Reduction of Fan Generated Tonal Noise in a Ventilation Duct with Applications to the International Space Station

Holly Smith
Workforce Development Grant
Arkansas Space Grant Consortium

Johnson Space Center Acoustics Office
Habitability and Environmental Factors Branch
Space and Life Sciences Directorate
Mentor: Christopher Allen

Abstract

The ventilation system aboard the International Space Station (ISS) is a crucial life-support system that provides the crew with circulated, filtered air; however, this system contains fans that generate unwanted tonal noise. The tonal noise produced by the fans may interfere with the daily activities of the crew as well as pose a potential health hazard. Because a Helmholtz resonator's unique geometry allows it to resonate at a specific frequency, it is possible to design a Helmholtz resonator that will eliminate the single frequency tonal noise when adjacently attached to a ventilation duct. Therefore, this project focused on how to incorporate Helmholtz resonators into a model ventilation duct in order to eliminate tonal noise produced by a fan.

This project was completed using two different methods: analytical and experimental. The analytical approach involved calculating transmission loss predictions in order to determine how various Helmholtz resonators would affect the sound level of the tonal noise when introduced into the ventilation duct. The experimental approach involved constructing a model ventilation duct from medium density fiberboard (MDF). Multiple, adjustable Helmholtz resonators constructed from PVC and MDF were introduced adjacently to the duct, and measurements of the Helmholtz resonators' effects on the sound level were obtained. These measurements are compared to the numerical predictions calculated during the analytical stage.

Contents

1 Theory

1.1 International Space Station Acoustic Requirements

The Crew Quarters (CQ) aboard the International Space Station (ISS) contains a ventilation system composed of a duct with two fans. The supply fan introduces filtered air into the CQ whereas the return fan removes the air from the CQ and back into the ventilation system. Due to the nature of axial fans, both fans are responsible for creating tonal noise that may affect the health and performance of the ISS crew. Therefore, it is imperative to eliminate any tonal noise that violates the currently existing acoustic safety standards.

The acoustic sound levels of the generated tonal noise must meet three basic criteria: (1) the sound levels must not pose a health hazard to the crew; (2) the sound levels should not affect crew performance; and (3) the sound levels should support a habitable and comfortable living and work environment.[1] Because the fans can operate at low, medium, and high settings[1], there are different noise criterion curves for the different settings. Currently, the fans are considered to produce continuous noise when operated at the low setting[2]. The maximum noise criteria curve for continuous noise in the CQ during sleeping hours is NC-40.[2] The noise produced by the fans in either the medium or high setting is considered to be intermittent noise[3]. The acceptable noise criterion curve for intermittent noise is NC-37.[2] For the sake of simplicity, this investigation focuses on limiting to the tonal noise produced by the return fan at its highest setting (24 Volts) to the NC-40 curve[4].

Along with the continuous and intermittent noise criteria, tonal noise must meet the sound pressure level specified by the Narrow-Band Annoyance criteria. According to this requirement, a single frequency tone must be ten decibels less than the broadband sound

[1] For this investigation, the fan speeds at the low, medium, and high settings were considered to be approximately 2000, 3300, and 4030 rotations per minute for the supply fan and 2567, 3667, and 4400 rpm for the return fan. These fan speeds are based on an approximation that is explained in Appendix A.

[2] This study assumes that the fans are operated at the low setting during the crew's sleep periods.[2]

[3] This study assumes that the duration of these settings does not exceed eight hours.

[4] Because multiple sound sources have sound pressure levels that logarithmically add to produce an overall sound pressure level, this fan must actually match the NC-34 curve.

pressure level of its octave band.[3] If tonal noise created by ventilation fans is higher than the accepted sound pressure level set by these criteria, then these ventilation systems may pose serious hazards to the health and safety of the crew. This project aims to minimize the amount of tonal noise produced by fans located in ventilation ductwork by investigating the incorporation of Helmholtz resonators as side-branches to the duct.

1.2 Fan Generated Tonal Noise

Tonal noise in ventilation ducts often occurs as a result of an operating fan within the duct. This tonal noise is produced by a periodic distubance of the fan's inflow or the interaction of the downstream flow with a stationary object.[4] If the noise occurs as a result of the fan's inflow, then the tonal noise can be predicted by the equation:

$$\nu_n = \frac{nKN}{60}, \text{ n=1,2,3,...} \tag{1}$$

In this equation, ν_n is the nth-harmonic frequency, n is an integer number, K is the number of fan blades, and N is the speed of the fan in revolutions per minute.[5]

1.3 Helmholtz Resonators

A Helmholtz resonator consists of a hollow neck attached to an empty volume. The behavior of the air within the flask is comparable to a driven, damped spring-mass system as shown in Figure 1. When a sinusoidal force acts upon the air within the flask, the air within the neck is comparable to a mass oscillating on a spring. The air within the cavity serves as the "spring" and is responsible for providing the system's stiffness element. Due to its contact with the neck's wall, the mass of air within the neck will experience thermoviscous losses, and this friction will cause a portion of the acoustic energy to be converted into heat.

Like a driven, damped spring-mass system, the Helmholtz resonator will resonate or produce sound when driven at its natural frequency. The resonator's natural frequency is determined by its dimensions and the speed of sound and is described by the equation:

$$\nu_o = \frac{c}{2\pi}\sqrt{\frac{S_n}{L'V}} \tag{2}$$

In this equation, ν_o is the natural frequency, c is the speed of sound in air, S_n is the the cross-sectional area of the neck, L' is the effective length of the neck,[5] and V is the volume.[6] The production of sound that occurs at resonance will lead to more energy loss due to radiation resistance at the opening.

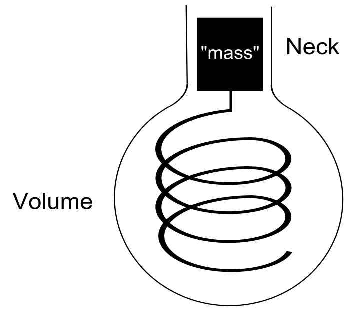


Figure 1: Motion of air within a Helmholtz resonator.

Helmholtz resonators can be incorporated into ventilation ducts as side branches in order to reduce the tonal noise generated by fans within the duct. The amount of tonal noise reduction can be described by the power transmission coefficient, T_Π, which describes how much acoustic power is transmitted through the duct. The power transmission coefficient for this type of band-stop filter is given by:

$$T_\Pi = \frac{1}{1 + \left(\frac{c/2S_d}{\omega L'/S_n - c^2/\omega V}\right)^2} \tag{3}$$

Here, S_d represents the cross-sectional area of the duct in which the Helmholtz resonator is being incorporated. When $T_\Pi = 0$, none of the incoming acoustic power is transmitted into the duct. Instead, the incoming acoustic energy enters the resonator and is reflected back towards the source, causing destructive interference. Solving Equation 4 for $T_\Pi = 0$ yields the resonance frequency of the Helmholtz resonator.[6] Therefore, by designing a Helmholtz resonator to resonate at the frequency of the tonal noise, the resonator can cause near tonal

[5]The effective length is related to the length of the neck by the equation: $L' = L + 1.4a$, where a is the radius of the neck's opening. The effective length accounts for the shape of the opening of the resonator. The openings for the Helmholtz resonators used in this experiment are unflanged.

reflection of acoustic waves with frequencies near that of the resonance frequency.

1.4 Transmission Loss

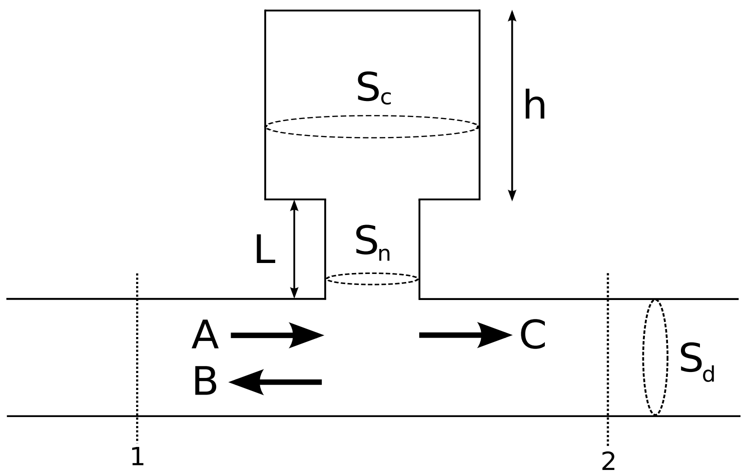


Figure 2: A cylindrical Helmholtz resonator attached to a duct as a side-branch. The dimensions of the Helmholtz resonator include a volume of cross-sectional area S_{cavity}, height h, neck of cross-sectional area S_{neck}, and length L. The duct has a cross-sectional area of S_{duct}. A represents the acoustic wave originating from a source, and B and C are the reflected and transmitted waves, respectively.

Figure 2 shows a duct with a Helmholtz resonator adjacently as a side-branch. The pressures and velocities at points 1 and 2 along the duct are related by the transfer matrix for a Helmholtz resonator:

$$\begin{bmatrix} p_1 \\ \rho S_1 u_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_r} & 1 \end{bmatrix} \begin{bmatrix} p_2 \\ \rho S_2 u_2 \end{bmatrix} \tag{4}$$

In this equation p_n is the pressure at a point within the duct, ρ is the air density, S_n is the cross-sectional area of the duct, u_n is the velocity, and Z_r is the Helmholtz resonator's acoustic impedance[6].[4] A common measurement of a Helmholtz resonator's effectiveness

[6] Acoustic impedance is defined as pressure divided by volume velocity or $Z = p/U$. Acoustic impedance can also be defined as $Z = \frac{\rho c}{S}$ where S is the cross-sectional area of the acoustic device in question. It is composed of both real and imaginary parts: $Z = R + jX$, where R is the acoustic resistance and X is the acoustic reactance. For a Helmholtz resonator, $Z = (R_r + R_w) + j(\omega m - s\omega)$, where R_r is the radiation resistance, R_w is the thermoviscous resistance, m is the mass of air in the neck ($m = \rho_0 SL'$), s is the stiffness of air in the volume ($s = \frac{\rho_0 c^2 S^2}{V}$), and ω is the angular resonance frequency.

as a side-branch in a duct can be determined with the insertion loss measurement, which a difference in the radiated sound pressure from the original duct and the radiated sound pressure from the attenuated duct, and can be predicted via the equation:

$$\mathrm{IL} = 20\ \log_{10}\left|\frac{T_{11}Z_T + T_{12} + T_{21}Z_T Z_S + T_{22}Z_S}{Z_T + Z_S}\right| \tag{5}$$

where T_{ij} is an element of the transfer matrix, Z_T is the termination impedance, and Z_S is the source impendance.[4] Inserting the transfer matrix elements for a Helmholtz resonator, Equation 5 reduces to:

$$\mathrm{IL} = 20\ \log_{10}\left|\frac{Z_T + \frac{1}{Z_r}Z_T Z_S + Z_S}{Z_T + Z_S}\right| \tag{6}$$

An insertion loss measurement is difficult to predict because the impedance of the source for this project is unknown[7]. However, the transmission loss, which is the difference between the incident and transmitted acoustic waves, is easy to calculate:

$$\mathrm{TL} = 20\ \log_{10}\left|\frac{T_{11} + \frac{S_d}{c}T_{12} + \frac{c}{S_d}T_{21} + T_{22}}{2}\right| \tag{7}$$

This prediction for transmission loss can be an approximate prediction of insertion loss when the source and silencer termination are anechoic.[4] For a Helmholtz resonator, Equation 7 reduces to

$$\mathrm{TL} = 20\ \log_{10}\left|\frac{2 + \frac{Z}{Z_r}}{2}\right| \tag{8}$$

where Z is the acoustic impedance of the duct.

This project expored two different means in which to calculate the transmission loss of a duct attentuated by a Helmholtz resonator. Both methods are further explained in Sections 1.4.1 and 1.4.2.

[7] It is experimentally possible to determine the source's impedance; however, due to time restrictions it was more feasable to calculation the effectiveness of the Helmholtz resonator via a transmission loss prediction.

1.4.1 Transmission Loss Prediction - Helmholtz Resonator with No Thermoviscous losses

Assuming that there are no thermoviscous losses is the resonator (i.e. R_r=0), then the resonator's impedance is equal to its reactance.[6]

$$Z_r = \rho(\omega L'/S_n - c^2/\omega V) \tag{9}$$

Inserting this definition for the resonator's impedance into Equation 8 and simplifying yields

$$\mathrm{TL} = 10\,\log_{10}\left[\frac{1}{T_{\Pi}}\right] \tag{10}$$

where T_{Π} is defined in Equation 4. Equation 10 would be used to calculate the transmission loss for a model duct with a Helmholtz resonator.

1.4.2 Transmission Loss Prediction - Cavity and Neck Impedance

The second method of prediction explored the effects of grazing flow on the impedance of the Helmholtz resonator. The assumption for this prediction is that the Mach number, M, is so small that it is effectively zero. Based on this assumption, the impedance is divided into two components $Z_r = Z_c + Z_t$, where Z_c and Z_n are the impedance of the resonator's cavity and neck. For this project, the cavity's impedance is assumed to be

$$Z_c = -j\frac{c}{S_c}\cot(kl_c) \tag{11}$$

This equation is for a cavity that consists of a transverse tube, which is appropriate for the design of the adjustable Helmholtz resonators discussed in Section 3.3.[4] The impedance for the neck is given by

$$Z_n = \frac{1}{n_h}\left(\frac{ck^2}{\pi} + j\frac{ck(L + 1.4r_n)}{S_n}\right) \tag{12}$$

where n_h is the number of necks and r_n is the neck's radius[8].[4] Adding Equations 11 and 12 yield the acoustic impedance of the resonator, and this value is inserted into Equation 8 to yield:

$$\mathrm{TL} = 20\,\log_{10}\left|\frac{2 + \frac{\frac{\rho_0 c}{S_d}}{-j\frac{c}{S_c}\cot(kl_c)+\frac{1}{n_h}\left(\frac{ck^2}{\pi}+j\frac{ck(L+1.4r_n)}{S_n}\right)}}{2}\right| \tag{13}$$

2 Emperical Predictions

2.1 Fan Generated Tonal Noise Prediction

Due to time limitations, the goal of this project was to show successful attentuation of the 366 Hz tone produced by the fan operating at 24 Volts by adjacently inserting a Helmholtz resonator into the duct. Prior to conducting the insertion loss experiment, it was necessary to predict the frequency values of the tonal noise and the effectiveness of a Helmholtz resonator designed to eliminate a specific tonal noise produced by a fan within a ventilation duct. These values would later be compared to experimental measurements.

The following frequency predictions for the fan were predicted using Equation 1 and the estimated fan speeds given in Table 4 for 12, 18, and 22 V (supply fan) supplied to the fan as well as 14, 20, and 24 V (return fan).

Volts Supplied to Fan	Fan Speed (rpm)	1^{st} Harmonic (Hz)	2^{nd} Harmonic (Hz)	3^{rd} Harmonic (Hz)	4^{th} Harmonic (Hz)	5^{th} Harmonic (Hz)
12	2200	183	367	550	733	917
18	3300	275	550	825	1100	1375
22	4033	336	672	1008	1344	1681

Table 1: The first five harmonic frequencies for the low, medium, and high settings of the supply fan.

[8] This equation differs from Beranek and Ver's in that the correction for the neck, $L + 1.4r_n$, is for an unflanged neck. Beranek nd Ver assume a flanged neck.

Volts Supplied to Fan	Fan Speed (rpm)	1^{st} Harmonic (Hz)	2^{nd} Harmonic (Hz)	3^{rd} Harmonic (Hz)	4^{th} Harmonic (Hz)	5^{th} Harmonic (Hz)
14	2567	214	428	642	856	1069
20	3667	306	611	917	1222	1528
24	4400	367	733	1100	1467	1833

Table 2: The first five harmonic frequencies for the low, medium, and high settings of the return fan. The frequencies listed in the third row would be compared to the measured tonal frequencies recorded during the experimental stage of the project. These results can be seen in Section 3.2.

2.2 Pressure Antinode Prediction

In order for the Helmholtz resonator to be effective within the duct, it was necessary to place the resonator at a location in the duct where there was maximum pressure. The tonal noise of interest for this experiment was at 366 Hz. If a speaker were to project a 366 Hz tone into a duct, the speaker's position would be that of maximum pressure and minimum velocity. One would expect the the pressure maximum to occur at integer multiples of half the tone's wavelength from the speaker:

$$P_{max} = \frac{0.94n}{2}, \text{ n=1,2,3,...} \tag{14}$$

A prediction of the duct's pressure as a function of position for the first 100 cm of the duct can be viewed in Figure 3.

2.3 Transmission Loss Prediction

Although it was not possible to determine the insertion loss due to incorporating a Helmholtz resonator side-branch into a model duct, calculating the transmission loss due to this insertion allowed for a means to predict the effectiveness of the Helmholtz resonator. One would expect that a large transmission loss would correspond to an effective Helmholtz resonator. This project explored two different means to calculate transmission loss. Because the calculation for transmission loss relies heavily upon the dimensions of the Helmholtz res-

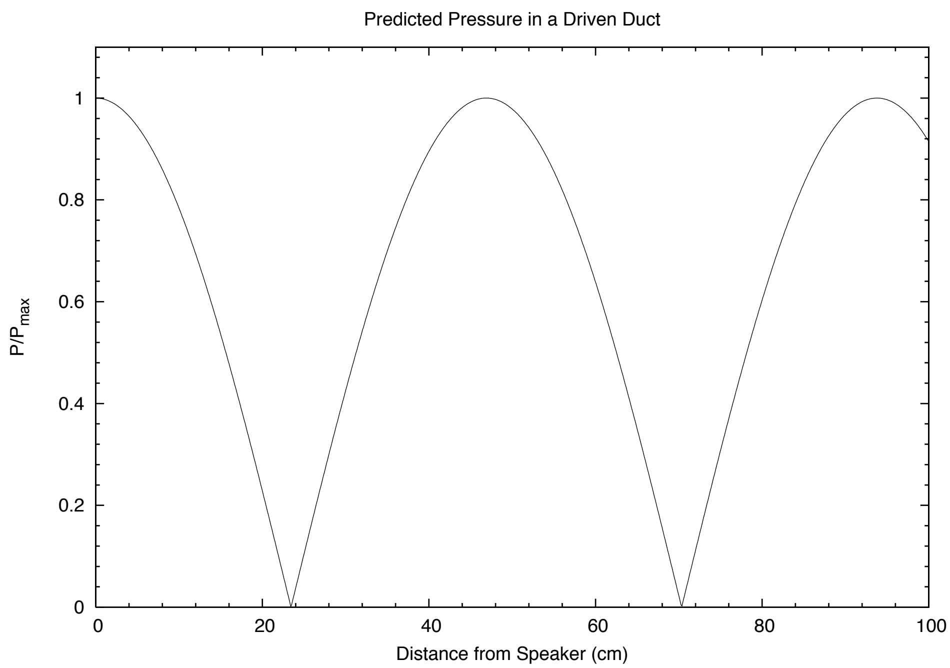


Figure 3: At x=0 (the theoretical position of the speaker), there exists a pressure maximum. For a 366 Hz tone, the next pressure maximum is located half a wavelength away or approximately 46.86 cm.

onator, the goal of each prediction was to optimize the dimensions for greatest transmission loss. Therefore, Mathematica notebooks were created in order to simplify the prediction process by calculating the transmission loss for given dimensions over a range of frequencies. Both notebooks were adjustable, which allowed for various dimensions (in SI Units) to be tested. Once the notebook completes the calculation, it generates a text file that can later be used to generate tranmission loss graphs. A sample Mathematica notebook can be viewed in Appendix B.

Three different Helmholtz resonator configurations were considered for this project and are further discussed in Section 3.3. The dimensions of the resonators are outlined in Table 3. Figure 4 shows the predicted transmission loss for each Helmholtz resonator using Equation 10. Note that these predictions are based on the assumption that there are no thermoviscous losses in the resonator; therefore, while these predictions may not be an accurate calculation of the transmission loss, they do offer insight as to which resonator design will be most efficient in the ventilation duct. Based upon Figure 4, the resonator with the 1-inch-diameter-neck Helmholtz resonator was predicted to be the most efficient at reducing the 366 Hz tone produced by the ventilation fan operating at 24 V.

Neck Diameter (in)	Neck Length (in)	Volume Diameter (in)	Volume Height (in)	Resonance Frequency (Hz)
0.50	0.5	3	1.125	366.3
0.75	0.5	3	2.1	366.2
1	0.5	3	3.1875	366.3

Table 3: Each row corresponds to the dimensions of a Helmholtz resonator. Each resonator was identified by the diameter of its neck. Note that the dimensions are given in standard units (i.e. inches). Dimensions in standard units were necessary for construction purposes and would later be converted into SI units for calculations.

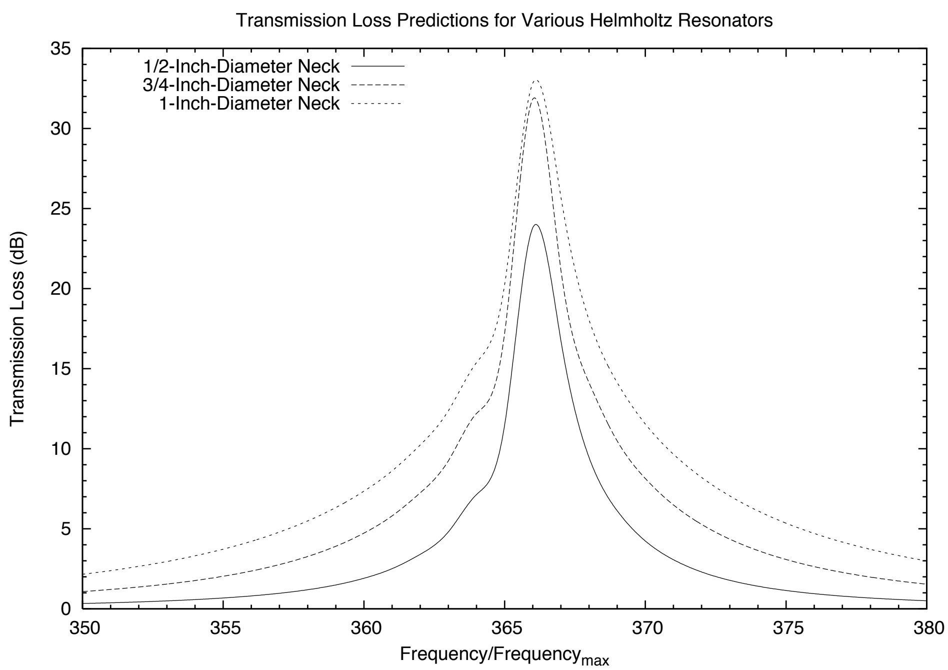


Figure 4: The transmission loss predictions for three Helmholtz resonators of varying size. The dimensions of each resonator is outlined in Table 3. The 'bump' located on the left of the three resonance curves is probably a result of the Mathematica program not iterating in small enough increments.

Equation 13 accounts for grazing flow within the duct where the Mach number, M, is negligible. Using the dimensions outlined in Table 3, the predictions for the three Helmholtz resonators are given in Figure 5. This graph is similar to Figure 4 in that the 1-in-diameter-neck Helmholtz Resonator is shown to be the most effective. However, unlike Figure 4 the predictions for transmission loss appear to be more realistic.

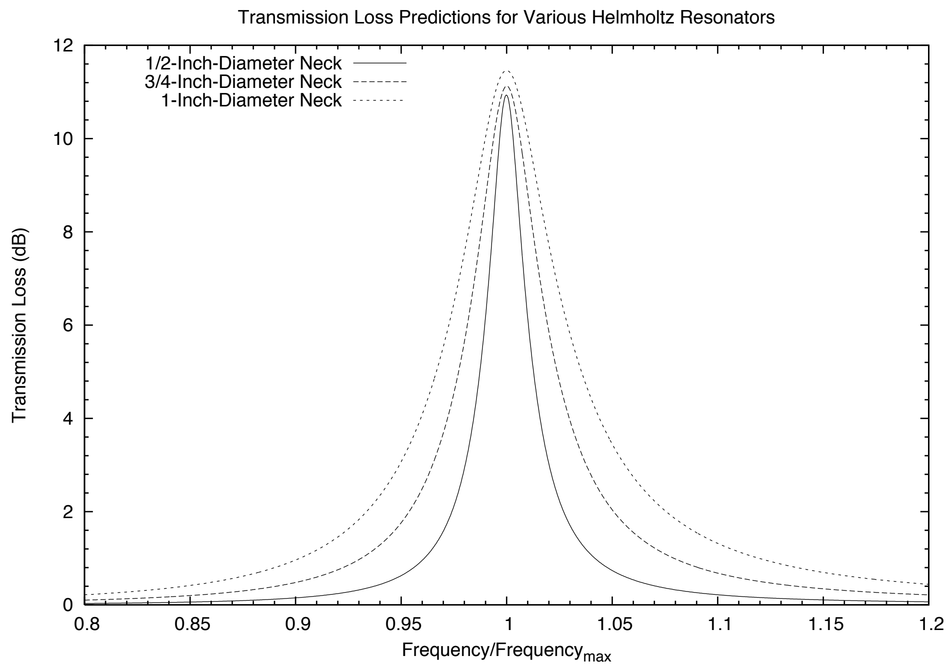


Figure 5: The transmission loss predictions using Equation 13, which accounted for grazing flow with a negligible Mach number. Note that the x-axis shows the frequency divided by the frequency at which there is maximum transmission loss. Because the resonance frequencies for each Helmholtz resonators were not equal to one another, this x-axis allowed the predictions to be aligned so that the effects of the resonators could be compared.

3 Experimental Procedure and Results

3.1 The Experimental Duct

In order for this project to be successful, it was necessary to accurately tune the Helmholtz resonators to 366 Hz and to place them at the exact location of the pressure antinodes within the duct. After properly turning the resonators and inserting them into the duct, insertion loss measurements for each resonator were obtained. The measurements taken for this project were conducted in the Acoustics Noise Control Laboratory at Johnson Space Center.

The experimental duct used in this experiment was constructed from medium density

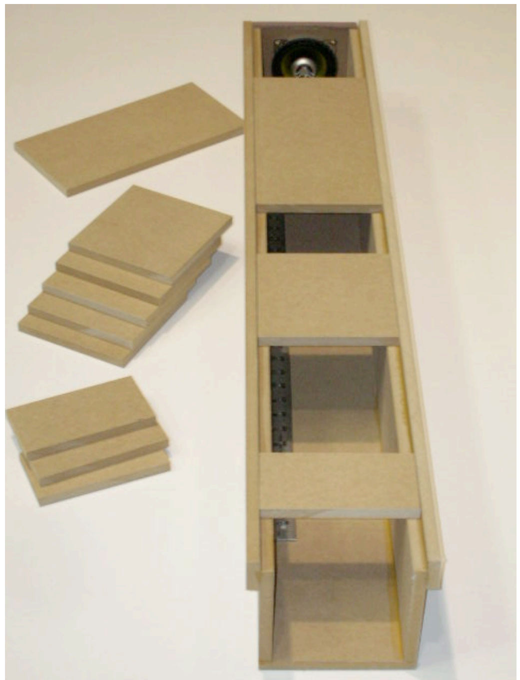


Figure 6: The experimental duct shown with its multiple, moveable lids. This picture shows the duct set up for measuring the pressure within the duct. A yardstick placed at the bottom of the duct allowed for accurate placement of the microphone used to make pressure measurements within the duct. The speaker mounted at the end of the duct served as the pressure source during this measurement. The speaker and its mount could be removed, allowing for the placement of a fan.

fiberboard (MDF) with a thickness of $\frac{1}{2}$ in. The duct had a cross-section of $5\frac{1}{8}$ in by $5\frac{1}{8}$ in and a length of $42\frac{9}{16}$ in. Two $5\frac{1}{8}$ in by $42\frac{9}{16}$ in boards were vertically adhered to one $6\frac{1}{8}$ in by $42\frac{9}{16}$ in board, and this arrangement served as the duct's base. Two $1\frac{1}{2}$ in by $42\frac{9}{16}$ in boards were attached to the sides of the duct such that they had a $\frac{1}{2}$ in overhang. This overhang would serve as a guide for the lids placed on top of the duct. The lids consisted of rectangular pieces of MDF with dimensions of either $12\frac{1}{2}$ in by $6\frac{1}{8}$ in, $6\frac{1}{8}$ in by $6\frac{1}{8}$ in, or $3\frac{1}{16}$ in by $6\frac{1}{8}$ in. The various sizes and mobility of the lids allowed for easier placement of the Helmholtz resonators at the duct's pressure antinodes.

In order to locate the pressure antinodes within the duct, a four inch, 120 W Fusion speaker was mounted to a $5\frac{1}{8}$ in by $5\frac{5}{8}$ in MDF rectangle that served to cap off one end of the duct. The other end of the duct remained open to the environment. A yardstick, which

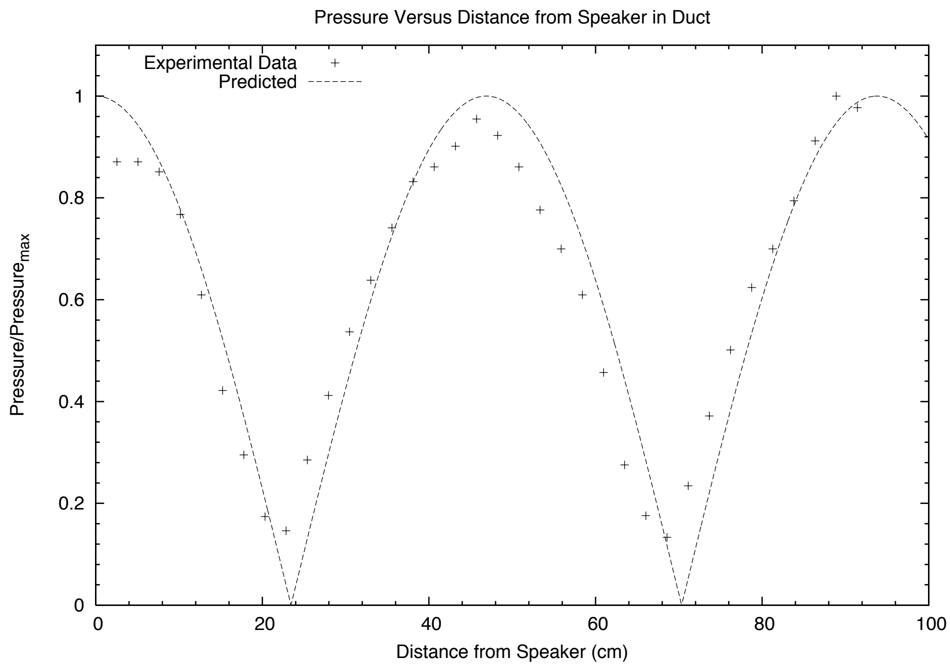


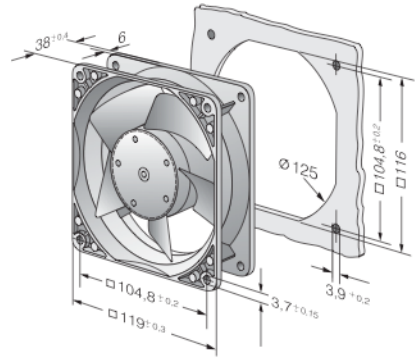
Figure 7: The horizontal difference between the experimental data and the predicted pressure curve may arise from the fact that 0 cm corresponded to the speaker's mount and not to the location at which the speaker was emitting maximum pressure.

was placed at the bottom of the duct, lied flush against the mount. A Larson-Davis Model 2541 $\frac{1}{2}$-in free-field microphone was placed in numerous locations within the duct while the speaker emitted a 366 Hz tone. The results of this pressure measurement can be viewed in Figure 7.

3.2 Fan Generated Tonal Noise Measurement

Figures 8(a) and 8(b) show the fan used in this experiment and its dimensions. In order to determine the tonal noise frequencies of the fan, it was inserted at one end of the experimental duct shown in Figure 6 and was operated at the high setting for the return fan-24 Volts. A Larson Davis Model 2541 $\frac{1}{2}$ in free-field microphone was placed approximately a foot away from the opening of the duct and was protected with a windscreen. A narrowband, 800 line measurement of the tonal noise within a 0 to 2500 Hz range was recorded by a Larson Davis 2900B analyzer. The narrowband tonal noise measurement shown in Figure 9 is an

(a) Back view of the fan (exhaust).[8]



(b) Dimensions of the fan in mm.[8]

Figure 8: The fan used in this experiment was an ebmpapst DC Axial 4184/2XH fan. The flow produced by the fan could be adjusted by increasing or decreasing the amount of voltage supplied to it. The linear relationship between the voltage and the fan speed can be viewed in Appendix A.

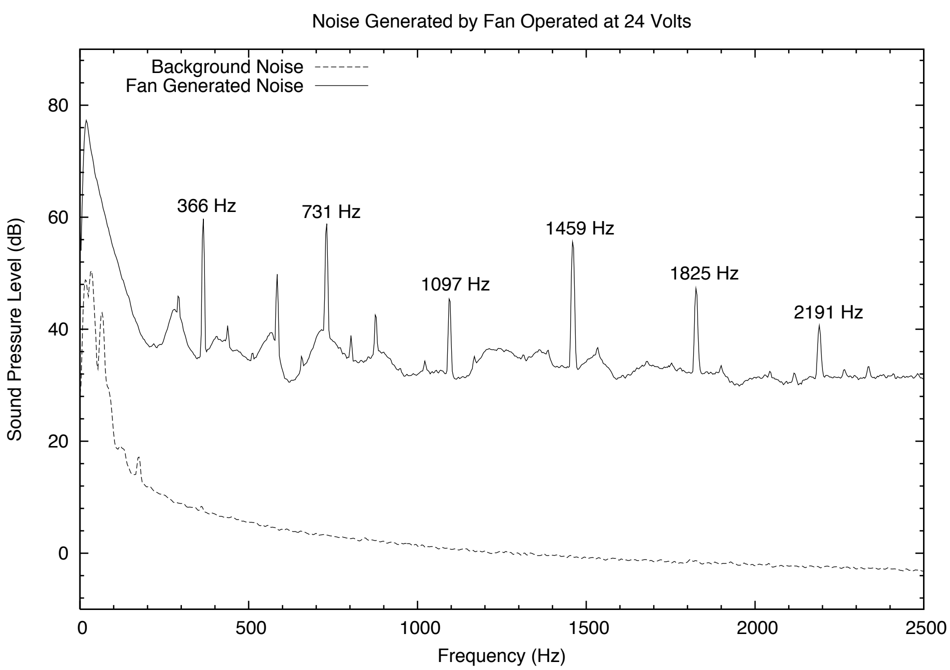


Figure 9: The harmonic frequencies of the fan are labeled with their respective frequencies. The frequency resolution for this average is approximately 3 Hz.

average of five tonal noise measurements that were each averaged over twenty seconds[9]. The tonal peaks labeled with their frequencies correspond to the predicted tonal noise values for the fan. The first five harmonic frequencies are listed in Table 2.

3.3 Adjustable Helmholtz Resonators

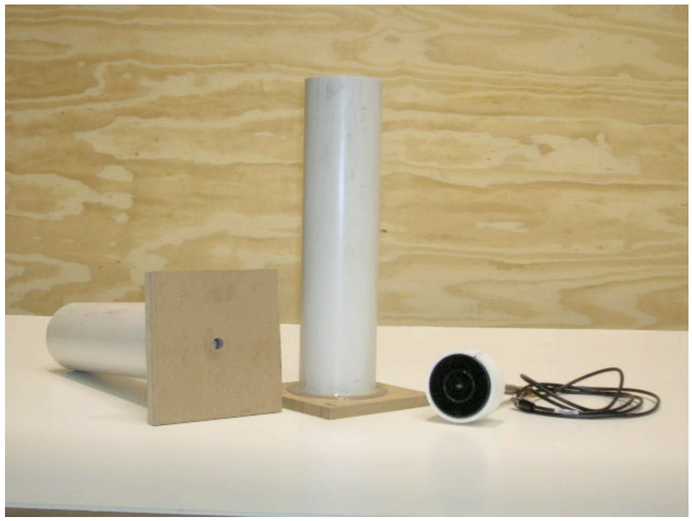


Figure 10: The two Helmholtz resonators pictured here have neck diameters of $\frac{1}{2}$ in and $\frac{3}{4}$ in. The plunger on the far right was equipped with a Brüel & Kjaer Type 4138 $\frac{1}{4}$-in microphone that served as a tool for accurate tuning of the resonator.

The Helmholtz resonators used in this experiment were constructed of MDF and PVC pipe. Two of the resonators ($\frac{1}{2}$- and $\frac{3}{4}$-inch-diameters) were constructed for a prior experiment. The necks of both resonators were created by cutting the appropriate diameter holes into the center of a $6\frac{1}{8}$ in by $6\frac{1}{8}$ in duct lid. Three-inch-diameter PVC pipes with lengths of 14 in were adhered to the lid using epoxy. Black plungers, which had a length of $1\frac{1}{2}$ in and a diameter of approximately 3 in when lined with white foam, were then inserted into the three-inch-inner-diameter PVC pipes. The mobility of the plungers within the pipe allowed the volume of this resonator's cavity to be easily changed, therefore allowing the resonator to be tuned to multiple frequencies[10]. Another Helmholtz resonator with a 1-inch-diameter

[9]Unless otherwise noted, each graph containing SPL narrowband measurements were evaluated at the same settings.

[10]The frequency range for which these resonators could be tuned was limited. Assuming that the cavity

neck was constructed in a similar procedure; however, the rectangular MDF board on which it was mounted had dimensions of $4\frac{3}{8}$ in by $6\frac{1}{8}$ in. The dimensions for each resonator can be viewed in Table 3.

Two methods were designed in order to ensure that each resonator was accurately tuned. The first method involved driving the flask with a speaker over a range of frequencies. A small hole cut into the center of a plunger allowed a Brüel & Kjaer Type 4138 $\frac{1}{4}$-in microphone to be placed flush with the plunger. The plunger was then inserted into the resonator's cavity, and by adjusting the plunger and recording the pressure response of the resonator as it was driven over a range of frequencies, the resonance frequency of the Helmholtz resonator could be determined by fitting the pressure data to the resonance curve for a Helmholtz resonator:

$$\frac{\text{Pressure}}{\text{Pressure}_{max}} = \frac{1}{\sqrt{1 + \left(\frac{\nu_0}{\nu}\right)^2 Q^2 \left[1 - \left(\frac{\nu}{\nu_0}\right)^2\right]^2}} \tag{15}$$

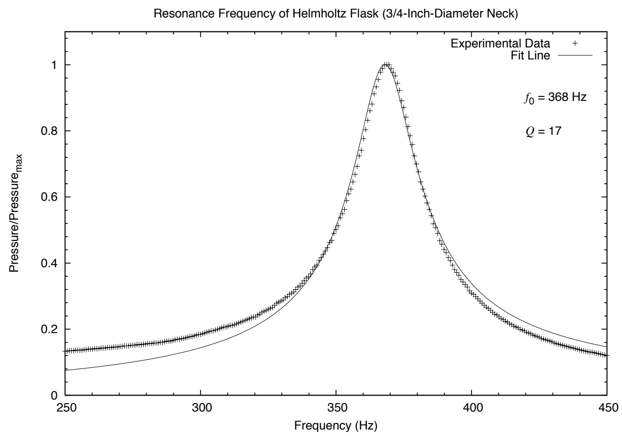
In this equation, ν is the frequency at which the resonator is being driven, ν_0 is the resonance frequency, and Q is the quality factor[11].

The results of these tuning experiments can be viewed in Figure 11. From Figure 11 one can see a discrepancy between the experimental data and the fit line. Although this method of tuning the resonator offers a fairly accurate resonance frequency, another method was devised in order to increase that accuracy. The experimental duct was set up as described in Section 3.2 with the speaker replacing the fan at the end of the duct. The speaker projected white noise into the duct, each Helmholtz resonator was individually introduced into the duct's lid, and the sound pressure level was recorded. The results are shown in Figure 12.

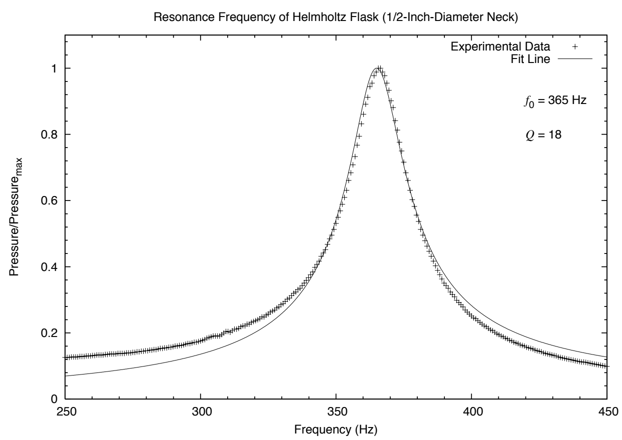
---

could achieve a minimum height of $\frac{1}{2}$ in and a maximum height of $12\frac{7}{8}$ in, the frequency ranges were limited to: 64-549 Hz for the $\frac{1}{2}$-inch-diameter-neck Helmholtz resonator; 87-751 Hz for the $\frac{3}{4}$-inch-diameter-neck Helmholtz resonator; and 182-925 Hz for the 1-inch-diameter-neck Helmholtz resonator. These limited frequency ranges were considered when selecting which fan-produced tonal peak would be attenuated for this project. Note that these ranges are predicted via Equation 2 and have not been experimentally proven.

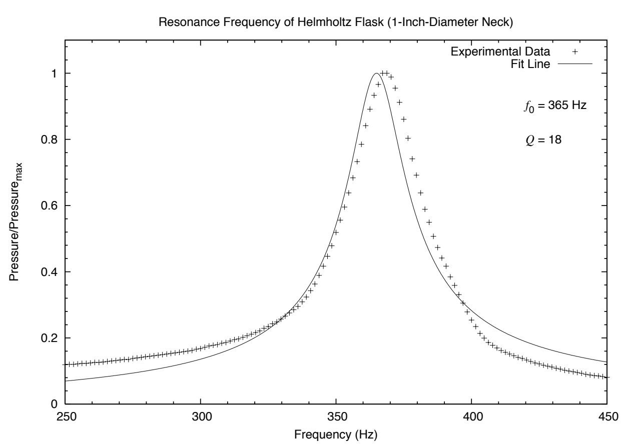
[11]The quality factor of a Helmholtz resonator is defined as $\frac{\omega_0 m}{R}$, where ω_0 is the angular resonance frequency, m is the mass of air in th neck, and R is the mechanical resistance. Higher quality factors correspond to narrow resonance curves whereas lower quality factors correspond to broader resonance curves.



(a) 0.75-inch-diameter Neck Helmholtz Resonator

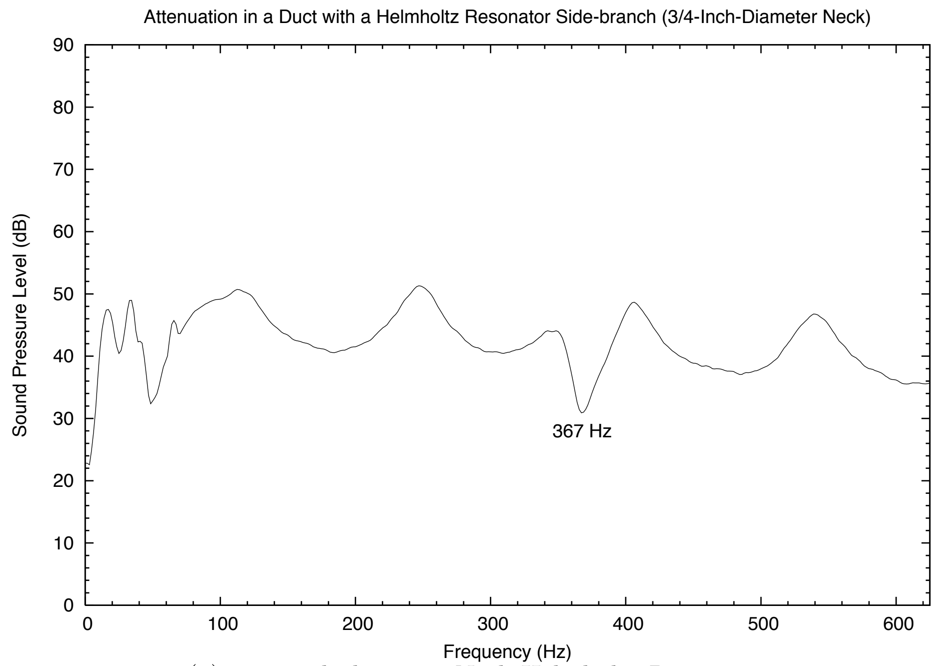


(b) 0.50-inch-diameter Neck Helmholtz Resonator

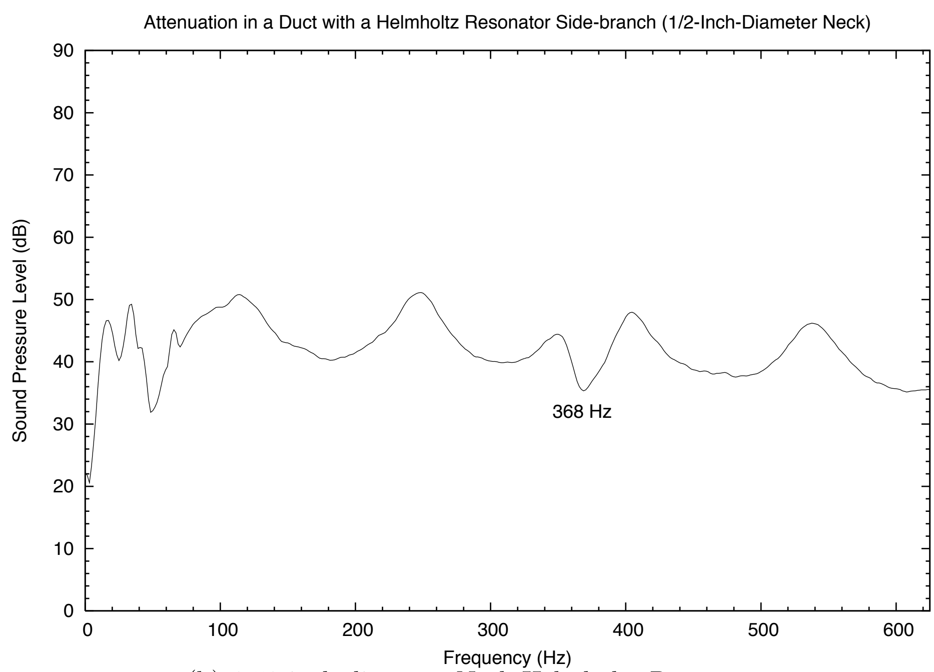


(c) 1-inch-diameter Neck Helmholtz Resonator

Figure 11: The labels f_0 and Q correspond to the resonance frequency and quality factor for each Helmholtz resonator as determined by the function's fit to the experimental data. The frequency resolution for this measurement is approximately 0.8 Hz.



(a) 0.75-inch-diameter Neck Helmholtz Resonator



(b) 0.50-inch-diameter Neck Helmholtz Resonator

Figure 12: The minimum of the sound pressure level peak is labeled with its corresponding frequency. The frequency resolution for this measurement is approximately 1.6 Hz. Such a tuning measurement was not made for the 1-inch-diameter Helmholtz resonator because it was not constructed at the time of these measurements.

3.4 Insertion Loss

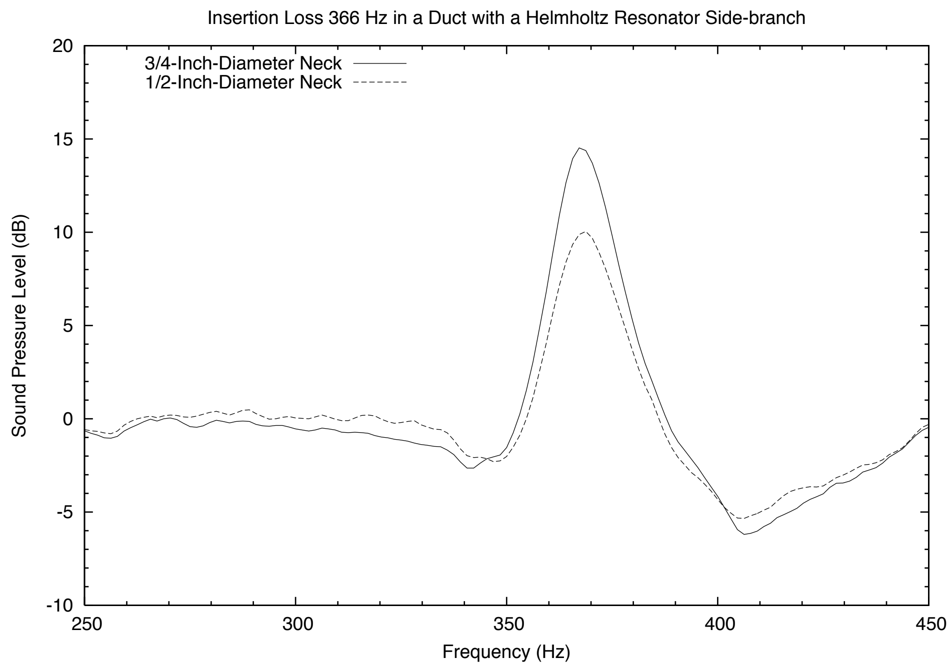


Figure 13: This graph shows three insertion loss measurments for the experimental duct attenuated by the three adjustable Helmholtz resonators. The duct was driven by a speaker producing whitenoise. The frequency resolution is approximately 0.8 Hz.

Measurements of insertion loss, which is the difference in the sound pressure level at the opening of the unattenuated and attenuated duct, were conducted in order to experimentally determine which Helmholtz resonator was most effective at attenuating the 366 Hz tone produced by the fan. Prior to making insertion loss measurements of the attenuated duct driven by the fan, insertion loss measurements were made for the duct driven by a speaker producing white noise. The insertion loss measurement consisted of measuring the sound pressure level one foot away from the open end of the duct while the speaker projected white noise at the other end and then making the same measurement with a Helmholtz resonator incorporated into the duct as a side-branch at a pressure antinode. The results can be viewed in Figure 13. From Figure 13, one can see that the 1-in-diameter neck was most effective at attenuating the 366 Hz tone.

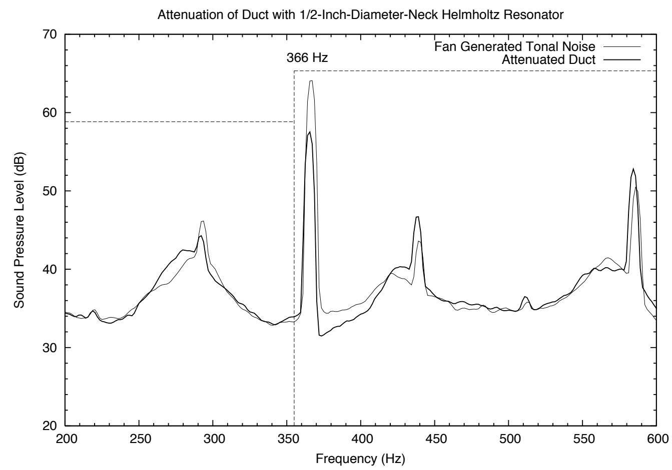
All three Helmholtz resonators were effective at attenuating the 366 Hz plane wave that was introduced into the duct by the speaker; however, the acoustic waves introduced into the duct by the ventilation fan were not uniform like those produced by the speaker. Therefore, it was uncertain how effective the Helmholtz resonators would be a attentuating the tonal noise produced by the fan. Figure 14 shows the attenuation for the duct with each of the Helmholtz resonators. Like Figure 13, the 1-inch-diameter neck Helmholtz resonator was most effective at attenuating the tone. However, unlike Figure 14, the insertion loss of the duct with tonal noise produced by the fan was much greater than than the insertion loss of the duct with the speaker producing the 366 Hz tone. These results can be seen in Figure 15.

4 Conclusion

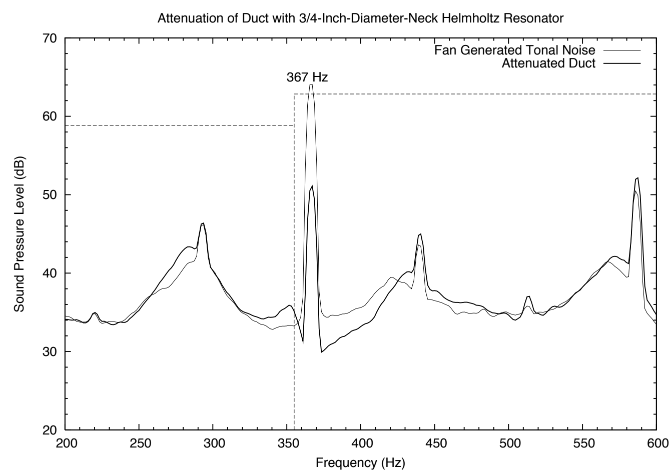
4.1 Project Conclusions

When designing a Helmholtz resonator to attenuate tonal noise generated by a fan in a duct, there are several factors to consider. First, in order to have the greatest attenuation, a Helmholtz resonator that is introduced adjacently to a duct should be placed such that its opening corresponds to a pressure antinode (or maximum pressure) of the duct. Secondly, the Helmholtz resonator must be tuned as precisely as possible to allow for maximum attenuation. One must also consider the acoustic waves produced by the fan are not constant, plane waves such as those produced by a speaker. Therefore, the transmission loss in a duct driven by a speaker is not adequate for the transmission loss in a duct driven by a fan.

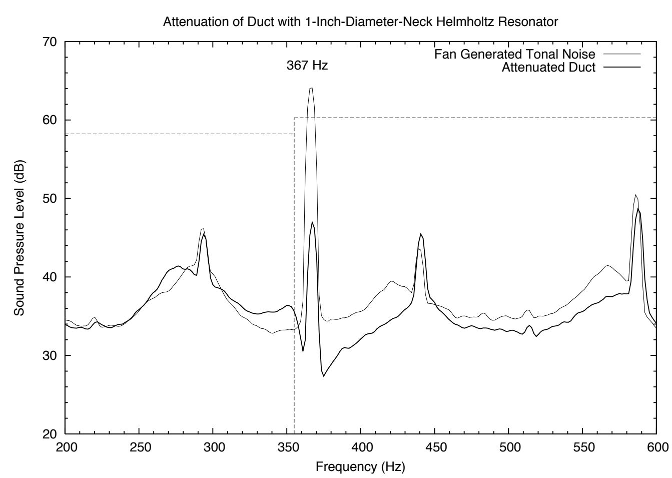
Based on the results of this project, the transmission loss predications calculated for this experiment were not an adequate substition for insertion loss predictions. Future projects would need to explore other prediction methods and suggestions for these new predictions can be viewed in the following section. However, the predicitions did offer valuable insight as to which resonator would be most effective at attenuating the unwanted 366 Hz tonal peak. As predicted, the 1-inch-neck Helmholtz resonator had the greatest attenuation of the tone



(a) 0.50-inch-diameter Neck Helmholtz Resonator

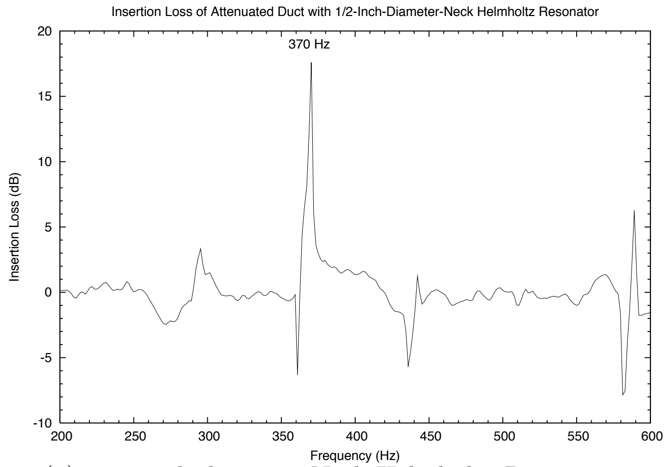


(b) 0.75-inch-diameter Neck Helmholtz Resonator

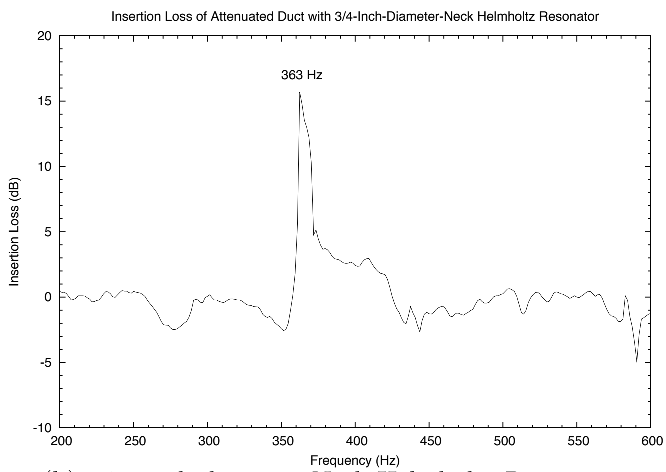


(c) 1-inch-diameter Neck Helmholtz Resonator

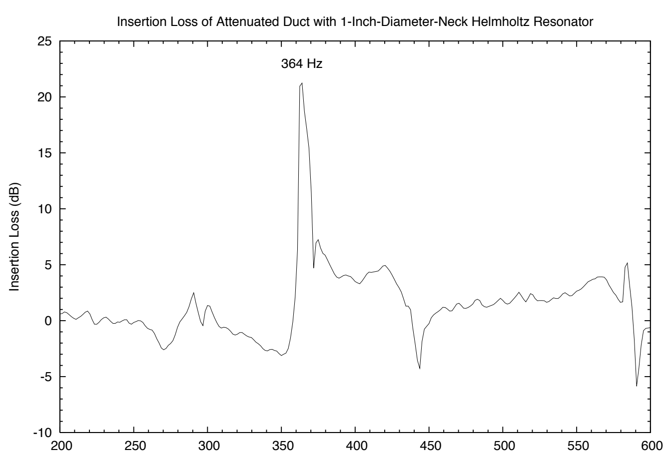
Figure 14: The dashed lines in the picture are the octave bands that correspond to the attenuated response of the duct. For the 0.75-inch-diameter neck and 1-inch-diameter neck Helmholtz resonators, the attenuated response is over 10 dB less than the octave band.



(a) 0.50-inch-diameter Neck Helmholtz Resonator



(b) 0.75-inch-diameter Neck Helmholtz Resonator



(c) 1-inch-diameter Neck Helmholtz Resonator

Figure 15: Insertion loss graphs for each Helmholtz resonator. The 1-in-Helmholtz resonantor was greatest at attenuating the tonal noise. Note that the greatest insertion loss for each resonator did not occur at the resonator's resonance frequency- 366 Hz.

whereas the 0.5-inch-neck Helmholtz resonator had the least attenuation.

4.2 Future Experiments

Based on the results shown in Figures 14 and 15, the transmission loss measurements made in Section 1.4 were accurate in predicting the most effective Helmholtz resonator; however, these predictions are not accurate in predicting insertion loss. Therefore, it is necessary to adjust these predictions for more accurate results. The adjustment to these predictions can be accomplished in two different ways. The first method involves experimentally determining the source's impedance and calculating insertion loss measurements using Beranek and Ver's definition for insertion loss.[4]

The second method involves using a grazing flow prediction for transmission loss where the Mach number, M, does not equal zero. If this prediction were to be calculated, then it would be necessary to make actual transmission loss measurements with the duct. Two $\frac{1}{2}$ in holes were drilled in the centers of two of the $3\frac{1}{16}$ in by $6\frac{1}{8}$ lids. The holes would allow for two Larson Davis $\frac{1}{2}$ in microphones to be placed in each lid, and each lid could then be placed on opposite sides of the Helmholtz resonator. The transmission loss could then be calculated based on the pressure responses recorded by the microphone.

Designing and creating various Helmholtz resonators would also be a useful extension to this project. One would need to be mindful of the limited space aboard the ISS during the design process. It might also be useful to consider lining a Helmholtz resonator's interior with acoustic lining. The lining would change the impedance of the neck and cavity, thus allowing for greater attenuation over a broader range of frequencies. Predictions for acoustically-lined Helmholtz resonators would need to be further researched.

4.3 Acknowledgements

I am very grateful to the following people for their support and encouragement:

Sue Hawkins and her colleagues at the Arkansas Space Grant Consortium for informing and granting me the opportunity to intern in the Acoustics Office at Johnson Space Center.

My mentor, Chris Allen, who proposed this project to me and guided me during its ten week duration.

Jeffrey Dornak, who was essential in the construction of my experimental setup and greatly contributed to the success of this project.

Dave Welsh, who taught me my first signal processing lesson as well as offered invaluable advice in acoustical engineering and measurement methods.

S. Reynold Chu and Shuo Wang, who provided me with resources and support.

Punan Tang, who offered me invaluable and practical advice on the incorporation of Helmholtz resonators into ducts.

Efram Reeves, who initially designed this experiment and willfully helped me with my questions.

William Slaton, who served as my faculty mentor for this project and offered valuable advice and support.

Appendix A:
Determining the Fan Speed of a 4184/2XH ebmpapst 4100N Series Tubeaxial Fan

The rotational speed of the fan was assumed to be linearly proportional to the voltage supplied to the fan. At a nominal voltage of twenty-four volts, the fan was stated to have a speed of 4400 rotations per minute.[8] This fact, along with the knowledge that the fan speed was zero rpm when no power was supplied to the fan, was used to generate a linear fit as shown in Figure 16 below. A summary of this relationship can also be viewed in Table 4. Therefore, it was possible to estimate the speed of the fan if the voltage supplied to the fan was known.

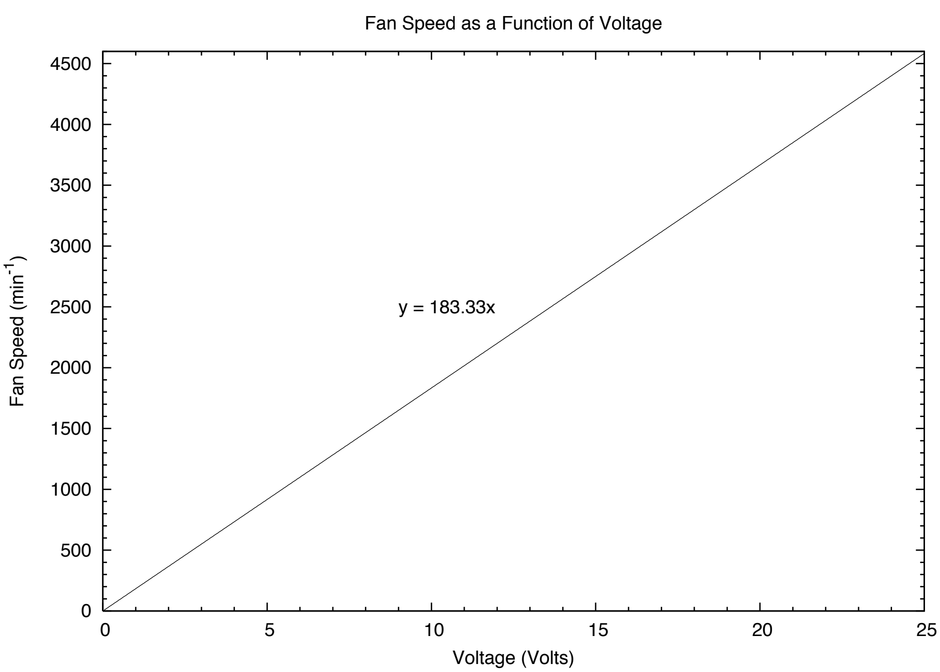


Figure 16: Assuming that the fan speed is linearly proportional to the voltage supplied to the fan, it is possible to use known information from the fan's specifications sheet to determine the proportionality constant. Multiplying the voltage by this constant should yield an approximation to the fan's speed.

Voltage (Volts)	Fan Speed (min^{-1})
1	183
2	367
3	550
4	733
5	917
6	1100
7	1283
8	1467
9	1650
10	1833
11	2017
12	2200
13	2383
14	2567
15	2750
16	2933
17	3117
18	3300
19	3483
20	3667
21	3850
22	4033
23	4217
24	4400
25	4583

Table 4: The fan's speed corresponding to integer values of the voltage sent to the fan.

Appendix B:
Sample Mathematica File for Determining Transmission Loss - First Prediction Method

Transmission Loss for a Duct with a Helmholtz Resonator Inserted as a Side-Brance

Dimensions of Helmholtz Resonator:
S_{cavity} = cross-sectional area of cavity (cylindrical)
h = height of cavity
V = volume of cavity
L = length of neck
r = radius of neck
$L_{\mathrm{effective}}$ = effective length of neck
S_{neck} = cross-sectional area of neck

S_{cavity}:=π * ((0.0381)^2)
h:=0.028575
V:=S_{cavity} * h
L:=0.0127
r:=0.00635
$L_{\mathrm{effective}}$:=L + 1.4 * r
S_{neck}:=π * ((r)^2)

Constants used in later equations:
c=speed of sound in air
ρ=density of air
S_{duct} = cross-sectional area of duct

c:=343
ρ:=1.21
S_{duct}:=0.130175^2

Resonance Frequency of Helmholtz Resonator:

$$\nu = \frac{c}{2*\pi} * \sqrt{\frac{S_{\mathrm{neck}}}{L_{\mathrm{effective}}*V}}$$

Open File to write transmission loss prediction:

Transmission = OpenWrite["/Users/hollysmith/Transmission Loss/366Hz.txt", PageWidth->Infinity];

Headers for File:

Write[Transmission, {"Frequency [Hz]", "Transmission Loss"}];

Calculations for the File:
x=$\frac{1}{T_{\Pi}}$
TL=10 $\log_{10}\left(\frac{1}{T_{\Pi}}\right)$
The Do Loop is continued for a frequency range of 200 Hz - 500 Hz, and the frequency and transmission loss are written to the file '366Hz.txt'.

Do[
$$x = 1 + \left(\frac{\frac{c}{2*S_{\text{duct}}}}{\rho*\left(\frac{2*\pi*i*L_{\text{effective}}}{S_{\text{neck}}} - \frac{c^2}{2*\pi*i*V}\right)}\right)^2;$$
TL = 10 ∗ Log[10, x];
Write[Transmission, {i, TL}]
, {i, 200, 500, 1}];

Closing the file:

Close[Transmission]

Appendix C:
Sample Mathematica File for Determining Transmission Loss - Second Prediction Method

Clearing Stored Symbols:

Clear["Global`*"]

Transmission Loss for a Duct with a Helmholtz Resonator Inserted as a Side-Brance

Dimensions of Helmholtz Resonator:
ρ = density of air
c = speed of sound in air
r_{n} = radius of neck
S_{n} = cross-sectional aread of neck
L_n = length of neck
δ_n = neck correction
V = volume
S_{d} = cros-sectional area of duct
r_{c} = radius of cavity (cylindrical)
h = height of cavity

ρ:=1.21
c:=343
r_n:=0.00635
S_n:=$\pi * (r_n{}^2)$
L_n:=0.0127
δ_n:=$1.4 * r_n$
V:=0.00013031
S_d:=0.130175^2
r_c:=0.0381
h:=0.028575

Resonance Frequency of Helmholtz Resonator:

$$\nu = \frac{c}{2*\pi} * \sqrt{\frac{S_n}{(L_n+\delta_n)*V}}$$

Open File to Write Transmission Loss:

Transmission = OpenWrite["/Users/hollysmith/NewTL.txt",

PageWidth->Infinity];

Headers for File:

Write[Transmission, {"Frequency [Hz]", "Transmission Loss"}];

Calculations for the File:

Do[

$$k = \frac{2*\pi*i}{c};$$

$$x = \text{Abs}\left[\frac{2+\left(\frac{\rho*c}{S_d}\right)*\left(\frac{1}{i*\left(\frac{c}{\pi*r_c^2}\right)*\text{Cot}\left[\frac{2*\pi*i}{c}*h\right]+\left(\frac{c*k^2}{\pi}-i*\frac{c*k(L_n+1.4*r_n)}{S_n}\right)}\right)}{2}\right];$$

$$\text{TL} = 20 * \text{Log}[10, x];$$

Write[Transmission, {i, TL}]

, {i, 0, 10000, 1}];

Closing the file:

Close[Transmission]

References

[1] Goodman, Jerry R. "International Space Station Acoustics." Proceedings of Noise-Con 2003. Cleveland, Ohio. 23-25 June 2003.

[2] Spratlin, Larry. "CQ Acoustics Assessment Report for CDR." June 27, 2008.

[3] "CQ Project Technical Requirements Specification for the ISS Crew Quarters," Revision A. Engineering Directorate, Crew and Thermal Systems Division, Johnson Space Center, June 25, 2007.

[4] Beranek, Leo L. and Ver, Istvan L. *Noise and Vibration Control Engineering*. John Wiley & Sons, New York, NY, 1992.

[5] Orr, W. Graham. *Handbook for Industrial Noise Control*. The Bionetics Corporation, Hampton, Virginia, 1981.

[6] L.E. Kinsler, A.R. Frey, A.B. Coppens, and J.V. Sanders. *Fundamentals of Acoustics*, 4th edition. John Wiley & Sons, New York, NY, 1982.

[7] Seo, Sang-Hyun and Kim, Yang-Hann. "Silencer design by using array resonators for low-frequency band noise reduction," Journal of the Acoustical Society of America, **118**, 2332-2338 (2005).

[8] "DC Axial Fans Specification Sheet." ebmpapst. `http://www.ebmpapst.co.uk/Assets/PDF/Press\%20Releases/Serie\%204100N_GB.pdf`.