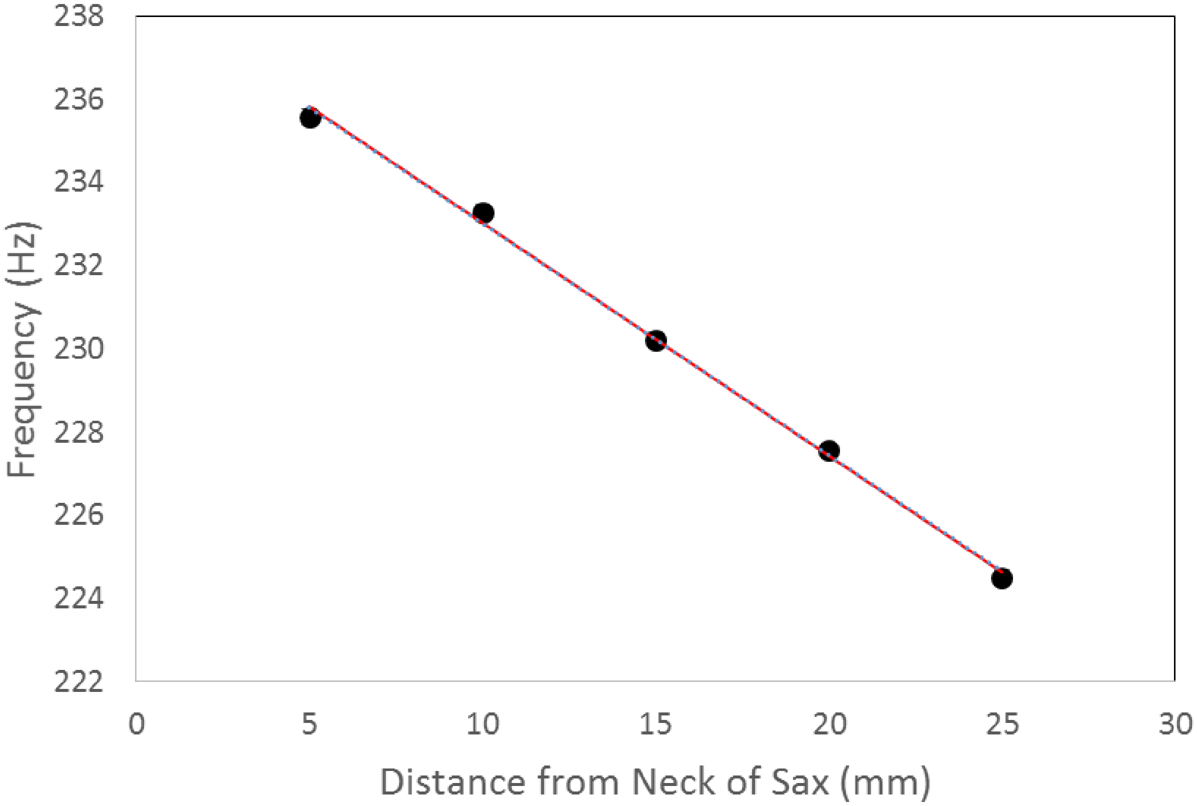

Figure 9: Output Frequency vs. the Distance of the Mouthpiece Base from the Neck of the Saxophone, where Frequency is Proportional to -0.558*(Distance from Neck)

The uncertainty in frequency of these results (as seen by the error bars in Figures 4,5,6,8,9) are brought upon by limitations of the Vernier microphone. Applying a fast Fourier transform to the output waveform of the sax yields a peak frequency with a range of uncertainty of 0.38 Hz. Therefore, all frequencies presented are done so with ± 0.19 Hz of accuracy.

Figure 10 indicates how one can use the predictable increase in pitch as distance of mouthpiece to neck of sax is decreased to counter the flattening of the pitch due to dropped temperature. Given an instrument temperature of about 11*C, the mouthpiece needs to be moved 4 mm from its neutral position towards the neck.

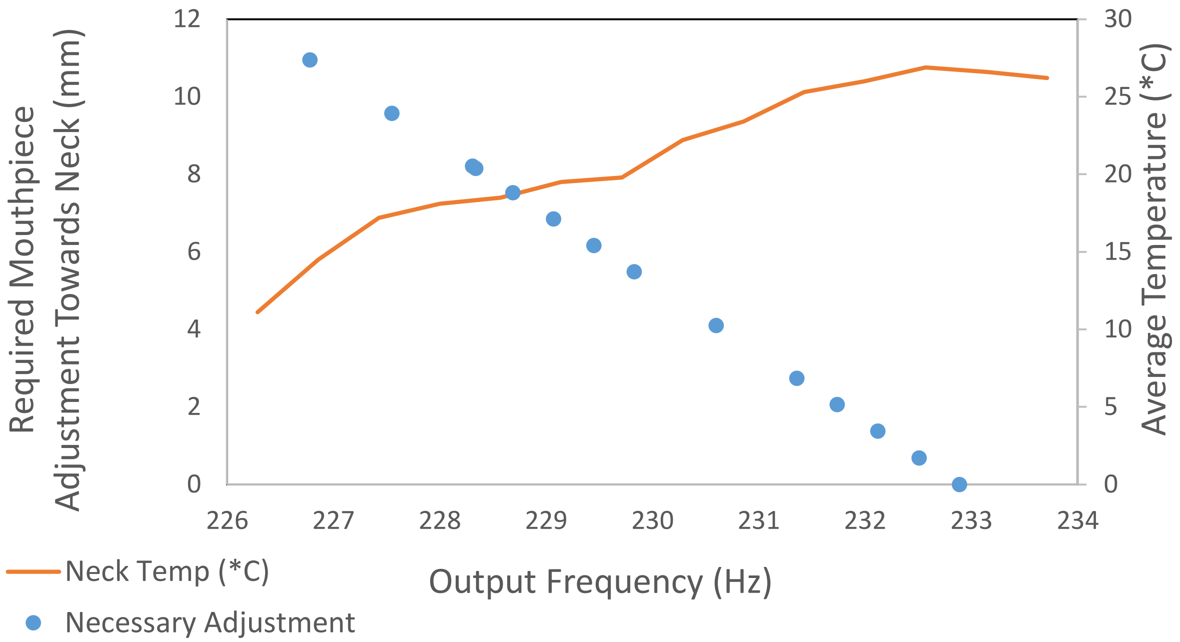

Figure 10: Mouthpiece Adjustment and Temperature vs. Frequency to analyze how to counter temperature variation

Overall, the investigation succeeded in examining the varying effects on frequency of humidity, temperature and mouthpiece positioning. For a musician, this insight is vital, as compensations can be made by controlling the mouthpiece position when in inclement circumstances, whether brought upon by humidity or temperature variations.

5. Conclusion

It was found that pitch dropped 6.110 ± 0.19 Hz for a low G given an initial temperature of 12.25*C, while the same initial temperature yielded a frequency decrease of 7.630 ± 0.19 Hz for D2. In parallel, a frequency drop of 12.590 ± 0.19 Hz was obtained for G2 at approximately 10.5*C. These frequency reductions are measured from the maximum obtained frequency. Similarly, decreases in relative humidity resulted in pitch drops of the output sound as well, as a 50% drop in relative humidity on average yields a 0.965 ± 0.19 Hz decrease in output frequency. These pitch variations brought upon by external conditions outside of a musician's control are hard to adapt to, and can often result in the instrument being out of pitch.

This research found that adjusting the positioning of the mouthpiece can be predictably used to control the final pitch of the instrument, given the linear response of mouthpiece distance from the sax neck to output frequency (Figure 9). Thus, a saxophonist in Michigan's pep band experiencing a flattening of their pitch of 10 Hz could push their mouthpiece to a position 7.1 mm from the neck in order to naturally sharpen their instrument which would otherwise sound flat due to the cold weather.

While cold weather and humidity are common factors that influence the pitch of an instrument, it remains to be examined the extent of effects hot temperatures can have on the pitch of the instrument. Only three separate notes were investigated on one instrument in this study, and there many other frequencies which can be generated by the instrument.

As such, humidity, mouthpiece position and temperature could all be analyzed for each note of the saxophone, to determine if some octaves experience more significant detraction from pitch when experiencing inclement conditions. Another area of future study would be to investigate the relationship of various pep band instruments, such as the trumpet and flute, to study how various instruments behave in cold weather. Additionally, the temperature can be taken at different points on the instrument to see which areas take the longest to warm up. This information could be used to focus warm up efforts at a single section of the instrument to optimize warm up efficiency. Another investigation topic would be to examine the effects of the reed on the pitch of the instrument, as temperature, moisture and wear are all factors that could influence the frequency of the output sound. Lastly, the effects of temperature on the saxophone geometry and how much these changes affects the output sound could be researched.

6. References

[1] Buck Bravo, "How Cold are Big Ten Football Games?" The Daily Gopher, 29 March 2010, (accessed on 4/3/15 from http://www.thedailygopher.com/2010/3/29/1394801/how-cold-are-big-ten-football-games)

[2] Sound Waves and Music, "Closed-End Air Columns," The Physics Classroom, 1996-2015 (accessed on 4/2/15 from http://www.physicsclassroom.com/class/sound/Lesson-5/Closed-End-Air-Columns)

[3] Speed of Sound in Air, Hyperphysics, (accessed on 5/12/2015 at http://hyperphysics.phy-astr.gsu.edu/hbase/sound/souspe.html)

[4] Saxophones, “Selmer SAS280 La Voix II Alto Saxophone Outfit Lacquer," Amazon, 2015 (accessed on 4/3/15 from http://ecx.images-amazon.com/images/I/71PcfLhs0gL._SL1200_.jpg)

7. Acknowledgments

- Dr. B. Hughey and Dr. W. Seering – for their continued advice and insight
- Colt T. Richter – for his advice in measuring the effect of mouthpiece positioning