[redacted] Noise Control W22

Presented to:

[redacted]

Presented by:

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Presented on:

11th of April 2022

Abstract

The objective of this report is to provide an analysis of the sound source in the machine shop to suggest a noise reduction solution. The analysis consists of determining the source's sound power level, directivity effects, and other physical characteristics of the room to model the sound field. This model is then used to find the experienced sound pressure level at the location of the observer taking into account both the direct sound field and the reverberant sound field in the room. Inspection of the model concludes that a noise barrier would be an effective noise-reducing measure because it can be shown that the direct field contributes significantly more than the reverberant field to the sound pressure experienced by the observer. The proposed solution consists of a half-inch thick plexiglass barrier between the source and observer located one-third of the way from the source. It was found the barrier decreases the sound pressure at the observer by 4 dB, effectively more than halving the sound pressure level experienced. The noise source's frequency spectrum was determined by comparing the background noise to the noise of the source and background together. It is found that the source's peak frequency is around 1200-1600 Hz.

Introduction

The [redacted] Machine Shop, where the source of the noise is located, is a large "L" shaped room with several other pieces of machinery and equipment, as well as supplies and materials often lining the walls of the shop. The source is located in a corner of the room, approximately 0.74 meters from the South and 0.84 meters from the East walls.

The sound caused by the motor/pump system was mapped out and profiled by taking sound measurements in 15 different locations. Directional measurements were taken in six different compass directions and each measurement was taken at two elevation planes, at a "lower" and an "upper" height. The directional measurement locations can be seen in [redacted]. Two measurements were taken without a direction, directly above the source at the same elevations as the directional measurements. One more measurement was taken where the operator would normally be positioned. The "observer" measurement location is in the North-West direction and is 3.375 meters away horizontally and 2 meters above the source.

The sound was recorded with the use of a G.R.A.S. microphone, with a range of approximately 3.15Hz – 20 kHz and a range of 15-146 dB.

The team was provided with dimensional data of the enclosed space as well as the location of the source within this space, and frequency and 1/3 octave data that contained the decibel level of each frequency or octave band. The sound profile data was broken up into different locations at different setups: with all machinery turned off, with the pump and VFD on, and with the saw cutting through a piece of plywood.

The objective of this project is to analyze the sound that is produced by the source with the use of the dimensions and noise data provided and propose a solution to reduce the noise level experienced by the operator due to the source, with predicted results and justification for the design.

Background Information and Theory

An acoustic wave is a pressure wave that is created by a vibrating object and then travels through a compressible medium. The characteristics of this pressure wave depend on the power and frequency of the oscillating object, as well as the properties of the medium that the pressure wave is traveling through. As the acoustic wave propagates, the transmission of power is implied, which can be defined as the integral of acoustic energy over an area surrounding the source. Because a point source would produce uniformly spherical waves, the most convenient/accurate surface area to use would be a sphere or part of a sphere, depending on the directivity. Directivity factor is defined as the ratio of the intensity of the sound wave on a designated axis and a specific distance from the source to the intensity that would be produced by a source radiating the same total acoustic energy in all directions. The directivity is defined by the geometry of the space surrounding the acoustic source. Because the acoustic energy propagates in the form of pressure waves, it is measured in Watts while the waves are measured in pascals. However, due to the large difference in human hearing threshold (6.9e-9 Pa) and the loudest possible sound (101.3 kPa), the scale needs to be logarithmic, and is called decibels [dB] and is relative to 20 micro pascals. The sound pressure level is measured in dB and because it is proportional to the sound pressure power, it too uses the logarithmic scale.

When a sound signal is recorded, an octave filter is used so that the results are manipulatable, are more easily interpretable, and comparable to other sound recordings. Several filters can be used, but the most common and the one that is used for parsing this data. For a 1/3 octave band, upper and lower frequencies are added to each center frequency, and then the sound signal is run through the octave band, shaping the sound profile.

The human ear is designed to hear a specific spectrum of frequencies and is more sensitive to frequencies in the range of 500Hz to 6kHz. To simulate the hearing range of a human ear, an A-weight scale can be applied, which is a set of factors that are added to each 1/3 band to give an accurate representation of what a human ear can hear.

Methodology

The average sound power of the source can be found using the following equation, where L_{p1} is the sound pressure level closer to the source and L_{p2} is the sound pressure level further from the source.

$$L_W = L_{p2} - 10\log\left(\frac{1}{S_1} - \frac{1}{S_2}\right) + 10\log\left(10^{\frac{L_{p1}-L_{p2}}{10}} - 1\right) - 10\log\left(\frac{\rho_{air}c}{400}\right)\ dB$$

The S variable represents the hemispherical surface area ($2 * pi * r^2$) with a radius equal to the distance from which the measurement was taken. ρ_{air} and c represent air density and speed of sound, and for this project are $1.225\,\frac{kg}{m^3}$ and $331.3\,\frac{m}{s}$ respectively.

The sound pressure levels at two different distances are needed. The resultant power levels in each direction were then averaged to give the mean sound power level.

The acoustic frequency spectrum refers to the dominant frequency range of the source. To filter the background noise out of the recorded data, the decibel level of both the “Pump On” and “Background” were converted to pascals and the difference was found, representing the sound made by the pump. After converting back to decibels and graphing, it was easy to see the frequencies here the pump noise dominated. Because decibels are a logarithmic scale, a small difference in decibel number between background noise and combined sound can scale and mean a very prominent frequency signal originating from the source.

As seen in Figure 1, the source is located close to the corner of two walls and the floor. It will be assumed that the source is in the corner of the room, giving the source a directivity factor of 8 and a directivity index of 9 dB.

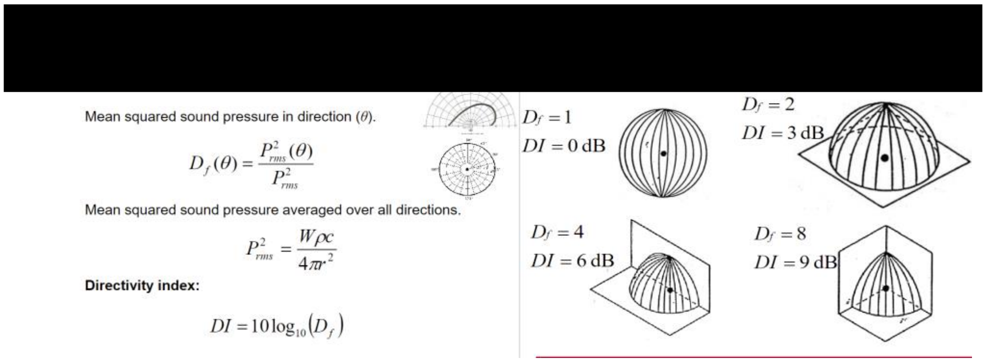


Figure 1: Directivity index due to the location of the source.

As the source is located in a corner, to determine the effect of the wall reflections, the sound pressure levels at the point of the observer can be calculated using the sound power level of the source and the directivity factor, D_f, for different wall reflection cases with the following equation:

$$L_p = L_W + 10\log_{10}(D_f) - 20\log_{10}(r) - 11 \quad dB$$

The current position of the source in the shop is near a corner, giving the source a directivity factor of 8. A directivity factor of 8 leads to a 9dB increase in sound pressure in the room, see the second term in the above equation. A directivity factor of 0 is the ideal scenario, where no surfaces reflect the sound, and the sounds propagate evenly in all directions. The directivity factor of 2 is the scenario if the source was positioned in the center of the room, with only floor reflections occurring. The directivity factor of 4 would represent the source being located next to one wall. The final directivity factor of 8 represents the source in its location in the shop, assumed to be in the corner of the room relative to the size of the shop.

The baseline sound pressure level in the shop can be found by adding the pressure levels of all the present frequencies in pascals and converting them back to decibels. The data at the operator was used as the location of interest.

The background noise can be attributed to the HVAC system present in the shop, as at the time of recording the data, all other systems were powered down. The background sound profile showed that the most dominant frequencies were in the low range, with an almost uniform sound profile in the higher frequencies.

The human ear is most sensitive to frequencies in the range of 500Hz to 6kHz, being the most sensitive to frequencies of about 2500Hz. The A-weighted scale adjusts the sound pressure level of the signal to reflect the sensitivity of the human ear and is used for risk mitigation regarding hearing loss to excessive noise. Low and high frequencies outside that range are not as dangerous to human ears, even at high decibel levels, and therefore are scaled-down significantly more.

An A-weighting was applied to the sound pressure level and gave a sound profile similar to what a human ear would hear. The total sound pressure level of the A-weighted scale is also much lower than the total pressure level of the unaltered signal. This is because the lower frequencies are almost entirely filtered out.

The most dominant frequencies that can be found in the A-weighted scale are 1250 and 1600 Hz. These are not only the most prominent frequencies but also in the middle of the scale, meaning the human ear is very sensitive to these frequencies.

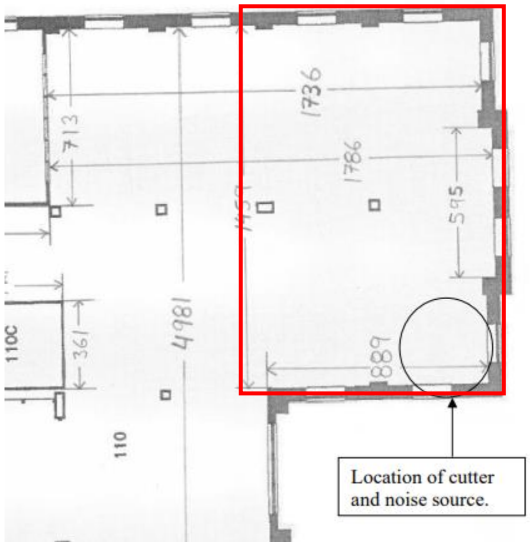


Figure 2: The approximated room dimensions that are used in the calculations and the results. The open wall of the approximation is considered an opening to infinitely open space.

To calculate the room constant of the shop, only the section highlighted is considered the room. The open plan will be represented as a wall with an absorption factor of 1, it is assumed that noise that travels through this plane will travel a significant distance to reflect and reach the observer again, essentially being fully absorbed. The average absorption constant is found by taking the weighted average by the surface area of each surface in the room. Table _ shows the material, absorption constants, and the surface areas of the room, as well as the calculated room constant.

Surface, Material	Surface Area, S_n [m^2]	Absorption Constant, α_n
Walls, Painted concrete block	63.1215	0.09
Walls, Plaster on block	43.113	0.04
Windows, Glass	24.864	0.03
Floor, Unpainted concrete	129.7	0.02
Ceiling, Plaster on block	129.7	0.04
‘Open Wall’	59.0895	1

Table 1: All surface areas found using the dimensions provided in Appendix B of the project outline. Absorption coefficients for the 2000Hz frequency are used as this frequency is the most important/troublesome.

$$\bar{\alpha} = \frac{\sum \alpha_n S_n}{S_o}$$

$$R = \frac{\bar{\alpha} S_o}{(1 - \bar{\alpha})}$$

To calculate the sound pressure level at the observer the following equations are used. The equation below is used to model the room. The equation takes into account both the reverberant sound field in the room, represented by the term including the room constant R, and the direct sound field is represented by the term including the directivity factor D_f and the distance r.

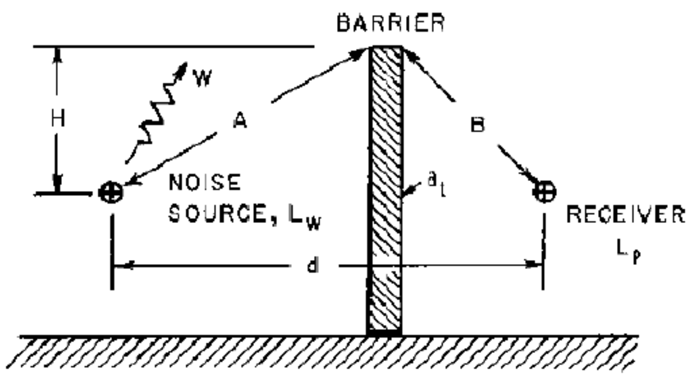
$$L_p = L_W + 10\log_{10}\left(\frac{4}{R} + \frac{D_f}{4\pi r^2}\right) + 0.1 \quad dB$$

The influence of the direct sound field term and the reverberant sound field term can be compared to determine the most effective noise reduction strategy. When the direct field term contributes approximately 6 times more than the reverberant field term, sound barriers will be a more effective method of reducing the sound pressure level at the observer. When the reverberant field is the larger contributor to the sound pressure at the observer, increasing the room absorption of the room will be a more effective method of reducing sound pressure level.

When modeling the addition of a sound barrier to the room, it will mainly have an impact on reducing the direct sound field, but it also has a small impact on the room constant as adding the barrier will increase the absorption of the room, increasing the room constantly. The room constant after adding the barrier R_b can be found using equation X where S_b is the surface area of the barrier and α_1/α_2 is the surface absorption coefficients for each side of the barrier.

$$R_b = \frac{\bar{\alpha}S_o + S_b(\alpha_1 + \alpha_2)}{1 - \bar{\alpha} - (S_b/S_o)(\alpha_1 + \alpha_2)} \qquad m^2$$

The following equations are used to find the sound pressure level of the observer. The barrier constant a_b depends on the Fresnel number and the geometry of the barrier. The geometry is expressed by A and B, which represent the distance from the source to the top of the barrier and the distance from the top of the barrier to the observer respectively, and where d is the distance between the source and observer. The barrier transmission coefficient is found using the experimentally found transmission loss of the material TL, values for which can be found in the appendix.



$$N = \frac{2f}{c}(A + B - d)$$

$$a_b = \frac{\tanh^2(\sqrt{2\pi N})}{2\pi^2 N}$$

$$a_t = 10^{-TL/10}$$

$$L_p = L_W + 10\log_{10}\left(\frac{4}{R_b} + \frac{D_f(a_b + a_t)}{4\pi(A+B)^2}\right) + 0.1 \quad dB$$

Results

Using the pressure levels at different locations, the resultant mean power level comes out to $L_w = 96.11\ dB$.

The mean sound pressure level is graphed out with the pump on, with only the background noise and with the pump sound isolated. The purple bars clearly show the frequency spectrum where the pump frequencies dominate. The graph below refers to the sound pressure level of the "middle lower" measurement location and the "top of box" measurement location for the background. The difference in frequencies was plotted as "Pump Isolated".

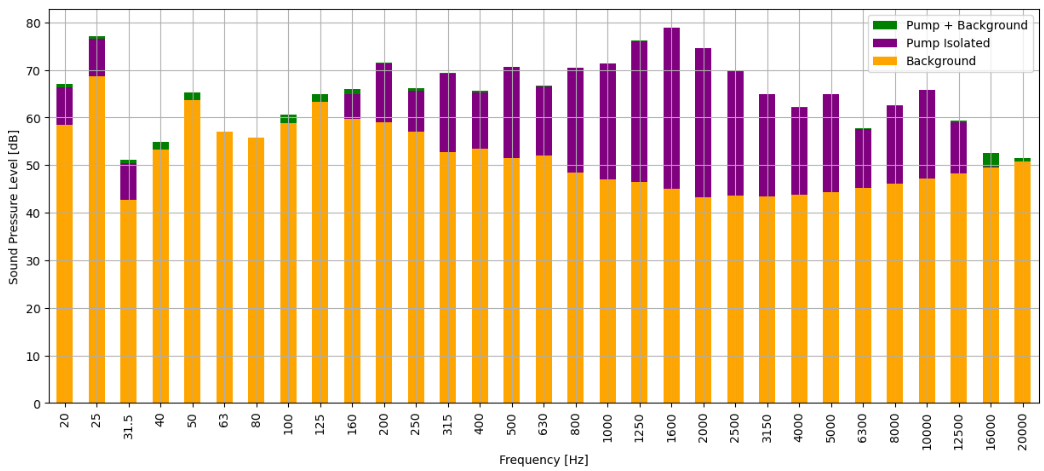


Figure 3: Bar graph of the pump on at the "middle lower" location, background noise at the "top of box" and the scaled sound pressure level difference between the background and the pump on noise.

It should be noted that the sound pressure level of the background noise at the "top of box" measurement location was found to be $L_{p_{bg}} = 69.71\ dB$ and the sound pressure level at the middle location was found to be $L_{p_{ML}} = 84.67\ dB$.

The same was done for the background noise and noise with the pump turned on at the location of the observer. The sound profile is very similar to the measurements taken close to the box, though the difference in decibels is smaller. The same dominant frequencies are seen. Another difference is that the spike in the lower frequencies that can be seen in the graph above is not present.

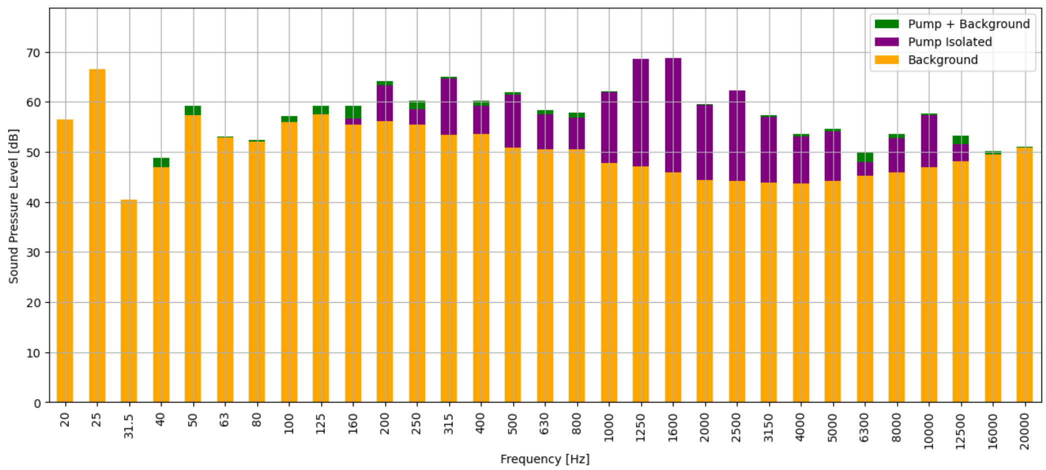


Figure 4: Bar graph of the pump on at the "observer" location, background noise at the "observer" and the scaled sound pressure level difference between the background and the pump on noise.

The sound pressure level at the observer was found to be $L_{p_{bg}} = 69.69\ dB$ for the background noise and $L_{p_{ob}} = 76.05\ dB$ when the pump is on.

There are 2 different spikes in the frequency pressure level of isolated pump noise. The first spike can be seen in the frequency range of the pump, from about 250Hz to 12.5kHz. The most likely cause is the imperfections in hydraulic and mechanical parts of the pump system. The hydraulic sources include cavitation, insufficient net positive suction head, fluctuation in fluid pressure, etc., and are the more likely reason behind the noise from the pump system. Mechanical sources of noise include defects/wear of the pump or motor, an imbalanced rotor, improperly lubed parts, friction from the belt, etc.

The second spike can be seen at the lower frequencies and can only be seen in the pump sound signal at the measurement locations close to the source. This spike in pump noise doesn't appear in Figure 4, but can still be seen in the background noise. This spike can be explained by several reasons. The first reason could be due to the fundamental motor driving frequency. Though the speed of the pump is unknown, an RPM of 1500 would result in a frequency of 25Hz and could contribute to strong low-frequency sounds. Another possible reason for the low-frequency spike could be the resonant frequencies and the fundamental acoustic resonant frequencies of the shop. Because the shop is an enclosed space with hard walls, the acoustic resonance frequency could be quite prevalent. The spike in the frequency range of 20-31.5Hz can be explained by the room resonance frequency. This is further proven by the fact that when the pump is on, the sound pressure level of these frequencies increases uniformly.

When the A-weight scale is applied to the sound pressure levels, the above bar graph takes on a slightly different profile. The A-weighted sound pressure levels clearly show the two dominant frequencies that are present from the pump noise: 1250Hz and 1600Hz. These frequencies should be isolated and reduced.

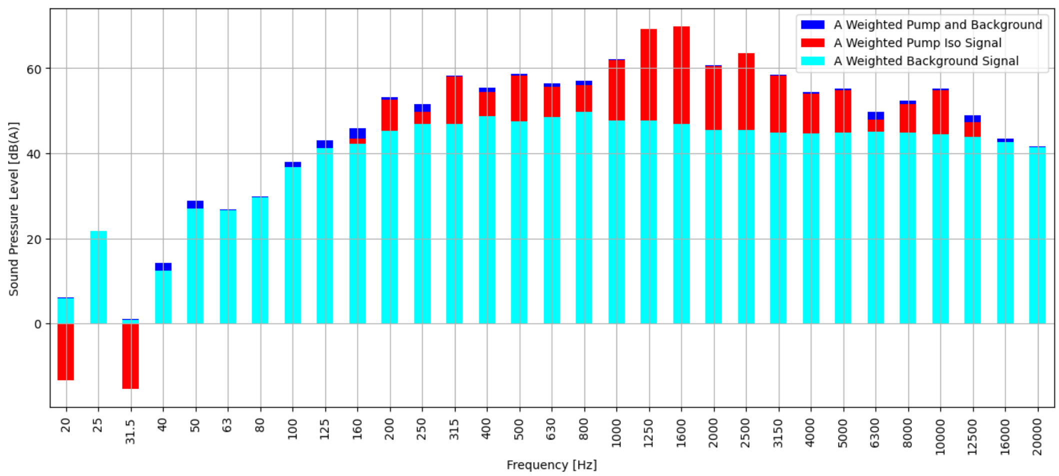


Figure 5: A-weighted sound pressure level at the observer. The A-weight scale represents the sensitivity of the human ear to each frequency.

The most dominant frequencies that can be found in the A-weighted scale are 1250 and 1600 Hz. These are not only the most prominent frequencies but also in the middle of the scale, meaning the human ear is very sensitive to these frequencies.

The average absorption coefficient, $\bar{\alpha}$, was calculated to be 0.166875. The room constant, R, was calculated to be 90.05. The total room surface area was calculated to be $S_0 = 499.58\ m^2$.

Solution

The proposed design is a 1/2 inch thick, 4 meters wide, and 2.5-meter-high plexiglass barrier, that would reside 1.125 meters away from the source, or 1/3 of the distance between the source and the observer. The total weight of the barrier was found to be 302.25 kilograms. At 270 $\frac{\$}{m^2}$, the total cost of the barrier would be $2700. A frequency of 1600Hz was used as the main frequency to be reduced, with a frequency of 2000Hz for the transmission loss and the absorption coefficient, a $TL = 32$, and $\alpha = 0.87$.

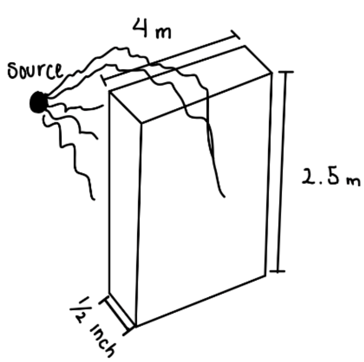


Figure 6: A sketch of what the proposed design would look like, with dimensions and sound waves from the source.

Plexiglass was chosen for the barrier for several different reasons; it has a high absorption coefficient, and transmission loss coefficient, it is accessible to purchase and it is completely clear, allowing the observer to see past the barrier. As [redacted] is used for educational purposes, a clear barrier has an advantage over opaque barriers.

A thickness of ¼ and 1 inch were considered for the barrier. However, it was found that for the 1-inch thickness, the extra thickness of the barrier provided a $0.01\ dB$ noise reduction while doubling the weight of the barrier, while the ¼ inch failed the Fresnel number criterion of $a_t < \frac{a_b}{8}$ and, therefore, was not a feasible solution. Other barrier heights of 2 and 3 meters were considered, however, the 2.5-meter barrier was picked. A 2-meter barrier could also be used, as it would only increase the sound pressure level by $0.2\ dB$ compared to the 2.5-meter barrier. Finally, the distance of the barrier to the source was varied, however, the resultant sound pressure only varied by $0.02\ dB$, even at the extremes.

The resultant sound pressure level at the observer dropped to $L_{p_{barrier}} = 71.611\ dB$. The sound pressure level at the observer without the barrier was also calculated to test the accuracy of the room model and simulation and found to be $L_{p_{model}} = 75.696\ dB$. When compared to the experimental result of the sound pressure level of $L_{p_{observer}} = 76.05$, the slight difference in the pressure level can be attributed to the overestimation of the room constant or the simplification of the size/shape of the room.

When using the time equivalent sound exposure method, an 8-hour exposure to $L_{p_{model}} = 75.696\ dB$ is equivalent to $T_{85} = 0.93\ hours$ spent at an $L_p = 85\ dB$, the safe limit for humans. Using $L_{p_{barrier}} = 71.611\ dB$ and comparing it to the safe limit, the time equivalent drops to $T_{85} = 0.349\ hours$.

Discussion

Using a strategically placed plexiglass sound barrier is the most feasible solution for the shop environment because it was shown that the sound pressure experienced by the observer is mainly due to the direct field rather than the reverberant field. Sound barriers that come in sectioned wall partitions are convenient because you can still visually monitor any machinery and they are easy to move around in the dynamic work environment of a machine shop.

The addition of an acoustic wall or ceiling treatment would help decrease the reverberant noise of the room, however for any subjects near the source the direct sound field is the priority. In shop and industrial environments moving out of the direct field of one source likely means you will be close to the direct field of another, however this analysis only takes into account the background noise and the one source. Since the proposed barrier solution reduces the sound pressure at the observer to acceptable levels for long periods. The average absorption coefficient of the room was found to be approximately 0.16, which is a considered an average room. This average absorption coefficient is most likely an underestimate as it does not account for people or other items in the shop which have greater surface absorption values than the majority of the reflective surfaces which were accounted for.

When the saw is cutting, the A-weighted sound pressure level at the observer is 87.04 dBA, greater than the 87 dBA threshold which you are allowed to continually experience for 8 hours, according to Canadian health and safety regulations. Although the focus of this analysis, is only on the noise from the pump and motor it can be recommended that the operator wear hearing protection during the cutting operation since a noise reduction method is required by law when the threshold is met. The sound pressure experienced by the observer while the saw is cutting would be reduced by the implementation of acoustic treatment to the walls and ceiling, as it would function to lessen the reverberant field as discussed earlier. Applying acoustic treatment for the entire room will greatly increase the room constant, lessening the contribution of the reverberant field. This type of solution is worth exploring as reducing background noise makes the shop safer by reducing the risk of hearing loss and making communication easier.

Conclusion

In conclusion, the sound levels at the operator satisfy regulations as the a-weighted sound pressure level at the observer produced by the source is approximately 76 dBA. This is below the maximum sound exposure of 87 dBA for 8 hours that is allowed in Canada. While this level of noise is permitted, reducing the sound pressure level would improve the comfort of the operator. While the sound experienced by the operator is significantly below the safe limit, as per the Canadian government, this is the ideal case when no other significant sources of sound in the shop. In a real case scenario, it is more than likely that the there will be other sources of sound at the same time as the motor and pump, resulting in higher sound pressure levels at the observer. In this case the proposed solution may be critical in reducing the sound pressure level below the critical threshold.

Appendix A: Data

	Notes
1	All measurements were recorded with the lights off, except for the ones that specify "lights on".
2	Every measurement (different positions) was recorded at different times because of technical limitations.
3	Measurements noted under "background" are measurements of the environment without the saw/pump/VFD turned on.
4	Measurements noted under "Pump…" are measurements with the VFD turned on. A VFD supplies power (high voltage/current) to the system.
5	Measurements noted "Saw On" are test runs. A piece of plywood was cut.
6	All measurements were conducted by holding the microphone upright.

	Equipment
1	RT Pro 6.21 Acoustic Software - Signal Analysis and Waveform Source Workbench
2	LDS Dactron Photon II DAQ device (Model: PHO 200)
3	G.R.A.S. Power Module Type 12AA (Gain of used: 0dB)
4	Handheld sound calibrator by ACOPacific, Inc. (Model 511E) (Calibration options 104dB and 94dB at 1kHz)
5	1/4" G.R.A.S. Type 26AC Microphone Preamplifier (ICP) and respective microphone
6	Microphone unmarked: Possible model numbers: G.R.A.S. {40AF, 40AN, 40AR, 40AP, 40AE, 40AQ or 40AD}. See specifications to the right.
-	It is likely a 40AE microphone.

Table 2: Notes and measurement devices used for data collection.

	BACKGROUND		
	Top of Box	**Inside Box**	**Operator**
X Unit(Hz)	Y Unit(dB/20.0µ Pa)	Y Unit(dB/20.0µ Pa)	Y Unit(dB/20.0µ Pa)
X Value	Y Value(dBMag)	Y Value(dBMag)	Y Value(dBMag)
20	56.93711568	58.53037402	56.37660191
25	67.00516789	68.59842334	66.44465367
31.5	40.98808128	42.7312385	40.427184
40	47.46812749	53.21059278	46.87401244
50	57.90857751	63.66732468	57.31539097
63	49.4186152	57.05478384	52.84366461
80	48.27280879	55.83538001	51.94666839
100	51.60830469	58.76360601	55.94591371
125	55.4717436	63.24463902	57.47671502
160	53.83613091	59.70844408	55.47299345
200	54.29720694	58.9613622	56.14424954
250	57.22681299	56.96032958	55.50911092
315	53.17477579	52.80254035	53.42144937
400	53.65831854	53.41647871	53.60867141
500	50.63948657	51.50110759	50.78838957
630	51.30231583	52.05853583	50.41415616
800	48.36115152	48.36629128	50.47472349
1000	47.26505074	47.04784562	47.69211973
1250	47.23015677	46.43011317	47.021482
1600	48.3794117	45.05342059	45.88745433
2000	45.70244845	43.26790445	44.37341401
2500	44.26849913	43.60208998	44.12745396
3150	44.1599329	43.40688856	43.76441081
4000	43.81248891	43.7466401	43.7622496
5000	44.23457038	44.28613227	44.22863133
6300	44.98848071	45.27154926	45.13585722
8000	45.94115553	46.12762941	45.90670421
10000	46.95083401	47.09083318	46.99917658
12500	48.13316928	48.19202835	48.16521154
16000	49.41444116	49.43483904	49.42204486
20000	50.77570202	50.79585629	50.81384625
L	6.971095e+001	7.253004e+001	6.969688e+001

Table 3: Sample 1/3 octave data that was used in the report. The X values in the left-most column are the frequencies of the 1/3 octave band. The sound pressure level can be seen as the Y values at each location in the table and was recorded in decibels with a reference of 20 µPa. The last row is the overall experimental sound pressure level, however, for the purposes of the report, the overall SPL was calculated using python code and the 1/3 octave band data.

Appendix B: Tables and Figures

Table 13.1 Transmission loss of some common material used for acoustical enclosures and isolation barriers

		Frequency (Hz)						
Material	lb/ft^2	125	250	500	1000	2000	4000	8000
Lead								
1/32 in.thick	2	22	24	29	33	40	43	49
1/64 in.thick	1	19	20	24	27	33	39	43
Plywood								
3/4 in.thick	2	24	22	27	28	25	27	35
1/4 in.thick	0.7	17	15	20	24	28	27	25
Lead vinyl	0.5	11	12	15	20	26	32	37
Lead vinyl	1.0	15	17	21	28	33	37	43
Steel								
18 gauge	2.0	15	19	31	32	35	48	53
16 gauge	2.5	21	30	34	37	40	47	52
Steel metal (vistoelastic laminate core)	2	15	25	28	32	39	42	47
Plexiglas								
1/4 in.thick	1.45	16	17	22	28	33	35	35
1/2 in.thick	2.9	21	23	26	32	32	37	37
1 in.thick	5.8	25	28	32	32	34	46	46
Glass								
1/8 in.thick	1.5	11	17	23	25	26	27	28
1/4 in.thick	3	17	23	25	27	28	29	30
Concrete, 4 in, thick	48	29	35	37	43	44	50	55
Concrete block, 6 in	36	33	34	35	38	46	52	55

Table 4: Transmission loss coeffiecient in dB.

Table 6.1 Subjective effect of changes in sound power level.

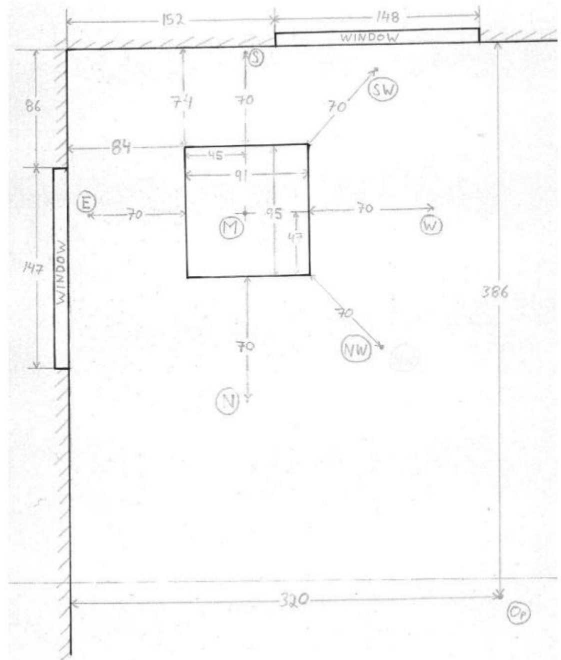
Change in sound level (dB)	Change in power		Change in apparent loudness
	Decrease	Increase	
3	1/2	2	Just perceptible
5	1/3	3	Clearly noticeable
10	1/10	10	Half or twice as loud
20	1/100	100	Much quieter or louder

Table 5: 3 Decibel rule.

Frequency (Hz)	20	25	31.5	40	50	63	80	100	125	160	200	250	315	400	500	630
A-weighting	-50.4	-44.8	-39.5	-34.5	-30.3	-26.2	-22.4	-19.1	-16.2	-13.2	-10.8	-8.7	-6.6	-4.8	-3.2	-1.9
Frequency (Hz)	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12500	16000	20000	
A-weighting	-0.8	0	0.6	1	1.2	1.3	1.2	1	0.6	-0.1	-1.1	-2.5	-4.3	-6.7	-9.3	

Table 6: A-weight factors

[redacted]



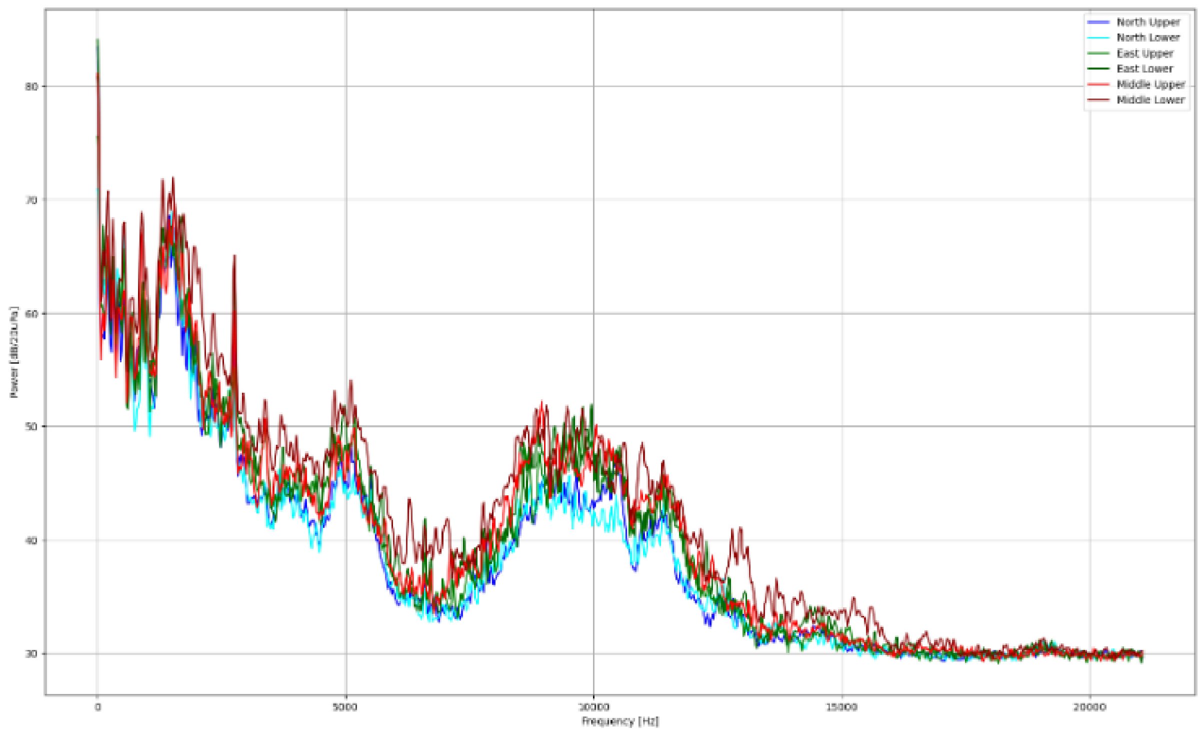
Appendix C: Code

```
def power(upper, lower, r2, r1):
    S1 = 2 * np.pi * r1 ** 2
    S2 = 2 * np.pi * r2 ** 2
    Lw = upper - 10 * np.log10((1/S1)-1/S2) + 10 * np.log10((10**(abs(lower-upper)/10))-1) - 10 * np.log10(rho*c/400)
    #print(r1, r2, S1, S2, lower, upper)
    return Lw

def band(fc):
    fl = fc/(2**(1/6))
    fu = fl*2**(1/3)

    return [fl, fu]

def convertToP(dB):
    P = Po * 10**((dB/10))

    return P

def convertTodB(P):
    dB = 10 * np.log10(P/Po)

    return dB

def dBsub(L1, L2):
    diff = 20 * np.log10(10**(L1/20)-10**(L2/20))

    return diff


def ABF(dist, h):

    A = np.sqrt((dist**2) + (h - sh)**2)
    B = np.sqrt((d-dist)**2 + (h - oh)**2)

    return [A, B]


def abF(N):

    ab = ((np.tanh(np.sqrt(2*np.pi)))**2)/(2*N*np.pi**2)

    if N > 12.7:
        return (0.004)

    else:
        return ab

def atF(TL):

    at = 10**(-TL/10)

    return at
```

```python

def abF(N):

    ab = ((np.tanh(np.sqrt(2*np.pi)))**2)/(2*N*np.pi**2)

    if N > 12.7:
        return (0.004)

    else:
        return ab

def atF(TL):

    at = 10**(-TL/10)

    return at

def NF(dist, h, f):

    N = 2*f*(ABF(dist, h)[0]+ABF(dist, h)[1]-d)/c

    return N

def RbF(alpha, h):

    Rb = (alphaBar * So + (h*w) * (2 * alpha)) / ((1 - alphaBar) - ((h*w)/So) * 2 * alpha)

    return Rb

def LpF(dist, h, f, alpha, TL, Lw):

    hold = (abF(NF(ABF(dist, h)[0], ABF(dist, h)[1], f)) + atF(TL))

    Lp = Lw + 10 * np.log10((4/(RbF(alpha, h))) + (Df*hold)/(4*np.pi*(ABF(dist, h)[0]+ABF(dist, h)[1])**2)) + 0.1

    if (8*atF(TL)) > abF(NF(ABF(dist, h)[0], ABF(dist, h)[1], f)):
        return 0

    else:
        return Lp

def LpEF(Lw):

    Lp = Lw + 10 * np.log10((4/(alphaBar*So/(1-alphaBar)))+(Df/(4*np.pi*r**2)))

    return Lp
```

Q2:

```
plt.figure(figsize=(20,12))
fr.NU.plot(label = "North Upper", color = 'b')
fr.NL.plot(label = "North Lower", color = 'cyan')
fr.EU.plot(label = "East Upper", color = 'g')
fr.EL.plot(label = "East Lower", color = 'darkgreen')
fr.MU.plot(label = "Middle Upper", color = 'red')
fr.ML.plot(label = "Middle Lower", color = 'darkred')
plt.xlabel('Frequency [Hz]')
plt.ylabel('Power [dB/20uPa]')
plt.legend()
plt.grid()
```

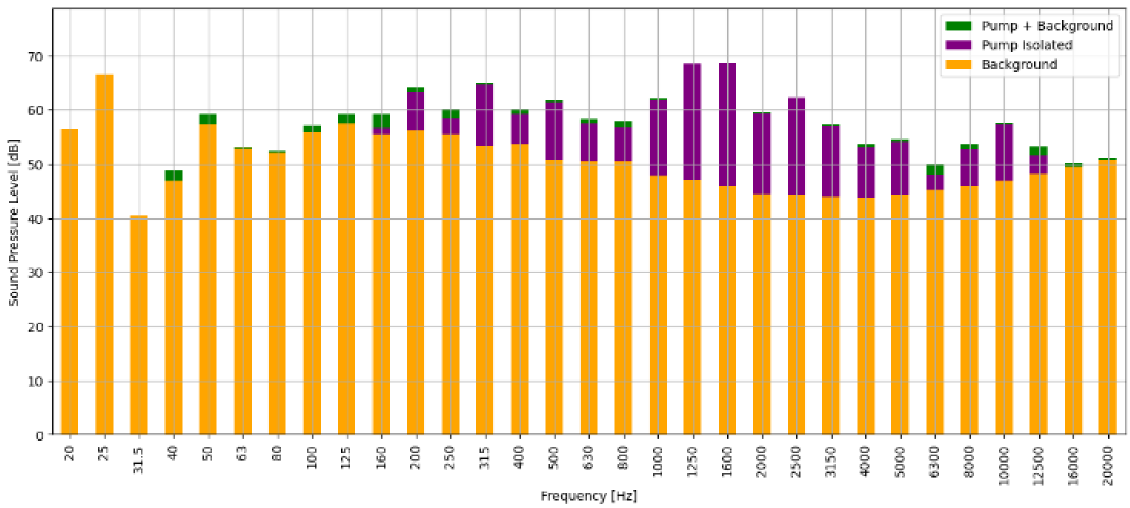


In [77]:

```python
plt.figure(figsize = (15,6))

ax = oc.Operator_PO.iloc[:-1].plot.bar(label = 'Pump + Background', color = "green")
ax = convertTodB(abs(convertToP(oc.Operator_PO)- convertToP(oc.iloc[:, 2]))).plot.bar(label = 'Pump Isolated', color = 'purp

ax = oc.Operator_B.iloc[:-1].plot.bar(label = 'Background', color = 'orange')
#ax = oc.iloc[:,1][:-1].plot.bar(label = 'Background Top Box')
#ax = dDB1.plot(label = 'Difference SUB')

#ax.axvline(19, color = 'purple', label = "1600 Hz")

plt.xlabel("Frequency [Hz]")
plt.ylabel("Sound Pressure Level [dB]")

plt.grid()
plt.legend()
```

Out[77]:

```
<matplotlib.legend.Legend at 0x1bb58e6dc70>
```



A-Weight

[64]:

```python
factors = [-50.4,-44.8,-39.5,-34.5,-30.3,-26.2,-22.4,-19.1,-16.2,-13.2,-10.8,-8.7,-6.6,
           -4.8,-3.2,-1.9,-0.8,0.0,0.6,1.0,1.2,1.3,1.2,1.0,0.6,-0.1,-1.1,-2.5,-4.3,-6.7,-9.3]



aWeightPumpIso = dDB[:-1].copy()
aWeightSaw = oc.Operator_SO[:-1].copy()
aWeightPump = oc.Operator_PO[:-1].copy()
aWeightBg = oc.Operator_PO[:-1].copy()
aWeightAll = pumpOnOc[:-1].copy()

for i in range(len(aWeightPump)):
    aWeightPumpIso[i] = convertTodB(abs(convertToP(oc.Operator_PO)- convertToP(oc.iloc[:, 2])))[i] + factors[i]
    aWeightPump[i] = oc.Operator_PO[i] + factors[i]
    aWeightSaw[i] = oc.Operator_SO[i] + factors[i]
    aWeightBg[i] = oc.Operator_B[i] + factors[i]

for i in range(len(aWeightAll.iloc[:,1])):
    for j in range(len(aWeightAll.iloc[1,:])):
        aWeightAll.iloc[i,j] = pumpOnOc.iloc[i,j]+(factors[i])



aWeightAll
```

t[64]:

Answers

In [100]:

```
#The Baseline pressure level in the shop
pumpP = convertTodB(np.sum(convertToP(dDB[:-1])))
baseP = convertTodB(np.sum(convertToP(bG[:-1])))
baseOpP = convertTodB(np.sum(convertToP(oc.Operator_B[:-1])))
operPumpP = convertTodB(np.sum(convertToP(oc.Operator_PO[:-1])) - np.sum(convertToP(oc.Operator_B[:-1])))
operTotP = convertTodB(np.sum(convertToP(oc.Operator_PO[:-1])))
aWeightP = convertTodB(np.sum(convertToP(aWeightPump)))
aWSsum = convertTodB(np.sum(convertToP(aWeightSaw)))


f = 1600
# Thickness plexiglass ( 1/4, 1/2, 1) inches

TL = np.array([28, 32, 34])
alpha = 0.87

heightWall = np.array([1.5, 2, 2.5])
distanceToSource = np.array([1/3, 1/2, 2/3]) * d

#def LpF(dist, h, f, alpha, TL, Lw):

reducedP = LpF(d/3, 2.5, f, alpha, 32, LwTotal)
normalP = LpEF(LwTotal)

reducedPA = LpF(2*d/3, 3, f, alpha, 32, LwTotalA)
normalPA = LpEF(LwTotalA)

print("Reduced SPL",reducedPA)
print("Model calculated SPL", normalPA)
```

```
Reduced SPL 71.40642112794417
Model calculated SPL 75.69630554555062
```

In [91]:

```
#print("The mean sound pressure level (SPL) in each direction is", meanP, "dB.")
print("The mean sound power level is", LwTotal, "dB.")
print("The mean A-weighted sound power level is", LwTotalA, "dB")
```

```
The mean sound power level is 96.11017554536569 dB.
The mean A-weighted sound power level is 86.11680782812758 dB
```

In [71]:

```
print("The background SPL at the top of box is", baseP, "dB.")
print("The isolated SPL of the pump is", pumpP, "dB.")
print("The total SPL at the operator when the pump is running is", operTotP, "dB.")
print("The isolated SPL at the operator from the pump is", operPumpP, "dB.")
print("The A-Weighted SPL at the operator is", aWeightP, "dB(A).")
print("The A-Weighted SPL at the operator with the saw on is", aWSsum, "dB(A).")
```

```
The background SPL at the top of box is 72.53004187302939 dB.
The isolated SPL of the pump is 84.6722542324215 dB.
The total SPL at the operator when the pump is running is 76.05229579447222 dB.
The isolated SPL at the operator from the pump is 74.90901161180724 dB.
The A-Weighted SPL at the operator is 74.47455353360168 dB(A).
The A-Weighted SPL at the operator with the saw on is 87.04709920515562 dB(A).
```