ACOUSTIC ANALYSIS OF R.E.E.L. SEMI-REVERBERANT SOUND CHAMBER

A Thesis

by

SEAN DAVID ELLISTON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Michael Pate
Committee Members,	Bryan Rasmussen
	William Lynn Beason
Head of Department,	Jerald Caton

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ABSTRACT

Acoustic Analysis of R.E.E.L. Semi-Reverberant
Sound Chamber. (May 2012)
Sean David Elliston, B.S., Texas A&M University at College Station
Chair of Advisory Committee: Dr. Michael B. Pate

The Riverside Energy Efficiency Laboratory at Texas A&M University conducts sound quality testing for the Home Ventilating Institute. When the Home Ventilating Institute initially established their sound quality test, the semi-reverberant sound chamber to conduct the sound quality tests was built at the Riverside Energy Efficiency Laboratory. The Home Ventilating Institute created a standard to specify the procedure for sound quality testing. This standard contained high consideration for performance, reliability, and accuracy. The standard was based on several ANSI standards for sound testing procedures, sound setup and equipment standards, and sound rating calculations.

The Riverside Energy Efficiency Laboratory presently continues sound quality testing for the Home Ventilating Institute using the semi-reverberant sound chamber. The standard has been revised and updated due to developments for better sound quality test result representation. Resourceful data to assist with further developments comes from the semi-reverberant sound chamber's characteristics.

This thesis's purpose was to conduct an analysis of the performance for the semi-reverberant sound chamber. The sound chamber's sound transmission loss was determined using a fan source with known sound power across the 24 tested 1/3 octave frequency bands, 50 Hz – 10,000 Hz. The sound pressure was recorded inside the chamber and outside the chamber at the sound source. The sound source was placed at three different locations around the sound chamber. In addition, the sound pressure was measured in real time to study the amount of sound pressure fluctuation and maximum amplitude. The background noise was measured inside the sound chamber for these tests.

The sound transmission loss profiles were identical for each location. The lowest two 1/3 octave bands, 50 Hz and 63 Hz, have low transmission losses. The profile jumps up at the following 1/3octave band and increases with a peak around 1600 Hz before slightly decreasing. The profile of the sound pressure in the time domain showed similar results. The most fluctuation with the greatest peaks was present in the lower 1/3 octave frequency bands, and diminished the higher the 1/3 octave frequency band. Sound sources around the sound chamber can be evaluated to determine whether an impact is possible on the sound quality tests from these results. The impact of modifications to the sound chamber can use the transmission loss values to help determine the expected performance increase.

ACKNOWLEDGMENTS

I would first like to thank my committee chair, Dr. Michael Pate, for giving me the opportunity to work at the Riverside Energy Efficiency Laboratory.

I would also like to thank my committee members Dr. Bryan Rasmussen who encouraged me time and time again to pursue a graduate degree and Dr. Lynn Beason.

I would like to give my thanks to the Riverside lab staff Kelly Milligan, James Sweeney, and Kathryn Wadle for assisting me whenever it was possible. I would like to give my thanks to the graduate students, Shankar Ravi and Grant Wheeler, who worked with me on the sound chamber. I would like to give my thanks to all the other graduate students that have been present at some time during my time at the lab; they each successfully put up with my unique character. I would like to give a special thanks to Joshua Kading for his guidance with his sound background knowledge.

Last but not least, a full-hearted thanks goes out to all my family who supported me through all my endeavors.

NOMENCLATURE

HVI	Home Ventilating Institute
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
ANSI	American National Standards Institute
dB	Decibel
L_p	Sound Pressure Level (dB)
L_w	Sound Power Level (dB)
BKG	Background Noise
TL	Sound Transmission Loss
τ	Sound Transmission Coefficient

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CHAPTER I

INTRODUCTION

The Riverside Energy Efficiency Laboratory (REEL) conducts sound quality tests on home appliances whose functional purpose is to provide ventilation. REEL predominantly sound quality tests two types of appliances, bathroom/utility fans and range hoods. Testing is done in accordance with the Home Ventilating Institute (HVI) Loudness Testing and Rating Procedure standard. In 1970, HVI established the sound testing and rating procedure as an additional test to its already established airflow testing and rating procedure. HVI provides third-party performance results for manufacturer verification as well as qualification verification in order for manufacturers to meet the Department of Energy's (DOE) standard for Energy Star qualification. The test chamber used to conduct the sound quality tests is a semi-reverberant sound chamber. HVI choose Texas A&M University's REEL facility to construct the sound chamber and use as a model for the presented information listed in the test procedure standard.

To continue the resourceful development as HVI's model sound quality testing facility, an acoustic analysis was completed to provide performance characteristics for the semi-reverberant sound chamber. The two areas of focus were the sound transmission losses through the chamber's exterior surfaces and the time variation of sound present inside the chamber. These results would provide a performance evaluation for the semi-reverberant sound chamber, and also provide information to better progress any updates and addendums to the current test procedure.

This thesis follows the style of *ASHRAE Transactions.*

Chapter II discusses the previous work conducted on the semi-reverberant sound chamber as well as the motive for the work presented in this thesis. Chapter II will also discuss the acoustic principals applied in this thesis. Chapter III discusses the entire semi-reverberant sound chamber layout along with the instrumentation installed inside and outside the chamber. Chapter IV discusses the entire sound testing procedure followed at REEL including the details of the HVI standards and the calculations to obtain the sone rating. Chapter V discusses the sone threshold as applied to the semi-reverberant sound chamber. This quantifies the sound level needed to impact the test and a point to evaluate the chamber's performance from. Chapter VI discusses the analysis and results of the sound transmission loss test, and Chapter VII discusses the analysis and results of the time capture test.

CHAPTER II

BACKGROUND

The HVI Loudness Testing and Rating Procedure was established in order to provide a standard testing and certification program the ventilating product companies could use for product comparison. The semi-reverberant sound chamber was designed based on accomplishing the original testing standards. The sound quality test procedure has undergone a few changes including some to the test setup itself since the test was first established in 1970.

The chamber itself has remained identical to when it was first constructed although two recent changes include the testing microphones used and the testing check for background separation. The sound pressure measuring instrument originally consisted of a single microphone on a rotating boom. The single microphone and rotating boom were later replaced with a stationary six microphone array. Work on the semi-reverberant sound chamber was conducted by Shankar Ravi to justify the change from the single microphone and rotating boom to the six microphone array. He found the rotating motion with the single microphone and rotating boom added to the sound pressure recorded. This had minimal effect on the louder-perceived fans, but had significant sone impact on quieter fans (Ravi 2011). Another recent change made was the required ratio between the fan measurement and the background measurement. The ratio used to be a fixed difference across the frequency spectrum. It currently has a varying ratio depending on the frequency band.

Since the founding of the sound quality testing procedure, HVI has acquired additional laboratories for testing. There is importance when using different laboratories for identical testing to have identical results amongst the laboratories. A popular method for gauging the consistency amongst laboratories is round robin test. Another approach is to set a performance standard for the laboratory to meet. The REEL is currently HVI's mark for sound quality testing.

In an ideal world, the semi-reverberant sound chamber should create a perfect sound enclosure isolated from the rest of the world. In the actual world, sound transmits into the semi-reverberant sound chamber during testing. There have been days when background noise was perceived as too high and would distort any sound quality testing. The point of this unapproved testing has been based on judgment rather an exact engineering value. This thesis looks into creating a quantifiable performance value using the semi-reverberant sound chamber’s transmission loss. Too better evaluate the impact the transmitted sound of a sound source has on the test, the background sound was observed in the time domain.

Sound Pressure and Sound Power

Sound propagates through a medium in the form of waves. In air, the particles will form compressions, areas of high pressure and rarefactions, areas of low pressure as sound travels away from its source. Leaving aside the psychological interpretation of sound the human brain creates, sound can be described physically in two ways. The first physical description for sound is sound power. Sound power is the rate of acoustical energy given off by a sound source. Sound power is only dependent on the source and independent of the distance from the source and the source's surrounding environment. The second physical description for sound is sound pressure. Sound pressure is the pressure disturbance caused by the sound waves. Unlike sound power, sound pressure diminishes the farther the sound travels from the sound source; therefore, sound pressure is dependent on the source's surrounding environment and distance from the source. The range for sound pressure detectable by the human ear stretches from 0.00002 Pa to 100,000 Pa. Since this is a large range, the decibel representation is more commonly used instead (Everest 2001). The decibel representation for sound power is shown in Equation 1.

$$L_W = 10\log\left(\frac{W}{W_0}\right) \qquad \text{Eq. 1}$$

where $W_0 = 10^{-12}$ W is the reference power

Sound power is proportional to the square of sound pressure. The decibel representation for sound pressure is shown in Equation 2.

$$L_P = 10\log\left(\frac{P}{P_0}\right)^2 = 20\log\left(\frac{P}{P_0}\right) \qquad \text{Eq. 2}$$

where $P_0 = 20$ µPa is the reference pressure (ASHRAE 2005)

The reference pressure P_0 corresponds to the lower end of the range for the human ear. This pressure corresponds with the threshold of human hearing. Since decibels is a ratio and unitless representation for sound pressure, 20 µPa has become the standard reference pressure in air.

The relationship between sound power and sound pressure is dependent on the source's surrounding environment and distance from the source since this is true for sound pressure alone (Everest 2001). The relationship between sound pressure and sound power is shown in Equation 3 and Equation 4.

$$L_W = L_P - 10\log\left(\frac{1}{4\pi r^2}\right) \qquad \text{Eq. 3}$$

$$L_W = L_P - 10\log\left(\frac{2}{4\pi r^2}\right) \qquad \text{Eq. 4}$$

where r is the distance between the sound source and the point where sound pressure is measured.

Equation 3 is used when the source is present in a free field while Equation 4 is used when the source is centered on a surface so that the sound would radiate over half a sphere (ASHRAE 2005). A free field is a space where sound is allowed to freely expand in all directions. The sound is not reflected nor absorbed. An example would be a sound source in the middle of a literal open field assuming the source was far from the ground.

Literature Review

The HVI Loudness Testing and Rating Procedure standard is a continuously improving standard to provide consistent and accurate sound quality testing the ventilating product companies can depend on. HVI Loudness Testing and Rating Procedure standard currently provides a methodology for calculating a sone rating to meet this consistent and accurate testing goal. An excerpt taken from the HVI Loudness Testing and Rating Procedure standard summarizes the desire of the standard.

> "HVI Certification relies on ANSI consensus standards. HVI adds specific test procedures, designates a third-party laboratory, provides consistent calculations, oversees laboratory integrity, and certifies loudness ratings that recognize human psychoacoustic response.
>
> Using those loudness ratings, HVI operates a comprehensive sound certification program that includes independent verification by HVI and the opportunity for competitors to challenge. The result is a full-featured loudness certification program. Consistent ratings make it easy for designers and consumers to compare the loudness of HVI-Certified products and to be confident people will hear the products in the same relationship when installed. Because of its thoroughness and quality, HVI certification is recognized in codes and standards throughout North America, as well as most green-building programs.
>
> HVI requires a quiet background for testing. Reasons for a quiet background are obvious, but the degree of background separation and the methods for dealing with insufficiently quiet background vary between other organizations that control sound testing. (HVI 2009)"

This thesis will present performance analysis on the REEL semi-reverberant sound chamber by evaluating the sound transmission loss of the chamber and the time capture inside the chamber. With these evaluations, a better determination can be made when backgrounds are not quiet enough and threaten the consistent calculations for the sone rating.

CHAPTER III

SEMI-REVERBERANT SOUND CHAMBER SETUP

The semi-reverberant sound chamber is located in the southwest corner of the REEL at the Texas A&M riverside campus. The chamber is a self-enclosed room separated from any exterior wall of the REEL. The floor is raised off the REEL floor. The chamber's interior dimensions are approximately 25 ft. x 20 ft. x 12 ft. with a volume of 6,000 cubic feet. The chamber has four openings: the inlet air duct, the outlet air duct, a walk-in door, and a pvc pipeline passage for the power and microphone cords. The pvc pipeline passage is sealed on both ends with a high density putty. The inside of the chamber contains the tested fan, the six microphones, the RSS, and the baffles. The baffles are situated in each of the chamber's corners to help create a diffuse field inside the chamber. The outlet air duct runs out of an anechoic chamber affixed to the side of the semi-reverberant chamber. The walls, floor, and ceiling were built to reduce all exterior sound waves from transmitting into the chamber interior. A top view of the entire chamber layout is shown in Figure 1.

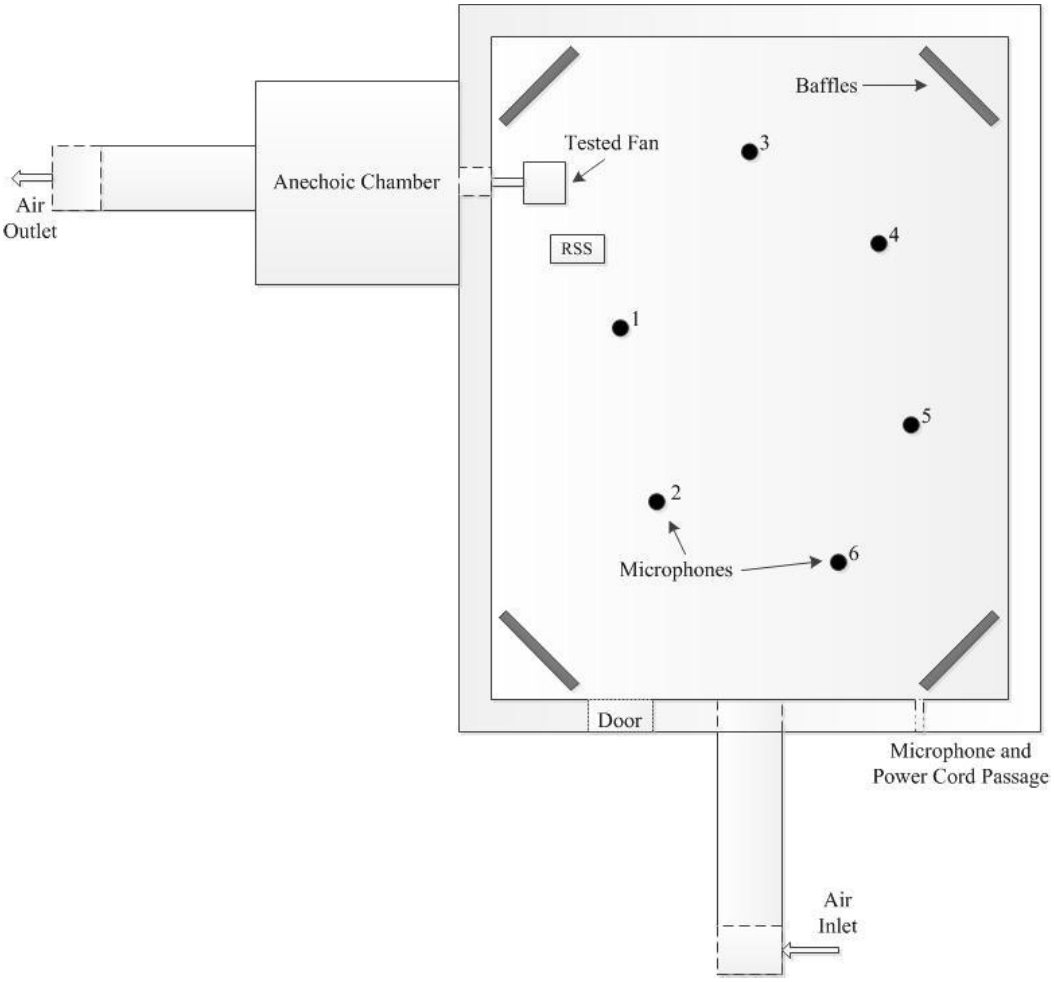


Figure 1. Schematic of the Semi-Reverberant Sound Chamber

To better show the layout of the semi-reverberant sound chamber, Figure 2 and Figure 3 show the inside of the sound chamber from the view when walking through the door. Figure 2 shows the inside of the door's right side. Panning left gives the image shown in Figure 3. The construction material and material thicknesses are presented in Table 1 (Ravi 2011). The materials are listed in the order they were constructed from the chamber interior to the chamber exterior. The floor, wall, and ceiling were constructed with different materials and each have a different total thickness.

Figure 2. Sound Chamber from Door's Right View

Figure 3. Sound Chamber from Door's Left View

Table 1. Construction Materials for the Semi-Reverberant Sound Chamber

Location	Material	Thickness (inches)
	FLOOR	
Chamber Interior	Concrete	Not Available
	Sand	20
Chamber Exterior	Concrete	5
	WALLS	
Chamber Interior	Sheet Rock	0.625
	Plywood	0.5
	2" x 6" Construction	Not Available
	Plywood	0.75
	Rockwool Insulation	2.0
Chamber Exterior	Concrete	Not Available
	ROOF	
Chamber Interior	Sheet Rock	0.625
	Plywood	0.5
	2" x 8" Construction	Not Available
	Sheet Rock	0.5
Chamber Exterior	Lead	0.0625

The semi-reverberant sound chamber was built to isolate the sound energy present inside the chamber from the sound energy outside the chamber while still allowing air to flow through the chamber (ANSI 2002). During testing operations, the interior of the chamber contains the tested fan, the six microphone array, the reference sound source (RSS), baffles in each corner, and all power and microphone cords. The inlet air duct has a sound muffler to reduce sound entering the semi-reverberant chamber. The exiting side of the semi-reverberant chamber leads into an anechoic chamber, this prevents echoing sounds from the fan reflecting back into the semi-reverberant chamber as well as preventing any sound entering through the air outlet duct.

Dampers are used at both the inlet and outlet ducts to assist with regulating the static pressure the fan is tested at. In addition, the entrance of the inlet air duct is a rigid wooden structure containing an assist blower; the assist blower is sometimes run in order to achieve the desired static pressure.

Instrumentation

The instrumentation used measures sound pressure inside the semi-reverberant sound chamber and feeds the data to the sound station computer. The hardware used for recording the sound measurements is manufactured by Brüel & Kjær. Brüel & Kjær is an international company that specializes in manufacturing hardware and software for sound and vibration testing applications. The hardware equipment includes the six microphones, the six preamplifiers, all microphone cords, the PULSE data analyzer, and sound level calibrator.

The six microphone array is the combination of the microphone and preamplifier assembly attached to one end of the microphone cord. This cord runs through the semi-reverberant sound chamber's wall and attached to one of the six channel inputs of the PULSE data analyzer. The PULSE data analyzer is connected directly to the designated sound station computer via an Ethernet cord. The sound level calibrator is a portable calibrator used before testing to calibrate each microphone individually. The sound level calibrator fits flushed over the top of the microphone and has an activation button to emit 93.8 dB @ 1000 Hz for ½" microphones for 30 seconds (ANSI 2005).

The RSS is a fan with predetermined sound power levels. The purpose of the RSS is to provide a sound recording that can be used to generate the profile for the semi-reverberant sound chamber's acoustic characteristics that are then used to compare to the tested fan. REEL annually sends the hardware to West Caldwell Calibration Laboratories Inc. for calibration. The RSS's designated location is next to the testing fan's zone as shown in Figure 1.

The remaining equipment includes the tachometer and multi-meter. The tachometer is used to read the RPM of the testing fan. The tachometer wire is relayed through the wall along with the microphone cords. The multi-meter is used to read the voltage sent to both the tested fan and the RSS. The multi-meter is International Organization for Standardization (ISO) certified. All the hardware used is summarized in Table 2.

Table 2. Equipment for Sound Quality Tests

Instrumentation	Manufacturer	Type / Model Number
Microphone	Brüel & Kjær	Type 4190
Preamplifier	Brüel & Kjær	Type 2669
PULSE Data Analyzer	Brüel & Kjær	Type 3560C
Sound Level Calibrator	Brüel & Kjær	Type 4230
Tachometer	Monarch	ACT - 3
Multimeter	Extech Instruments	EX470
Reference Sound Source	ILG Electric Ventilating Company	Model No. 17-05-066A

The software used to display the microphone readings is called PULSE. This software is also created by Brüel & Kjær. The PULSE data analyzer formats the data for PULSE. After the data is imported into the program, PULSE has several modules it can utilize to present the data. The version used on the sound testing computer is PULSE Labshop Version 11.1.0.58-2006-11-30 (PULSE 2006). PULSE is managed with a user interface toolbox called the Measurement Organizer. The Measurement Organizer allows the user to setup different plots for displaying the imported data. The selected module or data analysis method used is the constant percentage bandwidth (CPB) analyzer which performs

1/3 octave band analysis on each microphone individually. The PULSE user interface displays a separate window for each displayed microphone. The performed 1/3 octave band analysis looked at the frequencies from 50 – 10,000 Hz. The recorded decibel (dB) level for each frequency across the 1/3 octave spectrum is a 30 second average of each frequency band. These results are used in the sound quality assessment conducted at REEL in accordance with the HVI standard.

CHAPTER IV

SOUND TEST PROCEDURE

The sound test procedure used to evaluate the sound quality for the tested ventilated products involves a series of four consecutive sound measurements. Each measurement consists of a 30 second average of the 1/3 octave band analysis. The sound measurements recorded include a fan measurement, a background measurement, a RSS measurement, and a second background measurement in that order. The four measurements are taken quickly back-to-back to ensure a consistent background throughout the entire test procedure.

There are two programs running while the test is in progress. The first is the PULSE program, and the second is Microsoft Excel. The PULSE file opened contains the six microphone array configured under a CPB analyzer. This file is set to measure the 24 1/3 octave bands from 50 - 10,000 Hz. The microphones are checked for calibration with the sound level calibrator before testing. Adjustments to the microphones are under properties for each microphone individually. All other settings are already preset. Once a test is ready, PULSE is run. The averaged dB levels are displayed for each microphone across the measured frequency spectrum. The program automatically stops recording after 30 seconds. Figure 4 shows the PULSE interface.

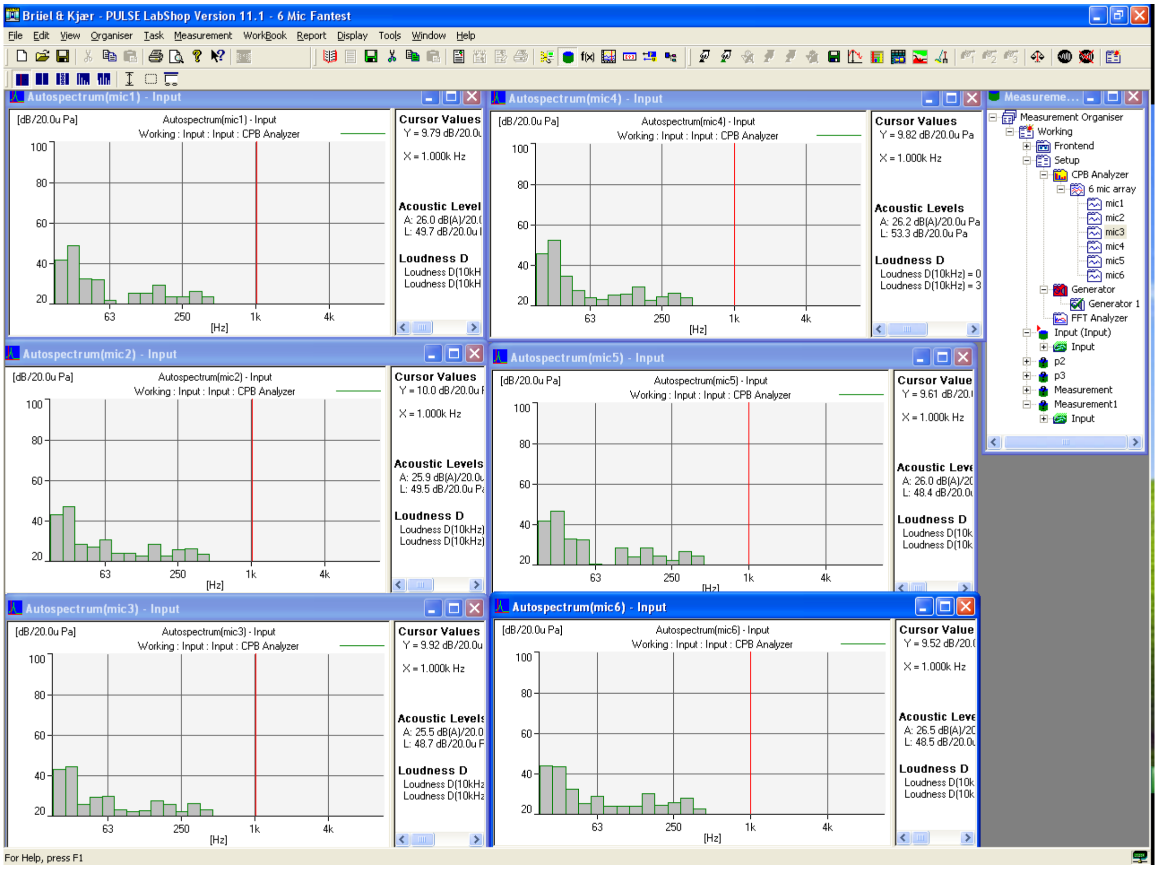
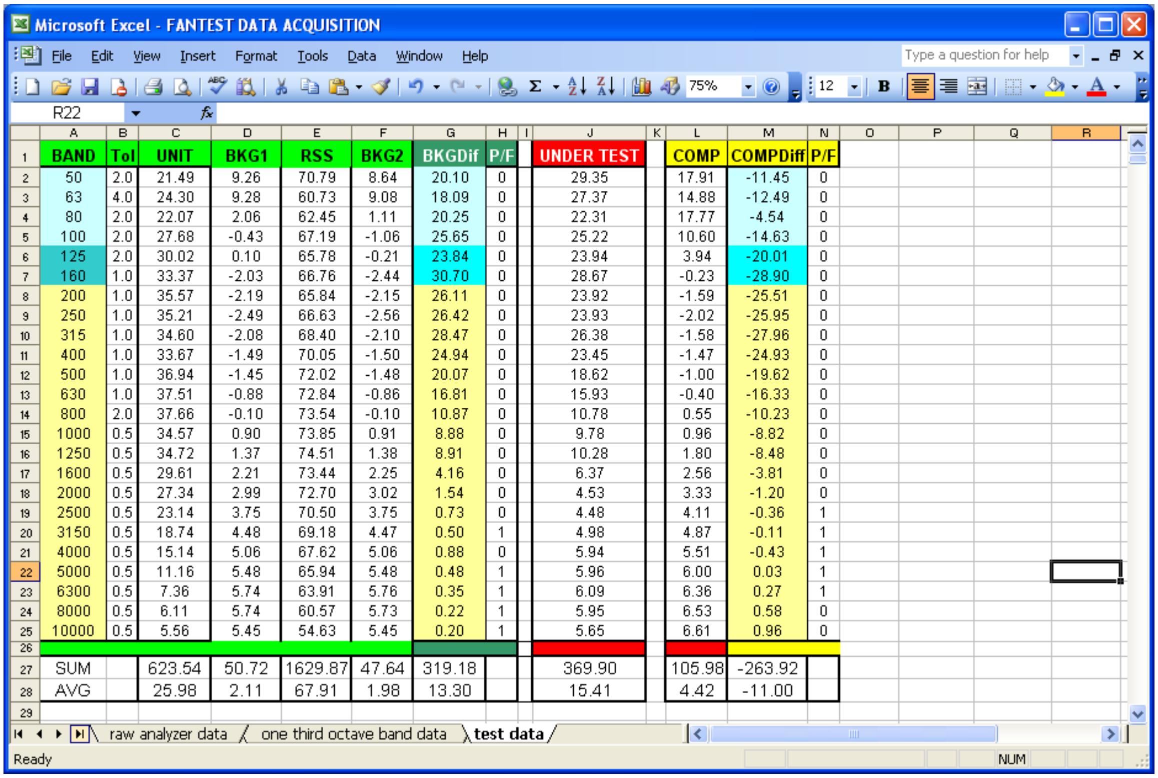


Figure 4. The PULSE Main Window with the Six Microphone Windows

The Microsoft Excel file is used as the database spreadsheet to store the data. PULSE is linked to the Excel file where the sound pressure readings are imported for each microphone. The Excel file then averages the six microphone array and displays a column of the averaged values on the main tab. Since there are occurrences where one of the four consecutive tests could be tested more than once, the current test values appear under the column ‘UNDER TEST’. The values are manually pasted into their respective test column so that a comparison can check the two background recordings for values within the appropriate tolerance for that frequency. Figure 5 shows the Microsoft Excel user interface.



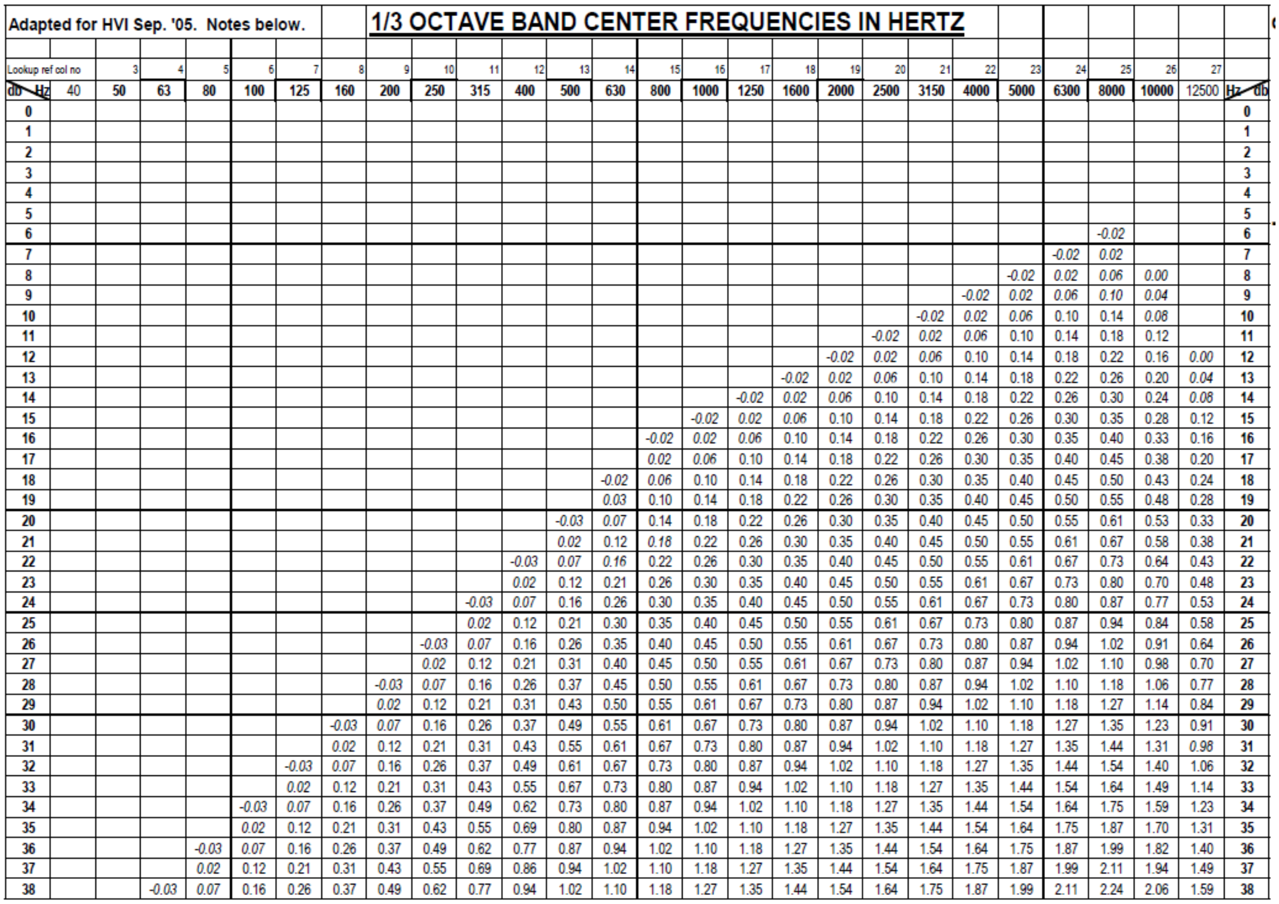
BAND	Tol	UNIT	BKG1	RSS	BKG2	BKGDif	P/F	UNDER TEST	COMP	COMPDiff	P/F
50	2.0	21.49	9.26	70.79	8.64	20.10	0	29.35	17.91	-11.45	0
63	4.0	24.30	9.28	60.73	9.08	18.09	0	27.37	14.88	-12.49	0
80	2.0	22.07	2.06	62.45	1.11	20.25	0	22.31	17.77	-4.54	0
100	2.0	27.68	-0.43	67.19	-1.06	25.65	0	25.22	10.60	-14.63	0
125	2.0	30.02	0.10	65.78	-0.21	23.84	0	23.94	3.94	-20.01	0
160	1.0	33.37	-2.03	66.76	-2.44	30.70	0	28.67	-0.23	-28.90	0
200	1.0	35.57	-2.19	65.84	-2.15	26.11	0	23.92	-1.59	-25.51	0
250	1.0	35.21	-2.49	66.63	-2.56	26.42	0	23.93	-2.02	-25.95	0
315	1.0	34.60	-2.08	68.40	-2.10	28.47	0	26.38	-1.58	-27.96	0
400	1.0	33.67	-1.49	70.05	-1.50	24.94	0	23.45	-1.47	-24.93	0
500	1.0	36.94	-1.45	72.02	-1.48	20.07	0	18.62	-1.00	-19.62	0
630	1.0	37.51	-0.88	72.84	-0.86	16.81	0	15.93	-0.40	-16.33	0
800	2.0	37.66	-0.10	73.54	-0.10	10.87	0	10.78	0.55	-10.23	0
1000	0.5	34.57	0.90	73.85	0.91	8.88	0	9.78	0.96	-8.82	0
1250	0.5	34.72	1.37	74.51	1.38	8.91	0	10.28	1.80	-8.48	0
1600	0.5	29.61	2.21	73.44	2.25	4.16	0	6.37	2.56	-3.81	0
2000	0.5	27.34	2.99	72.70	3.02	1.54	0	4.53	3.33	-1.20	0
2500	0.5	23.14	3.75	70.50	3.75	0.73	0	4.48	4.11	-0.36	1
3150	0.5	18.74	4.48	69.18	4.47	0.50	1	4.98	4.87	-0.11	1
4000	0.5	15.14	5.06	67.62	5.06	0.88	0	5.94	5.51	-0.43	1
5000	0.5	11.16	5.48	65.94	5.48	0.48	1	5.96	6.00	0.03	1
6300	0.5	7.36	5.74	63.91	5.76	0.35	1	6.09	6.36	0.27	1
8000	0.5	6.11	5.74	60.57	5.73	0.22	1	5.95	6.53	0.58	0
10000	0.5	5.56	5.45	54.63	5.45	0.20	1	5.65	6.61	0.96	0
SUM		623.54	50.72	1629.87	47.64	319.18		369.90	105.98	-263.92	
AVG		25.98	2.11	67.91	1.98	13.30		15.41	4.42	-11.00	

Figure 5. The Excel Tab Showing the Test Summary

Once all four tests are complete, the sone calculation is run with the recorded data and imported into the final airflow and sound report. The sone calculation is run through a program that applies the equal loudness index and rating calculation to the recorded data as stated in the HVI Loudness Testing and Rating Procedure.

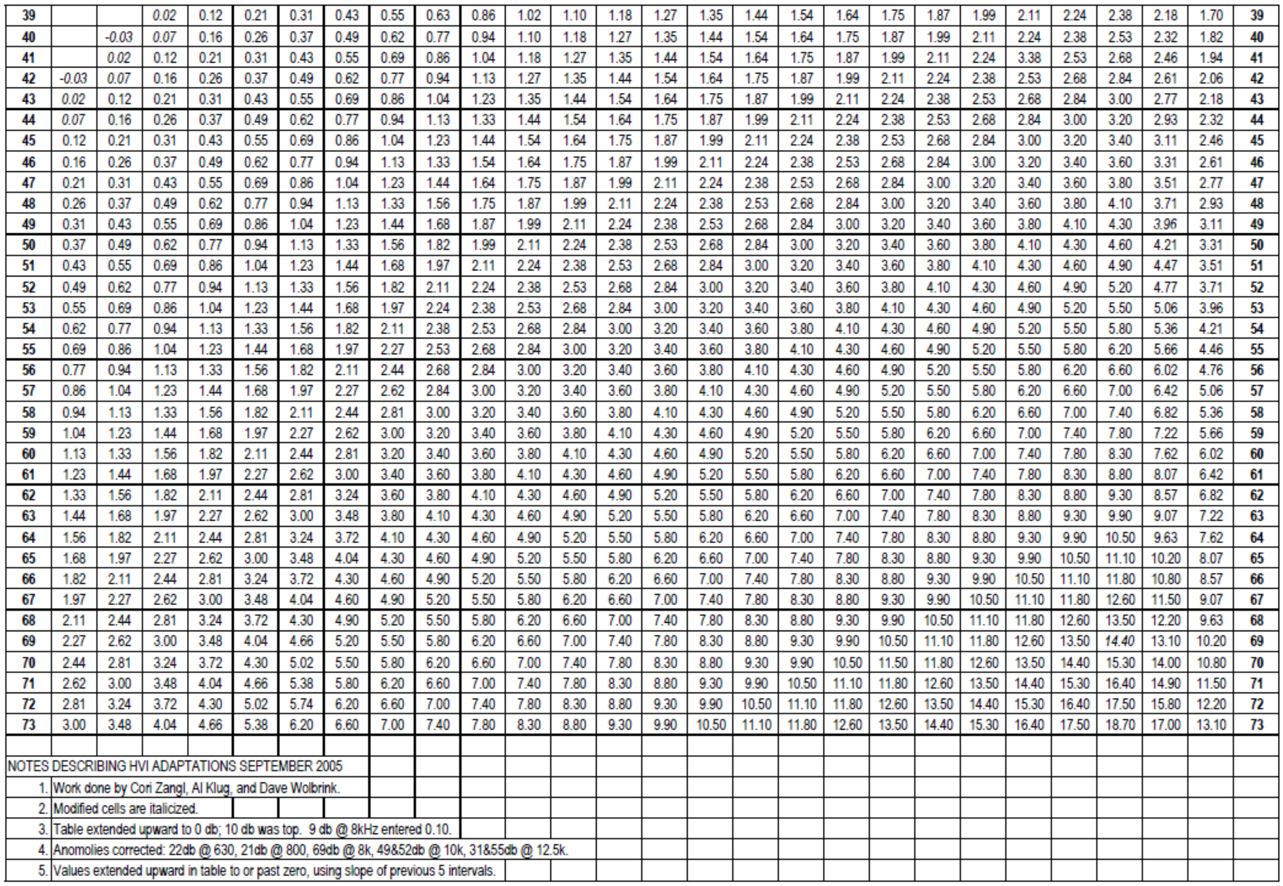
H.V.I. Standard

The HVI Loudness Testing and Rating Procedure provides full details for the equipment and setup, test procedure, and rating calculation. To compare product to product, the rating system established utilizes a scaling system with sone values, a unit of perceived loudness. Based on this rating system, a unit rated at two sones should be perceived as being twice as loud as a unit rated at one sone. The HVI Loudness Testing and Rating Procedure was formed using three ANSI standards: ANSI S12.51-2002 Determination of sound power levels of noise sources using sound pressure - Precision method for reverberation rooms, ANSI-AMCA 300-05 Reverberant Room Method for Sound Testing of Fans, and ANSI S3.4-1980 (R 2003) American National Standard: Procedure for the Computation of Loudness of Noise. The equal loudness index table used in the sone rating calculation is taken from ANSI S3.4 (HVI 2009). Figure 6 and Figure 7 show the entire index table.



Adapted for HVI Sep. '05. Notes below.								1/3 OCTAVE BAND CENTER FREQUENCIES IN HERTZ																			
Lookup ref col no		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
db Hz	40	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12500	Hz db
0																											0
1																											1
2																											2
3																											3
4																											4
5																											5
6																								-0.02			6
7																							-0.02	0.02			7
8																						-0.02	0.02	0.06	0.00		8
9																					-0.02	0.02	0.06	0.10	0.04		9
10																				-0.02	0.02	0.06	0.10	0.14	0.08		10
11																			-0.02	0.02	0.06	0.10	0.14	0.18	0.12		11
12																		-0.02	0.02	0.06	0.10	0.14	0.18	0.22	0.16	0.00	12
13																	-0.02	0.02	0.06	0.10	0.14	0.18	0.22	0.26	0.20	0.04	13
14																-0.02	0.02	0.06	0.10	0.14	0.18	0.22	0.26	0.30	0.24	0.08	14
15															-0.02	0.02	0.06	0.10	0.14	0.18	0.22	0.26	0.30	0.35	0.28	0.12	15
16														-0.02	0.02	0.06	0.10	0.14	0.18	0.22	0.26	0.30	0.35	0.40	0.33	0.16	16
17														0.02	0.06	0.10	0.14	0.18	0.22	0.26	0.30	0.35	0.40	0.45	0.38	0.20	17
18													-0.02	0.06	0.10	0.14	0.18	0.22	0.26	0.30	0.35	0.40	0.45	0.50	0.43	0.24	18
19													0.03	0.10	0.14	0.18	0.22	0.26	0.30	0.35	0.40	0.45	0.50	0.55	0.48	0.28	19
20												-0.03	0.07	0.14	0.18	0.22	0.26	0.30	0.35	0.40	0.45	0.50	0.55	0.61	0.53	0.33	20
21												0.02	0.12	0.18	0.22	0.26	0.30	0.35	0.40	0.45	0.50	0.55	0.61	0.67	0.58	0.38	21
22											-0.03	0.07	0.16	0.22	0.26	0.30	0.35	0.40	0.45	0.50	0.55	0.61	0.67	0.73	0.64	0.43	22
23											0.02	0.12	0.21	0.26	0.30	0.35	0.40	0.45	0.50	0.55	0.61	0.67	0.73	0.80	0.70	0.48	23
24										-0.03	0.07	0.16	0.26	0.30	0.35	0.40	0.45	0.50	0.55	0.61	0.67	0.73	0.80	0.87	0.77	0.53	24
25										0.02	0.12	0.21	0.30	0.35	0.40	0.45	0.50	0.55	0.61	0.67	0.73	0.80	0.87	0.94	0.84	0.58	25
26									-0.03	0.07	0.16	0.26	0.35	0.40	0.45	0.50	0.55	0.61	0.67	0.73	0.80	0.87	0.94	1.02	0.91	0.64	26
27									0.02	0.12	0.21	0.31	0.40	0.45	0.50	0.55	0.61	0.67	0.73	0.80	0.87	0.94	1.02	1.10	0.98	0.70	27
28								-0.03	0.07	0.16	0.26	0.37	0.45	0.50	0.55	0.61	0.67	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.06	0.77	28
29								0.02	0.12	0.21	0.31	0.43	0.50	0.55	0.61	0.67	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.14	0.84	29
30							-0.03	0.07	0.16	0.26	0.37	0.49	0.55	0.61	0.67	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.23	0.91	30
31							0.02	0.12	0.21	0.31	0.43	0.55	0.61	0.67	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.31	0.98	31
32						-0.03	0.07	0.16	0.26	0.37	0.49	0.61	0.67	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.40	1.06	32
33						0.02	0.12	0.21	0.31	0.43	0.55	0.67	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.49	1.14	33
34					-0.03	0.07	0.16	0.26	0.37	0.49	0.62	0.73	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.59	1.23	34
35					0.02	0.12	0.21	0.31	0.43	0.55	0.69	0.80	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.70	1.31	35
36				-0.03	0.07	0.16	0.26	0.37	0.49	0.62	0.77	0.87	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	1.82	1.40	36
37				0.02	0.12	0.21	0.31	0.43	0.55	0.69	0.86	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	1.94	1.49	37
38			-0.03	0.07	0.16	0.26	0.37	0.49	0.62	0.77	0.94	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.06	1.59	38

Figure 6. Part 1 of the Equal Loudness Index Table (ANSI 2003)



39			*0.02*	0.12	0.21	0.31	0.43	0.55	0.63	0.86	1.02	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.18	1.70	**39**
40		*-0.03*	*0.07*	0.16	0.26	0.37	0.49	0.62	0.77	0.94	1.10	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.32	1.82	**40**
41		*0.02*	0.12	0.21	0.31	0.43	0.55	0.69	0.86	1.04	1.18	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	3.38	2.53	2.68	2.46	1.94	**41**
42	*-0.03*	*0.07*	0.16	0.26	0.37	0.49	0.62	0.77	0.94	1.13	1.27	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	2.61	2.06	**42**
43	*0.02*	0.12	0.21	0.31	0.43	0.55	0.69	0.86	1.04	1.23	1.35	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	2.77	2.18	**43**
44	*0.07*	0.16	0.26	0.37	0.49	0.62	0.77	0.94	1.13	1.33	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	2.93	2.32	**44**
45	0.12	0.21	0.31	0.43	0.55	0.69	0.86	1.04	1.23	1.44	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.11	2.46	**45**
46	0.16	0.26	0.37	0.49	0.62	0.77	0.94	1.13	1.33	1.54	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.31	2.61	**46**
47	0.21	0.31	0.43	0.55	0.69	0.86	1.04	1.23	1.44	1.64	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	3.51	2.77	**47**
48	0.26	0.37	0.49	0.62	0.77	0.94	1.13	1.33	1.56	1.75	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	3.71	2.93	**48**
49	0.31	0.43	0.55	0.69	0.86	1.04	1.23	1.44	1.68	1.87	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	*3.96*	3.11	**49**
50	0.37	0.49	0.62	0.77	0.94	1.13	1.33	1.56	1.82	1.99	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.21	3.31	**50**
51	0.43	0.55	0.69	0.86	1.04	1.23	1.44	1.68	1.97	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	4.47	3.51	**51**
52	0.49	0.62	0.77	0.94	1.13	1.33	1.56	1.82	2.11	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	4.77	3.71	**52**
53	0.55	0.69	0.86	1.04	1.23	1.44	1.68	1.97	2.24	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.06	3.96	**53**
54	0.62	0.77	0.94	1.13	1.33	1.56	1.82	2.11	2.38	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	5.36	4.21	**54**
55	0.69	0.86	1.04	1.23	1.44	1.68	1.97	2.27	2.53	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	5.66	4.46	**55**
56	0.77	0.94	1.13	1.33	1.56	1.82	2.11	2.44	2.68	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	6.02	4.76	**56**
57	0.86	1.04	1.23	1.44	1.68	1.97	2.27	2.62	2.84	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	6.42	5.06	**57**
58	0.94	1.13	1.33	1.56	1.82	2.11	2.44	2.81	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	6.82	5.36	**58**
59	1.04	1.23	1.44	1.68	1.97	2.27	2.62	3.00	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	7.22	5.66	**59**
60	1.13	1.33	1.56	1.82	2.11	2.44	2.81	3.20	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	7.62	6.02	**60**
61	1.23	1.44	1.68	1.97	2.27	2.62	3.00	3.40	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	8.07	6.42	**61**
62	1.33	1.56	1.82	2.11	2.44	2.81	3.24	3.60	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	8.57	6.82	**62**
63	1.44	1.68	1.97	2.27	2.62	3.00	3.48	3.80	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	9.07	7.22	**63**
64	1.56	1.82	2.11	2.44	2.81	3.24	3.72	4.10	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	9.63	7.62	**64**
65	1.68	1.97	2.27	2.62	3.00	3.48	4.04	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	10.20	8.07	**65**
66	1.82	2.11	2.44	2.81	3.24	3.72	4.30	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	10.80	8.57	**66**
67	1.97	2.27	2.62	3.00	3.48	4.04	4.60	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	12.60	11.50	9.07	**67**
68	2.11	2.44	2.81	3.24	3.72	4.30	4.90	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	12.60	13.50	12.20	9.63	**68**
69	2.27	2.62	3.00	3.48	4.04	4.66	5.20	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	12.60	13.50	*14.40*	13.10	10.20	**69**
70	2.44	2.81	3.24	3.72	4.30	5.02	5.50	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.50	11.80	12.60	13.50	14.40	15.30	14.00	10.80	**70**
71	2.62	3.00	3.48	4.04	4.66	5.38	5.80	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	12.60	13.50	14.40	15.30	16.40	14.90	11.50	**71**
72	2.81	3.24	3.72	4.30	5.02	5.74	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	12.60	13.50	14.40	15.30	16.40	17.50	15.80	12.20	**72**
73	3.00	3.48	4.04	4.66	5.38	6.20	6.60	7.00	7.40	7.80	8.30	8.80	9.30	9.90	10.50	11.10	11.80	12.60	13.50	14.40	15.30	16.40	17.50	18.70	17.00	13.10	**73**

NOTES DESCRIBING HVI ADAPTATIONS SEPTEMBER 2005

1. Work done by Cori Zangl, Al Klug, and Dave Wolbrink.
2. Modified cells are italicized.
3. Table extended upward to 0 db; 10 db was top. 9 db @ 8kHz entered 0.10.
4. Anomolies corrected: 22db @ 630, 21db @ 800, 69db @ 8k, 49&52db @ 10k, 31&55db @ 12.5k.
5. Values extended upward in table to or past zero, using slope of previous 5 intervals.

Figure 7. Part 2 of the Equal Loudness Index Table (ANSI 2003)

The equal loudness index table indicates the perceived loudness by frequency. The table scales the loudness with the sound pressure present against the frequency band. As the sound pressure increases, so does the loudness value. The table also indicates the point at which the human ear perceives a particular frequency since a non-positive loudness value means there is no perceived sound. This threshold point for hearing perception differs amongst each 1/3 octave band frequency. At lower frequencies, the sound pressure level has to be relatively higher compared to the higher frequencies. As the frequency increases to 8,000 Hz, the sound level needed to perceive loudness decreases. The trend reverses after 8,000 Hz. The equal loudness index contains the tested frequency range of 50 – 10,000 Hz including the next 1/3 octave band frequency on each side of the range. The human hear is capable of detecting frequencies from 20 – 20,000 Hz, but most of the everyday noise falls into the tested range. Using the equal loudness index table, a sone rating can be calculated to represent the combination of perceived loudness across the tested frequency spectrum.

SONE Calculation

The sone calculation used at the REEL is in accordance to the one established in the HVI Loudness Testing and Rating Procedure manual. This methodology for calculating sones under HVI's manual differentiates amongst other institution's methodology. The HVI sone calculation is based on the sound pressure readings obtained from the sound test procedure and the sound power given for the RSS. The sone rating of the fan is supposed to represent what the fan solely produces under conditions expected in its normal application. The calculation steps are explained in full detail below to provide a better understanding of the sone value.

Once all four sound measurements are recorded and the sound quality test is complete, the sone calculation can be determined. The background measurements are first logarithmically subtracted from the fan and RSS measurements as shown in Equation 5 and Equation 6.

$$L_{p,fan} = [Fan + BKG] - [BKG] = 10\log\left(10^{L_{p,fan+BKG}/10} - 10^{L_{p,BKG}/10}\right) \qquad \text{Eq. 5}$$

$$L_{p,RSS} = [RSS + BKG] - [BKG] = 10\log\left(10^{L_{p,RSS+BKG}/10} - 10^{L_{p,BKG}/10}\right) \qquad \text{Eq. 6}$$

The RSS sound power is measured and determined by a third party company in their laboratory. The sound power values provided by the third party company are considered the calibrated sound power values for the RSS and constant.

$$L_{w,\ rss} = \text{RSS Calibration Data} \qquad \text{Eq. 7}$$

Since the sound power is known for the RSS, the RSS sound pressure measurements can be compared to give the acoustic characteristic for the semi-reverberant sound chamber. The room behavior is found from the room characteristic ratio (RCR) which arithmetically subtracts the measured RSS sound pressure from the calibrated RSS sound power.

$$\text{RCR} = L_{w,rss} - L_{p,rss} \qquad \text{Eq. 8}$$

The RCR can then be applied to a fan and used to calculate the fan power from just the sound pressure measurement. The RCR is added arithmetically to the measured fan sound pressure which will convert the fan sound pressure recording to fan sound power.

$$L_{w,fan} = L_{p,fan} + \text{RCR} \qquad \text{Eq. 9}$$

Once the fan sound power is determined, the sound pressure the fan produces can be determined based on the HVI setup conditions. The standard assumes the fan is 5 ft. from the center of the six microphone array and considers the acoustic field behavior as a spherical free field inside the chamber. The adjusted fan sound pressure is the fan sound power minus a constant, 14.65.

$$L'_{p,fan} = L_{w,fan} - 14.65 \qquad \text{Eq. } 10$$

where 14.65 can be determined using the distance term in Equation 3.

$$10\log\left(\frac{1}{4\pi r^2}\right) = 10\log\left(\frac{1}{4\pi(5\,ft.)^2}\right) = -14.65$$

(The 5 ft. was converted to meters for the calculation since the result is Pascals.)

The adjusted fan sound pressure represents what the sound pressure recording would be if the microphones were in the ventilating product's location. Sound pressure decreases as it travels through a medium. Since the microphones will read a lower sound pressure than the sound pressure exerted around the ventilating product, the sound pressure must be back calculated from the formula for the sound power and sound pressure relation in a free field. The adjusted fan sound pressure recording is then used to find the equal loudness index for each band, s, obtained from the HVI equal loudness index table. Once all the equal loudness indices have been obtained, the sone rating is determined using the formula in Equation 11.

$$\text{Sone} = 0.85*[\text{s\_max}] + 0.15*[\text{sum(s)}] \qquad \text{Eq. } 11$$

Since the sone rating is awarded to the fan, it is important for the background not to contribute to this value (HVI 2009). This is why a constant background is ideal although this is not realistic. The semi-reverberant sound chamber's floor, walls, and roof were built to counteract background fluctuations. A more in-depth analysis on the background fluctuations is evaluated in Chapter VII Time Capture.

CHAPTER V

SEMI-REVERBERANT SOUND CHAMBER SONE THRESHOLD

The sone value used to rate the loudness perceived by the human ear is based on the equal loudness index chart. This chart shows each rating value given to each sound pressure level and 1/3 octave band frequency. Since a positive value is needed to show the magnitude of loudness, a threshold profile across the frequency spectrum for when the sound pressure is great enough for loudness to be perceived. The factor that will alter the equal loudness index profile for sone contributing sound pressure readings is the semi-reverberant sound chamber's acoustic characteristics. As detailed in the sone calculation, the RCR is calculated based on the chamber profile from the RSS sound pressure measurements. The minimal sound pressure needed to correlate to a positive value or an audible loudness from the equal loudness index can be considered of as the threshold to human ear response. Figure 8 shows the threshold for sound pressure across the frequency spectrum needed to produce a greater than zero sone contribution for each frequency band in the semi-reverberant sound chamber.

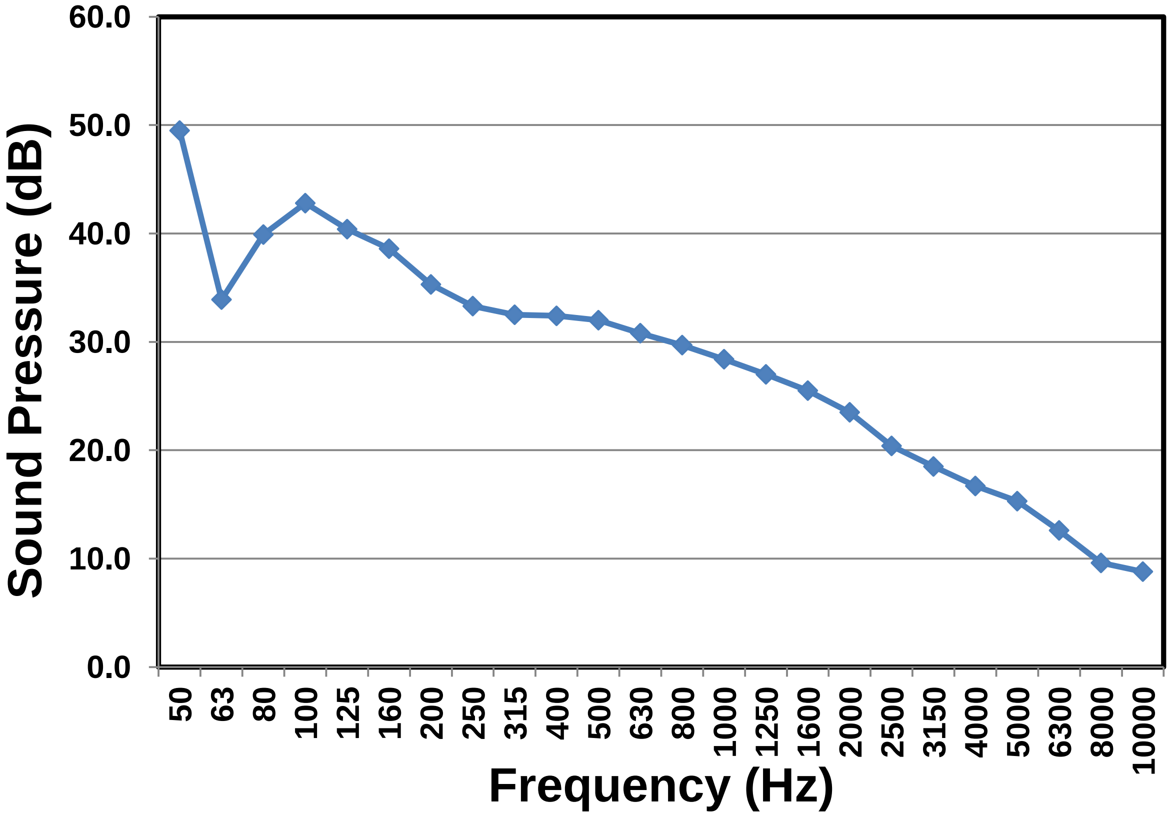


Figure 8. Zero Sone Threshold for the Semi-Reverberant Sound Chamber

This profile represents the sound pressure (dB) level threshold for a measured device inside the semi-reverberant sound chamber to be considered audible and contribute to the total sone rating. The profile is different than the equal loudness index threshold since the chamber alters this to fit the acoustical characteristics of the chamber. Anything under the curve does not have sufficient loudness to add to the total sone rating.

CHAPTER VI

SOUND TRANSMISSION LOSSES

To better quantify the performance of the semi-reverberant sound chamber, the transmission loss was determined across the 50 – 10000 Hz range. The approach taken uses sound power. In order to determine the transmission loss, the sound power on both sides of the chamber is needed. The sound power is known for the RSS whose values are obtained from the calibration report was used as a sound power source. The distance from the sound source to the receiving microphones was measured. The only calculation needed was the sound power reaching the sound receiving device.

The transmission loss represents the amount of sound energy lost from passing through a partition. The transmission loss can be mathematically described as ten times the logarithm of the ratio between the incident sound power on a material divided by the transmitted sound power through a material (Grimm and Rosaler 1997). Equation 12 shows the equation for the sound transmission loss.

$$TL = 10 \log (1/\tau) \qquad \text{Eq. 12}$$

where τ is the sound transmission coefficient and defined in Equation 13 as (ASTM 2009)

$$\tau = W_{rec} / W_{source} \qquad \text{Eq. 13}$$

Substituting Equation 13 into Equation 12 and then using Equation 1 to convert sound power into decibel notation, the result becomes Equation 14.

$$TL = L_{w,out} - L_{w,in} \qquad \text{Eq. 14}$$

The sound transmission loss calculation was used for each 1/3 octave frequency band. This provides a performance value for each individual frequency.

There are performance ratings given to partitions called Sound Transmission Class (STC) ratings. These ratings provide a simple method to gauge the sound transmission loss of a wall with a single number. A higher STC ranking performs better than a lower STC ranking although the lower STC is capable of providing a better transmission reduction at a specific frequency; the higher STC should provide a higher overall transmission reduction than a lower STC across all frequencies. The problem with this rating system is there is no way to know what the exact sound transmission loss is at a certain frequency (Crocker 2007). The transmission loss results gathered for the semi-reverberant sound chamber present the exact transmission loss across the tested frequency spectrum. This will allow for a better evaluation since it can be identified which frequencies perform better than others.

Transmission Loss Test Setup

The test setup equipment used to determine the transmission loss across the semi-reverberant sound chamber included the six microphone array, the PULSE data analyzer, PULSE, and the RSS. The RSS was placed at three different locations outside the semi-reverberant sound chamber along with three of the microphones while three microphones were kept inside the chamber. The microphones moved outside were selected so that the remaining three microphones were as best from their designated locations equally spaced around the center of the chamber. The microphones moved outside were spaced around the RSS in such a manner as to avoid being less than ten feet from a wall but still equally spaced surrounding the RSS. This was to avoid significantly larger reflections from the semi-reverberant sound chamber's surface on the microphone positioned next to the wall compared to the other microphones. Figure 9 shows RSS and three microphones outside the semi-reverberant sound chamber for location 1.

Figure 9. Transmission Loss Setup Outside the Semi-Reverberant Sound Chamber

Each microphone was measured from the microphone receiver to the RSS. The distances were manually measured using a tape measure in one dimension based on a xyz coordinate system and then solved for the diagonal distance. To determine the distance for the three microphones inside the chamber, the microphones were measured from the receiver to a reference point inside the chamber. Using the dimensions of the chamber and the distance measured outside the chamber, the distance for the three microphones inside the chamber could be determined. For each of the three outside locations the RSS was placed, the outside microphones were placed in the same relative position to the RSS for consistency. Table 3 lists the distances for each microphone to the RSS at location 1, Table 4 lists the distances for each microphone to the RSS at location 2, Table 5 lists the distances for each microphone to the RSS at location 3. Three recordings were taken at each location.

Table 3. Distances from Microphone to RSS for Location 1

Microphone Number	Distance (inches)
1	94
2	288.5
3	428.75
4	82.75
5	349.25
6	82.75

Table 4. Distances from Microphone to RSS for Location 2

Microphone Number	Distance (inches)
1	94
2	297.5
3	408.0
4	82.75
5	389.5
6	82.75

Table 5. Distances from Microphone to RSS for Location 3

Microphone Number	Distance (inches)
1	94
2	310.5
3	387.5
4	82.75
5	398.5
6	82.75

Transmission Loss Results

Using the sound pressure measurements and measured distance between each microphone receiver and the RSS, the measured sound power could be determined. Since microphones are only capable of reading sound pressure, Equation 4 was used to convert sound pressure to sound power. Equation 4 was used over Equation 3 because the RSS was located on the floor creating a hemisphere for the radiated sound from the RSS. This calculation was conducted for each microphone individually. The set of three outside microphones and the set of three inside microphones were each logarithmically averaged to obtain a single outside and inside value for comparison with each other and the calibrated sound power value provided for the RSS at each 1/3 octave band.

The measured sound power in dB for each microphone across frequency spectrum along with the calibrated RSS is shown for each location. Figure 10 shows the sound power calculations for location 1, Figure 11 shows the sound power calculations for location 2, and Figure 12 shows the sound power calculations for location 3.

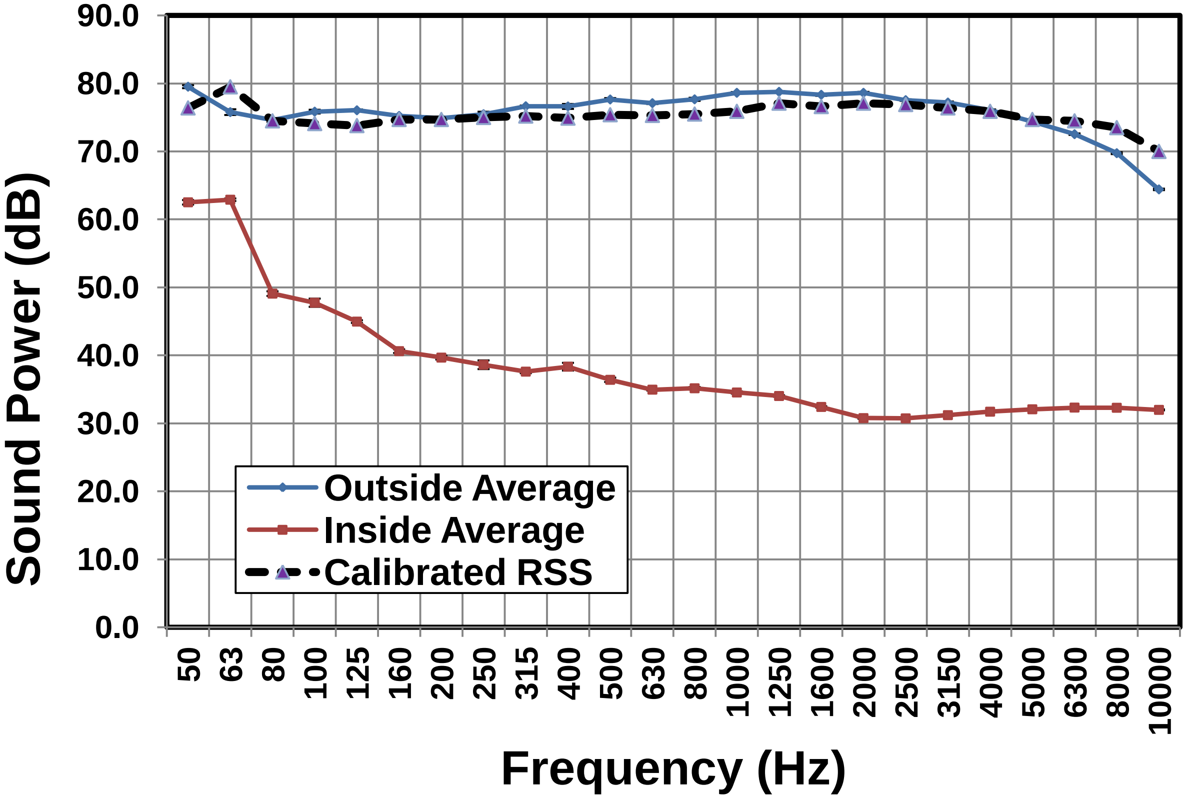


Figure 10. Averaged Sound Power Calculations for Location 1

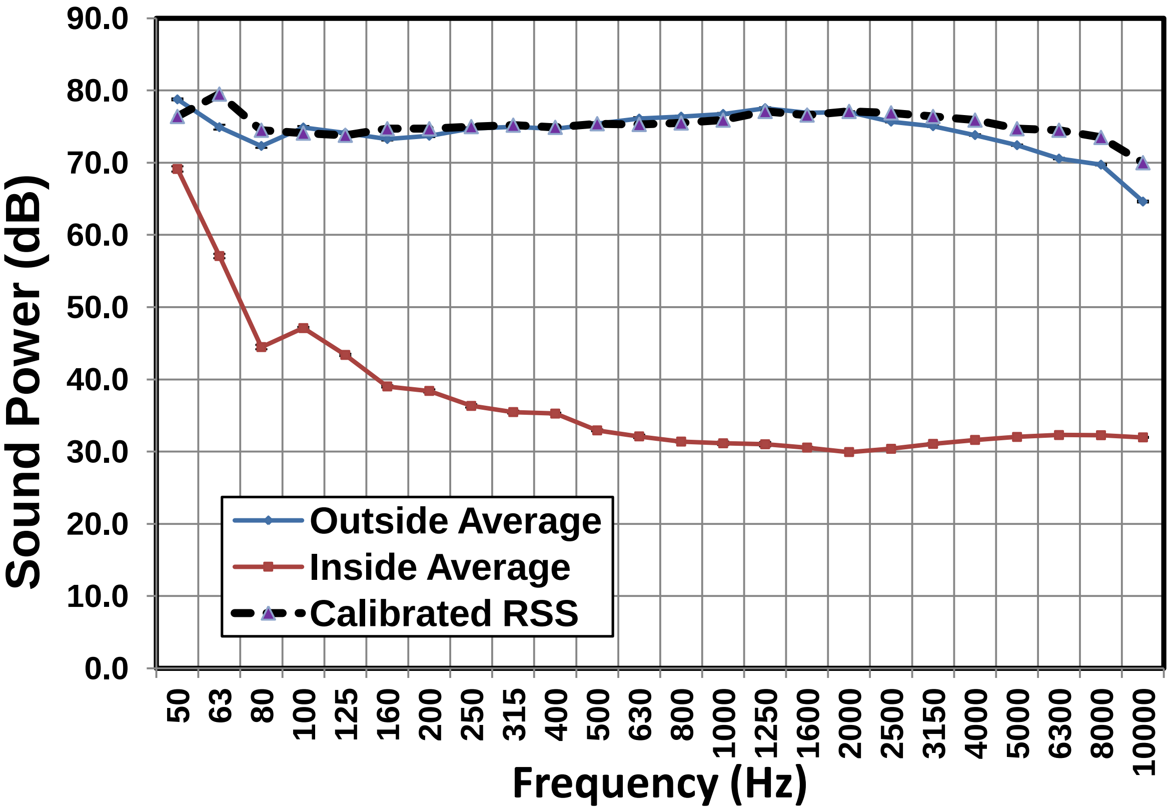


Figure 11. Averaged Sound Power Calculations for Location 2

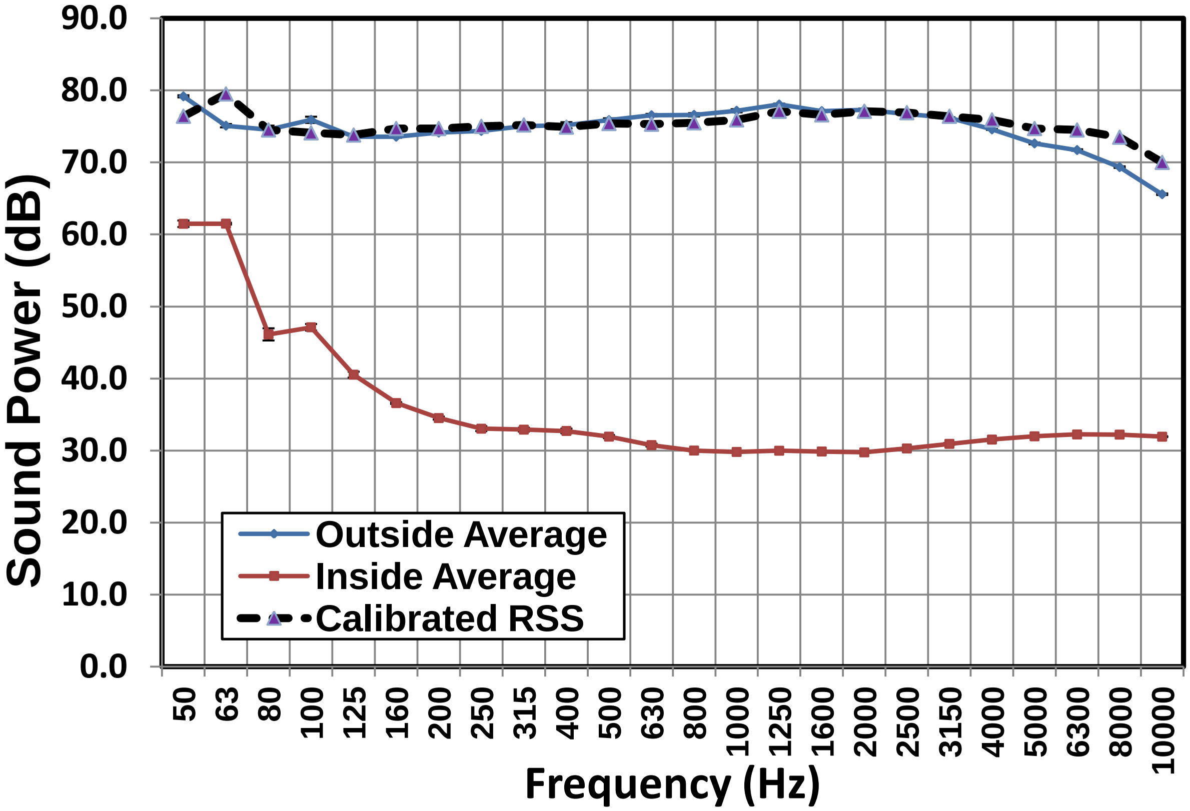


Figure 12. Averaged Sound Power Calculations for Location 3

The results show the three outside microphones correlating closely with the RSS, less than 1% for most of the 1/3 octave bands and less than 10% for the 1/3 octave bands at the ends of the frequency range.. The sound power determined with the outside microphones should match the RSS since sound power is not affected by distance and there should be no loss between the RSS and the three outside microphones. The three microphones inside the semi-reverberant sound chamber fall below those values since there is some sound energy absorbed by the chamber's walls. Several measurements were recorded at each location. Under a 95% confidence interval the uncertainty was performed for the sound power calculations. The figures were labeled with error bars ending with caps.

The transmission loss was calculated with Equation 14 using the logarithmically averaged values for each 1/3 octave frequency band. The sound transmission loss at each 1/3 octave frequency band is presented for each location. Figure 13 shows the transmission loss for location 1, Figure 14 shows the transmission loss for location 2, and Figure 15 shows the transmission loss for location 3.

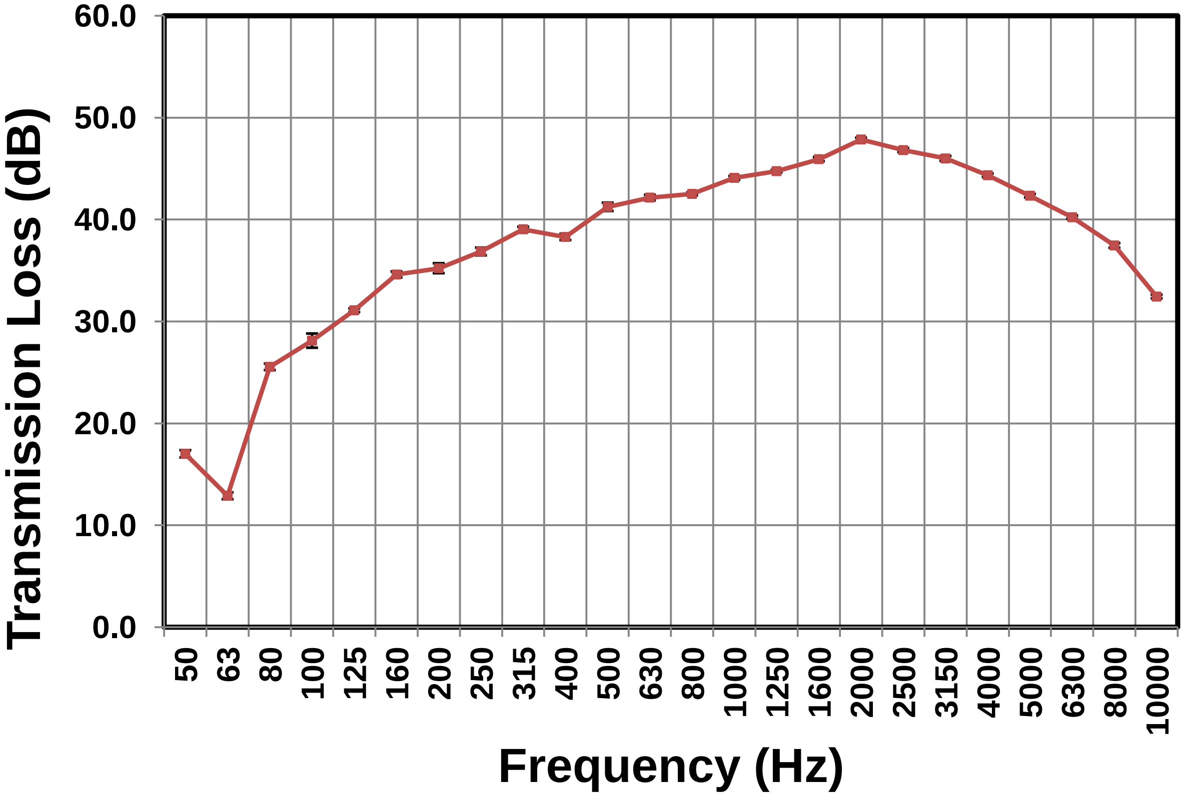


Figure 13. Determined Transmission Loss at Location 1

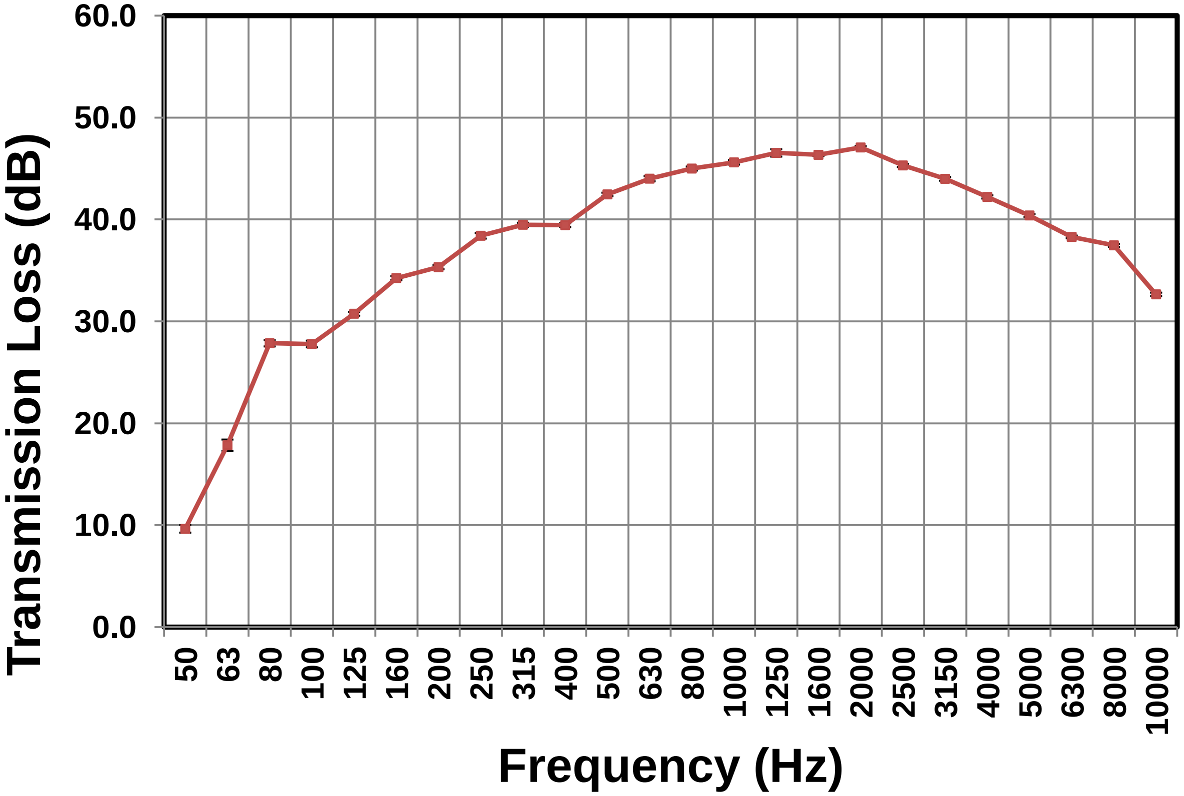


Figure 14. Determined Transmission Loss at Location 2

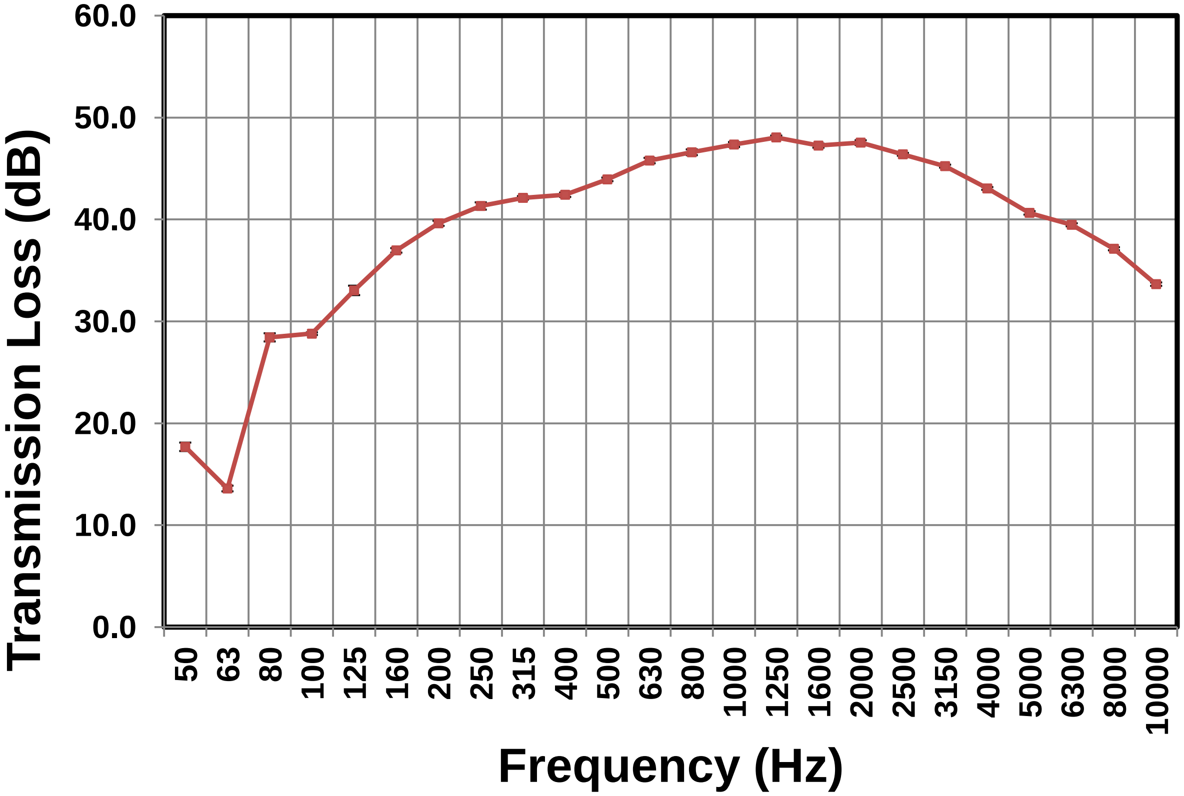


Figure 15. Determined Transmission Loss at Location 3

Under a 95% confidence interval the uncertainty was performed for the sound transmission calculations. The figures were labeled with error bars ending with caps. Comparing the entire frequency spectrum, the sound transmission loss for higher frequencies was greater than the transmission loss at lower frequencies. This was to be expected since lower frequencies travel through materials with more ease than higher frequencies. The three locations have slight variations from each other, but overall show the same profile. The discrepancies are most likely because some sides of the semi-reverberant chamber are not identical to the others. This is due to several factors: the door, the inlet and outlet airflow ducts, and the reverberation and reflection from the REEL building. There are points of strength and weakness for sound transmission through the semi-reverberant sound chamber. The anechoic chamber affixed to the east wall provides more sound transmission reduction while the pvc passage is a weak point for sound transmission. Looking amongst all three results, an overall transmission loss can be given for the semi-reverberant sound chamber for each frequency band. The transmission loss obtained provides quantifiable values for the acoustical performance for the semi-reverberant sound chamber that may be used for evaluating modifications for the chamber as well as the impact of sound sources present outside the sound chamber.

CHAPTER VII

TIME CAPTURE

Time capture is a measurement of sound pressure levels in real time. The sound test procedure looks at a 30 second averaged timeframe. To better glimpse into the real time fluctuation for each frequency, time capture measurements were evaluated. The current Brüel & Kjær software currently does not have the time module which would allow the use of the six microphone array. Since REEL previously used LabVIEW in conjunction with a sound and vibration measurement data acquisition card for sound quality testing, that was an available alternative and used instead.

The instrumentation used included an ACO Pacific microphone and preamplifier, its connected microphone cords, and a National Instrument (NI) PCI card. The ACO Pacific microphone is a free field microphone like the Brüel & Kjær microphones. The NI PCI card is a data acquisition card for sound measurements. The card has eight available channels as well as onboard filters. Like the Brüel & Kjær microphones, the ACO Pacific microphone cord feeds through the semi-reverberant sound chamber's wall where it connects to the PCI card and feeds into the computer. Table 6 summarizes the equipment list.

Table 6. Equipment for Time Capture Test

Instrumentation	Manufacturer	Type / Model Number
Microphone	ACO Pacific	Model 4012
Preamplifier	ACO Pacific	Model 4012
Signal Acquisition Board	National Instruments	NI PCI-4472
Tachometer	Monarch	ACT - 3
Multimeter	Extech Instruments	EX470
Sound Level Calibrator	Brüel & Kjær	Type 4230
Reference Sound Source	ILG Electric Ventilating Company	Model No. 17-05-066A

The software used with the time capture hardware was LabVIEW. LabVIEW is National Instruments's software program designed to manage instrumentation applications. The hardware to software connection is established in NI's Measurement and Acquisition program. This allows LabVIEW to recognize the installed hardware on the computer and set up channels for inputs into the program. The VI file created takes input from the NI PCI card and runs the measurement through a 1/3 octave band analysis in real time. The VI records the sound pressure (dB) across the measured 1/3 octave bands and stores the data in an array. The VI is set to a sampling rate of 51,600 samples per second. This is to ensure the capture of the highest frequency recorded, 10,000 Hz. The VI adds more and more recordings into the array as the programs runs. The VI construction is shown in Figure 16, and the user interface is shown in Figure 17.

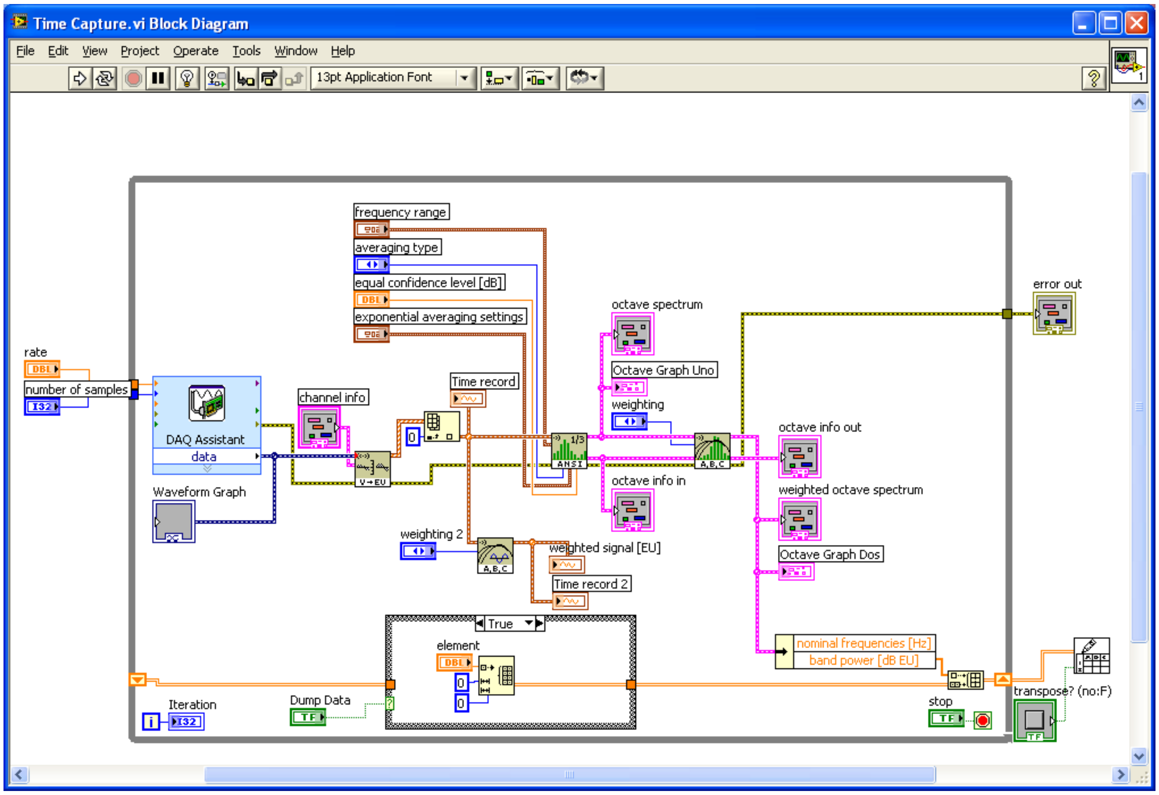
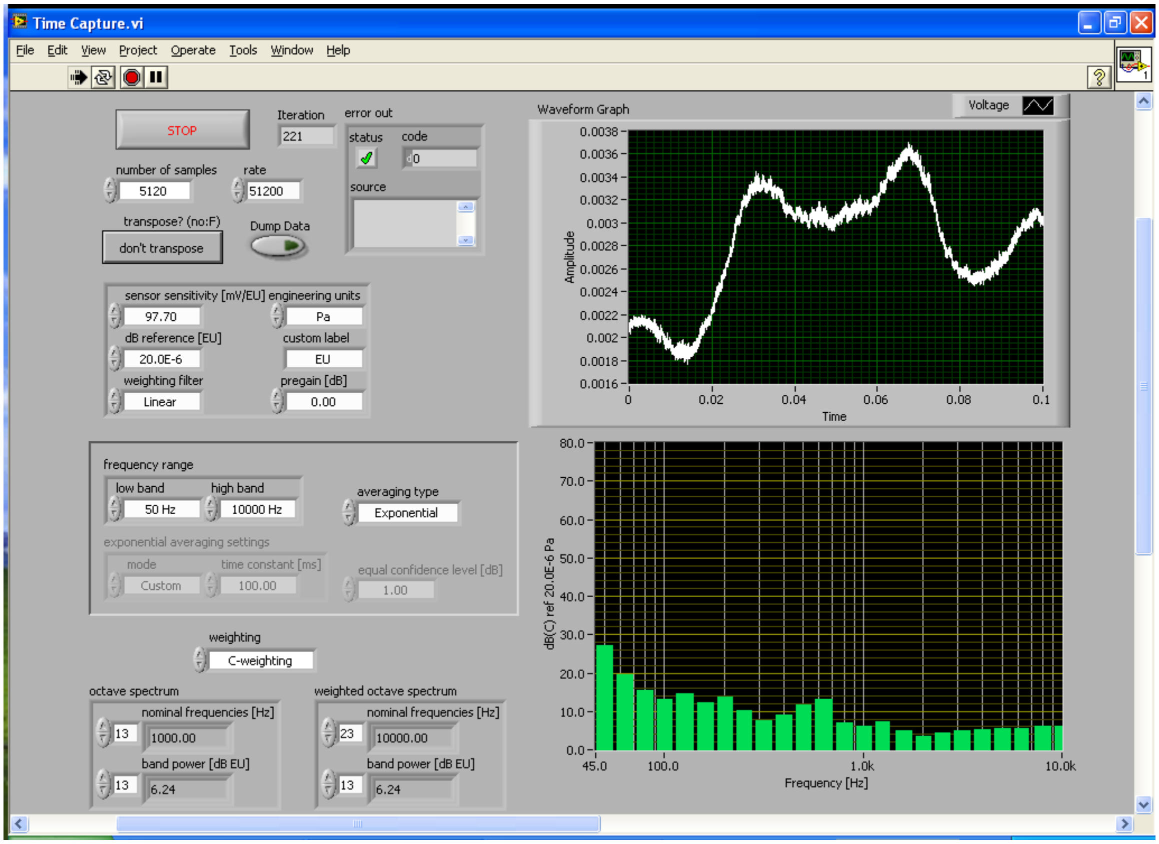


Figure 16. VI Block Diagram Showing Inputted Measurements



Iteration: 221

error out: status ✓; code 0; source

number of samples: 5120

rate: 51200

transpose? (no:F): don't transpose

sensor sensitivity [mV/EU]: 97.70

engineering units: Pa

dB reference [EU]: 20.0E-6

custom label: EU

weighting filter: Linear

pregain [dB]: 0.00

frequency range: low band 50 Hz; high band 10000 Hz

averaging type: Exponential

exponential averaging settings: mode Custom; time constant [ms] 100.00

equal confidence level [dB]: 1.00

weighting: C-weighting

octave spectrum: nominal frequencies [Hz] 13 1000.00; band power [dB EU] 13 6.24

weighted octave spectrum: nominal frequencies [Hz] 23 10000.00; band power [dB EU] 13 6.24

Figure 17. VI User Interface Displaying the Microphone Window

The measurements were taken inside the semi-reverberant sound chamber since the time variant profile would represent the measured fluctuation during a sound quality test. The ACO Pacific microphone was situated in the center of the chamber to best capture an average sound pressure value across the frequency spectrum. On three separate days, five time capture measurements were taken of the background only. The results were compared amongst the three days.

Time Capture Results

The time capture measurements can be as long or as short as desired since the VI runs until it is manually stopped. The goal was to record a long enough measurement that would accurately represent the background at that time. While the VI is running, the measurements are recorded into an array of data. The array stores the sound pressure at each time increment for each frequency band. When the VI program stops executing, a file is created with the array of data containing the measured sound pressure. This file is inputted into an Excel file that imports the data and displays plots of sound pressure versus time for each 1/3 octave band. Figure 18 shows a 30 second recording of the variation present across all 1/3 octave band frequencies. To show consistent representation in the background Figure 20 and Figure 21 in the Appendix show additional measurements. To better present the magnitude of the variation at each 1/3 octave band, Figure 19 shows the total difference between the highest and lowest sound pressure measurement at each 1/3 octave band.

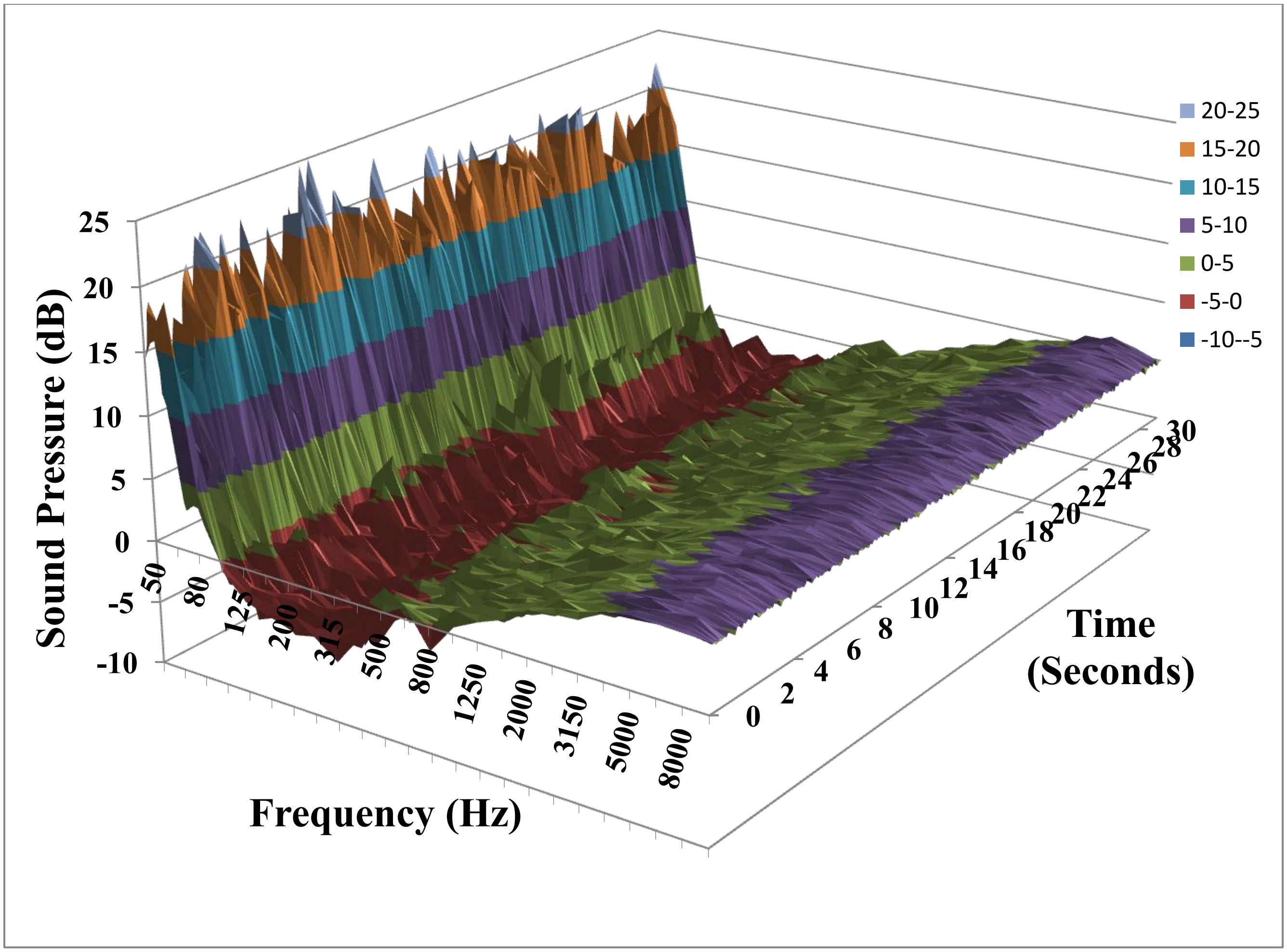


Figure 18. Sound Pressure Fluctuation for 30 Second Measurement

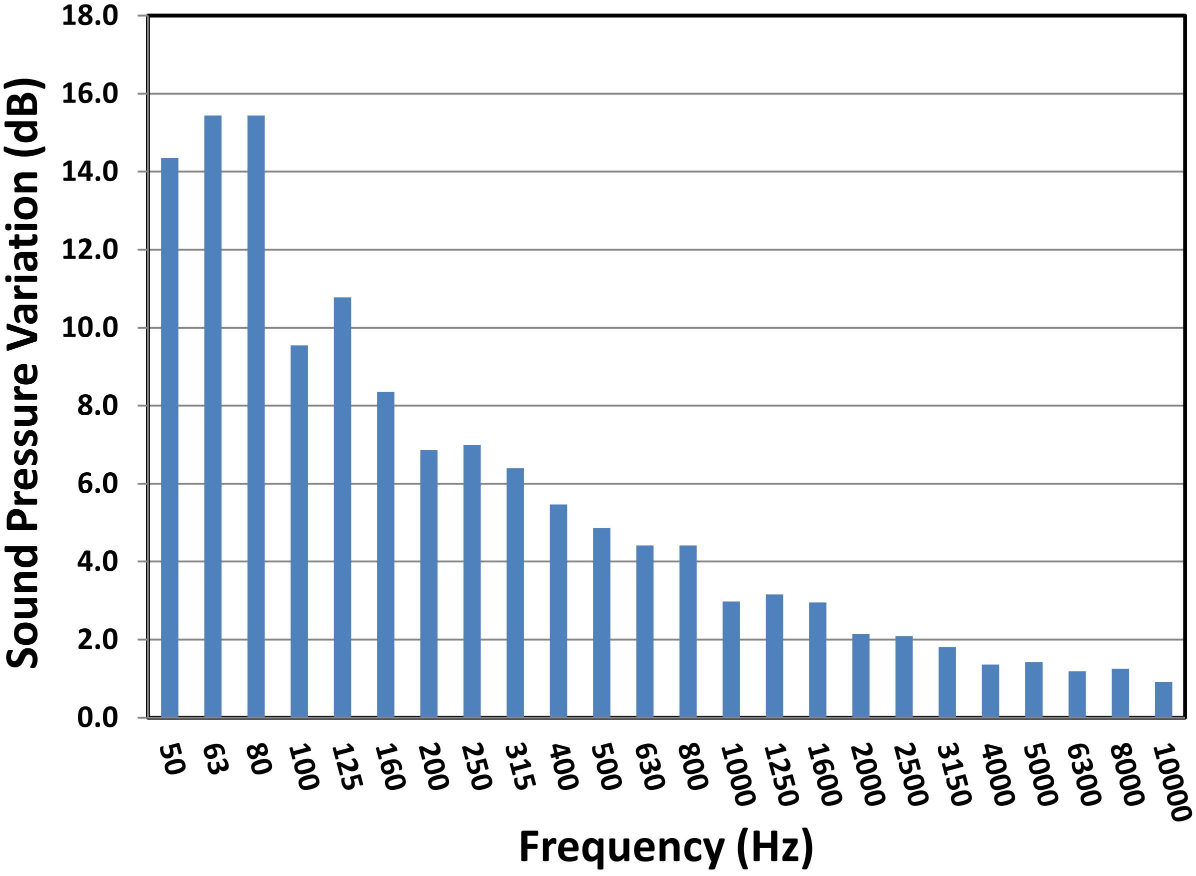


Figure 19. Magnitude of Sound Pressure Variation Across 1/3 Octave Bands

The time variation for the lower frequencies tends to vary significantly compared to the higher frequencies that remain relatively steady. This is an identical trend to the transmission losses where lower frequencies diminished less through the semi-reverberant sound chamber's walls while the higher frequencies had higher sound transmission losses. Since the lower frequencies inside the semi-reverberant sound chamber are closer to their behavior outside the chamber, the variation of the lower frequencies also carries through. These results show the frequencies that have the most potential to impact a sound quality test.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The semi-reverberant sound chamber's acoustic characteristics were evaluated by calculating the sound transmission loss through the chamber and recording the background sound in real time. The lowest frequencies performed the worst. This was expected because lower frequencies transmit better through materials than higher frequencies.

The sound transmission loss and time capture evaluations showed similar results. The frequencies that transmitted significantly compared to the others were the lowest two, 50 Hz and 63 Hz, although there was considerable improvement in transmission performance until 160 Hz where improvements lessened between each 1/3 octave band up to around 1600 Hz. Following a similar trend, the sound pressure variation is predominantly in the lower frequencies, below 160 Hz. Even though the lower frequencies appear to have the most potential to impact a sound quality test, zero sone threshold profile for the chamber show these frequencies impact the test results the least.

The sound loudness outside the semi-reverberant sound chamber required to impact testing would have to be very high. Even so, constant noise sources present during the background measurement are subtracted out in the sone calculation. Based on the transmission loss and time capture assessment, very loud unstable sources would need to be nearby. Using the evaluation results from this thesis it can be determined whether a sound source impacts a sound quality test. This can be done using the combination of the zero sone threshold profile in addition to the sound transmission loss characteristics. The time capture of the sound source can be used to gauge the steadiness of the sound source. In addition, these results can be used in determining any improvements for the sound chamber.

For future work, I recommend looking at sound sources present in the lab to determine their impact on a sound quality test. Sources external to the sound chamber can be evaluated using the sound transmission loss results with the zero sone threshold profile and the sources known sound power to calculate the sources sound magnitude inside the sound chamber. Sources internal to the sound chamber have been minimized although there are still the electrical wires for the sound equipment present. The 60 Hz electrical noise may be contributing to the 63 Hz octave band. Evaluating the magnitude of the 63 Hz for electrical noise will determine the magnitude for internal sound sources besides the tested fans.

I also recommend looking at the impact on sound variations from the background. The PULSE program is configured to average over 30 seconds. Fluctuations may not be accurately averaged with a 30 second window. Using the sone calculation, the recorded average should be compared to the range extremes of the fluctuation. The fluctuation can be recorded using the time capture setup. As part of the testing procedure, I recommend the time capture microphone to be used outside the sound chamber to monitor background sound variations.

These two future works on evaluating potential sound impacts on the testing procedure can help improve the testing procedure to become more reliable and consistent.

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APPENDIX

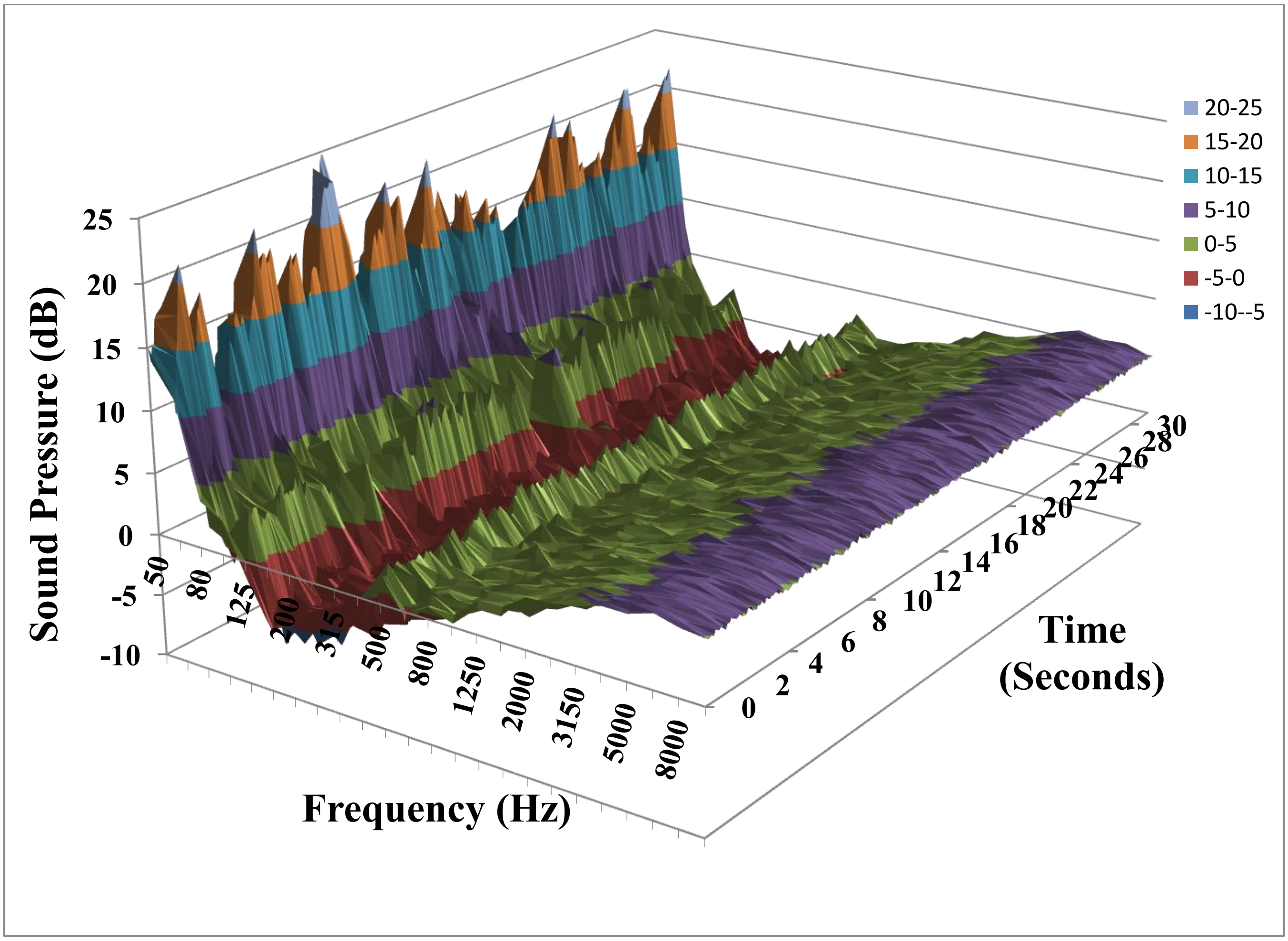

Figure 20. Reference Measurement One for Time Capture Analysis

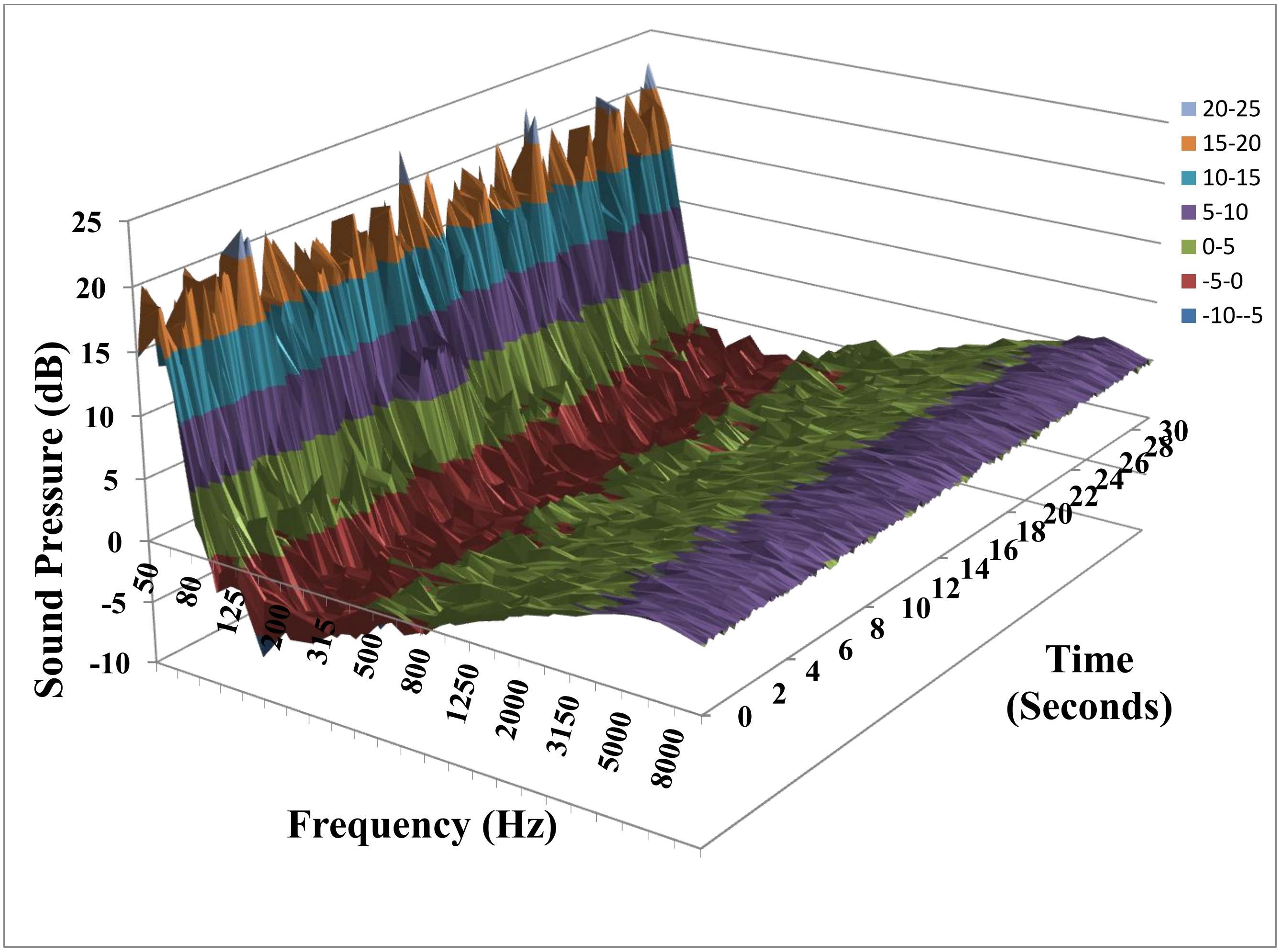

Figure 21. Reference Measurement Two for Time Capture Analysis

VITA

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