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Effects of surface finish on the tone quality of brass wind instruments

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EFFECTS OF SURFACE FINISH ON THE TONE QUALITY OF BRASS WIND
INSTRUMENTS

A Thesis

Presented to

The Faculty of the Department of Materials Science Engineering

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Erin Martin Hasenkamp

August 2004

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ABSTRACT

EFFECTS OF SURFACE FINISH ON THE TONE QUALITY OF BRASS WIND INSTRUMENTS

By Erin M. Hasenkamp

Ten brass lead pipes fitted for a trombone were used to determine if changing the internal surface finish would change the timbre. Four different surface finishing techniques were used: oxide growth, electropolishing, radial surface scratches, and longitudinal surface scratches. The note of B flat, ~236 Hz, was recorded for each lead pipe before and after modifying the internal surface. The resulting sound spectra were compared using audio processing software. Each lead pipe was sectioned and analyzed using an Atomic Force Microscope and contact profilometer. The oxide surfaces were analyzed using Auger and Scanning Electron Microscopy to determine the oxide thickness and surface texture. It was found that there was statistically no difference in the tone quality before and after each surface treatment. A small difference in the spectra decibel levels was found between the roughest radial and longitudinal surfaces; however, the difference was not sufficient to be heard.

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CHAPTER ONE INTRODUCTION

Instrument quality, also known as timbre, is defined by the Random House College Dictionary as, “the characteristic quality of a sound, independent of pitch and loudness but dependent on the relative strengths of the components of different frequencies, determined by resonance” [1]. What does this mean? It means that the quality of sound produced by an instrument is dependant upon its proportions, source of vibration, and material type.

First consider the length and width of an instrument. Varying these geometries will cause the instrument to resonate at different frequencies; short instruments, like a piccolo, resonate at high frequencies, and longer instruments, such as a flute, resonate at lower frequencies. It is easy to recognize this when considering an open-open tube geometry. Imagine a simple tube open at both ends, for example a pipe in a pipe organ. When oscillating at its lowest frequency, the pipe will accommodate one half of a wavelength, due to the ends being open [2]. Varying the length of the tube, while keeping the first mode of resonance the same, will cause the wavelength to change. A short tube, with a short wavelength, has a high frequency and pitch. A long tube, with a long wavelength, has a low frequency and pitch.

The geometry of the instrument also plays a role in the timbre. The resonant frequencies of an open-open cylindrical tube differ from those of a closed-open tube, yet a conical tube closed at one end resonates at the same frequencies as the open-open

cylindrical tube. Though the two resonate at the same frequencies, they will not sound the same.

As mentioned earlier, an open tube will resonate at a one half wavelength at its first mode. Its second mode of resonance contains twice the number of wavelengths as the first mode, and the third mode is three times the first, as shown in Figure 1. A closed-

Figure 1. An open-open tube of length L resonating at three different modes [2].

open tube has one end open and the other end closed. The first mode of resonance contains one quarter of a wavelength. The second mode contains three times the number of wavelengths as the first mode, the third mode contains five times, and each thereafter the multiplier increases by two, as shown in Figure 2. It is found that closing one end of the tube causes the pipe to resonate at a lower frequency; once again proving that a simple change in geometry can affect the timbre.

The addition of the bell and mouthpiece further complicates the matter. The bell is used to amplify the sound coming from the instrument, while acting as a high-pass

Figure 2. An open-closed tube of length L resonating at three different modes [2].

filter allowing the higher tones to escape more easily than the low tones. In fact, the bell allows for only a small fraction of sound to “leak out”; the rest of the energy is used in resonating the tube [3]. The mouthpiece is used for comfort, and helps to create a good connection between the lips of the musician and the tube resonator. A shallow cup and sharp edge throat, as shown in Figure 3, will produce brilliant tones, while a deeper cup and rounded throat generates a milder tone [4].

The type of material and thickness of the bell is also said to affect the timbre. “Gold brass, softer and more red than the standard yellow brass due to a higher copper content (85% as opposed to 70%), results in a warm tone. Sterling Plus bells (99.9% pure seamless silver) create a full complement of overtones” [5]. A lightweight bell will respond quickly for a lively sound, while a heavyweight bell will respond with little distortion.

Figure 3. Various mouth piece cross sections [6].

All of these contribute to the timbre of the instrument. Timbre can be thought of as a collection of all the frequencies and their amplitudes for a specific note. The collection is affected by the size and shape of the tube resonator, the curvature and size of the bell, the geometry of the mouthpiece, and perhaps the material type and thickness. What is not mentioned is the human factor. That is, the ability of the person playing the instrument. It is easily recognizable that a seasoned veteran can produce clear and crisp notes, while a student with the same horn, and two lessons under his/her belt, will produce a sound more akin to a wheezing goose. With all this known, what are the effects of surface finish?

There has been little mention of surface finish. It was mentioned in passing by Adam Carse that “the tube must be made of a material that is hard and rigid” and the “inside must be smooth” [6]. He continues on to say that because of this only certain material types have been used for wind instruments. Most of these are hard dense woods, bones or metals. But what does smooth mean? Is there a quantitative value that can be placed on surface roughness that does affect the timbre of an instrument?

It is not uncommon for musicians to piece together parts of an instrument to get the timbre they are looking for. Once the instrument is together, some believe that pouring buttermilk through it will help change the timbre [7]. Does this leave a thin coating or help to produce an oxide layer? Will modifying the surface change the timbre?

It is the intent of this investigation to answer these questions by examining how the tone quality changes by varying the internal surface finish of the lead pipe in a trombone.

CHAPTER TWO

CRITICAL REVIEW OF PERTINENT PAPERS

Research on the tone quality of brass instruments yielded a limited number of scientific articles on the material effects on tone quality. It is interesting to note that the articles pertaining to this differ, with a variety of results. B. Lawson and W. Lawson report that in 1937 and 38, a German researcher by the name of Lotermoser^{*} found that the measured spectra of different organ pipes made from various materials produced differing airborne sound spectra. Later, two other researchers, Backus and Hundley, disputed their findings [8]. Backus and Hundley reported that the airborne sound spectra would vary depending on where the recording device is placed, not because of the material used. Hundley followed up with another research project that demonstrated that a thin wall, which yields to the pressures generated by the vibrating column, will drop the frequency and sound level. He did not find an effect due to the material type.

An understanding of which areas have been explored is necessary and helpful in directing this investigation. Of the published material on the subject of sound quality and material aspects, two papers were reviewed in depth. Other interesting reports, that were not considered scientific, deserve some mention because they pertain to this subject.

In 1971 the coordinators of the Third Claremont Music Festival Institute decided to perform a double blind test to determine if their audience of musicians could discern the difference between brass and nickel-silver French horns [9]. In this test, three of the

^{*} It should be noted that this paper was written in German. Because the author does not speak German, the results of the project are assumed to be correct as reported by B. Lawson and W. Lawson.

coordinators, Jim Decker, Ralph Pyle and Barry Tuckwell, played the same C major scale on 12 different instruments while blindfolded. Each instrument was handed to the musician so they would not be able to identify the metal used to make the horns. A large curtain was placed between the 42 person audience and the three musicians to keep the audience from seeing which type of instrument was being played. In the end, it was determined that the audience was not able to determine the difference between the material types. Approximately 45% of the time the audience was correct, 15% of the time the audience was undecided. The musicians, on the other hand, were more accurate in determining the difference. The three were able to determine 65%-70% of the time from which material the instrument was made. Is it possible that the results could mean that, although the material type has little effect on tone quality as perceived by the audience, different materials do have an effect on the feedback perceived by the musician? Or, do the musicians know the makes of the instruments well enough to know how they respond while playing them? If the musicians can perceive a difference, will varying the surface finish help them detect a difference?

It was pointed out by Dr. M. Henderson [10], one of the presenting members at the festival, that the problem with using humans to test the instruments is that they will always want to sound good, and try to mask any “weak points on a horn.” Could it be that the players recognized weak points of certain makes of instruments, and that led to the more accurate detection?

J. W. Coltman [11] performed a similar experiment using flutes. Coltman’s experiment consisted of three flutes made from thin silver, heavy copper, and wood.

Each musician performed with the various flutes, and like Henderson's study, the audience was not able to discern a difference. However, the flute musicians were also not able to tell them apart. This is possibly due to the lack of feedback from the instrument. Flutes generate tones by forcing a stream of air towards a sharp edge. There is little contact between the player's lips and the vibrating air column. In the case of brass instruments, the lips are the source of vibration for the air column; there is direct feedback to the musician.

The effect of material properties in particular were reported, by B. Lawson and W. Lawson [12] and, by P. S. Watkinson, R. Shepherd, and J. M. Bowsher [13]. The first explored the effect of hardness on the timbre of French Horns, while the second examined how surface finish affects the attenuation of sound within a brass tube.

2.1. Annealing of French Horn Bells

B. Lawson and W. Lawson [12] were interested in determining if the hardness of a French horn bell changes the acoustical characteristics of the horn. Seven bell flares, with the same dimensions, were manufactured with screw rings to allow for easy attachment to the body of the horn. Four of the seven bells were yellow brass (C2600 70Cu-30Zn) the other three were nickel-silver (C75700 65Cu-23Zn-12Ni). Three of the brass bell flares and two of the nickel-silver bell flares were annealed to reduce the hardness. One of each type was kept in the hardened, as-received condition.

The annealing conditions were to produce various hardness values based on grain size. The grain size for each bell is listed in Table 1. It is unsure if the authors believed

Table 1. Bell flare hardness values [12].

Bell Flare No.	Alloy	Hardness
1	C26000	Hard brass from spinning
2	C26000	Annealed at 425 °C, grain size 0.020 mm
3	C26000	Annealed at 490 °C, grain size 0.030 mm
4	C26000	Annealed at 535 °C, grain size 0.040 mm
5	C75700	Hard nickel-silver from spinning
6	C75700	Annealed at 610 °C, grain size 0.020 mm
7	C75700	Annealed at 660 °C, grain size 0.020 mm

that having identical grain size in both materials would cause the hardness to be the same. This is not the case for differing alloys. It would have been more beneficial if the hardness values were chosen from a hardness scale, Rockwell or Vickers[†].

Another factor the authors considered was the shape of the bell flares. They were cautious to make sure the bell flare dimensions did not exceed the limits for a bad flare. This was determined by keeping the dimensions of the flare within the limits defined by the Bessel horn equation.

The airborne spectrum was measured by having a horn player stand in a reverberant chamber with a microphone 2 feet from him. The musician played the horn with each flare, with two different notes C₄ (262.5 Hz) and C₅ (523 Hz), for 4 seconds. The level was kept at a constant 95 dB for the duration of the note. This was repeated

[†] Rockwell and Vickers hardness are determined by pressing an indenter into the base material and measuring either the depth of penetration, or the size of the impression. This gives a comparable hardness value that is independent of grain size. Choosing to measure the hardness on either scale would allow a proper comparison of the different material types of the same hardness.

twice for each flare. The sound measured from the horn was fed into a spectrum analyzer.

A comparison between the annealed bell flares and the as-received bell flares was performed by averaging the two measured spectra, correcting the average for differences in loudness (recorded during the initial measurement stage), then subtracting the corrected average for each annealed bell from the as-received average spectrum. If all spectra were equal, the resulting graphs should show a horizontal line through zero dB. Negative values indicate the annealed horn produced more sound energy, and positive values indicate the hard, as-received horn produced greater sound energy.

It was reported that the annealed bell flare with a grain size of 0.030 mm was most like hard bell near the fundamental frequency, but at 1-3.5 kHz the hard bell

Figure 4. One third octave acoustic difference spectra of the annealed brass flare as compared to the hard brass bell [12].

produced tones that were as high as 2 to 4 decibels greater than other three bells, as shown in Figure 4.

The 0.040 mm grain size flare produced tones that were about 0.5 decibels louder at or below the fundamental frequency, but again, the hard bell produced tones that were as high as 4 decibels louder at frequencies above 1 kHz.

Increasing the fundamental frequency to C₅ demonstrated that the 0.040 mm grain size flare produced less sound energy than the hard bell, as can be seen in Figure 5. The opposite was found for the nickel-silver bells, Figure 6.

Lawson and Lawson concluded that the bell material “unequivocally” has an affect on the tone quality of the instrument. It would be more appropriate to say that

Figure 5. One-third octave acoustic difference spectra of the softest brass bell flare compared to the hard, as-received brass bell [12].

Figure 6. One-third octave airborne difference spectra of the nickel-silver bell flare compared to the hard, as-received nickel-silver bell [12].

hardness has an affect on the tone quality. This was demonstrated by bell 4 at lower frequencies. Yet, there seems to be no unequivocal correlation between decreasing hardness and changes in tone quality. Is it possible that the authors based their conclusion on the assumption that the hardness is equal for equal grain sizes? If this is true, the conclusion is not based on sound metallurgical principles.

2.2. Sound Attenuation Due to Surface Finish

Watkinson, Shepherd, and Bowsher [13] examined and measured the attenuation properties of a brass tube and a trombone due to surface finish, a topic which is more closely related to this research. After measuring the attenuation, they allowed musicians

to play the instruments to determine if they could discriminate between a simulated “corroded” horn and a clean horn.

The research project was broken down into three sections. The first section considered the attenuation in a cylindrical brass tube. A simple mathematical model was used to predict the attenuation in the tube. The model was compared to measured values from brass tubes (length of 4.5 ft, by diameter of 0.43 in) with varying internal surface finishes. The internal surface conditions for this test included a clean polished tube, a clean scratched tube, a tube with a coating of brandy and honey, a tube with a coating of peanut paste (to simulate corrosion), and a clean tube with a paper towel lining.

Each surface condition was compared to the mathematical model and it was found that a smooth internal finish, a brandy and honey coated internal finish, and a roughened internal finish all measured closely as compared to the model, as can be seen in Figures 7 and 8. Adding the peanut paste increased the attenuation, as shown in Figure 9, and was used to represent a severely dirty instrument. The paper towel lining was used to present

Figure 7. The attenuation coefficient of the clean brass tube. The dashed line represents the theoretical calculation [13].

Figure 8. The attenuation coefficient for the brass tube coated with a honey and brandy mixture. The dashed line represents the theoretical calculation [13].

an extreme case of attenuation. Even though the attenuation was much higher, as was predicted by the authors, it was used for comparison purposes to the other pipes.

The second of phase of the project was to create a more complex mathematical model[‡] and measure the attenuation of a real instrument. Although interesting, it did not consider the changing internal surface finish. It was found that including the bell and mouthpiece into the attenuation equation caused this more complex model to fail.

The last phase of the project was to obtain input from musicians playing a clean trombone and peanut paste coated trombone. As with other the studies, the musicians were not told which instrument they were playing. Scented oils were rubbed on the instruments to hide the smell of the peanut paste. Each musician was allowed to play the

[‡] The mathematical model attempted to take into account the varying diameter of a trombone. It assumed the changes in diameter were small and occurred slowly. The model failed, as pointed out by the authors, because both the horn bell flare and the bore in the mouth piece change rapidly in diameter.

Figure 9. The attenuation coefficient for the brass tube coated with a peanut paste. The dashed line represents the theoretical calculation [13].

instrument in any manner they chose, until they were satisfied that they could rate its quality.

The musician's ratings were compared and analyzed by using analysis of variance (ANOVA) at the 99% confidence level. The statistical comparison of the results proved that the musicians were able to differentiate the two types of horns.

It is important to know which factors affect the overall tone of a wind instrument. Previous studies demonstrated that material hardness does change the tone quality of the instrument. It was also shown that different surface finishes have an effect on the attenuation of sound from the instrument, and musicians can feel a difference between a "badly corroded" horn and clean horn.

CHAPTER THREE WORKING HYPOTHESIS

A wind instrument produces its tones by vibrating an air column; it is hypothesized that a perfectly smooth reflecting wall will not add any changes to the tone quality of the instrument. Figure 10 shows the standing wave of a perfectly smooth internal finish. Adding irregularities to the reflecting wall should cause the standing wave to be distorted. Figure 11 shows the standing wave within a rough reflecting wall. If the irregularities are not large enough, the effect on the sound quality may not be measurable. On the other hand, if the surface irregularities are large, a measurable difference may be detected. Knowing if these irregularities affect the tone quality of the wind instrument will help a musician better select the elements of his/her instrument.

It is the goal of this project to determine if different surface finishes change the sound spectrum, or timbre, of a brass instrument, and if a musician can distinguish a difference.

Figure 10. Diagram of a standing wave resonating in a tube with perfectly smooth internal walls.

Figure 11. Diagram of a distorted standing wave resonating in a tube with roughened internal walls.

CHAPTER FOUR EXPERIMENTAL MATERIALS

A trombone was chosen for this experiment because it is a relatively simple tube with no valves. It also contains a removable lead pipe that makes up the first nine inches of the instrument. When the lead pipe is removed, the tone quality decreases, giving a more “airy” quality to the note. Modifying the lead pipe of a trombone is the focus of this experiment.

A total of ten lead pipes, identical to the musician’s own, were purchased for this experiment. The musician’s lead pipe was used as a baseline for comparisons, and for practicing before recording.

4.1. Experimental Equipment

A variety of equipment was used during the course of this investigation. The equipment was broken down into three categories: Surface Finishing, Recording, and Measurement Equipment. The break down of each category is shown in Tables 2, 3, and 4, respectively.

Table 2 contains the list for surface finishing. Eighty grit sandpaper was used for creating the rough surface finish. Sandpaper with grits of 200 and 400 were for producing the medium roughness surface finish. The oxide layer was grown in a Cincinnati Subzero environment chamber.

Table 2. List of equipment used for treating the internal surface finish of the brass lead pipes.

Item	Equipment	Application
1	80 grit sandpaper	Used for rough surface finish of the lead pipes
2	200 grit sandpaper	Used for medium surface finish of the lead
3	400 grit sandpaper	Used for medium surface finish of the lead
4	Cincinnati Sub Zero Temperature Chamber, CSZ ZH Series	Environmental Chamber used to control temperature and humidity to grow surface oxide

Table 3 contains the list of equipment used for recording the sound spectra. The anechoic chamber is a sound deadening room that blocks out all external noises and minimizes all echoes and reverberations within the chamber. The walls are lined with large wedges that measure about two and half feet long with a one foot base. A flat

Table 3. List of equipment used for recording the sound spectra from the trombone.

Item	Equipment	Application
1	CAD Equiteck E 100 Flat Recording Studio Condenser Microphone	A flat recording microphone used to capture the trombone sound spectra
2	8ft x 8ft Anechoic Chamber	A sound deadening chamber that blocks out all external noises, and minimizes all echoes and reverberations within the chamber
3	Sony MZ R700 Minidisc Recorder	Used to digitally record the trombone spectra
4	Mackie 1202 VLZ Line Mixer	Used as a low pass filter between the microphone and the minidisc recorder
5	Extech 407736 Sound Level Meter	Used to measure the sound level in the anechoic chamber

recording Studio Condenser microphone ensures that there is no low or high frequency decibel gain. A Sony MiniDisc recorder was used to digitally capture the sound spectra, while a Mackie 1202 VLZ Line Mixer was used as a low pass filter between the microphone and the MiniDisc. The Extech Sound Level Meter was placed in front of the musician to monitor the level of each note played.

The equipment used for characterizing the surface finish is listed in Table 4. An Atomic Force Microscope (AFM) was utilized to obtain surface images and to calculate the surface roughness of a small $315\text{ }\mu\text{in} \times 315\text{ }\mu\text{in}$ area. The Mitutoyo Surftest 211 Surface Profilometer was used to measure the surface finish of the specimens along a 1 cm linear section.

Also contained in Table 4 are the Auger Electron Spectroscope (AES) and Scanning Electron Microscope (SEM) used for oxide depth profiling and surface imaging, respectively.

Table 4. List of equipment used for measuring the surface finish of the brass lead pipes.

Item	Equipment	Application
1	Atomic Force Microscope	Used for surface imaging and calculating the surface finish of an $315 \times 315\text{ }\mu\text{in}$ square area
2	Mitutoyo Surftest 211 Surface Profilometer	A contact surface measurement device used to calculate the surface finish of a 0.39 inch linear line
3	Auger Spectroscope	Used for surface analysis and depth profiling of oxides
4	Scanning Electron Microscope	Used for surface imaging

4.2. Surface Treatments

The ten lead pipes were treated with five different surface conditions. Each condition was quantified by measuring the surface roughness. The surface conditions obtained were to fall into the categories of smooth, medium, rough, and coated. As shown in Table 5, the smooth surface finish was selected to be a roughness average (Ra) of 5-10 μin and was measured using the AFM. The medium surface finish was chosen to be between a Ra of 50-100 μin , and was measured using a surface profilometer, and the AFM. The rough surface treatment was selected to be a Ra greater than 250 μin , and was measured using the surface profilometer and the AFM. The coated lead pipes were to have a copper oxide grown on the surface for the duration of one week and of four weeks.

The smooth surface condition was obtained by electropolishing[§] the interior of the tube. This process yields a surface finish better than the manufacturer's finished product. After the electropolishing had been completed, the lead pipe was placed in a vacuum-

Table 5. Lead Pipe surface conditions and measurement techniques.

Condition	Desired Surface Finish [Ra - μin]	Measurement Technique	Coating
Smooth	5 - 10	Atomic Force Microscope	-
Medium	50 - 100	Surface Profilometer/AFM	-
Rough	250+	Surface Profilometer/AFM	-
Coated 1	-	Auger Spectroscopy/SEM	Copper Oxide
Coated 2	-	Auger Spectroscopy/SEM	Copper Oxide

Experimental brass lead pipe, ~70%Cu 24%Zn

[§] Electropolishing is an electro-chemical process that yields a surface finish akin to a mirror like finish, with few to no surface variations.

sealed bag for storage, until further use.

The medium and rough surface finishes were obtained by running fine grit sandpaper through the interior of the lead pipe. Two variations of surface finishes were chosen: longitudinal and radial scratches. For the longitudinal scratches a long dowel, with 80, 200, and 400 grit sand papers, was ran along the interior length of the stationary lead pipes. The radial scratches were made by using similarly fashioned dowel rods; however the rods were placed in a drill fixture and rotated at medium speeds while the lead pipes were pressed down on the rotating dowel rods.

Growing an oxide coating on the interior of the lead pipe was the final surface finish. Two lead pipes were placed in an environmental chamber and allowed bake for 1 week and 4 weeks at 40°C and 60% relative humidity. The concentration of moisture only needs to be 1 ppb at 100 °C for the oxide to grow. After each lead pipe was processed, it was placed in a vacuum sealed bag for storage, until further use.

Once processing of all the pipes was completed, with the exception of the two coated lead pipes, the interior surface was thoroughly cleaned by ultrasonic cleaning. This helped ensure that no particles were left over from the sanding process, and no further etching occurred after the pipes had been electropolished.

4.3. Recording Techniques

A music professor from San Jose State University, Professor Robert Szabo, played the tuning note of B flat, 236 Hz, in an anechoic chamber into a flat recoding microphone. The calibration certificate for the microphone, as seen in Appendix A,

shows that the recording level for the microphone remains flat from 0 to 3kHz, which is within the range used for this project. For all recording sessions, Professor Szabo stood about one foot from the microphone and maintained a decibel level of approximately 110 dB for five seconds. The order in which he played each lead pipe was varied between recording sessions. Randomizing the lead pipes helped to produce unbiased results.

In a second room, the signal from the microphone was passed through a mixing board acting as a low pass filter, ** and then sampled onto a MiniDisc recorder. The signal from the recorder was then fed into a computer for analysis. Both the MiniDisc recorder and computer recording were sampled at 44 kHz. Appendix B contains additional explanation concerning digital recording and goes into further details on why capturing the sound spectra digitally is valid.

4.4. Measurement Techniques

Two surface finish measurements techniques were used: Atomic Force Microscopy, and Contact Profilometry. While each provides surface data in a similar fashion, the resolutions are vastly different.

4.4.1. Atomic Force Microscopy

Atomic force microscopy, AFM, can measure the surface roughness/finish of a specimen by running a scanning tip of about 4×10^{-4} μin (a few angstroms) in diameter over a small area. This technique is most useful for smoother specimens due to its small

** A low pass filter will remove frequencies above 22 kHz to help prevent aliasing.

scanning tip and small area, about $394\text{ }\mu\text{in} \times 394\text{ }\mu\text{in}$. By using a tip of only a few angstroms, the AFM returns a more accurate surface roughness. Yet, scanning a small surface area can make the roughest specimen appear smooth if the surface is not uniformly finished. Despite this drawback, the AFM was used to analyze each specimen because the data collected was fed into analysis software that returned surface measurements and constructed visual surface maps.

4.4.2. Contact Profilometry

As a secondary measurement technique, a contact profilometer was used to measure the surface roughness. The profilometer measures the surface roughness by running a cantilevered stylus, with a tip of about $4 \times 10^2\text{ }\mu\text{in}$ in diameter, across a linear distance of 0.4 in. Because the tip is large as compared to the AFM, the profilometer does not have the resolution of the AFM and can not detect surface variations smaller than the tips diameter. Ultimately, this means the profilometer does not always measure the fine roughness accurately.

For surfaces rougher than $4.7 \times 10^2\text{ }\mu\text{in}$, the contact profiler can be effective because the linear distance scanned is greater than the area scanned by the AFM. Unfortunately, because this is a linear measurement, no surface image is obtainable from the profilometer.

4.4.3. Auger Electron Spectroscopy and Scanning Electron Microscopy

Auger Electron Spectroscopy (AES) and Scanning Electron Microscopy (SEM) were used to characterize the relative thickness of the copper oxide and the surface texture, respectively. AES sputters off the surface atoms and records the concentration of each as the Auger electrons penetrate the surface of the specimen. As the surface oxide is sputtered away, the concentration of oxygen is reduced until it approaches the bulk concentration levels of the base metal.

4.5. Characterization of recording

Each lead pipe recording was characterized before and after altering the interior surface finish. Characterization consisted of measuring three sound spectra for each lead pipe in the note of B flat. Each recording was fed into two different audio analysis programs: Cool Edit Pro 2.0 by Syntrillium Software and SpectraPlus by Sound Technologies Incorporated. Cool Edit Pro was used to break the session recordings into smaller data files that were analyzed using SpectraPlus. The final peak values for the harmonic frequencies were documented. A statistical analysis of the peak values was performed to determine if variations in peak values were statistically different. Because a high number of harmonics exist in the same note, only the first six harmonics were analyzed.

For the qualitative portion of the experiment, Professor Szabo was asked to characterize the feel of the lead pipes. Because trained musicians can feel a difference between various manufacturers of the same instrument, it was likely that a musician

would be able to determine, through instrument feedback, if there were differences between each surface treatment. As with the quantitative analysis, the lead pipes were randomized to remove bias from the musician. The qualitative analysis was compared to the quantitative analysis to determine if there is a correlation between the two.

CHAPTER FIVE

RESULTS

It was the goal of this project to determine the effects of surface finish on the tone quality of a trombone. Both quantitative and qualitative results were considered.

Quantitatively, spectral analysis was performed with analysis software, while surface measurements were quantified using AFM, SEM, contact profilometry, and AES. After every lead pipe was used, Professor Szabo commented on his perceived differences for each one.

5.1. Surface Analysis

For each of the lead pipes the surface finish was measured using two techniques. As expected the AFM shows some variation in the surface finish. Table 6 contains the roughness values measured by the AFM and the contact profilometer. The AFM allows for the root mean square (RMS) and Ra [$\text{\AA}$ and μin] values to be determined; however the contact profilometer only measures in Ra [μin]. Table 6 contains the RMS values found by the AFM; however the comparisons between the contact profilometer and AFM were made using Ra values.

The highest value measured by the AFM was a Ra value of 3.843 μin for the 80 grit sandpaper in the longitudinal direction, while the smoothest was 0.235 μin for the electropolished specimen. It was no surprise that these were the roughest and smoothest specimens. The remaining surface Ra values for the lead pipes finished with sandpaper increased as the grit size of the sandpaper increased. However, there was an interesting

Table 6. Surface finish values measured by the AFM and contact profilometer.

Finish	AFM					PROFILOMETER		
	RMS [Å]	RMS [μin]	Ra [Å]	Ra [μin]	Delta [%]	Ra Å	Ra [μin]	Delta [%]
No Finish	517.0	2.035	411.0	1.618	0	1778	7	0
Electro Polish	59.7	0.235	45.1	0.178	-811	1778	7	0
1 Week Oxide	396.0	1.559	304.0	1.197	-35	1778	7	0
4 Week Oxide	342.0	1.346	250.0	0.984	-64	2286	9	22
400 Radial	269.0	1.059	198.0	0.780	-108	3302	13	46
400 Long	256.0	1.008	165.0	0.650	-149	3556	14	50
200 Radial	504.0	1.984	355.0	1.398	-16	4064	16	56
200 Long	691.0	2.720	351.0	1.382	-17	4318	17	59
80 Radial	887.0	3.492	695.0	2.736	41	12954	51	86
80 Long	976.0	3.843	676.0	2.661	39	7366	29	76

The percent changed column refers the percent of surface change as compared to the as-received finish. A negative value represents a smoother surface, while a positive value represents a rougher surface.

trend found. With the exception of the finish produced by the 80 grit sandpaper, all of the surfaces measured by the AFM were found to be smoother than the as-received lead pipe. The percent delta values reported in Table 6 show the percent change found. Negative values represent the percentage of change favoring a smoother surface, as compared to the lead pipe with no finish, while a positive value represents the percentage of change favoring a rougher surface, as compared to the lead pipe with no finish.

The surface of each specimen was also measured using a Surftest 211 contact profilometer, the results of which are shown in Table 6. As with the AFM, there was no surprise in that the roughest specimen was finished with the 80 grit sandpaper, while the smoothest was found to be the electropolished, untreated, and 1 week oxide growth lead

pipes. The latter three were measured to have a Ra of 7 μin . Not being able to determine a roughness difference exposes the limitation of using a contact profilometer on smooth surfaces. Closer to what was expected, the surfaces finished using sandpaper were found to be rougher than the lead pipe with no finish. The percent delta for the profilometer shown in Table 6 indicates the percentage of change favoring a rougher surface than the lead pipe with no finish.

It was interesting to note that the surface roughness results obtained with the AFM do not match those obtained with the profilometer. It was expected that the two would correlate more closely. The differences in the results are most likely due to the tip size and scanning differences between the two measurement techniques. The tip size of the AFM is only a few angstroms, while the contact profilometer is reported to be 197 μin , over 50000 times greater. A superimposed plot of the data points shows almost no trend in roughness peak values, as shown in Figure 12. The only matching data showing a trend are the measurements for the 200 and 80 grit sand papers.

Another interesting finding was that the oxide grown on the lead pipes caused the surface to become smoother as compared to the original surface finish when measured by the AFM. While there were concerns that the AFM may not have returned accurate measurements, the contact profilometer also could not measure a difference between the 1 week oxide growth and lead pipe with no finish. As seen in Table 6, the Ra surface value of the lead pipe with no finish was found to be 2.035 μin , while the 1 week was found to be 35% smoother. The AFM images for both the 1 week and 4 week oxide specimens can be seen in Figures 13 and 14, respectively. The SEM images can be seen

Figure 12. Superimposed roughness chart of the AFM and profilometer for each lead pipe.

in Figures 15 and 16, respectively. The surface images taken by the SEM as compared to the AFM are visually similar. In fact, the 4 week oxide growth appears to be smoother.

The data collected from the AFM was used to generate images of each finished surface. Figures 17 through 24 contain images generated from the AFM data. It is interesting to note that even though the grit size was larger in Figure 22 (80 grit), Figure 19 (200 grit) has similar scratch lines. The vertical scale on all the images is $0.75\text{ }\mu\text{m}$ ($29.5\text{ }\mu\text{in}$).

Figure 13. AFM surface map of the brass lead pipe with a 1 week oxide growth.

Figure 14. AFM surface map of the brass lead pipe with a 4 week oxide growth.

Figure 15. SEM image of the brass lead pipe with a 1 week oxide surface.

Figure 16. SEM image of the brass lead pipe with a 4 week oxide surface.

Figure 17. AFM surface map of the as-received brass lead pipe. No treatment applied.

Figure 18. AFM surface map of the electropolished brass lead pipe.

Figure 19. AFM surface map of the brass lead pipe finished with the 400 grit sandpaper, radial.

Figure 20. AFM surface map of the brass lead pipe finished with the 400 grit sandpaper, longitudinal.

Figure 21. AFM surface map of the brass lead pipe finished with the 200 grit sandpaper, radial.

Figure 22. AFM surface map of the brass lead pipe finished with the 200 grit sandpaper, longitudinal.

Figure 23. AFM surface map of the brass lead pipe finished with the 80 grit sandpaper, radial. Two large scratches from the sandpaper are clearly visible.

Figure 24. AFM surface map of the brass lead pipe finished with the 80 grit sandpaper, longitudinal. The smooth portion seen on the right back of the image is where the probe lost contact with the specimen.

5.2. Auger Electron Spectroscopy

Auger analysis was performed on the specimens to determine the depth of the oxide layer as compared to the as-received lead pipes, as well as to verify that an oxide layer had grown. For comparison, the oxide thickness for this project was defined as the thickness at which the atomic concentration of oxygen is measured to be approximately 5% atomic weight. The atomic concentration levels of oxygen and copper for the three lead pipes are shown in Figure 25. At 5% oxygen concentration level, the as-received lead pipe had an oxide thickness of about 430 Å. The 1 week oxide growth specimen had an oxide thickness of approximately 600 Å, while the 4 week oxide growth resulted in a thickness of about 1450 Å.

Figure 25. Plot of oxygen and copper concentration levels in the as-received, 1 week oxide, and 4 week oxide growth lead pipes.

5.3. Spectral Analysis

After it was determined that there were differences in the surfaces, the audio spectra were analyzed.

The average peak amplitudes for the preprocessed lead pipes are shown in Table

7. It was found that there was less than one dB standard deviation for harmonics 1-3, 5 and 6. The fourth harmonic had a standard deviation of 0.55 dB. It was established that the mean harmonic decibel levels were not statistically different after running a F-test

Table 7. The preprocessed lead pipe average peak harmonic amplitudes for a B flat note sustained over a five second period before surface finishing.

Lead Pipe	Harmonic Amplitude of the First Six Harmonics					
	1st [236.4 Hz]	2nd [474.3 Hz]	3rd [711.2 Hz]	4th [947.3 Hz]	5th [1183.9 Hz]	6th [1413.8 Hz]
Control	-34.42	-31.44	-30.69	-33.56	-36.56	-37.58
1	-33.32	-30.31	-29.65	-33.78	-36.20	-36.76
2	-32.77	-29.81	-29.05	-32.60	-35.14	-35.34
3	-34.10	-30.12	-29.61	-33.25	-35.89	-37.04
4	-33.48	-31.03	-29.72	-34.03	-37.49	-37.28
5	-34.04	-30.86	-30.36	-34.74	-37.13	-37.79
6	-34.08	-31.86	-30.44	-34.07	-36.60	-37.49
7	-34.40	-31.76	-29.45	-33.58	-36.71	-37.42
8	-33.43	-31.06	-29.02	-34.36	-36.33	-36.66
9	-34.58	-31.75	-30.55	-34.20	-37.43	-37.32
10	-33.71	-30.94	-29.22	-34.00	-36.37	-36.63
Min	-34.58	-31.86	-30.69	-34.74	-37.49	-37.79
Max	-32.77	-29.81	-29.02	-32.60	-35.14	-35.34
Delta	1.81	2.05	1.67	2.14	2.35	2.45
Variance	0.31	0.48	0.38	0.34	0.46	0.46
Std Dev	0.53	0.66	0.59	0.55	0.65	0.65

The control lead pipe is the lead pipe that the musician regularly uses. The columns labeled 1 through 6 represent the first six harmonics. The peak harmonic frequency is listed within the brackets. Basic statistical calculations are shown at the bottom of the table.

against the first six harmonic frequencies. The analysis of variance (ANOVA^{††}) tables are shown in Appendix C.

The spectral analysis software could only display 5 spectra at a time; however there were 11 lead pipes that needed comparison. The comparisons were broken into two charts, Figures 26 and 27. Figure 26 contains the spectra for lead pipes 1-5, while Figure 27 contains the spectra for lead pipes 5-10. It is clear that there is not a significant difference between the peak values recorded for either set. The control lead pipe was not plotted in either Figure 26 or 27; however the peak frequency numbers contained in Table 7 lead to the conclusion that it is comparable to lead pipes 1 through 10.

The same procedure was used to analyze peak frequencies of the lead pipes after preparing the internal surface finish. The results are shown in Tables 8 and 9. As was seen after the first recording, there were very few changes in the peak amplitudes. However it was noticed that the harmonic frequencies had shifted twice during the recording phase. The shift of the harmonic frequencies is most likely due to the musician not playing the tuning note consistently. It had been a number of months since the previous recording sessions. As a result of the shift, the post process comparison was broken down into two groups. Group I contained the control lead pipe, and lead pipes 1, 4 and 9. Group II contained lead pipes 2, 3, 5, 7, 8, and 10. Table 8 contains the peak harmonic amplitudes for Group I, while Table 9 contains the peak harmonic amplitudes for Group II. During the recording session it was found that lead pipe 6 had defective

^{††} ANOVA is a statistical method for making simultaneous comparisons between two or more means. The method allows for values that can be tested against a theoretical value at a given confidence level.

threads and was getting caught in the trombone. This lead pipe was eliminated from the experiment to prevent damage to the trombone.

Figure 26. First six harmonic frequencies for lead pipes 1 through 5. Lead pipes 1 through 4 are shown as overlays being compared to the fifth lead pipe, shown in yellow.

Figure 27. First six harmonic frequencies for lead pipes 6 through 10. Lead pipes 6 through 9 are shown as overlays being compared to the tenth lead pipe, shown in yellow.

The standard deviation for Group I was less than 1 dB for each of the first six harmonics. Table 8 contains the standard deviation for each harmonic. The statistical F-test run for this group found that they were not statistically different. The ANOVA tables for these tests are included in Appendix D.

A separate analysis was run for Group II, shown in Table 9. As with Group I, the standard deviation found across all six harmonics was found to be less than 1 dB. The F-test run against Group II helped to conclude that the standard deviations were not statistically different. The ANOVA tables for Group II are also included in Appendix D.

Table 8. Group I post processed lead pipe average peak harmonic amplitudes for a B flat note sustained over a five second period after surface finishing.

GROUP I	Harmonic Amplitude of the First Six Harmonics					
	1st	2nd	3rd	4th	5th	6th
Lead Pipe	[229.5 Hz]	[458.3 Hz]	[687.7 Hz]	[916.5 Hz]	[1145.3 Hz]	[1374.8 Hz]
Control	-46.91	-41.29	-42.01	-43.16	-45.18	-46.99
1	-48.03	-43.33	-43.07	-43.07	-47.19	-49.10
4	-46.52	-42.40	-42.04	-44.24	-47.04	-48.04
9	-46.36	-42.56	-41.73	-44.57	-47.00	-49.48
Min	-48.03	-43.33	-43.07	-44.57	-47.19	-49.48
Max	-46.36	-41.29	-41.73	-43.07	-45.18	-46.99
Delta	1.67	2.04	1.34	1.50	2.01	2.49
Variance	0.57	0.71	0.35	0.57	0.91	1.26
Std Dev	0.65	0.73	0.51	0.66	0.82	0.97

The control lead pipe is the lead pipe that the musician regularly uses. The columns labeled 1st through 6th represent the first six harmonics. The peak harmonic frequency is listed within the brackets. Basic statistical calculations are shown at the bottom of the table.

Figures 28 through 30 contain the overlay graphs of the sound spectra for the post processed lead pipes. Visually, there appears to be some differences in Figure 29, at least as compared to the closer range found during the pre-processed recordings. The eighth lead pipe seems to show higher harmonic amplitudes as compared to the other lead pipes. The largest difference found for the pre-processed lead pipes was 2.45dB at the sixth harmonic, 1413.8 Hz, while for the post processed lead pipes the difference was found to be 2.49 dB, at the sixth harmonic, 1347.8 Hz.

Table 9. Group II post processed lead pipe average peak harmonic amplitudes for a B flat note sustained over a five second period after surface finishing.

GROUP II	Harmonic Amplitude of the First Six Harmonics					
	1st	2nd	3rd	4th	5th	6th
Lead Pipe	[209.3 Hz]	[419.2 Hz]	[628.5 Hz]	[837.8 Hz]	[1047.1 Hz]	[1257.0 Hz]
2	-47.01	-42.59	-42.56	-44.49	-47.31	-49.25
3	-46.02	-41.86	-41.68	-44.04	-46.58	-48.76
5	-46.17	-42.24	-41.46	-44.13	-47.04	-48.54
6	-	-	-	-	-	-
7	-46.09	-41.15	-41.16	-43.80	-47.01	-48.19
8	-45.27	-41.01	-41.16	-43.37	-45.71	-48.51
10	-46.48	-42.66	-42.04	-44.70	-47.39	-48.98
Min	-47.01	-42.66	-42.04	-44.70	-47.39	-48.98
Max	-45.27	-41.01	-41.16	-43.37	-45.71	-48.19
Delta	1.74	1.65	0.88	1.33	1.68	0.79
Variance	0.33	0.84	0.26	0.46	0.78	0.16
Std Dev	0.52	0.75	0.41	0.55	0.72	0.32

The control lead pipe is the lead pipe that the musician regularly uses. The columns labeled 1st through 6th represent the first six harmonics. The peak harmonic frequency is listed within the brackets. Basic statistical calculations are shown at the bottom of the table.

5.4. Qualitative Analysis

Finally after each recording session, both pre and post-processing, the trombonist was asked if he could “feel” a difference when using each lead pipe in his trombone. Was there any feedback perceived that he had to overcome to maintain the sustained note? The response was the same for each; there was no difference felt.

Figure 28. Post processing chart for the first six harmonic frequencies using lead pipes 1, 4 and 9. Lead pipes 1 and 4 are shown as overlays being compared to the ninth lead pipe shown in yellow.

Figure 29. First six harmonic frequencies for lead pipes 2, 3, 5, 7, and 8. Lead pipes 2, 3, 5, and 7 are shown as overlays being compared to the eighth lead pipe shown in yellow.

Figure 30. First six harmonic frequencies for lead pipes 2, 3, 5, 7, and 10. Lead pipes 2, 3, 5, and 7 are shown as overlays being compared to the tenth lead pipe shown in yellow.

CHAPTER SIX DISCUSSION

Trombone lead pipes were chosen for this project because they were easily obtained and could be removed and processed while keeping the rest of the instrument intact. A drawback to using them is that the lead pipe is only a small portion of the internal surface. In fact, it only makes up about 8% of the internal surface. The entire length of the internal chamber is used to create the tone quality of the trombone. Changing such a small length may not have an audible effect on the tone quality of the instrument. However, this was realized as an accepted risk before starting the project.

The most difficult obstacle to overcome during the project was attempting to determine if the recording process was valid. The recording session used for the data set for the pre-processed lead pipes was actually the fourth recording attempt in the as-received condition. The first attempt at a recording session only resulted in collecting a spectrum from the control lead pipe. It was found that the first set of lead pipes were too big for the trombone.

The second attempt to record the lead pipes went well; however there was some doubt as to whether or not the recording process could be repeated. Therefore a third recording session was scheduled. After attempting to compare the second and third sessions, it was found that they were not the same. The decibel levels recorded for the harmonic frequencies, even though it was monitored to be 110 dB within the anechoic chamber, were not close enough to be able to overlay the spectra. It was thought that

maybe the settings on the mixing board had caused problems. So a fourth session was scheduled.

Before the fourth recording session, the settings of the mixing board were verified against those in the third session. Both the placement of the microphone and the setting for the MiniDisc recorder were also verified. Every controllable variable for the recording setup was checked. In the end, the spectra across all the last three recording sessions could not be compared. However, during this process it was found that within the same recording session, the results were consistent. Each lead pipe overlaid nicely with the previous lead pipe. This is seen in Figures 26 and 27, although some variation was found between the harmonics. These variations could be due to background noises within the chamber, for example, shuffling of Professor Szabo before playing, or him taking a deep breath before playing the sustained note. These sounds could be heard in the back ground between each note.

After it was realized that comparisons could be made within the same recording session, the internal lead pipe surfaces were changed. During this phase, the main concern was uniformity of the scratches. Also, with the wall thickness of the lead pipes being only 0.008 in thick, deep scratches that would produce a 500+ Ra finish were not possible. It would not be until the lead pipes were sectioned could the surface uniformity and roughness be truly analyzed. Once this was done, the lead pipes would no longer be useful, therefore careful surface treatment and uniformity had to be maintained.

The oxide growth and electropolishing were straightforward and presented no problems. After each process had been completed, the lead pipes were placed in vacuum-sealed bags for storage to prevent any further environmental interaction.

The fifth and final recording session was no different than the previous three. All settings were verified. It was observed again that the spectra were not comparable to the previous recordings. This time, it was accepted that even though these recordings could not be overlaid with the previous recordings, the spectra could be confidently compared within the same session.

Comparing the final spectra led to the conclusion that there might be some variations between surface finishes. This was most noticeable when comparing directional scratches. Figure 31 shows the overlapped spectra for lead pipes 8 and 10, which were finished with 80 grit sandpaper longitudinally and radially, respectively. It was noticed that lead pipe 8 had higher peak values at each harmonic as compared to lead pipe 10. When the numbers were compared using the statistical F-test there was no significant difference seen. Possibly direction does make a difference, however the size of modified surface area, or the size of the scratches could have been too small for it to affect a change in tone.

An area not researched in this project was analysis of the sound spectra sampled at rates greater than 44 KHz and frequencies larger than 2 KHz. Possibly the lower frequencies, with higher decibel levels, are more stable and have a tendency to maintain their levels with small surface variations. At higher frequencies, the peak decibel levels

gradually decrease; because the frequencies have less energy the surface variations may affect greater change.

Finally, it was recognized that all the coatings used in the project are hard surfaces. That is, as compared to previous research projects that used lacquer coated instruments, coatings consisting of brandy and honey, or even peanut paste, the oxide coatings and all the scratched surfaces are hard. Prior research has shown that softer coatings affect the tone quality by absorbing some of the sound energy and generating a lower tone quality. The consistency of comparing all hard surfaces has helped to eliminate the possibility that any noticeable differences are due to the surface scratches, and not the interaction of a softer resonating surface.

Figure 31. Overlay of lead pipes 8 and 10. Lead pipe 8 was finished with 80 grit sandpaper longitudinally, while lead pipe 10 was finished with 80 grit sandpaper radially. The chart shows that lead pipe 8 has higher peaks at each harmonic.

CHAPTER SEVEN

CONCLUSION

It was found that varying the lead pipe surface finish did not have a significant effect on the sound quality of the trombone. Characterization of the surface finish by AFM, contact profilometry, SEM, and Auger Electron Spectroscopy proved that varying surface changes had been achieved. Analysis of the sound waves through signal processing and statistical analysis provided no significant evidence that there was any difference between the pre and post processed lead pipes.

During the recording process, the qualitative analysis collected supported the quantitative results; no differences were detected by the musician.

While the results support no detected differences, there was a hint of change observed, though statistically not significant. The differences were found in the sound spectra recorded from the lead pipe finished radially and longitudinally with 80 grit sandpaper. The peak harmonic values were consistently higher for the radial scratches than the longitudinal scratches.

CHAPTER EIGHT FURTHER RESEARCH

Although no difference in tone quality was found during this project, further research into the effects of surface finish on tone quality needs to be continued. The primary reason for this recommendation is the fact that this investigation was restricted to only modifying the internal surface of the lead pipe, and not the entire instrument. This is thought to have been the main reason why no significant timbre changes were observed. The fact that differences in tone quality were ultimately decided by a human could also have resulted in differences not being adequately detected because human nature has a tendency to correct flaws even if the best intentions are to be impartial.

Another approach to this research project would be to use a setup similar to that of a marimba. A marimba consists of a series of wooden bars suspended over metallic resonating tubes. The tube length and bar size varies depending on the note desired. A more simplistic test would be to take one bar, and record the output from a series of identical tubes. The force of the strike on the bar could be repeated by dropping a known weight from the same height each time. While this is similar to the trombone in theory, the resonating tubes have a larger diameter, making surface finishing easier. At the same time, the entire length of the tube could be modified. The ability to modify the entire length of the resonating tube may help curb any doubt that surface finish affects timbre

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APPENDIX A
CALIBRATION CERTIFICATE FOR CAD EQUITTEK E-100 STUDIO CONDENSER
MICROPHONE

E-100

S.N. # 20649

Sign MK

APPENDIX B BACKGROUND FOR DIGITAL RECORDING

Digital recording is the process of taking samples of an analogue wave and attempting to reproduce it as accurately as possible using discrete points from the analogue curve. It is important for the software that will interpret the digital signal to have enough data points to properly reproduce the waveform. Digital sampling can do this given the right conditions. Figure 1A shows an analog signal that has been sampled at discrete points.

Harry Nyquist is attributed with the sampling theorem, which states, “that a continuous band-limited signal can be replaced by a discrete sequence of samples without loss of any information and describes how the original continuous signal can be reconstructed from the samples; furthermore, the theorem specifies that the sampling frequency must be at least twice the highest signal frequency.”^{††}

Bandlimiting refers to limiting the audio levels. Low-pass filtering an audio signal bandlimits the audio signal to filter out all the levels that are beyond the human hearing range. Typically this maximum audio level heard by humans is 22kHz.

So what happens when a signal is sampled using a sampling rate less than twice the highest frequency rate? The process signal will produce aliasing. Aliasing is a recorded sample rate that can get confused as to which proper signal it actually is. To determine what the aliasing signal could be, the following equation is used.

^{††}. K.C. Pohlmann, *Principles of Digital Audio, Third Edition*, McGraw-Hill, Inc, pg. 24.

a) Data samples are taken at discrete points.

b) The values of the samples are stored or transmitted.

c) The data points are held at to form a stair case representation.

d) The wave form is reconstructed by a low pass filter.

Figure 1A. With discrete data points, an analog signal can be sampled and reconstructed in a digital format. §§

$$F_f = \pm NS \pm F$$

Where:

F_f = new frequency (aliased frequency)

N = is an integer

S = sampling rate

F = sample greater than the 2x the sampling rate

§§. K.C. Pohlmann, *Principles of Digital Audio, Third Edition*, McGraw-Hill, Inc, pg. 24.

If a sampling rate of 44kHz is used to record an audio signal, and that signal contains frequencies above 22kHz (twice the sample rate), those frequencies will produce an aliased signal. For example a 36kHz sample can be confused for a new frequency (F_f) $S-F$, or $44-36\text{kHz}$ so a new signal of 8 kHz remains. When a low-pass filter is applied, all frequencies greater than 22kHz are removed, so the 36kHz frequency is removed and the 8 kHz frequency remains. This is shown in Figure 2A.

Figure 2A. A 36 kHz signal is sampled at 44 kHz, resulting in an 8 kHz aliased signal when the data points are reconstructed. ***

*** K.C. Pohlmann, *Principles of Digital Audio, Third Edition*, McGraw-Hill, Inc, pg. 29.

APPENDIX C
ANOVA TABLES FOR PRE PROCESSED LEAD PIPES BROKEN DOWN BY
FREQUENCY

Anova: Single Factor **236.19 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-99.15	-33.05	0.99
Lead Pipe 1	3	-93.83	-31.28	0.62
Lead Pipe 2	3	-92.82	-30.94	1.07
Lead Pipe 3	3	-97.85	-32.62	1.13
Lead Pipe 4	3	-97.27	-32.42	2.86
Lead Pipe 5	3	-92.80	-30.93	0.25
Lead Pipe 6	3	-97.22	-32.41	0.95
Lead Pipe 7	3	-97.22	-32.41	0.95
Lead Pipe 8	3	-94.72	-31.57	0.03
Lead Pipe 9	3	-95.68	-31.89	1.02
Lead Pipe 10	3	-94.61	-31.54	0.08

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	16.15	10	1.62	1.88	0.10	2.30
Within Groups	18.90	22	0.86			
Total	35.05	32				

Anova: Single Factor 471.71 Hz

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-87.17	-29.06	0.18
Lead Pipe 1	3	-85.63	-28.54	0.21
Lead Pipe 2	3	-86.28	-28.76	0.67
Lead Pipe 3	3	-85.80	-28.60	1.41
Lead Pipe 4	3	-87.44	-29.15	1.01
Lead Pipe 5	3	-84.93	-28.31	0.01
Lead Pipe 6	3	-88.29	-29.43	0.37
Lead Pipe 7	3	-88.29	-29.43	0.37
Lead Pipe 8	3	-88.28	-29.43	0.73
Lead Pipe 9	3	-87.71	-29.24	2.06
Lead Pipe 10	3	-86.59	-28.86	0.72

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	4.31	10	0.43	0.58	0.81	2.30
Within Groups	16.32	22	0.74			
Total	20.63	32				

Anova: Single Factor 707.9 Hz

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-87.61	-29.20	1.26
Lead Pipe 1	3	-84.90	-28.30	0.22
Lead Pipe 2	3	-84.45	-28.15	0.89
Lead Pipe 3	3	-83.36	-27.79	0.98
Lead Pipe 4	3	-83.71	-27.90	1.38
Lead Pipe 5	3	-80.54	-26.85	0.35
Lead Pipe 6	3	-82.88	-27.63	0.96
Lead Pipe 7	3	-82.88	-27.63	0.96
Lead Pipe 8	3	-82.62	-27.54	0.66
Lead Pipe 9	3	-82.15	-27.38	0.17
Lead Pipe 10	3	-80.16	-26.72	1.77

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	14.11	10	1.41	1.77	0.13	2.30
Within Groups	17.54	22	0.80			
Total	31.65	32				

Anova: Single Factor 943.42 Hz

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-95.11	-31.70	0.81
Lead Pipe 1	3	-97.08	-32.36	0.78
Lead Pipe 2	3	-93.37	-31.12	1.06
Lead Pipe 3	3	-96.07	-32.02	5.42
Lead Pipe 4	3	-96.70	-32.23	1.88
Lead Pipe 5	3	-93.34	-31.11	0.62
Lead Pipe 6	3	-95.76	-31.92	0.08
Lead Pipe 7	3	-95.76	-31.92	0.08
Lead Pipe 8	3	-95.47	-31.82	2.76
Lead Pipe 9	3	-96.93	-32.31	0.52
Lead Pipe 10	3	-95.73	-31.91	0.26

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	5.90	10	0.59	0.46	0.90	2.30
Within Groups	28.52	22	1.30			
Total	34.42	32				

Anova: Single Factor 1179.6 Hz

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-105.61	-35.20	2.04
Lead Pipe 1	3	-106.96	-35.65	3.24
Lead Pipe 2	3	-104.20	-34.73	0.67
Lead Pipe 3	3	-104.57	-34.86	6.21
Lead Pipe 4	3	-111.17	-37.06	4.15
Lead Pipe 5	3	-103.97	-34.66	1.52
Lead Pipe 6	3	-106.24	-35.41	0.09
Lead Pipe 7	3	-106.24	-35.41	0.09
Lead Pipe 8	3	-106.73	-35.58	2.84
Lead Pipe 9	3	-108.03	-36.01	1.83
Lead Pipe 10	3	-105.08	-35.03	3.80

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	15.36	10	1.54	0.63	0.77	2.30
Within Groups	53.26	22	2.42			
Total	68.62	32				

Anova: Single Factor **1415.1 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-108.91	-36.30	0.53
Lead Pipe 1	3	-108.21	-36.07	3.60
Lead Pipe 2	3	-104.86	-34.95	0.66
Lead Pipe 3	3	-107.25	-35.75	5.64
Lead Pipe 4	3	-106.71	-35.57	5.63
Lead Pipe 5	3	-104.72	-34.91	0.89
Lead Pipe 6	3	-106.62	-35.54	0.75
Lead Pipe 7	3	-106.62	-35.54	0.75
Lead Pipe 8	3	-109.60	-36.53	3.59
Lead Pipe 9	3	-108.80	-36.27	3.05
Lead Pipe 10	3	-109.39	-36.46	3.77

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	14.59	10	1.46	0.57	0.82	2.30
Within Groups	56.51	22	2.57			
Total	71.10	32				

APPENDIX D
ANOVA TABLES FOR POST PROCESSED LEAD PIPES BROKEN DOWN BY
FREQUENCY

Group I

Anova: Single Factor **229.5 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-144.42	-48.14	1.93
Lead Pipe 1	3	-143.06	-47.69	3.32
Lead Pipe 4	3	-141.39	-47.13	3.33
Lead Pipe 9	3	-139.29	-46.43	0.21

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	4.90	3	1.63	0.74	0.56	4.07
Within Groups	17.58	8	2.20			
Total	22.48	11				

Anova: Single Factor **458.3 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-124.28	-41.43	2.47
Lead Pipe 1	3	-125.46	-41.82	0.35
Lead Pipe 4	3	-125.65	-41.88	1.32
Lead Pipe 9	3	-125.41	-41.80	0.01

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.38	3	0.13	0.12	0.94	4.07
Within Groups	8.30	8	1.04			
Total	8.68	11				

Anova: Single Factor **687.7 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-130.86	-43.62	3.30
Lead Pipe 1	3	-129.51	-43.17	2.46
Lead Pipe 4	3	-130.58	-43.53	2.64
Lead Pipe 9	3	-127.33	-42.44	0.29

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	2.57	3	0.86	0.39	0.76	4.07
Within Groups	17.39	8	2.17			
Total	19.96	11				

Anova: Single Factor **916.5 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-136.38	-45.46	1.76
Lead Pipe 1	3	-137.24	-45.75	0.57
Lead Pipe 4	3	-137.96	-45.99	1.21
Lead Pipe 9	3	-137.94	-45.98	0.15

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	0.56	3	0.19	0.20	0.89	4.07
Within Groups	7.38	8	0.92			
Total	7.94	11				

Anova: Single Factor **1145.3 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-141.02	-47.01	2.36
Lead Pipe 1	3	-145.01	-48.34	2.93
Lead Pipe 4	3	-149.29	-49.76	0.39
Lead Pipe 9	3	-145.55	-48.52	0.96

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	11.44	3	3.81	2.30	0.15	4.07
Within Groups	13.26	8	1.66			
Total	24.70	11				

Anova: Single Factor **1374.8 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Control	3	-144.50	-48.17	1.71
Lead Pipe 1	3	-149.48	-49.83	4.47
Lead Pipe 4	3	-153.55	-51.18	2.23
Lead Pipe 9	3	-152.73	-50.91	1.53

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	16.84	3	5.613	2.260	0.159	4.066
Within Groups	19.87	8	2.484			
Total	36.71	11				

Group II

Anova: Single Factor **209.3 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Lead Pipe 2	3	-121.84	-40.61	0.00
Lead Pipe 3	3	-121.97	-40.66	0.40
Lead Pipe 5	3	-124.82	-41.61	2.91
Lead Pipe 7	3	-122.67	-40.89	0.70
Lead Pipe 8	3	-121.28	-40.43	1.37
Lead Pipe 10	3	-121.73	-40.58	0.06

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	2.71	5	0.54	0.60	0.70	3.11
Within Groups	10.90	12	0.91			
Total	13.62	17				

Anova: Single Factor **419.2 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Lead Pipe 2	3	-134.03	-44.68	0.03
Lead Pipe 3	3	-134.30	-44.77	0.40
Lead Pipe 5	3	-135.50	-45.17	0.36
Lead Pipe 7	3	-134.93	-44.98	1.93
Lead Pipe 8	3	-134.06	-44.69	1.88
Lead Pipe 10	3	-133.02	-44.34	0.05

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	1.20	5	0.24	0.31	0.90	3.11
Within Groups	9.31	12	0.78			
Total	10.51	17				

Anova: Single Factor **628.5 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Lead Pipe 2	3	-144.66	-48.22	0.19
Lead Pipe 3	3	-144.07	-48.02	0.54
Lead Pipe 5	3	-144.85	-48.28	1.89
Lead Pipe 7	3	-145.99	-48.66	0.94
Lead Pipe 8	3	-146.83	-48.94	8.69
Lead Pipe 10	3	-142.61	-47.54	1.26

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	3.63	5	0.73	0.32	0.89	3.11
Within Groups	27.03	12	2.25			
Total	30.66	17				

Anova: Single Factor **837.8 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Lead Pipe 2	3	-164.87	-54.96	3.48
Lead Pipe 3	3	-165.66	-55.22	1.26
Lead Pipe 5	3	-168.98	-56.33	3.88
Lead Pipe 7	3	-170.83	-56.94	0.23
Lead Pipe 8	3	-166.05	-55.35	6.87
Lead Pipe 10	3	-168.81	-56.27	3.71

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	9.12	5	1.82	0.56	0.73	3.11
Within Groups	38.87	12	3.24			
Total	47.99	17				

Anova: Single Factor **1047.1 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Lead Pipe 2	3	-184.08	-61.36	0.68
Lead Pipe 3	3	-183.26	-61.09	1.02
Lead Pipe 5	3	-186.59	-62.20	2.51
Lead Pipe 7	3	-188.03	-62.68	0.61
Lead Pipe 8	3	-185.01	-61.67	10.61
Lead Pipe 10	3	-190.44	-63.48	1.00

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	12.00	5	2.40	0.88	0.53	3.11
Within Groups	32.86	12	2.74			
Total	44.87	17				

Anova: Single Factor **1257.0 Hz**

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Lead Pipe 2	3	-207.20	-69.07	3.25
Lead Pipe 3	3	-204.93	-68.31	1.81
Lead Pipe 5	3	-208.11	-69.37	0.67
Lead Pipe 7	3	-211.82	-70.61	0.41
Lead Pipe 8	3	-203.86	-67.95	9.18
Lead Pipe 10	3	-208.82	-69.61	21.94

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	13.57	5	2.71	0.44	0.81	3.11
Within Groups	74.50	12	6.21			
Total	88.07	17				