Reducing Exhaust Emissions and Investigating Sound Deadening Materials for a Two Stroke Snowmobile

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Abstract

For the 2017 SAE Clean Snowmobile Challenge, the University of Minnesota Clean Snowmobile Team has chosen to modify a 2015 Polaris Indy 600 SP. The 600cc, semi-direct injected, two stroke engine was chosen because of the power to weight ratio it provides. A new engine management system was implemented to accommodate running on flex fuel ethanol. In order to improve emissions, a new muffler was designed with the addition of a three way catalyst. The team has also produced an impedance tube and matching software for testing sound deadening materials. The device determines the absorption coefficient of a material at a multitude of frequencies. This allows the material best suited for certain situations and locations on the sled to be chosen quantitatively based on target frequencies.

Introduction

Snowmobiling is a recreational activity that many people around the world participate in. In the United States alone there are 1.2 million registered snowmobiles [1]. Many snowmobile trails run next to roads, through private property, and on public land such as state and national parks. As a result, millions of people and many environmentally sensitive areas are affected by the noise and emissions produced by snowmobiles each year. While there are regulations on snowmobiles in place to help reduce the impact on the surrounding community, further improvements are possible. Currently, the National Park Service limits the noise level of snowmobiles to 78 dBA while operated at full throttle at a distance of 50 feet [2]. The following equation describes the current standards set by the Environmental Protection Agency (EPA) regarding emissions where HC_{STD} is hydrocarbon emissions in g/KW-hr and CO is carbon oxide emissions in g/KW-hr [3].

$$\left(1 - \frac{HC_{STD}}{150}\right) * 100 + \left(1 - \frac{CO_{STD}}{400}\right) * 100 \geq 100; \qquad (1)$$

$$HC_{STD} \leq 75; \;\; CO_{STD} \leq 275$$

Through SAE International's Clean Snowmobile Challenge, college students create innovative solutions addressing the noise, efficiency, and emissions challenges associated with snowmobiles while maintaining marketability to consumers.

The main categories of the Clean Snowmobile Challenge are Performance, Emissions, and Noise. The University of Minnesota-Twin Cities team has placed emphasis on reducing noise while creating a reliable, well-performing snowmobile that includes flex fuel compatibility and emissions controls.

Performance

A main goal for the University of Minnesota-Twin Cities Clean Snowmobile Team is to produce a snowmobile that not only exceeds current standards for emissions and noise, but also has a high level of performance, and would appeal to snowmobiling enthusiasts.

This strategy began with the selection of a stock chassis and engine. The 2015 Polaris Indy 600 SP was chosen because of its two stroke engine and handling characteristics.

Engine

The Polaris Liberty 600 engine is rated stock at 125 horsepower. This is close to the Clean Snowmobile Challenge's maximum power output of 130 horsepower. It is also a very lightweight engine, especially compared to many four strokes.

For the competition, the snowmobile was modified to run on flex fuel mixtures of up to 87% ethanol mixed with gasoline. To accomplish this task, and ensure that the snowmobile's performance did not degrade when ethanol was introduced, a Continental ethanol sensor was implemented, using a Performance Electronics PE3 ECU. A stoichiometric tuning strategy was utilized with the help of lambda sensors to accommodate the addition of a catalyst to improve emissions.

Handling

The handling characteristics of a snowmobile are just as important as engine performance, and the UMNCST did not want to neglect this area.

The Polaris Pro-Ride chassis was selected because of its on-trail handling performance. The Indy SP was selected for its suspension upgrades over the base model Indy.

Beyond selecting a snowmobile that had good handling stock, a set of C&A Pro skis and a pre-studded Camso track were added, further improving handling and traction.

Emissions Control

The use of a fuel and oil mixture, as well as the loss of fresh air and unburned fuel charge into the exhaust make two stroke engines more difficult to implement emissions controls strategies on. In addition to increasing exhaust emissions, these problems can damage emissions control devices. The UMNCST's strategy to reduce emissions consists of the proper selection and packaging of a catalyst.

The chosen catalyst utilizes a BASF TEX-0587 coating. The catalyst loading is 60g/ft3 at a 2/9/1 ratio (Pt:Pd:Rh). The catalyst was placed directly after a 90 degree elbow in the exhaust system, downstream of the expansion chamber. A location further from the exhaust ports of the engine lessens the risk of unburned fuel and oil combusting on the catalyst, damaging it. A vertical orientation allows for any excess oil to drain through the catalyst resulting, in a lower likelihood of catalyst clogging or fouling. If the catalyst were to become blocked, the number of catalytic sites would be lowered, and lower flow would occur, reducing engine performance.

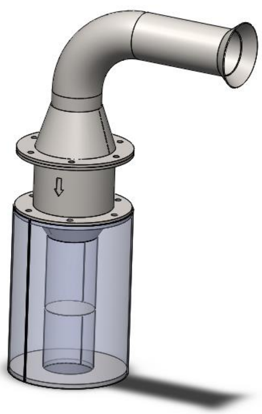

Figure 1: Visual representation of exhaust system post-expansion chamber. The catalyst is marked with a flow direction indicating arrow.

In theory, the implementation of a catalyst in the snowmobile would improve emissions. Combustion in an engine is incomplete and causes excess amounts of greenhouse gases that are ultimately introduced into the atmosphere. The most common emissions produced by combustion are uncombusted hydrocarbons ($H_xC_yO_z$), nitrous oxides (NO_x), carbon dioxide (CO_2), and carbon monoxide (CO). These emissions are detrimental to the environment and human health, especially carbon monoxide and nitrogen monoxide. Therefore, a three-way catalyst was selected. Three-way catalysts aid in the process of oxidizing carbon monoxide to carbon dioxide and reducing nitrous oxides to inert nitrogen gas. These chemical reactions are shown below.

$$NO \rightarrow N_2 + O \qquad (2)$$

$$CO + O_2 \rightarrow 2CO_2 \qquad (3)$$

The hydrocarbons present in the exhaust as a result of incomplete burning of fuel can be further combusted to form carbon dioxide and water. The reaction is shown below.

$$HC + O_2 \rightarrow CO_2 + H_2O \qquad (4)$$

There are three metal components in the catalyst. They are Platinum, Palladium, and Rhodium. The Platinum and the Rhodium are primarily responsible for the reduction process and the Platinum and Palladium are responsible for the oxidation process. Platinum also has excellent resistance to poisoning that might occur from unburned oil in the exhaust stream.

These emissions are the major components of harmful exhaust gasses and are the reason three way catalysts are chosen over other emissions control strategies.

The catalyst is cylindrical in shape, and the coating is applied to a monolith with multiple channels running through it. These channels permit the flow of exhaust. The selected catalyst has a cell density of 300 cells per square inch. This cell density introduces a smaller flow restriction then some catalysts, which can contain up to 600 CPSI. As the gas molecules move through the catalyst's cells, the molecules interact with the catalyst materials. The various precious metals in the coating are rich in D orbital electrons [4]. This excess of electrons promotes catalytic activity through lowering the activation energy required to react, speeding up naturally occurring reactions.

Noise

Along with exhaust emissions, sound pollution from snowmobiles can also disturb other people and wildlife.

Two solutions were used for noise reduction in the 2017 CSC entry. Sound deadening material was strategically chosen and placed in inside of the snowmobile's hood and side panels to dampen sound from the engine and mechanical noise from elements of the drivetrain and other moving parts located inside the bodywork. A new muffler incorporating a baffle was designed to reduce the sound emitted from the exhaust.

Muffler Design

The introduction of a catalyst into the exhaust system required a considerable amount of space. This introduced a challenge in muffler design, where a muffler's ability to reduce noise is highly dependent on its volume [5].

To overcome this volume constraint, a baffle was added to the muffler, that forces exhaust gasses to pass through muffler packing before exiting the muffler. See Figure 1 for a visual representation of the muffler including a baffle. This baffle will introduce a flow restriction, and may reduce engine performance. It was determined that the addition of a baffle was worthwhile because of the emphasis the team is placing on sound reduction, and the stock engine's power rating being so close to the maximum allowable by CSC rules.

Impedance Tube

Acoustics is a field in which many variables are at play. Theoretical models are developed to explain acoustical phenomenon; however, these models become complex for applications dealing with real life geometries. To overcome the short comings of the theoretical models, empirical models are created.

When acoustical waves strike a material, some of the energy is reflected off the surface like light on a mirror. The remainder of the energy enters the material where it is either absorbed or passed through. The amount of acoustical energy that is absorbed by a material over the amount of energy incident to the material is defined as the absorption coefficient [6]. While the absorption coefficient should have units of inverse length, it can also be thought of as the amount of energy absorbed by a specific material sample. So, absorption coefficients can be without units. The definition of absorption coefficient presented here closely resembles the process acoustical waves go through to exit the engine bay of the sled. Waves hit the side panels, where some of the energy is reflected back into the engine bay. As the wave progresses through the side panel, some energy is dissipated as heat. The remaining energy associated with the wave then exits the sled as noise. The absorption coefficient represents the decrease in energy of the acoustical wave as it tries to pass through a material. The absorption coefficient has also been defined as the amount of energy not reflected by a surface, which applies more directly to architectural applications and will not be used here [6].

An impedance tube or reverberation chamber is the typical testing setup used to determine acoustical absorption coefficients. The reverberation chamber is essentially a room lined with the material to be tested. A sound is then played, and a microphone is used to measure the amount of noise not absorbed. Reverberation chambers take up considerable space and are therefore not practical for most organizations to create. An impedance tube is essentially a pipe with a material sample mounted somewhere along its length. A speaker plays a sound and a microphone records what is reflected or passes through. After a review of literature, it was decided that an impedance tube would be the easiest and most cost effective way to determine absorption coefficients [7][8]. There is a considerable amount of variance in impedance tube design methodologies. The speaker and single microphone design shown in figure 2 represents the conditions of the sled accurately. At one end of the impedance tube, a speaker plays a range of frequencies toward a sample in the middle of the tube. A microphone in the other end of the tube then measures the sound that passes through the material.

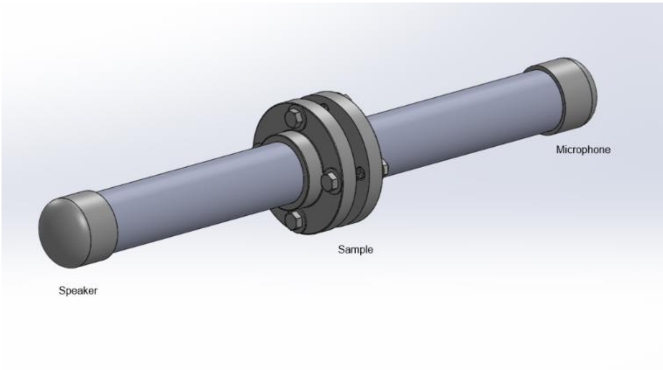

Figure 2: Visual representation of the impedance tube.

Producing planar waves in the impedance tube is more desirable than producing spherical waves. Spherical waves could produce nodes and anti-nodes that vary along all three coordinate directions. If nodes and anti-nodes are produced by planar waves, one only has to move along the axis of the tube to locate them. This may reduce measurement uncertainty. Whether a wave is planar or spherical is heavily dependent on frequency and the diameter of pipe used [8]. Deshpande and Rao give equation 5 as the upper frequency that will produce planar waves in a tube of a specific diameter [8].

$$f_{upper} \leq \frac{Kc}{d} \qquad (5)$$

Where c is the speed of sound taken to be 13,386 in/s, K is the tube constant which is 0.586 for circular pipe, and d is the inner diameter of the pipe. PVC pipe with an inner diameter of 3.04 inches was used to construct the impedance tube. This gives an upper frequency limit of 2,580 Hz. Commercially available PVC pipe has been used before to create low cost impedance tubes with acceptable results [7][8].

The method used to align and secure the material sample can have major ramifications on the accuracy and repeatability of the data [8]. Creating custom sample holders was considered, but it was decided against as being too costly. Standard PVC pipe flanges were used as specimen holders. There are two major disadvantages with using pipe flanges. The first is the amount of work needed to insert and remove a specimen. The second disadvantage is unequal bolt torque causing the pipe flanges to clamp down on a specimen at an angle. This opens the microphone and speaker up to the ambient environment, so normal room noise interferes with tests. To overcome this, a rubber gasket was applied to each flange. The microphone is mounted to a PVC end cap via a spacer. The PVC end cap reflects acoustical waves which creates constructive and destructive interference which is not indicative of the material being tested. To reduce this interference, sound deadening foam was added behind the microphone.

Figure 3: Impedance tube setup

Electrical Hardware

An electret condenser microphone was selected for use in the impedance tube. The microphone contained a built in amplifier and had a flat frequency response range from 50 Hz to 5 kHz. This covers the upper limit at which the impedance tube can operate due to its diameter. A DC blocking capacitor was included on the output voltage of the microphone. However, the capacitor had sufficient leakage for around 0.7 volts DC to pass through. The 0.7 volt DC offset can be removed later during signal analysis, so it is not overly concerning.

A 0.2 watt speaker was placed in the other end of the impedance tube. The speaker was driven with a square wave at a discreet frequency, see figure 4 in appendix A. A square wave was a limitation imposed by the NI myRio that was used to control the impedance tube. A square wave can be decomposed into many sinusoidal waves super imposed over each other. When the speaker is driven with the square wave, it produces the intended frequency and also many higher frequency components. This is undesirable, but a majority of the extra noise can be removed via processing the microphone signal later.

Software

The NI programing language, LABView, was used to control the NI myRio. With the impedance tube closed without a sample in it, a set of discrete frequencies were played at one-third octave bands. The sound pressure level (SPL) of the frequencies was determined using the built in fast Fourier transform (FFT). The SPL has units of decibels. The material sample was then inserted into the tube and the same set of discrete frequencies were run. The results of the FFT were then imported into an Excel Macro for further processing. The SPLs with and without the sample installed are known, so the absorption coefficient can now be calculated. The absorption coefficient is equal to the amount of energy absorbed by a material over the total amount of energy incident to the material.

$$\alpha = \frac{E_1 - E_2}{E_1} = 1 - \frac{E_2}{E_1} \qquad (6)$$

Where E_1 is the incident energy, and E_2 is the energy passed through. The power transmitted by an acoustical wave is given by equation 7, where p_{rms} is the root mean square pressure, ρ is the nominal density, and c is the speed of sound.

$$W = \frac{{p_{rms}}^2}{2\rho_0 c^2} \quad (7)$$

Equation 6 can also be written in terms of energy over a specific time interval which is power. The nominal density of the air inside the impedance tube does not change significantly from test to test. Since nominal pressure and temperature is the same between the two tests, the speed of sound is constant. Combining equations 6 and 7 yields equation 8 after the above assumptions have been applied.

$$\alpha = 1 - \frac{{p_{2_{rms}}}^2}{{p_{1_{rms}}}^2} \quad (8)$$

RMS pressure is related to SPL by equation 9 where p_0 is the reference pressure of $20x10^{-6}$ Pa.

$$p_{rms} = p_0 * 10^{\frac{L_p}{20}} \quad (9)$$

Substitute equation 9 into equation 8 and simplify.

$$\alpha = 1 - 10^{\frac{L_{p2} - L_{p1}}{10}} \; (10)$$

The SPL at the test frequency is calculated from the FFT of the pressure collected by the microphone. Equation 10 is then used to determine the absorption coefficient.

System Verification

As with any measurement system, the accuracy of the impedance tube must be assessed. Five tests were run without a sample. This should give an absorption coefficient of zero since the amount of air between the speaker and the microphone is the same. As figure 4 in appendix A shows, there is a fair amount of variance in the data.

The spread of the data increases dramatically in the upper frequency ranges. One possible explanation for the large deviation in the upper frequency range is the mass of air in the tube may resonate near 2.5 kHz. The speaker also does not have a flat response curve, so it could be producing a louder sound at the higher frequencies. The lower frequencies have significantly better accuracy than the higher frequencies, as seen in Figure 5, Appendix A.

Material Testing

The stock Polaris Indy 600 has sound deadening foam covering parts of the side panels and hood. A sample of this foam was removed from the side panel and the absorption coefficients were found. See figure 6 in appendix A. Sound deadening foam from McMaster-Carr was obtained and tested in the impedance tube as well. At frequencies below 500 Hz the foams did not absorb much energy. In the 500 to 1000 Hz range, the foams absorb most of the incident energy which is a range more heavily weighted on the decibel A scale. The McMaster foam was found to absorb more sound than the stock Polaris foam. Hence, the stock foam was removed, and the McMaster foam installed.

A sound deadening paint was obtained and applied to a sample of ABS plastic. Sound absorption coefficients were obtained for the bare plastic, one coat, and two coats of paint, see Figure 7, Appendix A. It appears that the paint is more effective at higher frequencies, i.e. at and above 2000 Hz. Given the amount of error in the absorption coefficients at higher frequencies, the data is inconclusive as to the effectiveness of the paint. A smaller diameter tube will be needed to test at higher frequencies to confirm the effectiveness of this material.

Summary/Conclusions

For the 2017 Clean Snowmobile Challenge, the University of Minnesota-Twin Cities Clean Snowmobile Team has modified a snowmobile to include features such as flex fuel capability, cleaner emissions, and reduced sound output. These goals were accomplished without sacrificing features that enthusiasts want, such as the good handling characteristics and high power to weight ratio that come with a two stroke engine. The improvements made in testing capabilities also leave room for further investigation into the concepts explored in this paper.

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Definitions/Abbreviations

ECU – Engine Control Unit

UMNCST – University of Minnesota Clean Snowmobile Team

CPSI – cells per square inch

CSC – Clean Snowmobile Challenge

Appendix A

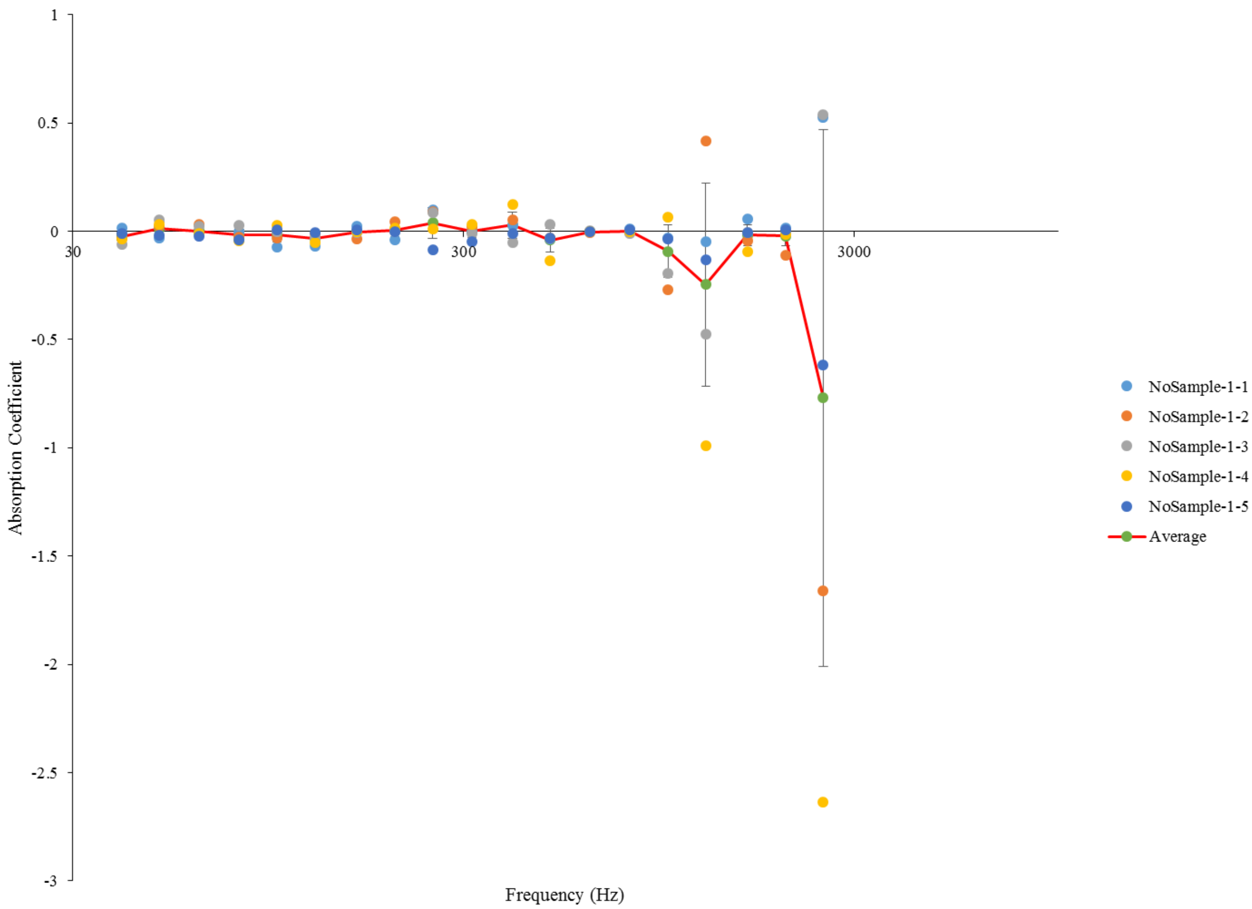

Figure 4: Absorption coefficients from 40 Hz to 2500 Hz when no samples are present in the tube. The error bars are two standard deviations. Theoretically, the absorption coefficient should be zero.

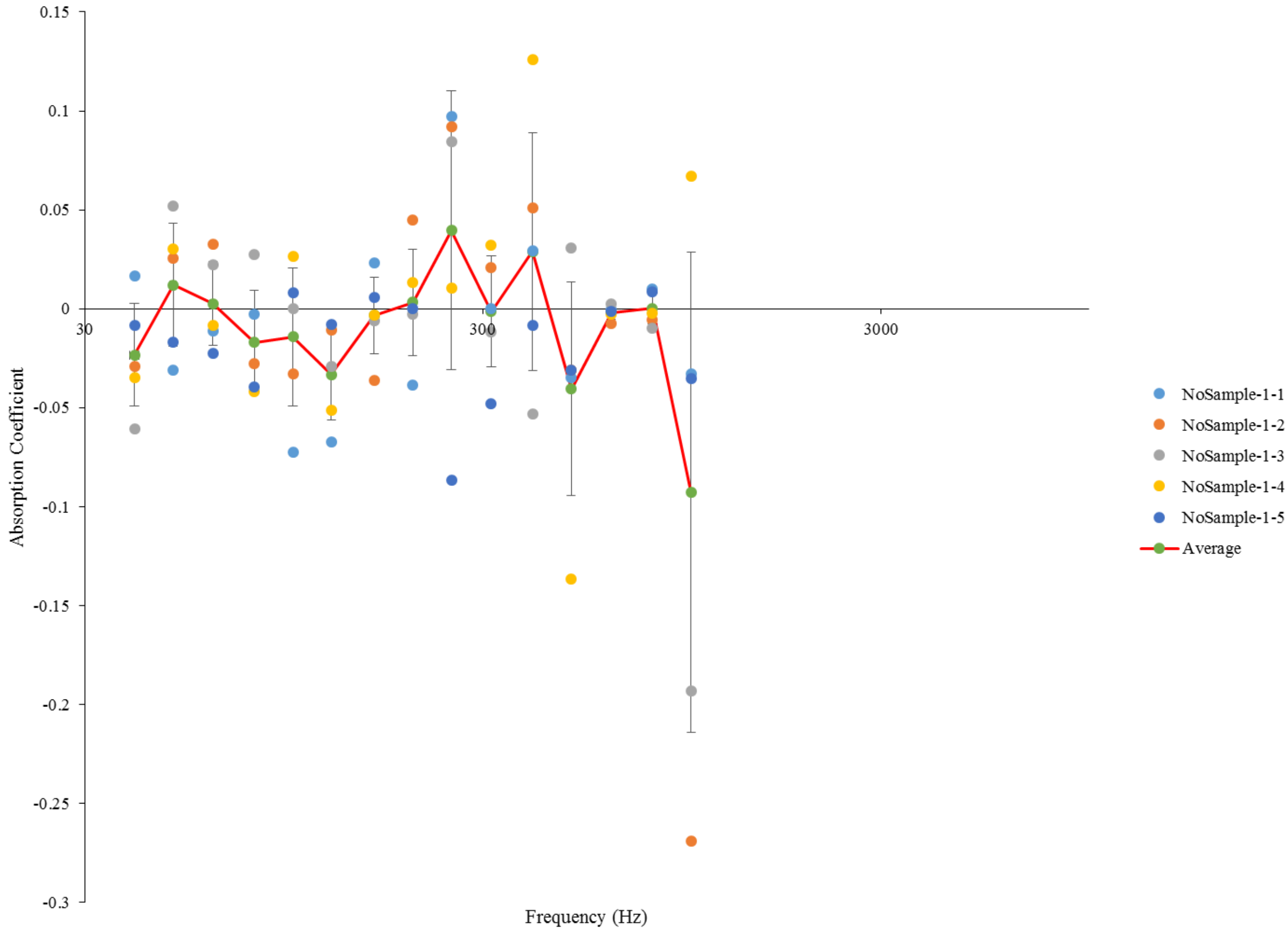

Figure 5: The sub 1000 Hz frequencies are close to zero with an uncertainty range which includes zero which aligns with the theoretical value.

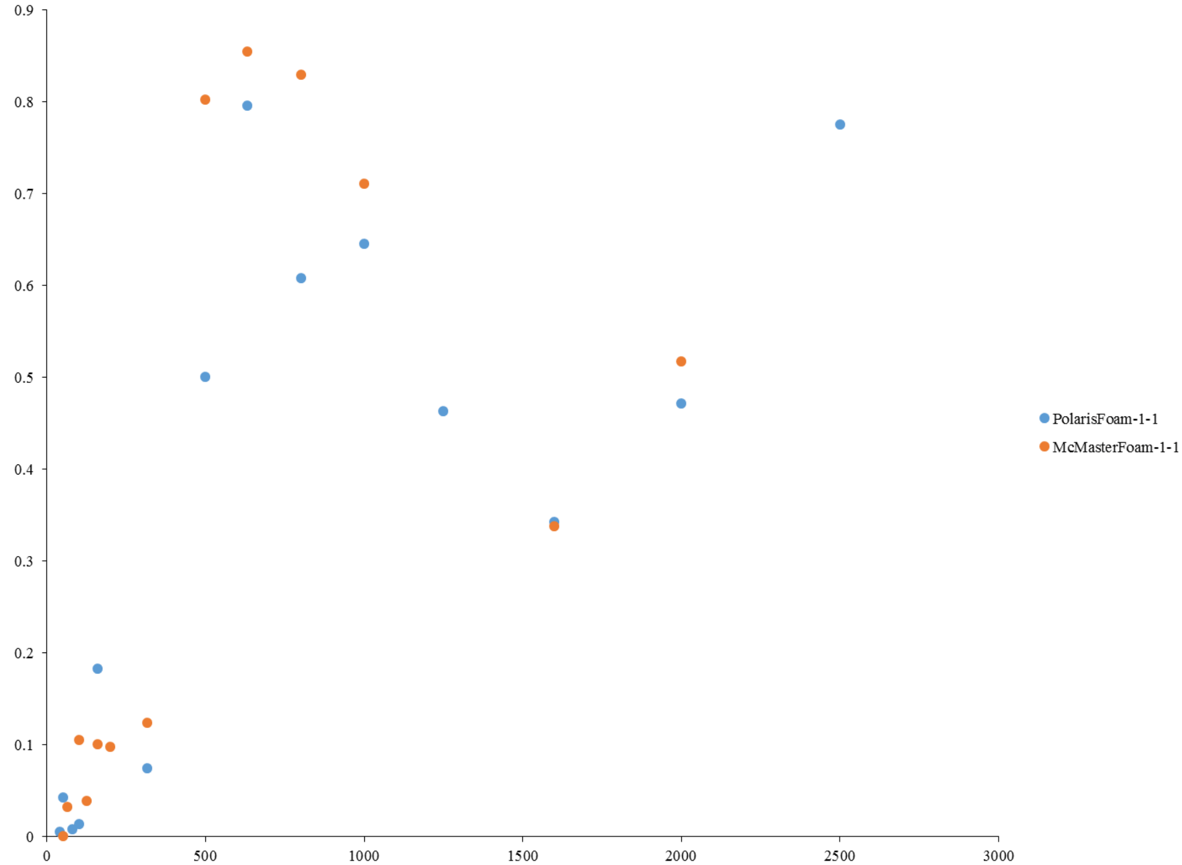

Figure 6: Absorption coefficients for the stock Polaris foam and the McMaster foam. Measurements below zero were discarded for clarity.

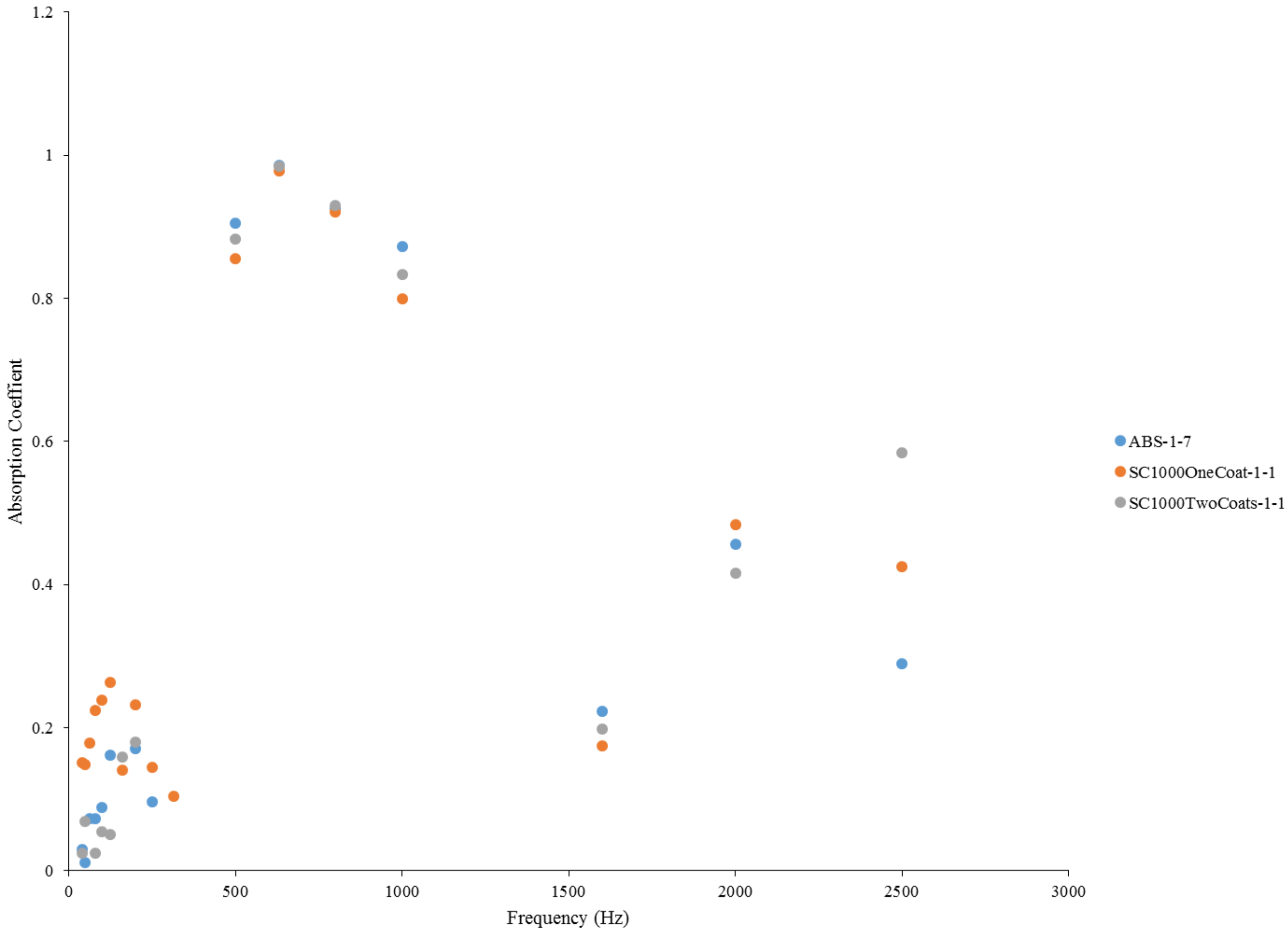

Figure 7: Absorption coefficients for the sound deadening paint.