THE RELATIONSHIP BETWEEN SOUND INTENSITY AND PROJECTILE VELOCITY OF A BB CANNON

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ABSTRACT

The BB cannons used by radio controlled battleships are believed to have a qualitatively positive correlation between the speed of the BB projectile and the sound intensity of the shot, yet no quantitative analysis has been conducted to date. The work here examined the relationship between the projectile velocity from a BB cannon and the sound intensity of the shot, using a "speed trap" device along with sound pressure readings of the shot from a microphone. The O-ring compression settings on the cannons can be adjusted to change the dynamics of the gun, and twelve different compression settings were used in this experiment. The relationship between the projectile velocity and the sound intensity of the shot was found to be 6.353 ± 1.616 m/s per relative unit increase in sound intensity, with a correlation coefficient of 0.917. While a positive correlation between projectile velocity and sound intensity of the shot was found, the dynamics of the gun at high compression settings merit further study.

INTRODUCTION

The hobby of radio controlled model warship combat has existed for 30 years, and until now, no scientific analysis has been conducted on the firing dynamics of the BB cannons onboard the boats. Radio controlled model warship combat is a hobby where 1-2m long boats battle each other on the high seas, shooting BB's at the enemy boats in an attempt to sink them. Compressed CO2 powered cannons are used to shoot the BB's from one boat towards the side of another. The boats have thin balsa wood sides, such that the BB's will penetrate the sides of the enemy boat and allow water to leak in. If a boat is shot enough times, the water leaking in through the holes will overpower the small bilge pump carried onboard the boat, and the boat will sink to the bottom of the pond. In order to inflict maximum damage to the enemy, BB cannon's are designed to shoot BB's through the surface of the water such that they penetrate the side of the boat below the waterline. As such, model warship operators strive to have their boat's cannon's shoot BB's fast enough that the BB can break the side of the enemy hull even after traveling through about 5cm of water.

A BB cannon operates by using CO2 to push the BB though a compressed O-ring, which will accelerate the BB to a high velocity. In order to adjust the dynamics of the BB cannon, operators can change the compression on this O-ring by tightening or loosening a threaded nut. In the hobby, this process is called "tweaking" the guns, where the operator tries to tighten the nut as much as possible, without over tightening it such that there is not enough pressure to expel the BB. With the increase in O-ring compression, it is a commonly held belief in the hobby that the BB's then travel faster, and that the shot is "louder," relative to a gun that is not "tweaked."

The scope of this experiment was to quantify the velocity of the projectile as a function of the sound intensity of the shot. This study used a microphone to measure the time it took for a BB to travel from the gun to a target and used these values to calculate the velocity of the BB. A metal plate was used as a target, such that the microphone could clearly hear the sound of the impact. The microphone also measured the "pressure" of the sound, from which the sound intensity could be derived. This allowed the use of a single sensor to take both sets of data, which would eliminate the error that arises from coordinating two sensors at once. To test the measurement system, an air rifle, which has a known projectile velocity, was used and compared against the derived velocity from the sound calculations. Additionally, this study would also show how consistent the guns were, whether they shot at the same velocity each time, or whether there was a significant variance in the data.

PROJECTILE VELOCITY, SOUND INTENSITY AND BB CANNONS

PROJECTILE VELOCITY

This study uses the basic laws of physics to derive the projectile velocity from its time and distance of flight. The starting point of this derivation comes from the equation d=v*t, where d is distance, v is velocity, and t is time. However, the time measured in this experiment is not just the time it takes for the BB to travel from the gun to the target. When a sound originates at a location that is a given distance from the sound sensing device, the speed of sound must be factored in. In order to calculate the speed of sound in the experimental conditions, Equation 1 was used:

$$v_s = 20.05\sqrt{T} \qquad (1)$$

where *T* is the temperature of air in degrees Kelvin, and v_s is measured in meters per second. The constant 20.05 is derived from the properties of air, including the molar mass, the ratio of specific heats, and the universal gas constant. In this experiment the microphone was placed at the target line. The microphone reads the sound of the shot after it has been fired because the sound must travel from the cannon to the microphone over the distance to the target. With this knowledge, the equation to obtain the speed of the projectile from the time recorded by the microphone is shown in Equation 2:

$$v_p = \frac{(L * v_s)}{(v_s * t + L)} \qquad (2)$$

where L is the distance from the barrel of the gun to the point of impact, and t is the time recorded by the microphone between the sound of the shot and the sound of the impact of the projectile with the plate.

SOUND INTENSITY

Sound intensity is a measure of the ratio of two sound powers, commonly measured in decibels. Sound power is measured in Watts, and is independent of distance away from the source, as it is a measure of the total energy being carried in a sound wave. Unfortunately, it is commonly reported that sound power cannot be directly measured. To get around this fact, it is common practice to measure sound power as proportional to the square of the sound pressure.1

Microphones are used to quantify relative changes in the pressure of sound waves. According to Vernier, a microphone manufacturer, the values that the microphone outputs for sound pressures cannot easily be converted to useful units. Instead, the output values should only be treated as relative values between different readings. If the microphone was calibrated, it would measure in units of kPa; however, for the microphone used in this experiment, there are no units attributed to the output readings.2 Taking this into account, this experiment will only consider relative changes in sound pressure, and the output readings will be squared to obtain a measurement that represents the sound power, however no units can be assigned to this value either. Finally, the sound intensity will be found by taking a ratio of the sound power of a given shot to that of a reference shot, which again will not be assigned units.

An alternative to the microphone approach would be to use a sound level meter. However, this would prove ineffective as the sound level meter would only provide an impulse response to a sharp sound, rather than a direct reading for the instantaneous sound intensity. For this study this is not desirable because the sound of the shot takes place over a few milliseconds, and the sound level meter could output a response function with nonlinearities. With no simple way to calibrate a sound level meter for this test, the microphone method described above will be used.

ROOT MEAN SQUARE

The root mean square (RMS) algorithm is used to measure the magnitude of a varying quantity. The equation to find the RMS value at a particular point is shown in Equation 3:

$$RMS = \sqrt{\frac{(x_1^2 + x_2^2 + x_3^2 + \cdots + x_n^2)}{n}} \qquad (3)$$

where *n* is the number of points in the sample. As shown by Eq. 3, the value of the RMS at a point x_n is a function of all of the preceding points. Therefore, it is important to be cognizant of where the RMS is started from. In this experiment, the RMS will be used to smooth the raw data from the microphone, as described in Section 4.

BB CANNONS

The BB cannon and radio controlled model warships were first invented in the early 1980's. While there have been changes and improvements since then, the basic design still remains the same. The schematic of a BB cannon system is shown in Figure 1:

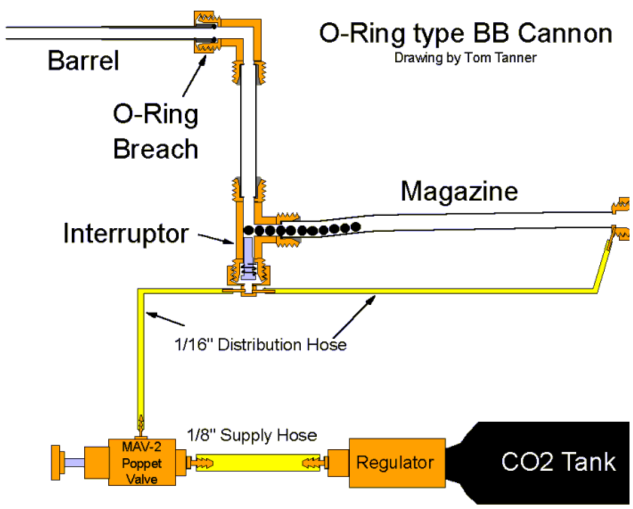

Figure 1: Schematic of BB cannon and firing system

The BB cannon system uses the pressure from compressed CO2 to shoot BB's through an O-ring. The function of the BB cannon begins at the CO2 tank. Within the tank, liquid CO2 is stored at a pressure on the order of 800 psi. The CO2 then leaves the tank through a pressure regulator that reduces the pressure to 150 psi, to make it safe for use in this hobby. After going through the regulator, the CO2, now in gas form, travels through 1/8" tubing to a poppet valve. When this valve is actuated, it allows the CO2 to travel through 1/16" tubing to the gun. When the CO2 reaches the gun, it splits between the interrupter and the magazine. The magazine is a piece of brass tubing that has an ID of 3/16" to guide the BB's to the interrupter. The interrupter is a spring loaded pin that is pushed upward when the gun is fired, such that it only allows a single BB to shot by the gun. The BB then travels up to the breach, where it contacts the O-ring, which has been discussed above. Once the BB hits the O-ring, the pressure builds up behind the BB until it is ejected through the barrel. This process takes around 100ms.

The "tweaking" process involves varying the compression on the O-ring, such that the maximum amount of pressure is required to fire the BB, without the BB being delayed at the O-ring. In this case, there is an audible pause from when the BB first reaches the O-ring to when it is ejected. This pause is not desirable for a few reasons. First, when this happens it lowers the maximum rate of fire, as the delay causes the process of shooting a single BB to take longer. Additionally, there is the possibility that the BB will not be ejected at all, and will instead be stuck behind the O-ring such that the gun will not be able to fire during the battle.

INSTRUMENTED SPEED TRAP

MEASURING THE VELOCITY OF A BB

In order to measure the velocity of a BB, a "speed trap" was created to measure the time it took for the BB to travel from one location to another, a distance of 8.90 ± 0.02m away. The uncertainty of this distance is because the BB could have impacted any point on the metal plate and it would have registered as a successful test, so this uncertainty accounts for the range of distances possible. An assumption was made that the BB traveled at constant velocity, since the only force that acted on the BB while in flight was air resistance. The boundaries for the speed trap were the gun itself, and the metal plate, which made a clear sound when the BB impacted it. To measure the time that it took for the BB to travel this distance, a Vernier Microphone (MCA 7) was used. This microphone can sample at frequencies up to 10,000 Hz, and it outputs a reading of sound pressure versus time. In order to prevent the microphone pressure output from becoming saturated by the sound of the shot, where every shot would have yielded a maximum pressure reading, the microphone was placed at the metal target. This resulted in different shots yielding different pressure readings from the microphone.

The experimental set up is shown in Figure 2.

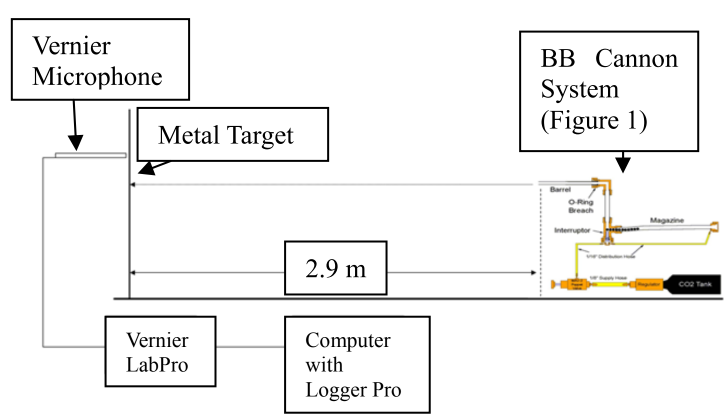

Figure 2: Experimental Set-up

As shown in Figure 2, the length of the "speed trap" was limited by the supplied cables for the Lab Pro and microphone. There are two systems involved in this experiment – the BB cannon system, described in Section 2.3, and the microphone system. The microphone is attached to Vernier LabPro hardware, which is then attached to a computer via a USB cable. The data is presented on the computer with Logger Pro version 3.6.1.

TESTING THE SYSTEM

In order to assess whether the system would output reasonable data, the system was tested using a shot from an air rifle. After the air rifle was pumped to its maximum input pressure, the air rifle was shot from the location of the BB cannon into the metal target. Using Equations 1 and 2, the calculated velocity of the shot was 688 ± 2 feet per second. The specifications for the air rifle list a maximum velocity of 685 feet per second. This test showed that the system could plausibly measure the velocity of a BB.

SEQUENCE OF DATA ACQUISITION

The sequence of data acquisition was designed to collect a wide range of data, while additionally quantifying the consistency of the system. This was accomplished by testing the BB cannon at a variety of O-ring compression settings, and taking four individual shots at each compression setting. The first compression setting was at the point where the nut first contacted the O ring, resulting in nominally zero O-ring compression. Four shots were taken and recorded at this compression setting. The nut on the barrel was then tightened approximately 1/16th of a turn, increasing the compression on the O-ring. Four more shots were then taken and recorded. This process of increasing compression and then taking data was repeated until the O-ring compression was too great for a BB to pass through it.

RESULTS AND DISCUSSION

The projectile velocity and sound intensity of the shot from the BB cannon was recorded at twelve different O-ring compression settings, for a total of 42 data points. The raw output from the microphone was put through a RMS algorithm in order to obtain a smooth plot. Because the data recorded for a given pressure varied, the RMS was used to provide a less variable measure of the magnitude. After the data was put through the RMS, an algorithm was used to measure the flight time of the BB, as well as the peak magnitude of the sound intensity. Additionally, the algorithm measured the time delay from when the shot was triggered until the BB left the barrel of the gun. After all of the data was analyzed, a plot was made of the projectile velocity versus the sound intensity. Finally, some of the data points were removed from the data set because of too great a delay occurred between when the shot was triggered and when the BB left the barrel of the gun.

MEASUREMENT OF PROJECTILE VELOCITY, SOUND INTENSITY AND SHOT DELAY

The typical raw data plot from the microphone of the sound pressure as a function of time is shown in Figure 3.

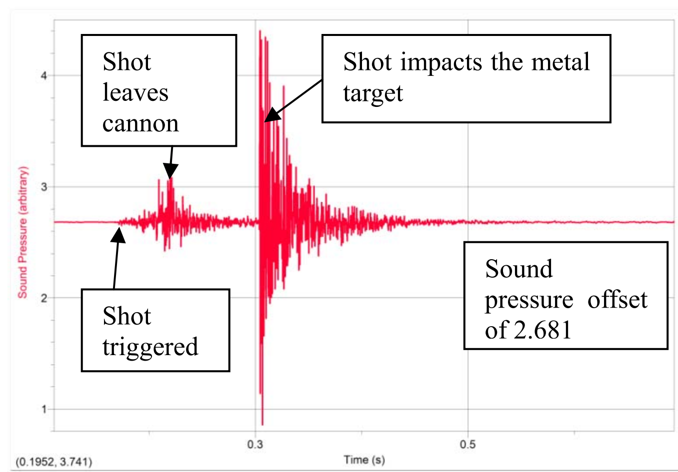

Figure 3: Typical output data from the microphone

Figure 3 shows that the raw output from the microphone was not adequate to draw conclusions about the data recorded. The time that the shot was triggered is indicated by the beginning of oscillation in the sound pressure reading. This would be the time when the valve to the gun was opened and CO2 started to exit the gun. The time when the shot left the barrel of the cannon is denoted by the relatively large spikes in the pressure reading, which is caused by the BB expanding the O-ring as it exits the gun. Since the microphone was placed at the target, the time when the BB impacts the target shows the largest variation in sound pressure. Finally, the entire data set is offset by a value of 2.681 pressure units on the readout.

In order to make the data understandable, the raw pressure readings from the microphone will be put through a root mean square algorithm. The first step in this process is to remove the 2.681 offset in order to center the data about the value of 0. Then, the adjusted pressure readings are squared to make the data represent the sound power, as described in Section 2.2. The next step is to take the RMS of the data, starting at the time when the shot was triggered. The resulting plot is shown in Figure 4.

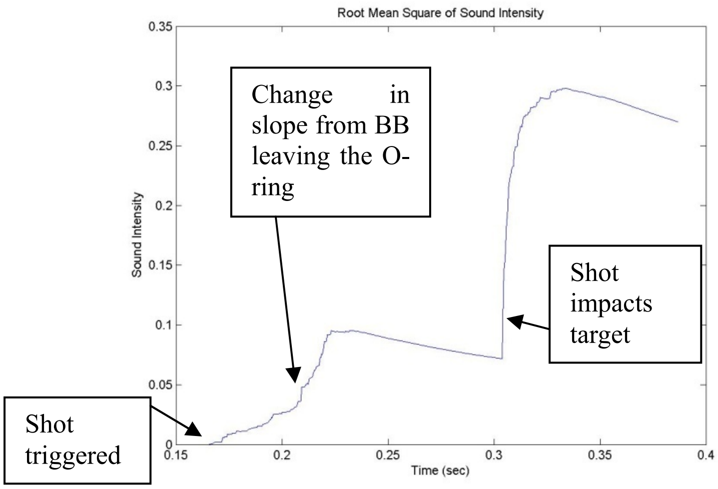

Figure 4: RMS of the sound power data, beginning from when the shot was triggered

At this point in the experiment, the data represented in Figure 4 gave a qualitative view of the RMS of the shot; however this had to be adjusted to obtain a more accurate reading of the data. As described in Section 2.3, the RMS value of a point is a function of all of the preceding points. To obtain accurate values for the sound power of the shot, the RMS will be taken beginning at the time when the BB leaves the O-ring, indicated in Figure 4 as the point where the change in slope of the data occurs. The reason for doing this is that if there is a large delay from when the shot is triggered to when the BB leaves the O-ring, then the values of the sound power for when the BB is leaving the O-ring will be decreased by the preceding large quantity of low values. Figure 5 shows this new RMS plot, which will be superimposed on the original RMS plot to show the difference between the two.

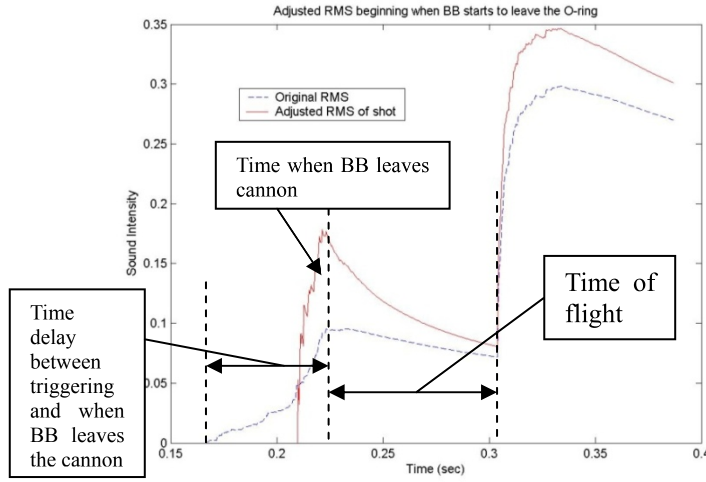

Figure 5: Adjusted RMS of the BB leaving the O-ring. Note the large difference between the peak height of the adjusted RMS against the original RMS

As shown in Figure 5, the adjusted RMS plot gives a data set that shows a more accurate sound power reading for the time when the BB is leaving the O-ring, which is when the main sound of the shot is produced. Additionally, Figure 5 denotes the various times that are needed to calculate the time delay as well as the velocity of the shot, including the time at which the BB leaves the O-ring. The "time of flight of the BB" was inserted into Equation 2 to yield a velocity for the shot.

DETERMINING APPROPRIATE DATA AND ANALYSIS

For this experiment, sound intensity will be defined as the sound power for a given data point divided by the smallest sound power recorded throughout the experiment. Figure 6 shows the plot of the projectile velocity versus the sound intensity for all of the data collected.

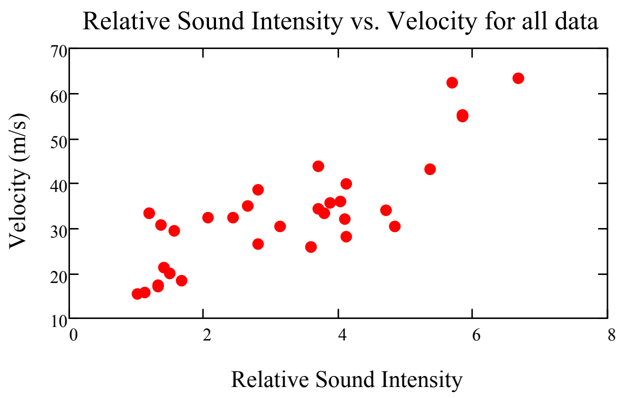

Figure 6: Projectile Velocity vs. Sound Intensity for all data recorded

As shown in Figure 6, there is a wide range on the velocities for sound intensities greater than 5, spanning from 30 m/s to over 60 m/s. While taking the data, it was observed that some of the shots showed significant hesitation from when the shot was triggered to when the BB released, particularly at the higher compression settings. This hesitation is quantified by the time delay value shown in Figure 5, and described in Section 4.1. Looking back to the original raw data from the microphone, the delay can be seen very clearly, as shown in Figure 7:

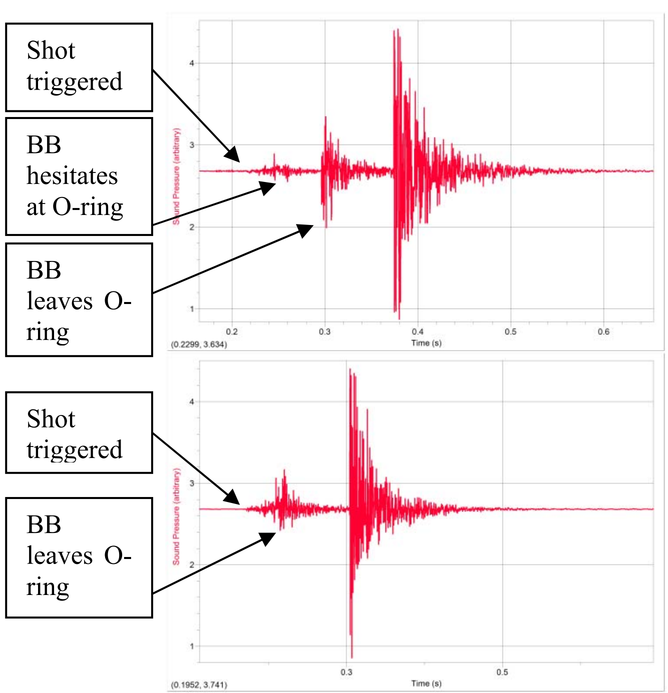

Figure 7: Comparison of plots with (image on left) and without (image on right) significant time delay from the triggering to when the BB releases from the O-ring

This time delay also showed up on the RMS plots discussed in Section 4.1. After examining a number of plots, it was determined that a time delay of 0.070 sec or greater was an indication of significant hesitation at the O-ring. In the hobby, the guns are configured such that there is no hesitation in the shot. Therefore, all data points with a time delay of 0.070 sec or greater were removed, which eliminated 10 data points from the data set.

QUANTIFYING RESULTS

The data presented in Figure 6 shows an increasing trend between the projectile velocity and the sound intensity. Figure 8 shows a linear fit of the finalized set of data.

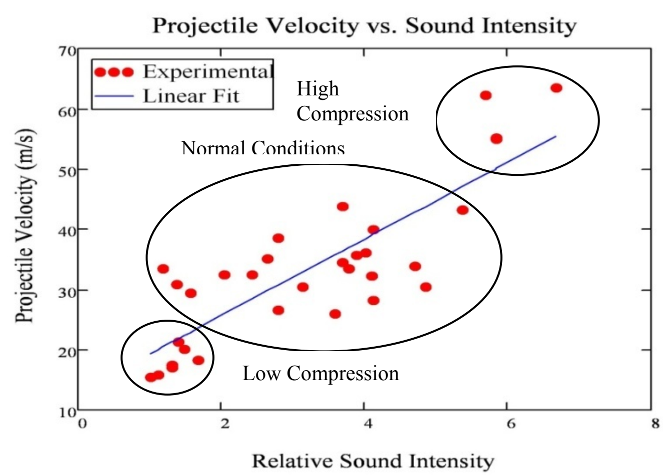

Figure 8: Linear fit of experimental data. The relative sound intensity does not have units, as described in Section 2.2, and all of the values are relative to the lowest value recorded. The three groupings shown indicate different characteristic clusters of data

The slope of the linear fit, with 95% confidence, was found to be 6.353 ± 1.616 m/s per relative unit of sound intensity increase. The correlation coefficient of this data was found to be 0.917. This value shows the linearity between the data sets, as 91% of the data is encompassed by the fit line shown. The large confidence interval corresponds to the spread of the data for a few sound intensity values, particularly for low values around 1 to 2 units. In this range, there is a spread from 15 m/s to 33 m/s, which means that the sound intensity is not a good means for determining projectile velocity for this region.

GROUPING ANALYSIS

Qualitatively, there are three main regions to the data. The first region is the Low Compression grouping, with relative sound intensity values between 1 and 2 and velocities around 20 m/s. This grouping of shots is from when the barrel nut did not compress the O-ring. The slope for this region was 6.640 ± 7.643 m/s per relative unit sound intensity increase, which does not strongly support a linear relationship between the projectile velocity and the sound intensity for this region.

The second grouping is data with a projectile velocity from 25 to 45 m/s. This grouping represents the performance of the BB cannon under Normal Compression conditions, with light to moderate compression on the O-ring. The average velocity of the shots in this group is 33.710 ± 4.808 m/s. The slope for this region is 1.379 ± 1.807 m/s per relative unit sound intensity increase. Just as in the Low Compression region, again this data does not support a linear relationship between velocity and sound intensity.

The final grouping is the High Compression region, characterized by projectile velocities over 50 m/s. These data points occurred when the O-ring was at optimal compression, or even over-compression. The existence of only four data points in this region indicates that the cannon cannot repeatedly fire at this velocity. Rather, these points show that the optimal compression setting is very sensitive, such that any small adjustments to it will adversely affect the performance of the cannon. The fitted slope for the High Compression data was found to be 5.575 ± 19.562 m/s per relative unit sound intensity increase, once again not strongly supporting a linear relationship between velocity and sound intensity in this region.

Figure 9 shows the plots of the three different groupings.

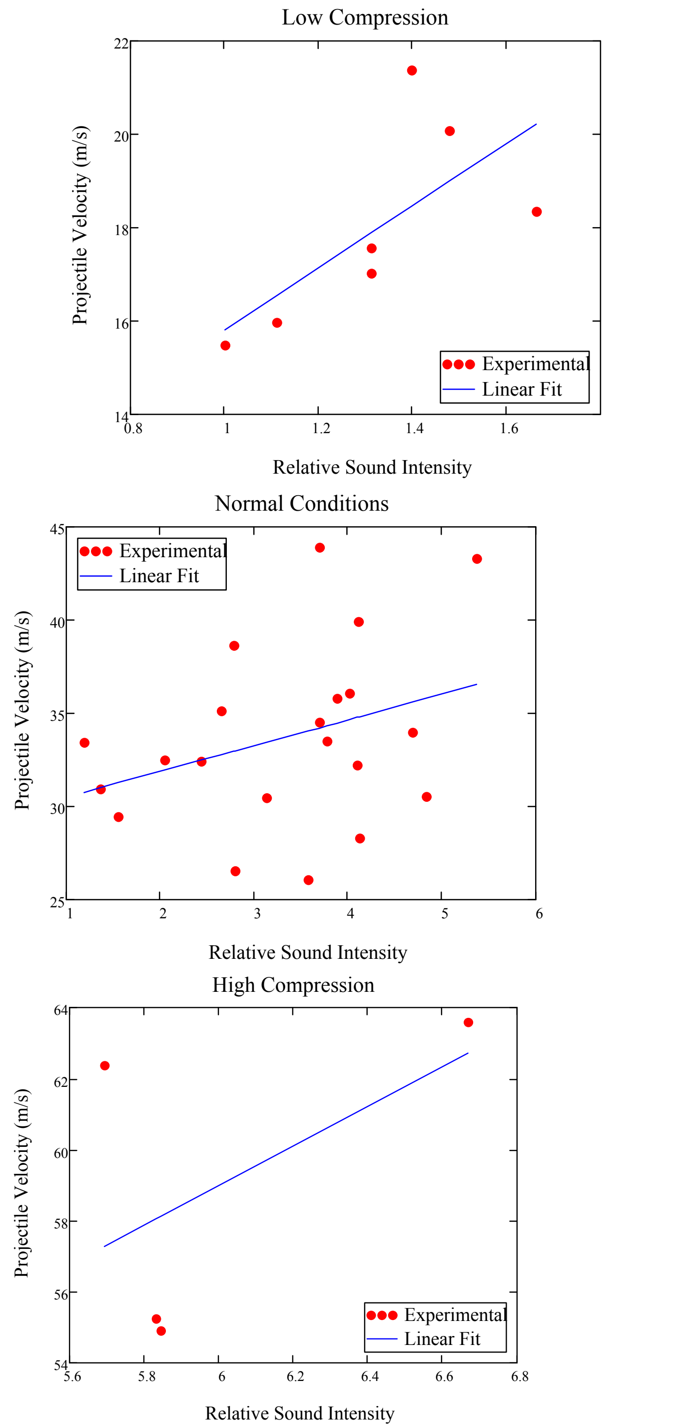

Figure 9: Plot of individual groupings of data. When taken as a single set of data, none of the groups show a significant relationship between projectile velocity and sound intensity

Though each of the three regions appears non-linear locally, the entire set of data does yield a positive linear correlation between projectile velocity and sound intensity, as shown in Figure 8. The local non-linearities do indicate that the BB cannon is not a high grade product, such that it has low consistency and high variability in regions of similar compression settings. Additionally, the BB's that are shot through the cannon consistently have imperfections that would change the interaction between the BB and the O-ring.

METHODS FOR IMPROVED FURTHER STUDY

Errors in the measuring technique include errors in length of the BB trajectory, as it was observed that many of the BBs did not fly straight, but rather they curved once they left the barrel. This can be attributed to the fact that when the BB leaves the O-ring, one edge of the BB is likely to release first, causing a significant spin to the BB. Since this spin is not normal to the flight path, it will cause the BB's to curve significantly.

Another undesirable situation was placing the microphone at the target, rather than at the gun. The reason for this was that the first time this experiment was conducted, the microphone was saturated, meaning that all of the sound pressure readings were roughly the same, indicating that they hit the maximum input for the microphone. Therefore, it is possible that the decrease in sound pressure over distance is non-linear, which would skew the results presented here.

Finally, more data could have been presented about the Vernier Microphone, as the manufacturer's website indicated that there are non-linear regimes for the sound pressure input, in that the system dynamics change at different frequencies. Since the processes recorded here occurred at a high frequency, it is possible that this affected the results as well.

CONCLUSIONS

The BB cannons used by radio controlled battleships are believed to have a qualitatively positive correlation between the speed of the BB projectile and the sound intensity of the shot, yet no quantitative analysis had been conducted before this experiment. The work here examines the relationship between the projectile velocity from a BB cannon and the sound intensity of the shot, using a "speed trap" device along with sound pressure readings of the shot from a microphone. The O-ring compression settings on the cannons can be adjusted to change the dynamics of the gun, and twelve different compression settings were used in this experiment. The relationship between the projectile velocity and the sound intensity of the shot was found to be 6.353 ± 1.616 m/s per relative unit increase in sound intensity, with a correlation coefficient of 0.917. While a positive correlation between projectile velocity and sound intensity of the shot was found, the dynamics of the gun at high compression settings merit further study. Additionally, a microphone with a higher maximum input would allow placement of the sensor at the gun, which would negate error caused by the sound waves traveling a significant distance to the microphone.

ACKNOWLEDGMENTS

The author would like to thank Prof. Neville Hogan of the Department of Mechanical Engineering at the Massachusetts Institute of Technology for guidance on data analysis for this study and Dr. Barbara Hughey for the lab equipment used here.

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