PERFORMANCE EVALUATION OF REVERBERANT CHAMBER BACKGROUND NOISE LEVELS

A Thesis

by

SANKARANARAYANAN RAVI

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

December 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Michael B. Pate
Committee Members,	Timothy J. Jacobs
	George Kattawar
Head of Department,	Dennis O'Neal

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ABSTRACT

Performance Evaluation of Reverberant Chamber
Background Noise Levels. (December 2010)
Sankaranarayanan Ravi, B.E. (Hons), Birla Institute of Technology & Science
Chair of Advisory Committee: Dr. Michael B. Pate

An improved test system for acoustical rating of air-movement devices was installed and evaluated at the Riverside Energy Efficiency Laboratory at Texas A&M University where measurements of sound pressure levels were carried out using an array of six-microphones instead of the existing rotating boom- microphone setup. The new array setup did not generate any inherent transient noise peaks, which provided adequate signal-to-noise ratios suitable for low sone fan testing.

The reverberation chamber was qualified for broad-band testing in the frequency range 50 Hz to 10 kHz. Important acoustical parameters, namely, reverberation time and natural modes of the chamber, were determined.

The purpose of this study was to identify potential background noise sources by computing the coherence functions between microphones placed outside the chamber and a microphone placed within the chamber. No strong coherence was observed, thus indicating adequate sound attenuation characteristics of the chamber walls.

The effect of background noise levels on the loudness rating of fans was evaluated. A low sone fan and a louder fan (loudness greater than one sone) were tested during night time when the background noise is the least and during daytime and with the air conditioners running (high background noise level). While both fan types showed no significant change in loudness when tested during daytime and during the night, accurate ratings were not obtained with the air-conditioners running due to inconsistent spectrum.

Finally, it was observed that with the six decibels separation requirement between the fan and background noise spectra for a low sone fan, at very low frequencies (below 63 Hz), despite inadequate fan- background separation, the loudness rating of the fan does not change as the minimum perceived loudness at these frequencies is very high. At very high frequencies (greater than 5 kHz), the fan does not generate any noise and hence the fan and the background noise sound pressure levels are very close to each other.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Michael Pate, for his guidance and support throughout the course of this research.

I would also like to thank Dr. Jacobs and Dr. Kattawar for serving on my committee.

Thanks go to Mr. David Larson for his guidance during the room qualification.

I would also like to extend my gratitude to Dr. Yong Joe Kim for providing guidance with the spectral analysis study.

Special thanks go to The Riverside lab staff, Mr. Kelly Milligan, Mr. James Sweeney, Ms. Kathryn Wadle, and graduate students, Mr. Daniel Escatel and Mr. Sean Elliston, for providing a memorable work environment.

Finally, thanks to my parents for their encouragement and support.

NOMENCLATURE

SPL	Sound Pressure Level (decibels- dB)
L_p	Sound Pressure Level (decibels- dB)
L_w	Sound Power Level (decibels – dB)
BKG	Background Noise
CPB	Constant Percentage Bandwidth
FFT	Fast Fourier Transform
ANSI	American National Standards Institute
HVI	The Home Ventilating Institute
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers

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1. INTRODUCTION

Proper Ventilation is essential in order to maintain acceptable indoor air quality. Ventilation is primarily provided through mechanical devices such as inline fans, bathroom/utility fans, range hoods etc. Federal qualification programs like ENERGY STAR (Ventilating Fans Key Product Criteria 2009) require these air movement devices not only to be energy efficient but also to operate without compromising human comfort. As per this requirement, there is a set maximum allowable sound level (loudness level) for these devices. Table 1 lists the various noise values for various products.

Table 1 Maximum Sound Levels Criteria for ENERGY STAR

Airflow (CFM)	**Maximum Allowable Sound Level (Sones)**
Range Hoods — up to 500 CFM (max)	2.0
Bathroom & Utility Room Fans: 10 to 139 CFM	2.0
Bathroom & Utility Room Fans: 140 to 500 CFM	3.0

The loudness rating for these devices is done in reverberation chambers. Typical acoustical measurements carried out in a reverberation chamber include sound power level determination and sound transmission loss (Narang 1998).

This thesis follows the style of *ASHRAE Transactions.*

Sections 1-3 provide an introduction to fan noise characteristics and the terminologies used in sound measurement systems. Section 4 presents an overview of the reverberation chamber theory and the literature review on reverberation chamber testing. A detail chamber description, including important acoustical parameters such as reverberation time and modal characteristics of the chamber, instrumentation, data acquisition system description and sound testing procedure, are provided in Section 5.

Four tasks were completed as a part of this thesis. Firstly, the reverberation chamber was qualified for broad-band testing. The results of the qualification are presented in Section 6. Secondly, spectral analysis of the BKG sources is presented in Section 7. Thirdly, the influence of BKG levels on the loudness rating was analyzed in Section 8. Finally, the importance of fan-BKG SPL separation requirement during a fan test is discussed in Section 9.

2. SOUND PRESSURE/POWER LEVELS

Sound waves are propagating pressure disturbances in air. They can be measured in terms of sound pressure levels (decibels, dB-SPL) or sound power levels (decibels, dB-SWL). Sound pressure levels depend on the distance of the observer from the source and the surrounding environment. Sound pressure level is computed as (Kinsler et al. 2000):

$$L_P\ (re\ P_{ref}) = 10 \log (P_e/P_{ref})^2 = 20 \log (P_e/P_{ref})$$

where,

L_P (re P_{ref}) = Sound pressure level in decibels (dB) at P_{ref}

P_e = Root mean square of the acoustic pressure in Pascal (Pa)

P_{ref} = Reference pressure in Pascal (Pa) , typically 20 μPa

Humans respond to sound power rather than sound pressures and hence sound power levels are used in acoustical rating of devices. The sound power level of a source is defined as the rate of emission of acoustical energy and is expressed as a dimensionless quantity, such as sound pressure level, measured against a reference power level (typically 10^{-12}W or 1 Pico watt). It is calculated by using the formula (Kinsler et al. 2000):

$$L_W = 10 \log (w/ 10^{-12})$$

where,

L_W = Sound power level (dB)

w = Sound power emitted by the source in watts (W)

2.1 Sound Spectra and Analysis Bandwidths

A microphone converts sound pressure levels to electronic signals that are processed and represented as a function of frequency by using a sound analyzer. Such spectra are complex and consist of both discrete or pure tones and broad-band components of sound. Discrete tones are produced due to the emission of acoustical energy at discrete frequencies and their harmonics. Broad-band sound has energy distributed over a range of frequencies and is not harmonically related.

Different types of spectrum are employed based on the application. A constant bandwidth analysis expresses acoustical pressure levels as a spectrum where each data point represents the same spectral width in frequency. An octave band is a frequency band with an upper frequency limit twice that of its lower frequency limit. Octave bands are identified by their center frequencies, which are the geometric means of the upper and lower band limits. One-third octave band analysis is used in product rating. Three one-third octave bands make up an octave band. Table 2 (ASHRAE 2009) shows the various mid-band and approximate upper and lower cutoff frequencies for octave and one-third octave band filters.

Table 2 Upper, Mid and Lower Frequencies of Octave and 1/3 Octave Bands

Octave Bands, Hz			1/3 Octave Bands , Hz		
Lower	**Mid-band**	**Upper**	**Lower**	**Mid-band**	**Upper**
11.2	16	22.4	11.2	12.5	14
			14	16	18
			18	20	22.4
22.4	31.5	45	22.4	25	28
			28	31.5	35.5
			35.5	40	45
45	63	90	45	50	56
			56	63	71
			71	80	90
90	125	180	90	100	112
			112	125	140
			140	160	180
180	250	355	180	200	224
			224	250	280
			280	315	355
355	500	710	355	400	450
			450	500	560
			560	630	710
710	1000	1400	710	800	900
			900	1000	1120
			1120	1250	1400
1400	2000	2800	1400	1600	1800
			1800	2000	2240
			2240	2500	2800
2800	4000	5600	2800	3150	3550
			3550	4000	4500
			4500	5000	5600
5600	8000	11200	5600	6300	7100
			7100	8000	9000
			9000	10000	11200
11200	16000	22400	11200	12500	14000
			14000	16000	18000
			18000	20000	22400

2.2 Loudness Levels (Sones)

The loudness level of a sound is measured by making a subjective comparison between the loudness of the sound and that of a pure tone of specified frequency that seems equally loud. The sound pressure level of the pure tone is called loudness level of the sound. One sone is equal in loudness to a pure tone of loudness level 40 decibels above threshold of hearing at 1000 Hz.

S.S Stevens (1961), developed a procedure for calculating the loudness of a complex noise spectrum. According to his procedure, loudness indices are assigned to each frequency based on the band pressure level and the geometric mean frequency of that band. These indices can be found in the equal loudness index Table (HVI 2009). The total loudness is calculated by using the formula

$$S_t = S_m + F(\Sigma S - S_m)$$

where,

S_t = total loudness of the sound (sones)

S_m = greatest loudness index (sones)

ΣS = sum of all loudness indices of all bands

F = weighting factor dependent on the bandwidth used for analysis (no unit) and is presented in Table 3 below.

Table 3 Weighting Factors for Loudness Calculation

Bandwidth	**F**
One third Octave	0.15
Half - Octave	0.2
Octave	0.3

2.3 Loudness Rating System

Since each fan design has its own loudness rating, it necessitates the need for rating classes to simplify the huge range of products. All products shall be rated in accordance with the HVI rating system. According to this, all devices with loudness up to 0.3 sones shall be rated as “below 0.3 sones”. All devices from 0.4 sones up to 1.5 sones shall be rounded to the nearest 0.1 sones. All devices above 1.5 sones shall be rounded to the nearest 0.5 sones.

3. FAN NOISE CHARACTERISTICS

Fan noise characteristics depend on a number of factors, such as fan type, flow rate, pressure head, efficiency and specific sound power level. The sound power of a fan can be approximated using the following equation (ASA 1997):

$$L_w = K_w + 10 \log Q + 20 \log P + BFI + C_N$$

where,

L_w = Sound Power Level of the fan (dB)

K_w = Specific Sound Power Level (dB)

It is defined as the sound power level generated by a particular fan when operating at a flow rate of $1 m^3/s$ (2120 cfm) and a pressure of 1 kPa (4.0 inches of water (gauge)). This is based on empirical data provided by the manufacturer.

Q = Volumetric flow rate (cfm)

BFI = Blade Frequency Increment

Every time a blade passes a given point, the air at that point receives an impulse. The repetition rate of this impulse is called the blade passing frequency (BPF) and also called the fundamental tone for the fan. It is computed as:

$$BPF = n * N$$

where,

BPF = Blade passing frequency (Hz)

n = fan speed, rotations per second (rps)

N = number of blades in the fan rotor

BFI is assigned to the computed octave band as a weighting factor for the fundamental tone produced by the blade. Table 4 shows the BFI values for the various fan types.

Table 4 Blade Frequency Increments

Fan Type	BFI
CENTRIFUGAL FANS	
Airfoil	3
Backward Curved	3
Backward Inclined	3
Low Pressure Radial(4"-10" w.c)	7
Medium Pressure Radial (10" - 20" w.c)	8
High Pressure Radial (20" - 60" w.c)	8
Forward Curved	2
AXIAL FANS	
Vane-axial	6
Tube-axial	7
Propeller	5

C_N = efficiency correction and is given by the formula,

$$C_N = 10 + 10 * \log (1-\eta)/ \eta$$

where,

η = Hydraulic efficiency of the fan = $Q * P/(6350 * HP)$

HP = nominal horsepower of the fan drive motor

Figure 1 shows the efficiency correction term plotted over a range of hydraulic efficiencies. When the fan operates near the best operating efficiency, it makes less noise and the noise level increases if operated off their optimal flow conditions.

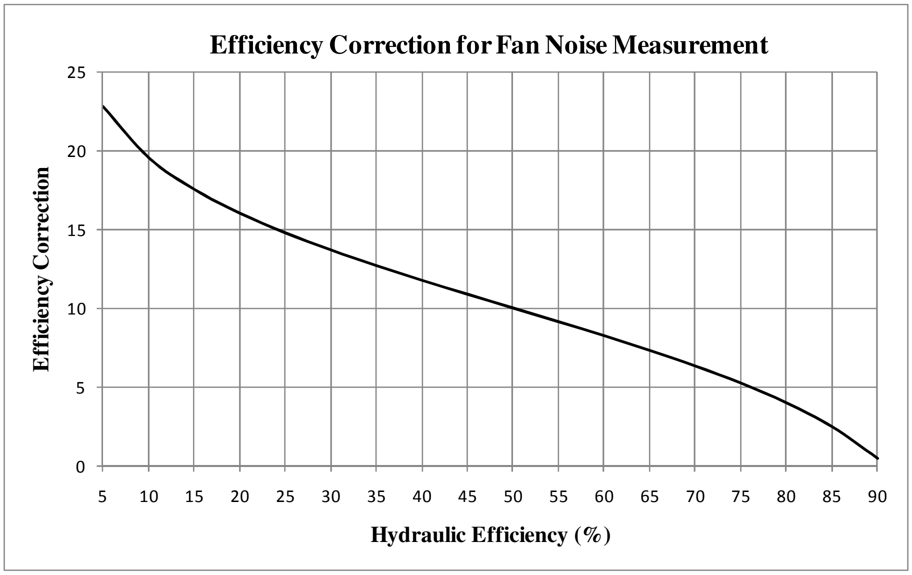


Figure 1 Efficiency Correction for Fans

For a given fan type, volume flow rate and pressure head, there is only one particular fan size that is more efficient than other sizes. The fan law that governs sound power level is given by,

$$(L_w)_a = (L_w)_b + 70 * \log (d_a/d_b) + 50 * \log (n_a/n_b)$$

where,

L_w = sound power level in decibels (dB *re 1picowatt*)

d = rotor diameters in meters (m)

n = rotor speed (rpm)

subscripts: a = data at required performance condition

b = data at base curve performance condition

It is widely misconstrued that the fan noise is due to the rotational speed of the fan, and hence the lower speed fan is assumed as the solution for the noise generated. This is true only if the speed change is sufficient to lower the blade passing frequency to lower frequencies that are not picked up by human ears. While the acoustic power radiated by the fan is the same , there is a reduction in the loudness of the sound radiated by the fan, which is regarded as an improvement.

Replacing a high speed fan with a larger fan which rotates slowly, will not only result in reduced air delivery performance (pressure and flow rate) but also decreased efficiency, which in turn increases the sound power level. Similarly, increasing the number of blades on a small fan so that it can rotate at a lower speed would only shift the blade passing frequency to higher octave bands, thereby increasing the loudness of the fan.

For better system design, it is necessary to obtain the sound power signatures of the fan in the various octave bands rather than a single rating number for sound power level. Laboratory fan noise measurement standards (AMCA 2008, HVI 2009) require that sound power levels of fans be measured in eight octave bands (centered at

63,125,250,500,1000,2000,4000,8000 Hz) by using a reverberant room with a calibrated reference sound source.

4. REVERBERATION CHAMBERS

Reverberation chambers are specially designed chambers whose walls are made to reflect sound waves produced by the device under study.

4.1 Theory

The ray model for sound propagation (Sabine 1922) assumes sound to travel as outward diverging rays from the source. Hence the direct sound field gets reflected off the wall, and the energy density of the sound field grows within the chamber. However, since surfaces are not perfectly reflecting, sound rays get partially reflected and absorbed at the boundaries. The conservation of sound power of the source states that the energy provided by the source in the chamber is equal to the rate of increase in energy density and the rate at which the energy is absorbed by the surfaces of the chamber.

If the total sound absorption of the chamber is A (m^2 or ft^2), then the rate at which energy is absorbed by the surfaces is $\frac{Ac}{4}\varepsilon$, where c = speed of sound in air. The final governing equation for growth of sound energy in a live chamber of volume V(m^3) is given by:

$$V\frac{d\varepsilon}{dt}+\frac{Ac}{4}\varepsilon=\Pi \; ... \; (1)$$

where,

Π is the sound power of the source.

If a sound source is started at t=0, then the governing equation yields the solution,

$$\varepsilon = \varepsilon(\infty)\left(1 - e^{-t/\tau}\right)$$

where,

$\varepsilon(\infty) = \left(4\Pi/Ac\right)$, is the equilibrium energy density

$\tau = \dfrac{4V}{Ac}$ is the time constant for the growth of acoustic energy in the chamber.

After a large number of reflections ($t >> \tau$), the acoustical energy density ε reaches the equilibrium energy density ε (∞)and all directions of propagation are equally likely. The field is said to be diffuse and the total sound power can be measured.

In a reverberant chamber standing waves may exist due to wall reflections. To eliminate the effects of standing waves, multiple locations of SPL measurements with diffusers installed or a rotating boom microphone setup is adopted.

4.2 Literature Review

Table 5 presents the survey of all relevant literature on reverberant chamber testing with a particular attention to sound power measurement testing facilities.

Table 5 Literature Review on Reverberant Chamber

Author(s)	Type of Testing	Instrumentation	BKG Level	Chamber Volume
Wise et al. 1976	Designed for determination of sound power radiated by sources of broad-band noise	Mic on a turntable	-	231 m^3
Pallett et al. 1976	Designed for sound power measurements, impact noise studies of floor ceiling assemblies and studies for acoustic radiation from mechanically excited panels	12 mic array	-	425 m^3
Rainey et al. 1976	Designed for the determination of sound power rating of HVAC devices	Rotating boom microphone type	-	269 m^3
Lang & Rennie, 1981	Designed for pure tone and broad-band sound power measurement	Linear microphone traverse	-	94 m^3
Duanqi et al. 1991	Designed to measure performance of loudspeakers and microphones and absorption coefficients of materials.	6 mic array	30 dB(A)	286.6 m^3
Giuliano et al. 1996	Designed for measurement of acoustical absorption coefficient of materials and objects in random incidence conditions	6 mic array	22 dB(A)	189 m^3
Narang, 1998	Designed two large reverberation chambers adjacent to each other for sound power and sound transmission testing	Rotating boom microphone type	22.3 dB(A)	209 m^3 & 231 m^3

5. TEST CHAMBER DESCRIPTION

The sound test chamber is a diffuse reverberation chamber built as a building inside a building. Figure 2 shows the reverberation chamber.

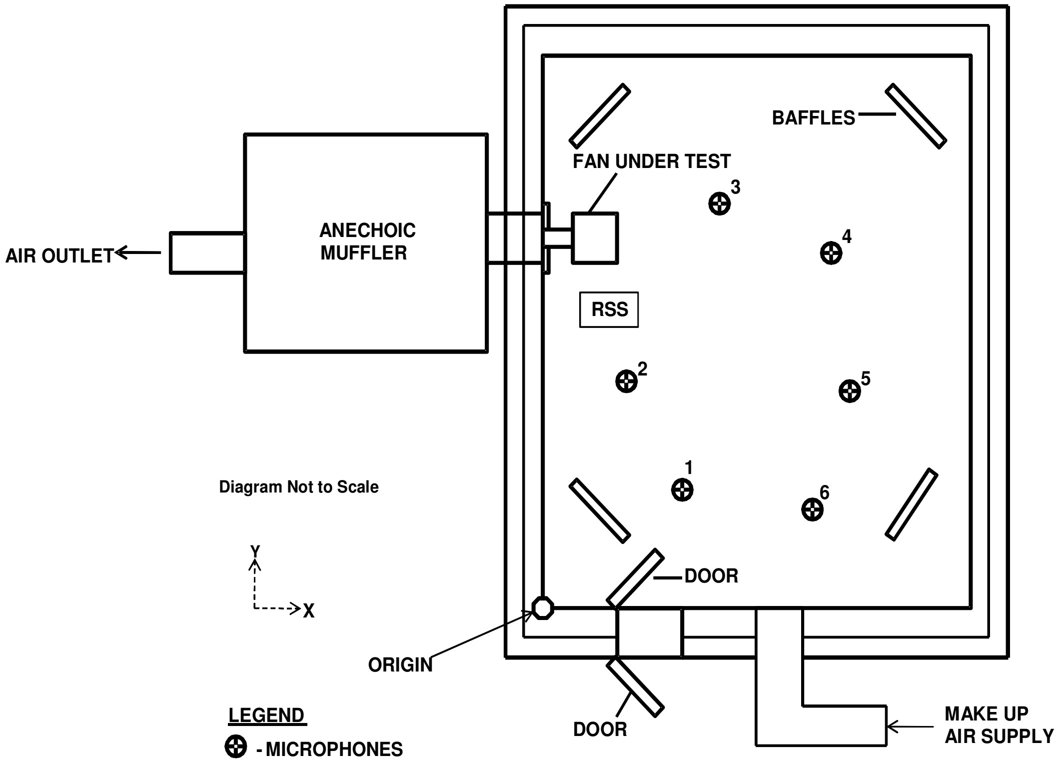


Figure 2 Schematic of the Reverberant Chamber

The chamber has heavy, multilayered, insulated and hard reverberant surfaces. Figure 3 and Table 6 shows the structural details of the roof, floor and sidewalls of the chamber. The numbers in Figure 3 correspond to the different layers in Table 6.

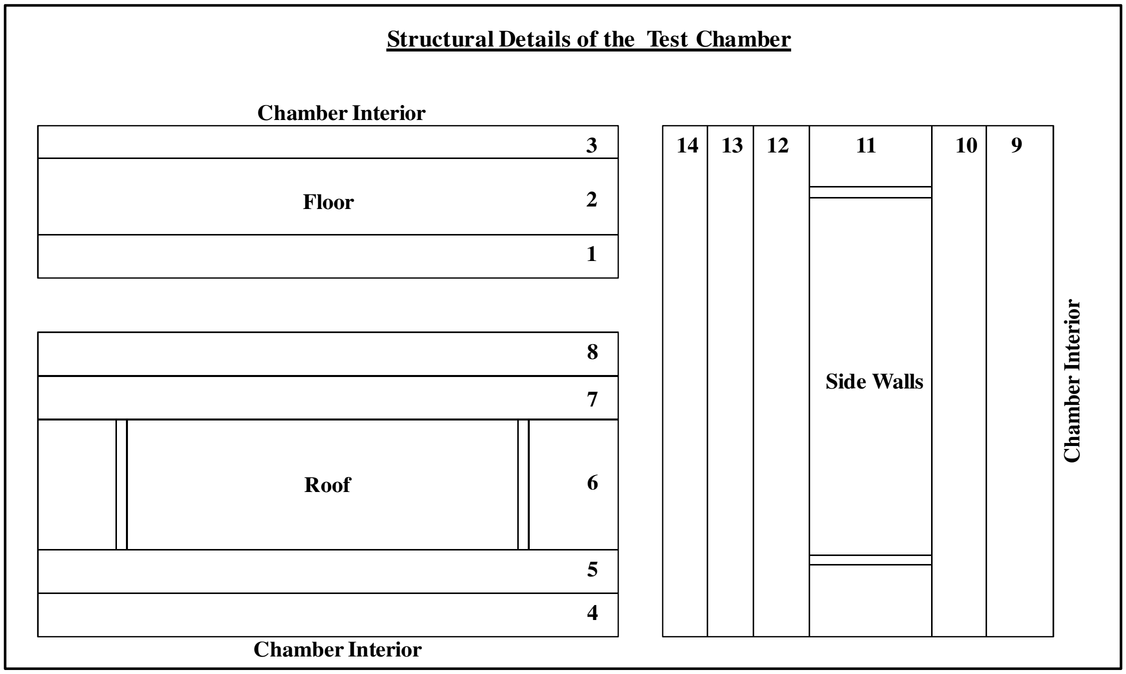


Figure 3 Structural Details of the Reverberant Chamber

Table 6 Structural Details of the Reverberant Chamber

Layer	Material	Thickness [inches] (meters)
	FLOOR	
1	Concrete	N.A.
2	Sand	[20] (0.508)
3	Concrete	[5] (0.127)
	ROOF	
4	Sheet Rock	[0.625] (0.015)
5	Plywood	[0.5] (0.0127)
6	2 x 8 Construction	N.A.
7	Sheet Rock	[0.5] (0.0127)
8	Lead	[0.0625] (0.0015)
	SIDE WALL	
9	Sheet Rock	[0.625] (0.015)
10	Plywood	[0.5] (0.0127)
11	2 x 6 Construction	N.A.
12	Plywood	[0.75] (0.019)
13	Rockwool Insulation	[2] (0.051)
14	Concrete	No Data Available

The dimensions of the chamber are 25ft (7.58 m) x 20ft (6.06 m) x 12ft (3.56 m), with a volume of 6000 cubic feet (163.5m^3). In terms of the room dimension ratios (non-dimensional ratios) for a rectangular room,

we have: $l_y/l_x = 0.8$; $l_z/l_x = 0.48$

where,

l_x=25 ft; l_y=20 ft; l_z=12 ft

The chamber is equipped with baffles to minimize three dimensional standing waves. Provisions for the supply of makeup air through an insulated labyrinthine inlet duct is also available. An adjustable speed air supply blower is fitted to the duct inlet to supply additional air for devices requiring high airflow. The duct has an inner lining made of acoustically absorbent material. The other end of this duct is fitted with a sound muffler to prevent airborne sound transmission. The chamber exhausts air into an anechoic muffler through an expendable panel with close fitting test duct openings. The dimensions of the anechoic muffler are 8ft (2.4m) x 8ft(2.4m) x 8ft(2.4m) and is connected to the test chamber through an airtight, rectangular isolation duct. The outlet of the muffler is connected to the atmosphere to prevent entry of environmental sound. The outlet to the muffler is also provided with a damper to control airflow inside the chamber.

5.1 Reverberation Time (T_{60})

An important acoustic factor for the design of the reverberant room is the reverberation time (T_{60}). It is defined as the time taken for the sound to drop 60 dB from the original value after the sound source is turned off. When a source is turned on and allowed to operate continuously its intensity grows rapidly and exceeds the acoustic intensity of the source itself. This gain in intensity is directly related to the reverberation time. Hence the reverberation time is a direct measure of the persistence of sound within an enclosure. The reverberant acoustic energy tends to mask the immediate recognition of any new sound, unless sufficient time has elapsed for the reverberation to have fallen below 5to 10 dB. The longer the reverberation time, then the more audible is a weak source.

The method of estimating reverberation time is by studying the decay plot of an impulse sound input in the chamber. The sound pressure level is plotted against time, so that the slope of a linear data fit is directly proportional to the reverberation time of the chamber. The reverberation time for the room was estimated from the average response of all six –microphones to an impulse sound input. Figure 4 shows the average sound pressure level(SPL) in dB for all microphones.

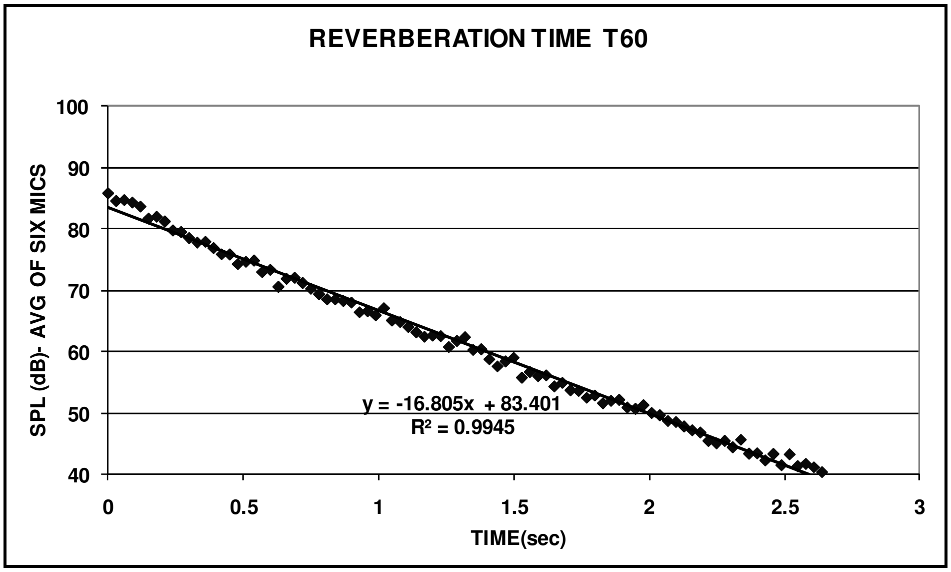


Figure 4 Reverberation Time for the Chamber

The reverberation time is calculated from the slope of the graph by the formula:

$$T_{60} = \frac{60[dB]}{Slope[dB/\sec]}$$

Ten sample studies were performed and the reverberation time for the room was found to be $T_{60} = 3.96$ s.

5.2 Modal Characteristics of the Chamber

Natural frequencies of a chamber play a vital role in determining the acoustical properties of the chamber. For rectangular spaces, all pressure antinodes exist in the corner and fully excite a mode if a source is placed there. For the chamber, the first twenty lowest natural modes and their Eigen frequencies are calculated by using the formula (Bies and Hansen 2009):

$$f_{n_x n_y n_z} = \frac{c}{2}\left[\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2\right]^{\frac{1}{2}}$$

where,

n_x, n_y, n_z: the natural modes of the chamber

$f_{n_x n_y n_z}$: natural frequency/Eigen frequency [Hz] of the chamber

c= 340m/s (761 mph); speed of sound in air

L_x, L_y, L_z: dimensions of the chamber

There are three types of normal modes of vibrations, such as axial mode (only one mode is non-zero), tangential (two modes are non-zeros) and oblique mode (no mode is zero). Table 7 below shows the various Eigen modes and their Eigen frequencies. It should be noted that the fundamental frequencies of the chamber lie within the 63 Hz.

Table 7 Natural Frequencies and Modes of the Chamber

Modes			**Frequency (Hz)**
n_x	**n_y**	**n_z**	**f_{nxnynz}**
	AXIAL MODES		
1	0	0	22.43
0	1	0	28.05
0	0	1	47.75
	TANGENTIAL MODES		
1	1	0	35.92
1	0	1	52.76
0	1	1	55.38
	OBLIQUE MODES		
1	1	1	59.75
2	1	1	71.27
1	2	1	77.01
1	1	2	102.04

5.3 Instrumentation

This section provides a detail description of the various instrumentation involved with both the rotating boom system and the six microphone array system.

5.3.1 Rotating Boom Microphone System

The rotating boom system is comprised of a random incidence ½ inch (0.0127m) microphone that is sensitive to low sound pressures. The microphone is mounted on a 60 inch (1.52m) rotating boom capable of rotating the microphone approximately 180° during each data collection period. The output of the microphone is fed to a sound analyzer that performs real-time averaging of the signals and provides data for the 24 one third octave bands with center frequencies from 63Hz to 8000Hz. Table 8 below shows the various instrumentation in detail.

Table 8 Equipment List for the Rotating Boom –Microphone System

Instrumentation	**Manufacturer (Model No)**	**Description**
Microphone	ACO Pacific (4102)	1/2-inch Free-field Microphone, 2 Hz to 200 kHz, 200V Polarization
Rotating Boom	Bruel & Kjaer (3923)	100 cm in length with rotational speed set at 64s/rev
Sound Level Calibrator	Bruel & Kjaer (4230)	Handheld sound level calibrator
Reference Sound Source (RSS)	Bruel & Kjaer (4204)	Specially designed centrifugal fan

5.3.2 Six Microphone Array System

The microphone array system consists of six microphones placed at various locations within the chamber. The outputs of the microphones are fed into a sound analyzer, which provide data in the third octave bands. Table 9 lists the major instrumentation for the six-microphone array system.

Table 9 Equipment List for the Six-Microphone Array System

Instrumentation	**Manufacturer (Model No)**	**Description**
Microphones	Bruel & Kjaer (4190)	1/2-inch Free-field, 3 Hz to 20 kHz, 200V Polarization
Preamplifiers	Bruel & Kjaer (2669)	½-inch Microphone Preamplifier
Pulse Multi-Channel Data Analyzer	Bruel & Kjaer (3560C)	Portable Data Acquistion System with 6 inputs /1 output channels
Sound Level Calibrator	Bruel & Kjaer (4230)	Handheld sound level calibrator
Reference Sound Source (RSS)	Bruel & Kjaer (4204)	Specially designed centrifugal fan
Tachometer	Monarch (ACT-3)	Laser Tachometer
Multi-meter	Fluke 87	For voltage measurement

5.4 Data Acquisition System

Data acquisition is interfaced through the PULSE Lab shop 10.2 (Pulse 2008). A Pulse project was created to make all the necessary measurements. The Pulse project involves configuring four major organizers, namely, configuration organizer, measurement organizer, function organizer and display organizer.

5.4.1 Configuration Organizer

All microphones are connected to the front end of the analyzer using cables. The transducers (microphones) are automatically detected and the transducer types are selected from the transducer database. Transducer data, such as sensitivity and polarization voltages, are entered from their respective calibration reports.

5.4.2 Measurement Organizer

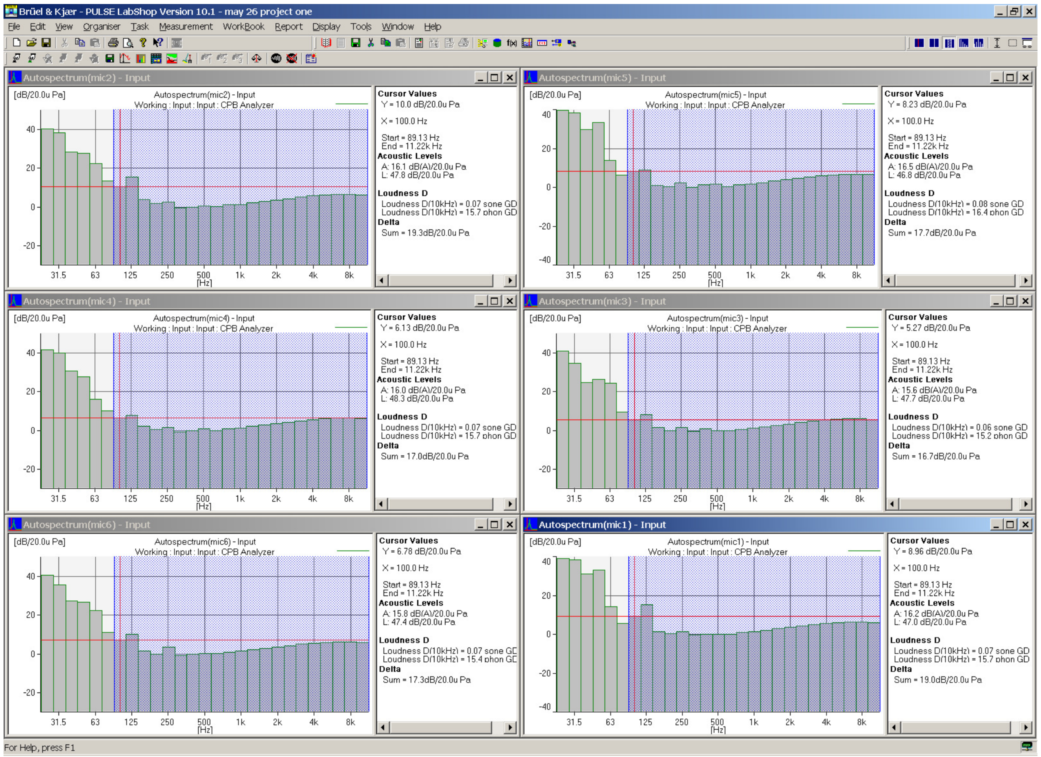
A signal group consisting of all the microphone is created. This signal group is fed into a CPB analyzer. The CPB analyzer is setup to provide a real-time digital-filter based one-third octave analysis(desired bandwidth). The lower center frequency is set to 25 Hz and the upper center frequency is set to 10 kHz. Thirty second linear averaging is invoked to be consistent with the test standards (AMCA 2008, HVI 2009). Linear acoustic weighting is used for post processing.

5.4.3 Function Organizer

The auto spectrum is used to measure the mean square of the filtered output (measured data) stored in the multi-buffer. This constitutes the function group for the Pulse project.

5.4.4 Display Organizer

The display organizer is configured appropriately to display the auto-spectra of all microphones. The function group, consisting of the auto-spectra of all six microphones, is selected as the function to be displayed with real part of the sound pressure levels (SPL) being displayed. The spectral unit is set to the root-mean square scale. A root-mean-square (RMS) scale is a useful scale because of the nature of the spectra obtained. The spectra consists of line spectra with discrete frequency components. Such deterministic signals are frequently described in terms of their root-mean-square amplitude (RMS), as a function of frequency. Hence the RMS values of the SPL (db/20µPa) are displayed as a function of the frequency. The same linear acoustic weighting as the CPB Analyzer is applied. The graph type is set to a bar chart with frequency on the X-axis and SPL on the Y-axis. Figure 5 shows the spectrum of all six microphones.



Autospectrum(mic2) - Input

Cursor Values
Y = 10.0 dB/20.0u Pa
X = 100.0 Hz
Start = 89.13 Hz
End = 11.22k Hz
Acoustic Levels
A: 16.1 dB(A)/20.0u Pa
L: 47.8 dB/20.0u Pa
Loudness D
Loudness D(10kHz) = 0.07 sone GD
Loudness D(10kHz) = 15.7 phon GD
Delta
Sum = 19.3dB/20.0u Pa

Autospectrum(mic5) - Input

Cursor Values
Y = 8.23 dB/20.0u Pa
X = 100.0 Hz
Start = 89.13 Hz
End = 11.22k Hz
Acoustic Levels
A: 16.5 dB(A)/20.0u Pa
L: 46.8 dB/20.0u Pa
Loudness D
Loudness D(10kHz) = 0.08 sone GD
Loudness D(10kHz) = 16.4 phon GD
Delta
Sum = 17.7dB/20.0u Pa

Autospectrum(mic4) - Input

Cursor Values
Y = 6.13 dB/20.0u Pa
X = 100.0 Hz
Start = 89.13 Hz
End = 11.22k Hz
Acoustic Levels
A: 16.0 dB(A)/20.0u Pa
L: 48.3 dB/20.0u Pa
Loudness D
Loudness D(10kHz) = 0.07 sone GD
Loudness D(10kHz) = 15.7 phon GD
Delta
Sum = 17.0dB/20.0u Pa

Autospectrum(mic3) - Input

Cursor Values
Y = 5.27 dB/20.0u Pa
X = 100.0 Hz
Start = 89.13 Hz
End = 11.22k Hz
Acoustic Levels
A: 15.6 dB(A)/20.0u Pa
L: 47.7 dB/20.0u Pa
Loudness D
Loudness D(10kHz) = 0.06 sone GD
Loudness D(10kHz) = 15.2 phon GD
Delta
Sum = 16.7dB/20.0u Pa

Autospectrum(mic6) - Input

Cursor Values
Y = 6.78 dB/20.0u Pa
X = 100.0 Hz
Start = 89.13 Hz
End = 11.22k Hz
Acoustic Levels
A: 15.8 dB(A)/20.0u Pa
L: 47.4 dB/20.0u Pa
Loudness D
Loudness D(10kHz) = 0.07 sone GD
Loudness D(10kHz) = 15.4 phon GD
Delta
Sum = 17.3dB/20.0u Pa

Autospectrum(mic1) - Input

Cursor Values
Y = 8.96 dB/20.0u Pa
X = 100.0 Hz
Start = 89.13 Hz
End = 11.22k Hz
Acoustic Levels
A: 16.2 dB(A)/20.0u Pa
L: 47.0 dB/20.0u Pa
Loudness D
Loudness D(10kHz) = 0.07 sone GD
Loudness D(10kHz) = 15.7 phon GD
Delta
Sum = 19.0dB/20.0u Pa

Figure 5 Auto-Spectra for Six-Mic Array Setup

Sound pressure spectrums for all six microphones are recorded for thirty seconds by using a multi-buffer. The logarithmic average of all six microphones are eventually recorded for each run.

5.5 Advantages of the Array System

The main reasons for switching the sound test procedure from the rotating boom to the six microphone array are as follows:

- The rotating boom has inherent noise levels and acts as an additional noise source, which makes it unsuitable for low noise devices (less than 1 sone). Figure

6 shows the total BKG measured inside the test chamber (A-weighted) for the case of the boom alone without the fan switched on. The sound pressure levels on an average is 18 dB(A) with peaks as high 33 dB(A) due to transient events like boom torque reversal. Figure 7 presents the BKG observed in the chamber without the boom moving which would be the BKG observed if using the six microphone array. The peak SPL here is approximately 12 dB(A) and the spectrum is uniform, devoid of any transient peaks. Thus the array system provides better signal-to-noise ratios than the rotating boom microphone system.

- The rotating boom system has a lot of mechanical parts, and hence maintenance is a major issue. The six microphone array system has the ability to provide spatially resolved sound pressure level data without involving any moving parts.

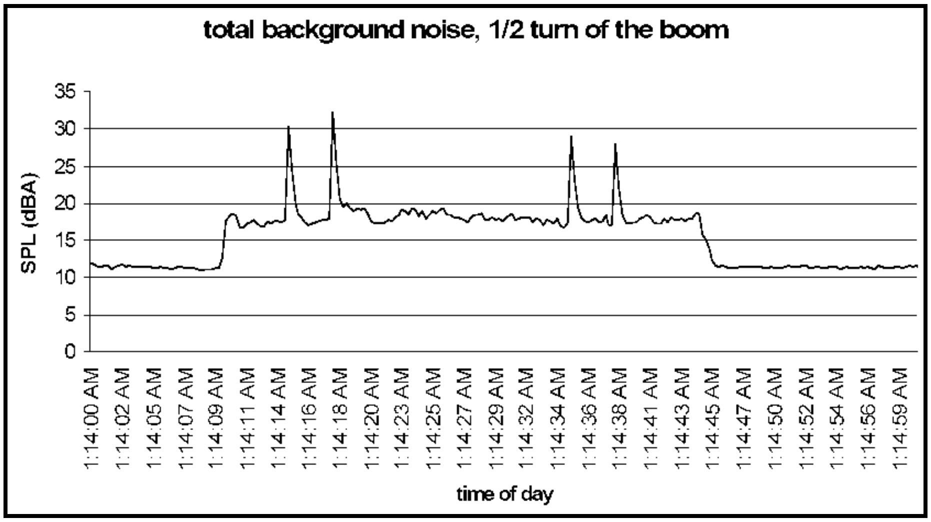


Figure 6 Total BKG for ½ Turn of the Boom

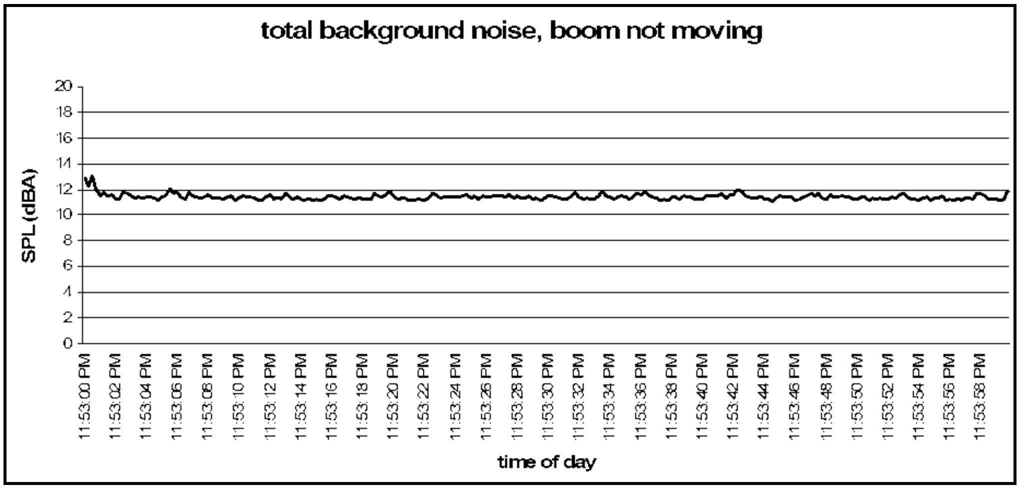


Figure 7 Total BKG without the Boom Moving

5.6 Sound Test Procedure

The procedure estimates the sound power level of the fan by comparing it with a reference sound source.

First, the microphones are calibrated using a handheld calibrator. The test consists of four 30-seconds runs namely,

1. FAN+BKG
2. BKG 1
3. RSS+BKG
4. BKG 2

Sound pressure levels (dB SPL) are recorded in all one third octave band frequencies (50Hz-10kHz) for all the above runs. Steadiness in BKG throughout the test and arithmetic separations between the fan SPL and BKG SPL are checked for each frequency band. Based on the calibration data for the RSS, the chamber characteristic ratio (RCR) is calculated. Using RCR, the sound power level(dB SWL) for the fan is computed from the measured sound pressure level. From the sound power data, the sound pressure of the fan at a distance is calculated by using a rating distance constant (taken as 14.65 dB-SWL @ 5 feet for a spherical free field). Loudness indices for each frequency band are assigned from the equal loudness chart (HVI 2009). The equal loudness indices are then combined to a single rating number which is weighted for human dominant tone sensitivity (85% for the dominant tone), thus yielding a single fan loudness number in sones. All relevant formulae can be found in the test standard (HVI 2009).

6. ROOM QUALIFICATION- PROCEDURE AND RESULTS

The qualification standard (ASA 2002) sets the lowest one-third octave frequency at which the SPL can be measured as a function of the volume of the chamber. This is shown in Table 10.

Table 10 Lowest Measurable Frequency

Lowest One-Third-Octave Frequency [Hz]	**Minimum Volume of the Test Room [m^3]**
100	200
125	150
160	100
200 and Higher	70

As a result, the test facility was qualified to do testing for a frequency band up to 125 Hz. However, the acoustical test procedure requires the measurement of SPL in the frequency range 50Hz-10kHz and hence the test chamber was qualified for broad-band testing to cover the additional range of frequencies.

6.1 Broad-Band Qualification

According to the qualification standard (ASA 2002), the guidelines for the microphone placement include:

1. No microphone shall be closer than 1meter to any wall

2. No microphone shall be closer than λ/2 to any other microphone location for the lowest frequency of interest (λ/2= 1.7meters for 50 Hz)
3. The minimum distance between the noise source and the nearest microphone position shall not be less than dmin = 0.16* $\sqrt{V/T_{rev}}$

where,

V= volume of the reverberant room (163.5 m^3)

T_{rev}= the reverberation time for the room = 3.96s, yielding **d_{min}= 1.02meters**

Following the above guidelines, the microphone positions were selected in the room. For each frequency band, the standard deviations in the microphone readings were computed. Microphone positions were adjusted until the standard deviations were within the specified allowable limits. Table 11 shows the final coordinates of the microphones, the test item and the RSS in the sound room. Figure 2 shows the position of the microphones, the test item and the RSS.

Table 11 Coordinates of Test Item, Microphones and RSS

	X -Coordinate [inches] (meters)	**Y- Coordinate [inches] (meters)**	**Z -Coordinate [inches] (meters)**
Microphone 1	[63] (1.60)	[135](3.43)	[72](1.83)
Microphone 2	[95] (2.41)	[101](2.57)	[82.5](2.10)
Microphone 3	[116] (2.95)	[236](5.99)	[91](2.31)
Microphone 4	[179] (4.55)	[209](5.31)	[58](1.47)
Microphone 5	[176] (4.47)	[141](3.58)	[75.5](1.92)
Microphone 6	[144] (3.66)	[90](2.29)	[57.5](1.46)

Table 11 Continued

	X -Coordinate [inches] (meters)	**Y- Coordinate [inches] (meters)**	**Z -Coordinate [inches] (meters)**
RSS	[57] (1.45)	[189](4.81)	[0](0.00)
Test Item	[31] (0.79)	[224](5.70)	[96](2.44)

Figures 8 and 9 show the standard deviation values and the averaged sound spectrum for all six microphones, respectively. The sound room was qualified for broad-band sound measurements.

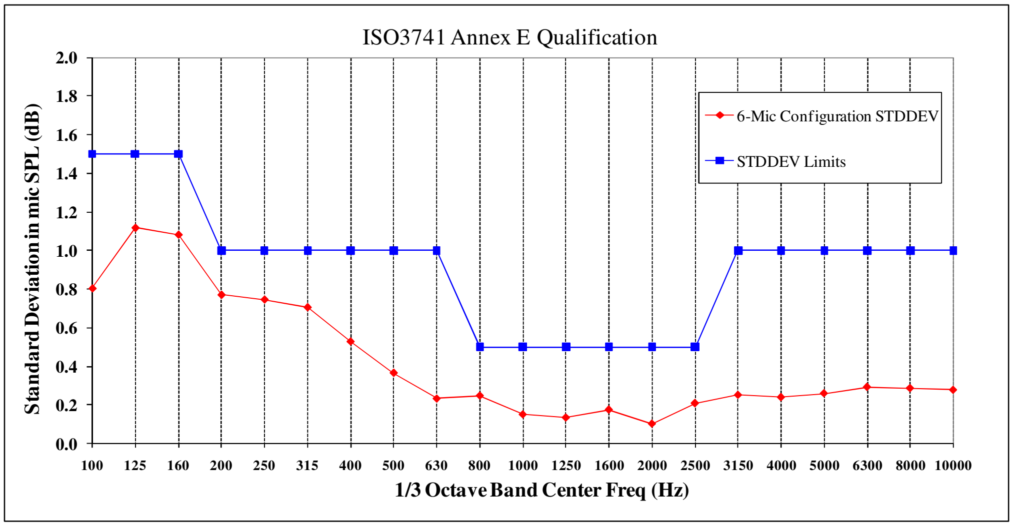


Figure 8 Measured Standard Deviations in the Microphones Readings

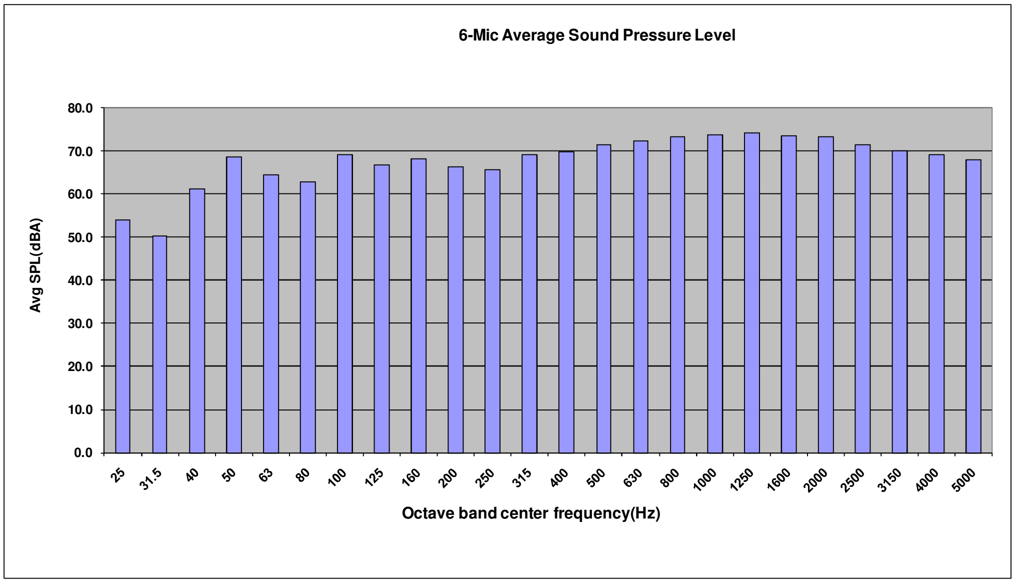


Figure 9 Averaged Sound Spectrum for All Microphones

6.2 Evaluation of the Need for Additional Microphones

Reverberation chambers ideally produce diffuse fields, and hence a single microphone can be considered sufficient for measuring the SPL. However, standing waves can exist inside the chamber due to its geometry (parallel surfaces), and hence rotating boom microphone setup or an array of microphones with additional modifications such as diffusers are installed. The ASA (2002) standard prescribes a minimum number of microphones in an array type system based on the standard deviations in the SPL recorded by the microphones. This is shown in Table 12.

Table 12 Minimum Number of Microphones

1/3 Octave Bands Frequency [Hz]	Minimum Number of Microphones		
	Standard Deviation (s_m) [dB]		
	$s_m \leq 1.5$	$1.5 < s_m \leq 3$	$s_m > 3$
100,125,160	6	6	6
200,250,315		6	12
400,500,630		12	24
≥ 800		15	30

From Table 12 and Figure 8, it is evident that an array with six microphones is adequate for the facility.

7. SPECTRAL ANALYSIS OF BKG SOURCES

BKG levels are very critical while analyzing fan noise spectrum . ASA (2002) sets the upper limit on the BKG level to be at least 10 dB below the SPL of the reference sound source in each frequency band. Laboratory observations reveal that the BKG levels are always well separated from the reference sound source (>50 dB) (see figure on page 54 for an example) and hence the background level observed within the chamber is feasible for loudness rating. Two main criteria are used in determining acceptable back ground noise levels during a test. They are:

1. Consistency/ Steadiness:- The BKG levels should be consistent throughout a fan test. This is ensured by measuring BKG levels two times, once after the fan noise run and then after the reference sound source is run. The absolute difference in the BKG level measurements should be within a tolerance limit set for each of the frequencies in the one-third octave bands. This is shown in Table 13.
2. Acceptable signal-to-noise ratio:- There is a set six decibels required separation between the fan SPL and the BKG SPL in all the frequency bands during measurement.

Table 13 BKG Steadiness Limit

	Frequency (Hz)	Limit (dB)		Frequency (Hz)	Limit (dB)
1	50	2.00	**13**	800	2.00
2	63	4.00	**14**	1000	0.5
3	80	2.00	**15**	1250	0.5
4	100	2.00	**16**	1600	0.5
5	125	2.00	**17**	2000	0.5
6	160	1.00	**18**	2500	0.5
7	200	1.00	**19**	3150	0.5
8	250	1.00	**20**	4000	0.5
9	315	1.00	**21**	5000	0.5
10	400	1.00	**22**	6300	0.5
11	500	1.00	**23**	8000	0.5
12	630	1.00	**24**	10000	0.5

Larson (2008) conducted a study to identify the sources for BKG in the chamber. Nine sources were identified and are listed in Table 14 below.

Table 14 Noise Sources for Reverberant Chamber

SNO	Source	Type: Internal/External	Comments
1	Transformer Hum	Internal	Switched off during a fan test
2	Air conditioners	Internal	Switched off during a fan test
3	Air compressors	Internal	Switched off during a fan test
4	People Noise	Internal	Minimal during fan test
5	Firing Range Noise	External	Not present during a fan test
6	Cooling Towers	External	Cannot be controlled
7	Train &Airplane	External	Not present during a fan test
8	Highway Traffic	External	Cannot be controlled
9	Wind	External	Cannot be controlled

The present study focuses on the impact of the above sources on the BKG levels measured during a fan test that was not quantified earlier. Seven Microphones were setup around the chamber with one microphone placed inside the chamber as shown in the Figure 10. The microphone positions and their target measurement are listed in the Table 15. This setup has the capability of simultaneously recording the noise levels both inside and outside the reverberant chamber.

A FFT analysis was conducted by using a linear frequency scale from 0Hz-12.8kHz with a spectral resolution of 2Hz (6400 lines). Linear averaging (178 averages) over thirty was used to ensure convergence of results. All microphones were calibrated by using a handheld calibrator. A high pass filter (22.4Hz) was applied to eliminate DC effects. The auto-spectra for all microphones were recorded. The auto spectra of all microphones are shown in Figures 11-13. Figure 14 shows the auto spectrum of microphone 1 in the frequency range 0 – 100 Hz. The coherence functions between the microphones outside the chamber and the microphone inside were also calculated with the results shown and Figures 15-17. The experiment was repeated twice by changing the position of microphone 1 (1’, 1’’- Figure 10) to ensure spatial independence in the data collected.

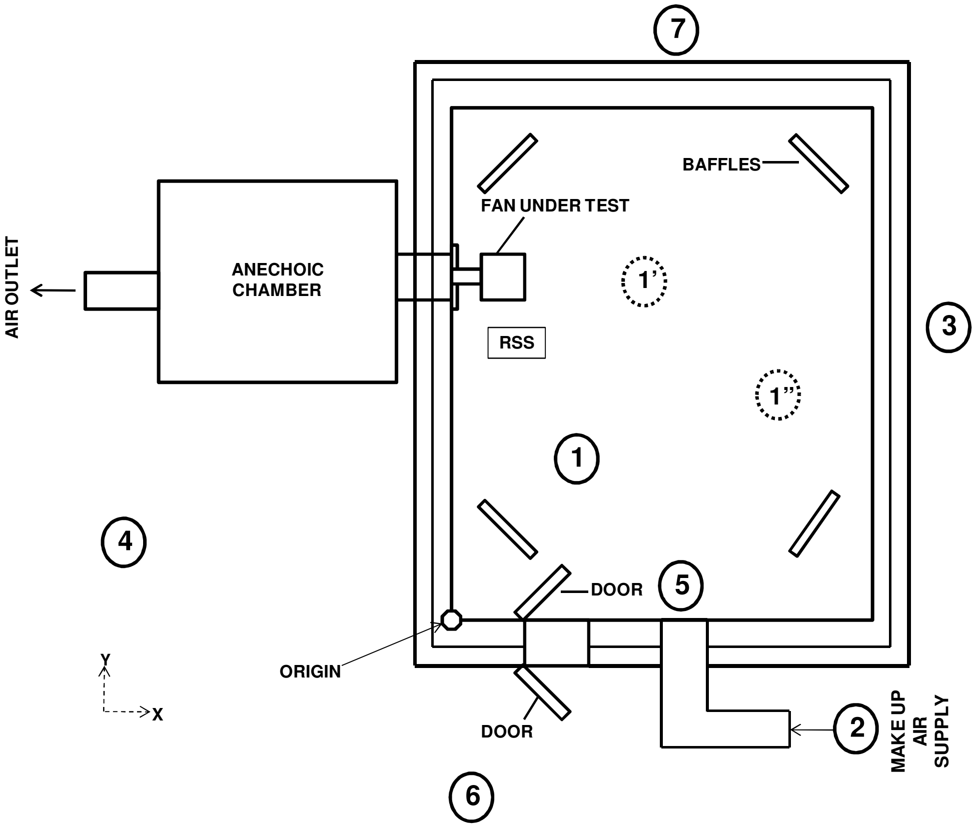


Figure 10 Microphone Positions for the BKG Study

Table 15 Microphones and Their Measurement Targets

SNO	Microphone	Measures
1, 1’, 1’’	Chamber	Noise inside chamber
2	Make up Air Fan	Noise at the fan inlet
3	TTI Wall	Highway/wind noise
4	Exhaust Side	People and movement noise
5	Inlet of Assist fan inside chamber	Duct Noise
6	Airflow bench	Lab-machinery Noise
7	Back wall	Wind/ Noise from surrounding labs
8	Roof	General Ambient

7.1 Auto-Spectra

Figures 11-13 show the auto-spectra for all microphones in the 0-2kHz frequency range. The Appendix Section contains the data in the entire frequency range used in this study. For frequencies above 100 Hz, the SPL recorded inside the chamber is lesser than the SPL recorded at various locations outside the chamber. The microphones 2, 3 and 4 recorded noise peaks in the 1400 Hz octave band. The close proximity of these microphones to the data acquisition system is a possible cause for peaks in the SPL. However, the SPL for microphone 1 in this band is below 2 dB(A) implying sufficient sound attenuation of the chamber. Table 16 compares the SPL values for the noise peaks recorded by microphones 2, 3 and 4 to the corresponding SPL for microphone 1.

Table 16 SPL Peaks for Mic 2-4 Compared to Mic 1

Frequency (Hz)	**SPL (dB)**			
Mic	**1**	**2**	**3**	**4**
1310	1.123	40.37	37.25	38.01
1624	1.234	34.70	35.13	34.41
1910	1.243	20.18	32.87	31.21
2530	1.071	35.87	35.80	37.68
2668	0.4088	30.42	31.72	33.12

Microphone 1 measures a higher SPL at frequencies below 50 Hz as shown in Figure 14. As discussed earlier, a majority of natural modes of the room also lie in this frequency range, and hence the SPL peaks could be due to structure borne vibrations inside the chamber. However, these frequencies are located outside the frequency range of interest (50 Hz- 10 kHz), and hence have no effect on the fan test.

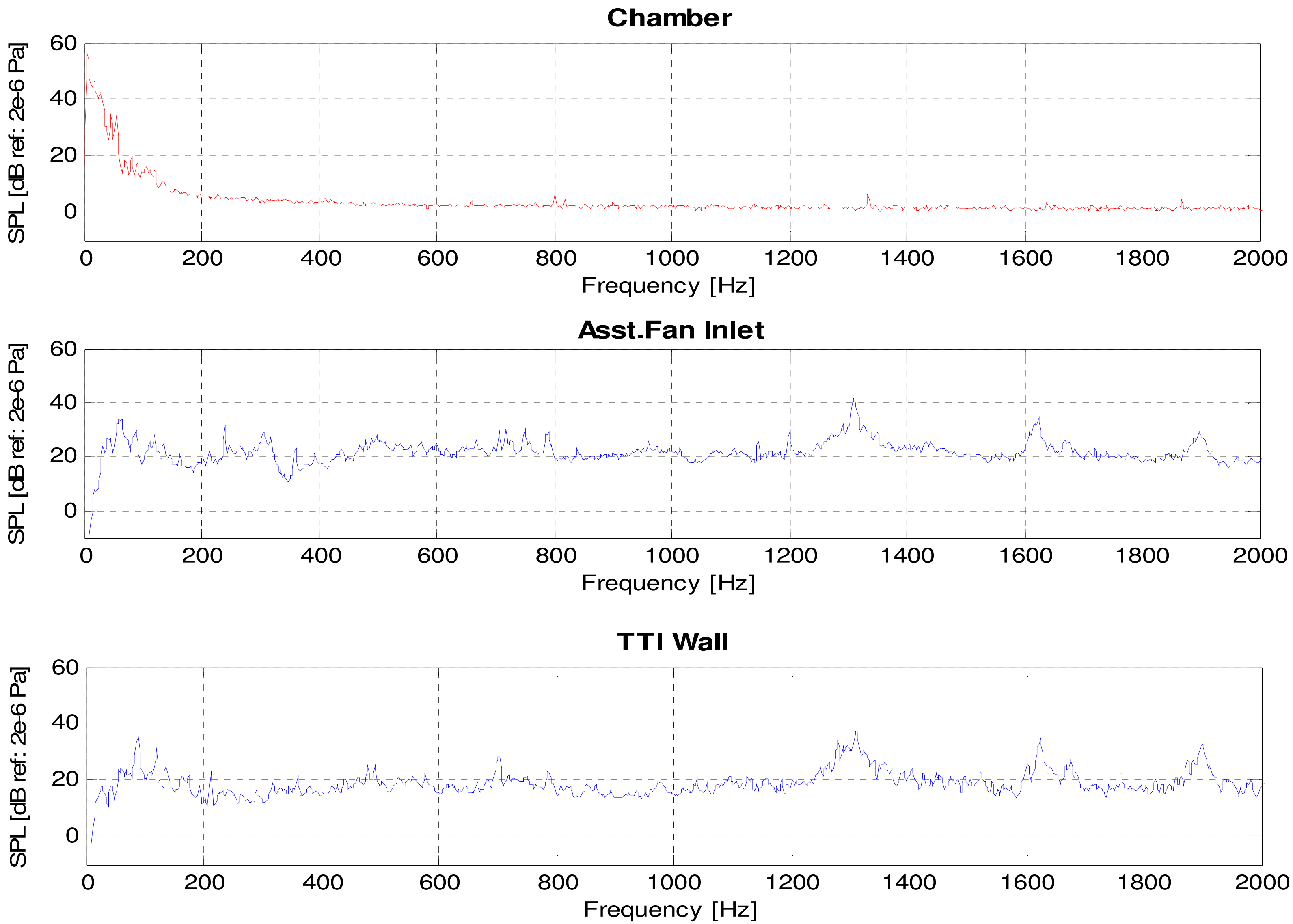


Figure 11 Auto-Spectra of Mics 1, 2 and 3

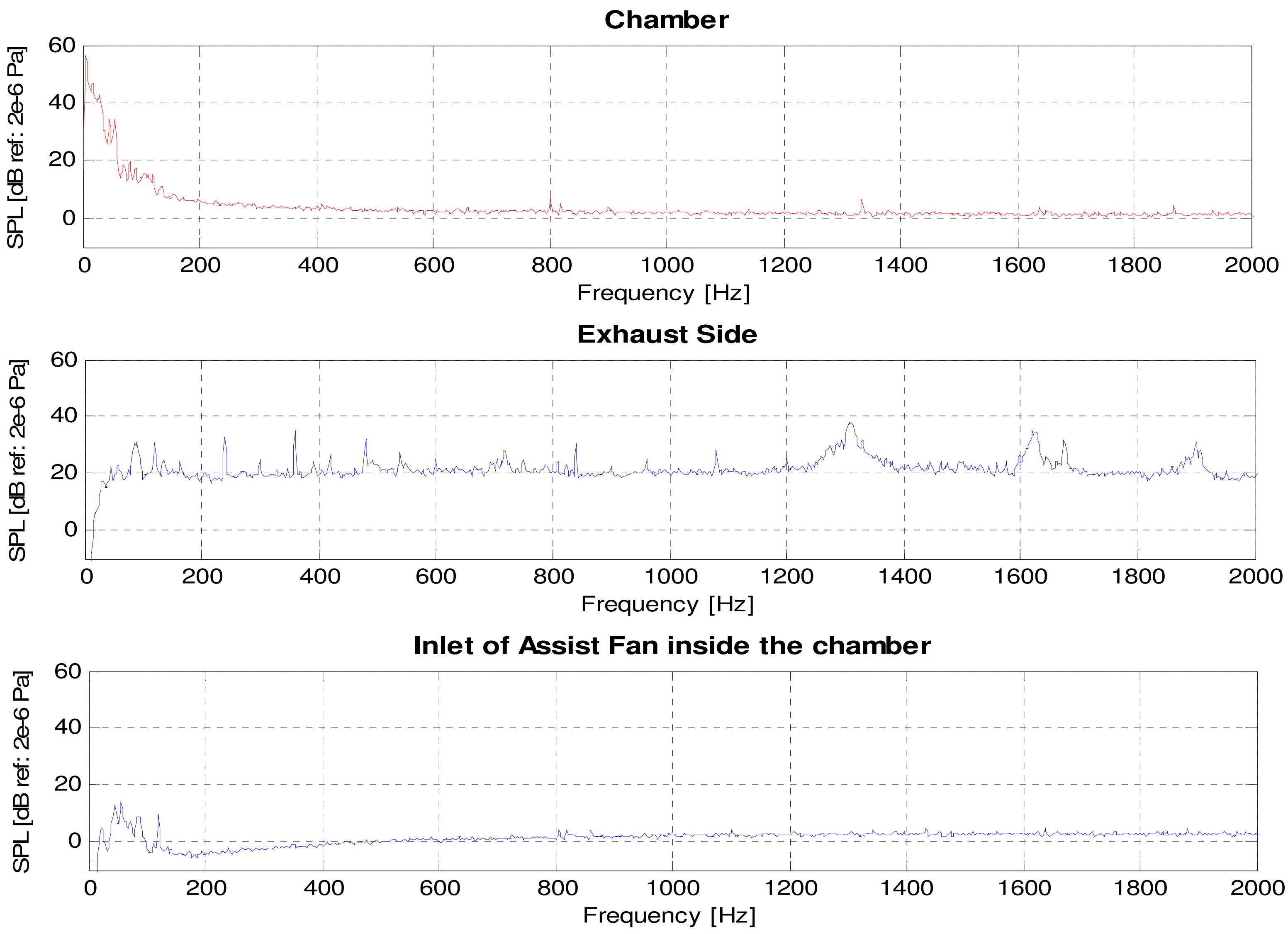


Figure 12 Auto-Spectra of Mics 1, 4 and 5

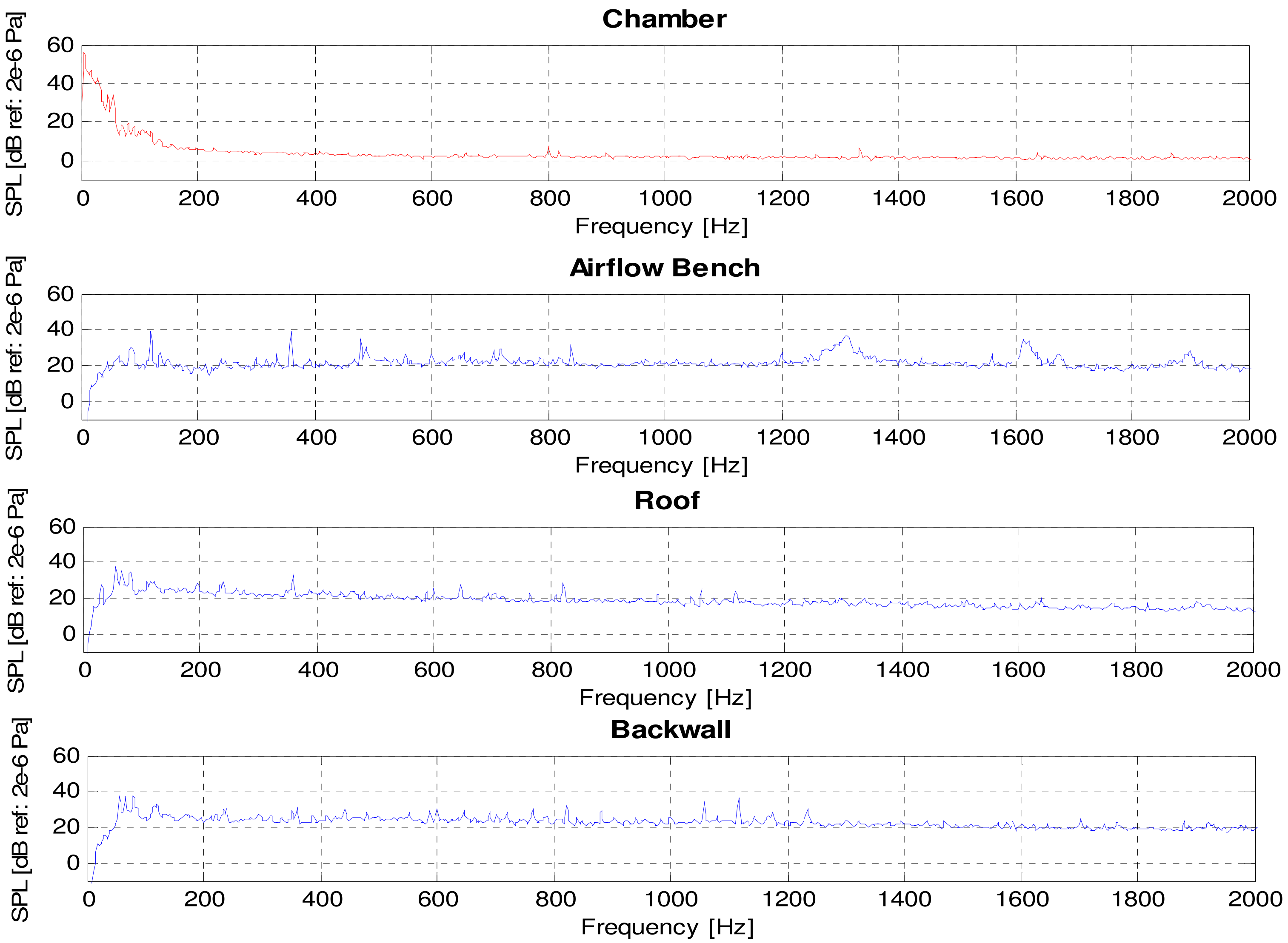


Figure 13 Auto-Spectra of Mics 1, 6, 7 and 8

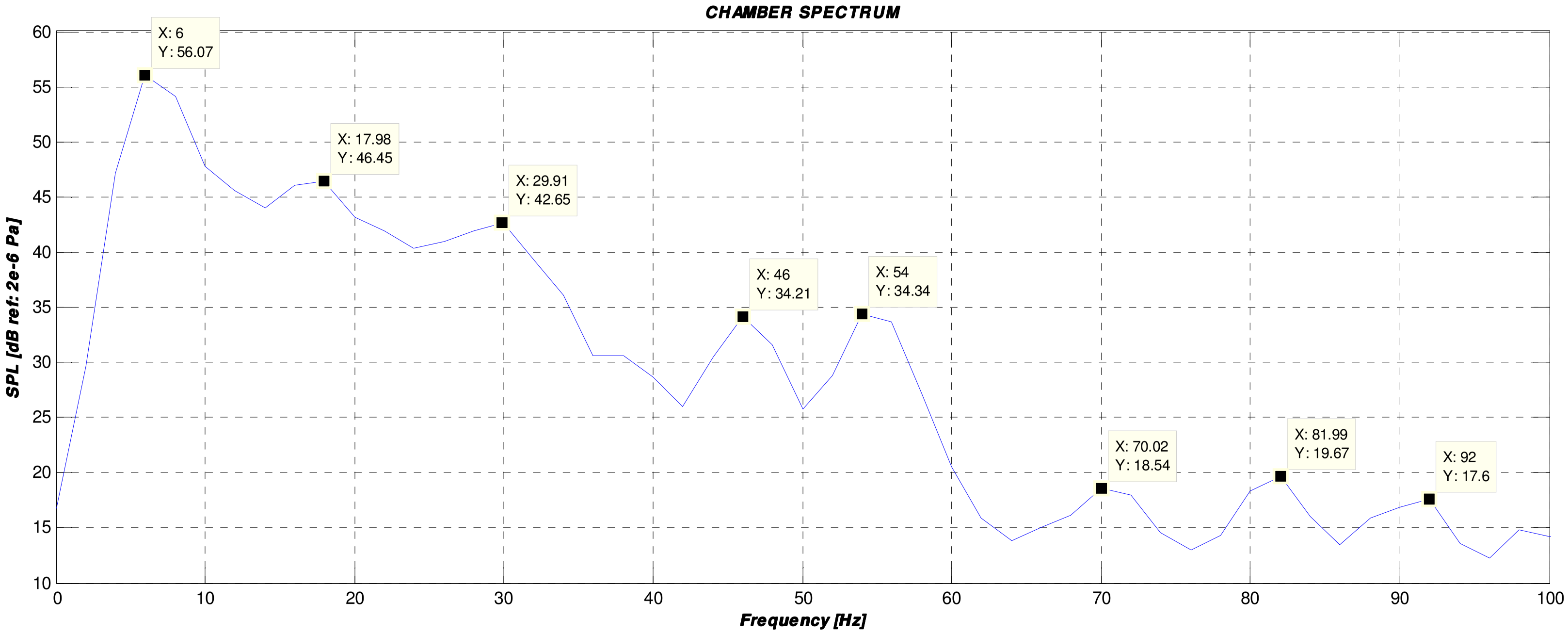


Figure 14 Auto-Spectrum (0-100 HZ) of Mic 1

7.2 Coherence Function

The coherence function gives a measure of the linear dependence between two signals as a function of frequency. It is computed from the cross spectrum and auto-spectra of both the signals.

The coherence function is calculated as:

$$\gamma^2(f) = \frac{\left|G_{xy}(f)\right|^2}{G_{xx}(f) * G_{yy}(f)}$$

where,

$G_{xy}(f)$ = cross spectrum between the microphone inside the chamber & a microphone outside the chamber $[\mathrm{dB}]^2$

$G_{xx}(f)$ = auto-spectrum of the microphone inside the chamber $[\mathrm{dB}]^2$

$G_{yy}(f)$ = auto-spectrum of the microphone outside the chamber $[\mathrm{dB}]^2$

f = frequency

The value of the coherence function ranges between 0 to1. A value of 1, corresponding to perfect coherence, implies that the noise level recorded outside the chamber is fully transmitted inside the chamber.

Figures 15-17 show the coherence functions for microphones (2-8) with microphone 1 in the 0-2 kHz frequency range. Strong coherence was not observed, which indicates sufficient acoustical insulation of the chamber walls. The maximum coherence occurs at frequencies less than 100 Hz. The coherence function for microphone 5 with microphone 1, has several peaks due to the fact that microphone 5 was also inside the chamber.

Table 17 shows the values of maximum values of coherence functions for each microphone with microphone 1.

Table 17 Maximum Values of Coherence Function

Microphone	Frequency [Hz]	Coherence Function
2	40	0.5254
3	24	0.2423
4	46	0.4788
6	44	0.4231
7	82	0.7401
8	56	0.6505
	80	0.6489

The appendix shows the auto-spectra and coherence functions for all microphones over the entire frequency range (0Hz-10 kHz).

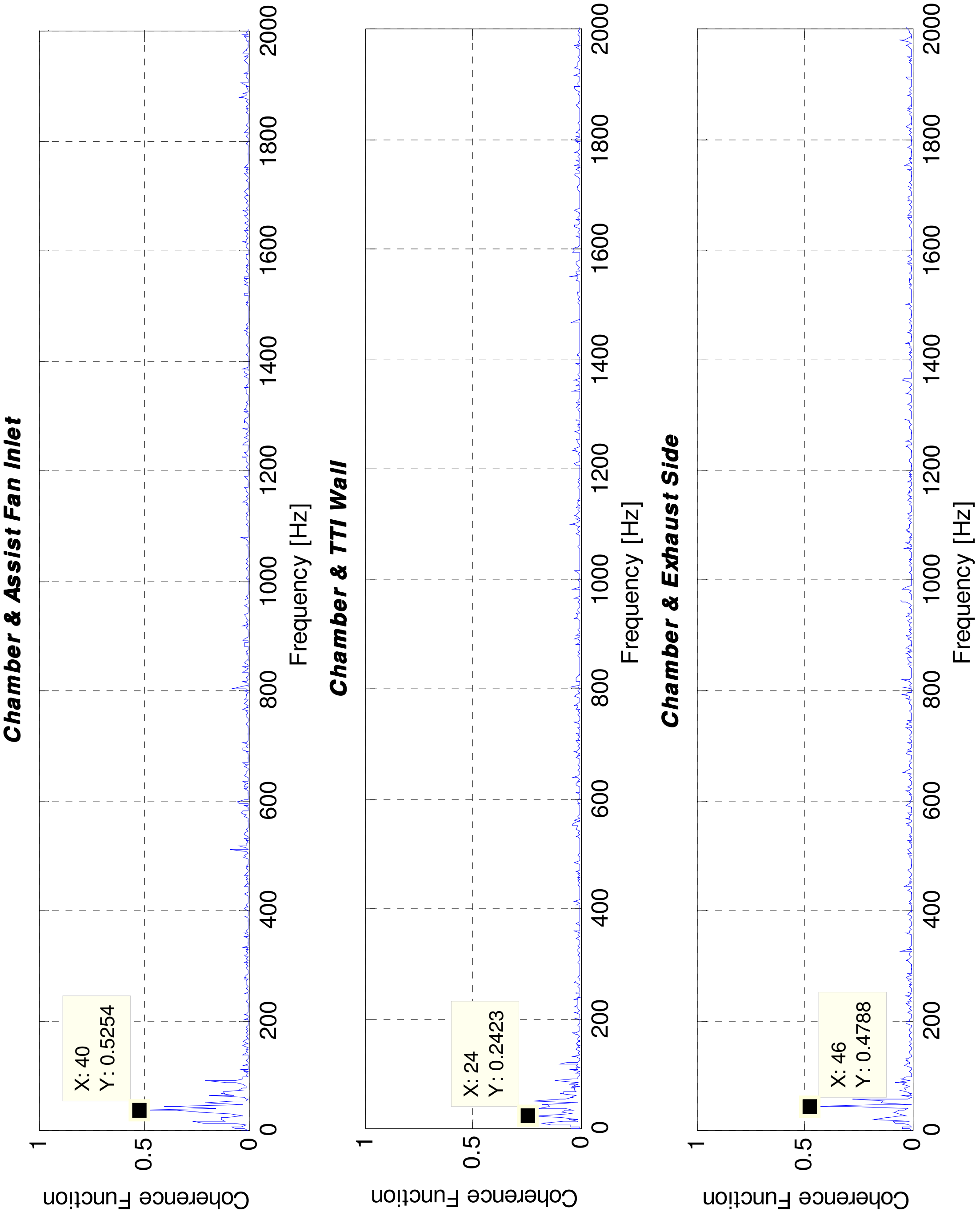


Figure 15 Coherence Functions for Mic1 with Mics 2, 3 and 4

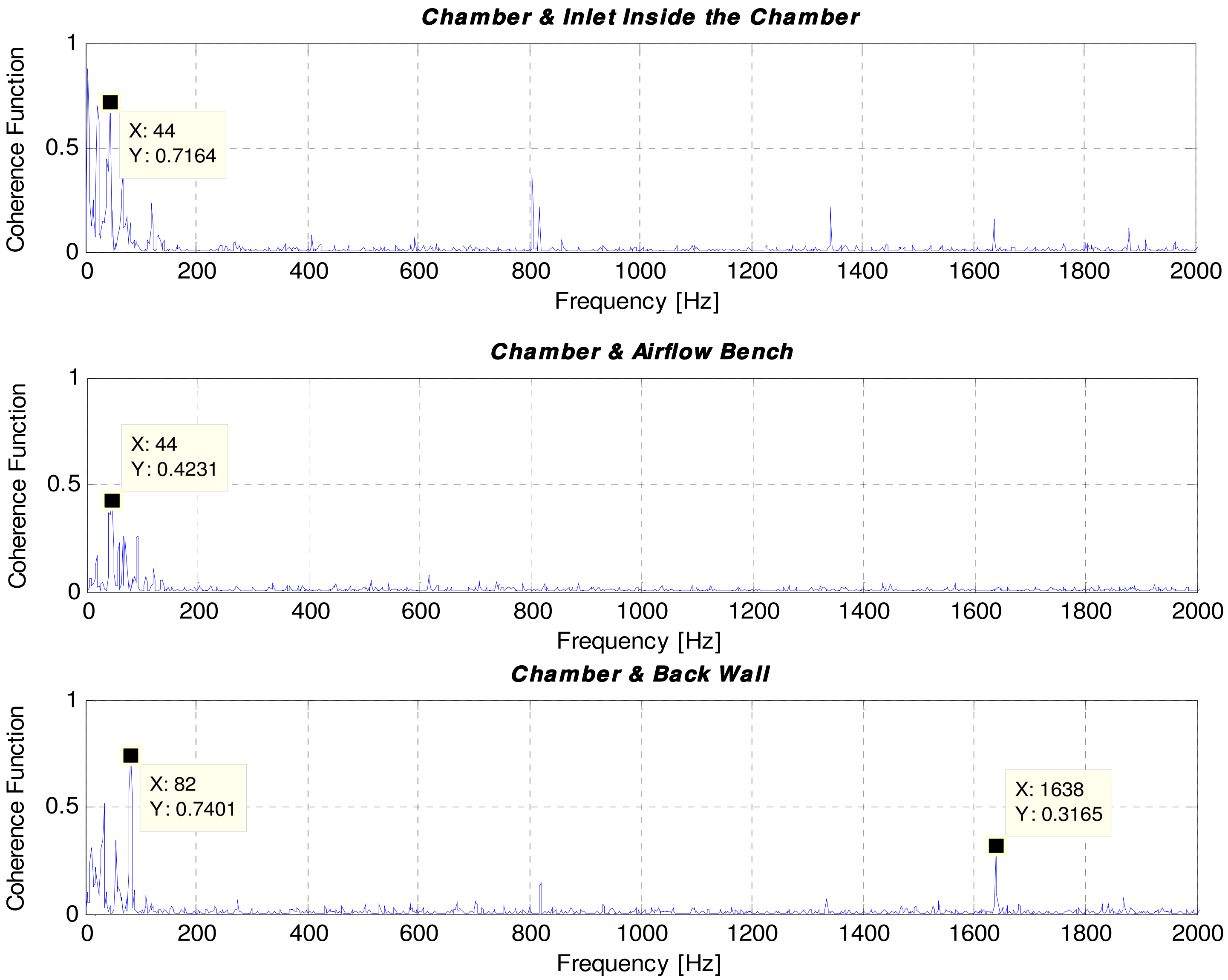


Figure 16 Coherence Functions for Mic1 with Mics 5, 6 and 7

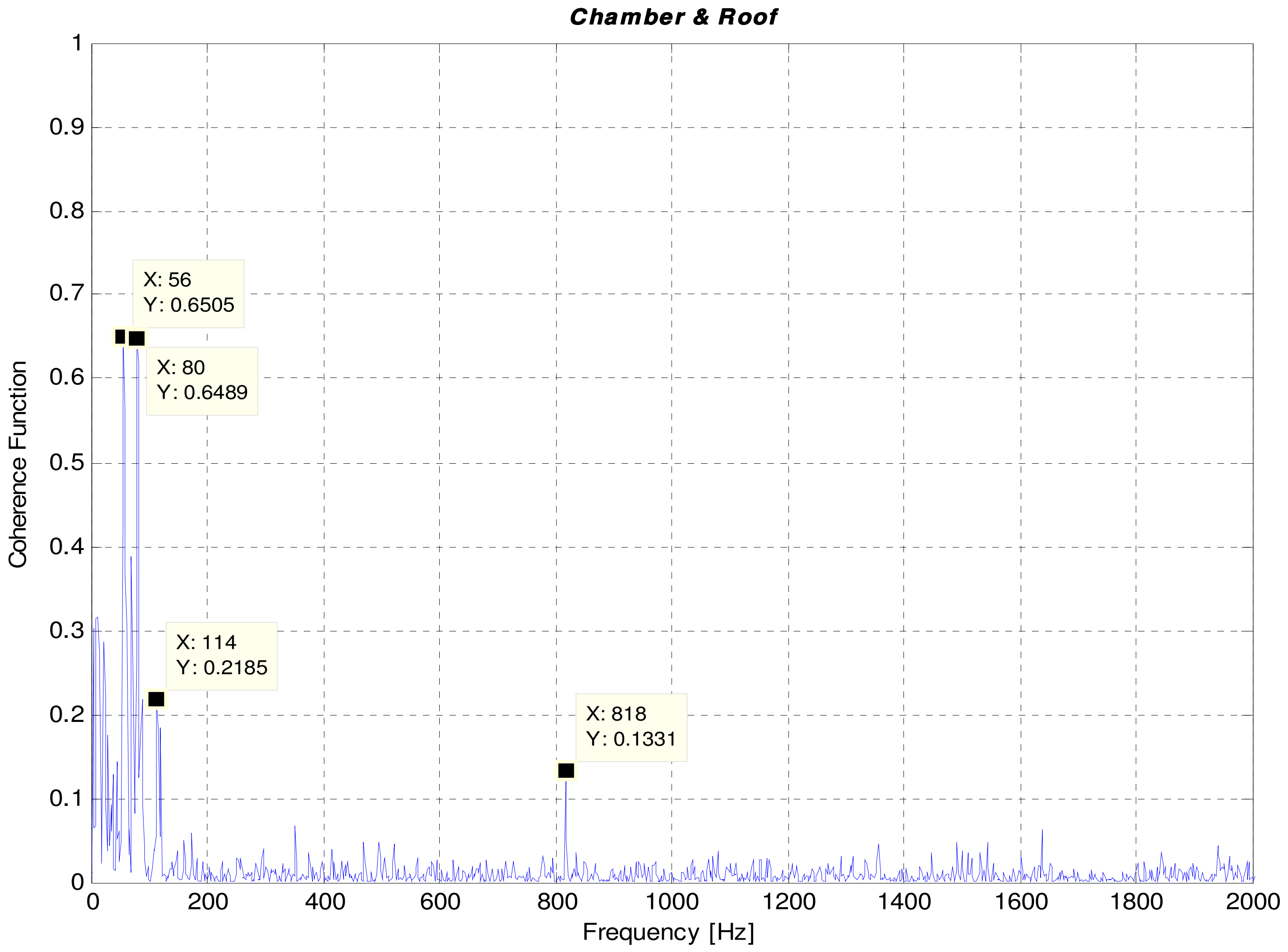


Figure 17 Coherence Functions for Mic1 with Mic 8

8. INFLUENCE OF BKG LEVELS ON THE LOUDNESS RATING

BKG levels are logarithmically subtracted from the fan SPL to get the true SPL of the fan alone. A study was conducted to analyze the effect of BKG levels on the loudness rating. Two fans- one below 1 sone (low sone fan) and a louder fan (above 1 sone rating) were each tested in different BKG levels and their loudness ratings were computed. BKG Levels used were daytime noise levels, night-time noise levels and noise levels with the air conditioner running. Figures 18 & 19 show the different BKG levels for the two fan types. The loudness ratings of the fans are presented in the Table 18.

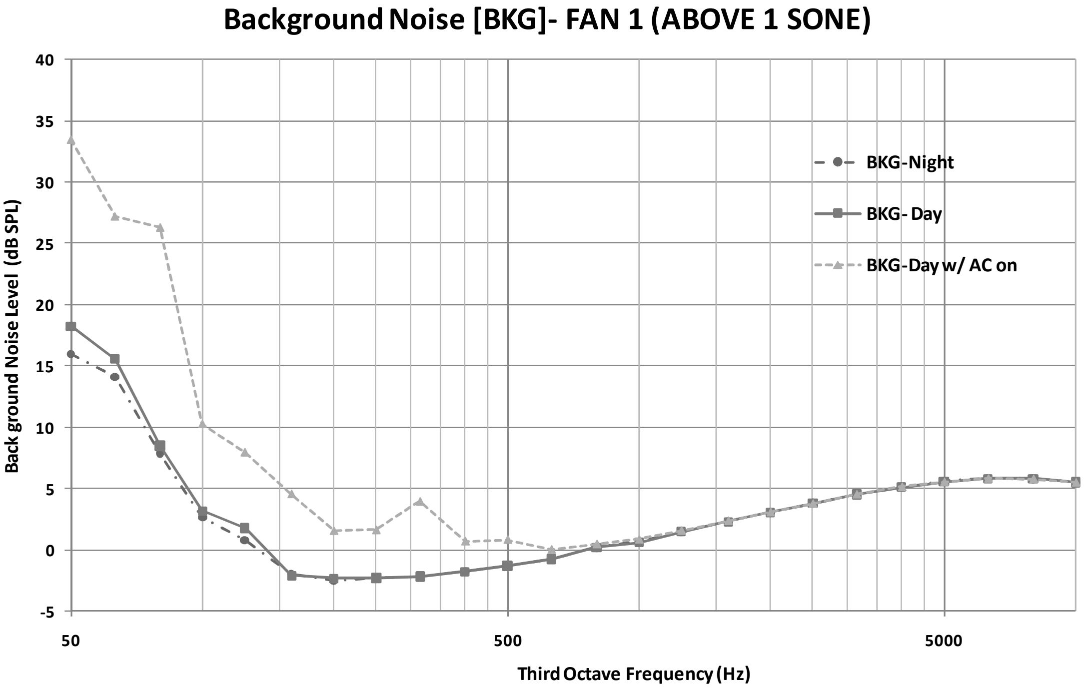


Figure 18 BKG Levels for the Loud Fan

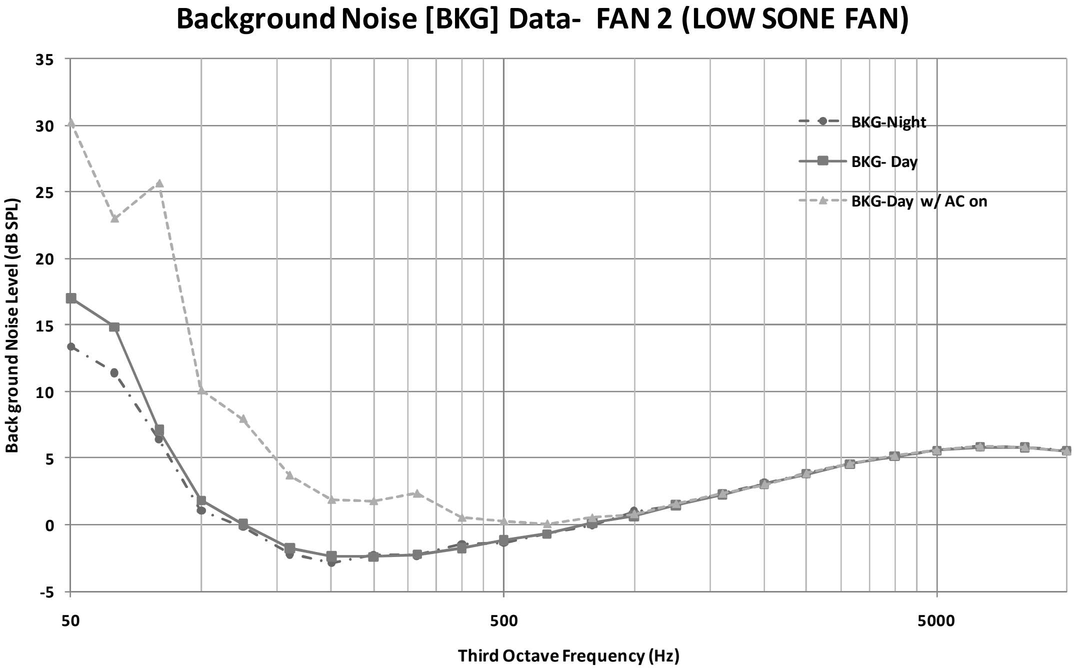


Figure 19 BKG Levels for the Low Sone Fan

Table 18 Loudness Rating with Different BKG Levels

Background Noise Level	Fan 1 (Loudness >1 sone)	Fan 2 (Low sone sample)
Night Time (After 8PM)	1.025	0.272
Day Time (3PM)	1.067	0.281
Air conditioner On*	1.069- 1.076	0.277-0.308

There is no significant variation in the loudness rating between the night-time and the daytime for both fan types. This is attributed to the fact that the BKG levels are almost the same during both daytime and night time (see Figures 18 and 19). With the air conditioner running ,fluctuations in the BKG SPL up to 800 Hz are observed. This is shown in Figure 20. Fluctuations are a result of transient noises, which affects the accuracy of the loudness rating since transient noises cause convergence problems during a measurement. A transient noise recorded while measuring fan SPL will result in a higher loudness rating for the fan. Similarly, a transient noise source recorded while measuring the BKG SPL will invalidate the test (BKG SPL is greater than the fan SPL) or will result in a lower loudness rating if consistency is maintained. The sound test duration is two minutes (four 30-sec runs). However, for the tests done with the air conditioner running, the test duration exceeded two minutes due to the difficulty in getting a consistent BKG level.

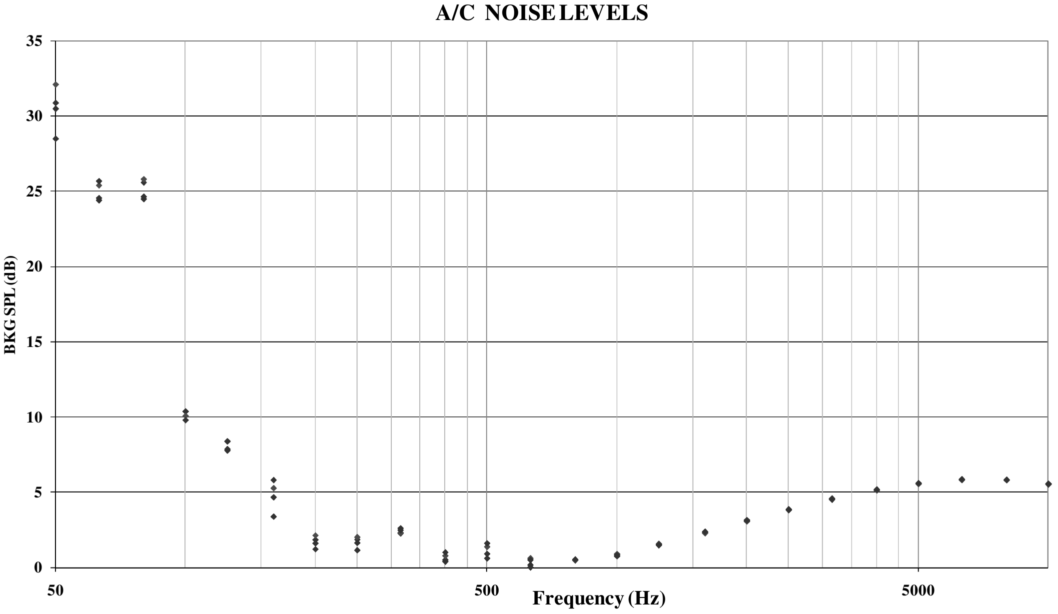


Figure 20 Air-Conditioner Noise Levels

9. FAN- BKG NOISE SPL SEPARATION REQUIREMENT

For the ideal reverberation chamber, BKG levels recorded within the chamber should be zero throughout the frequency range of interest for fan testing.

Despite the fact that no transient noise source was identified during spectral analysis, it becomes necessary to establish the feasibility of testing low sone fans in the measured BKG levels.

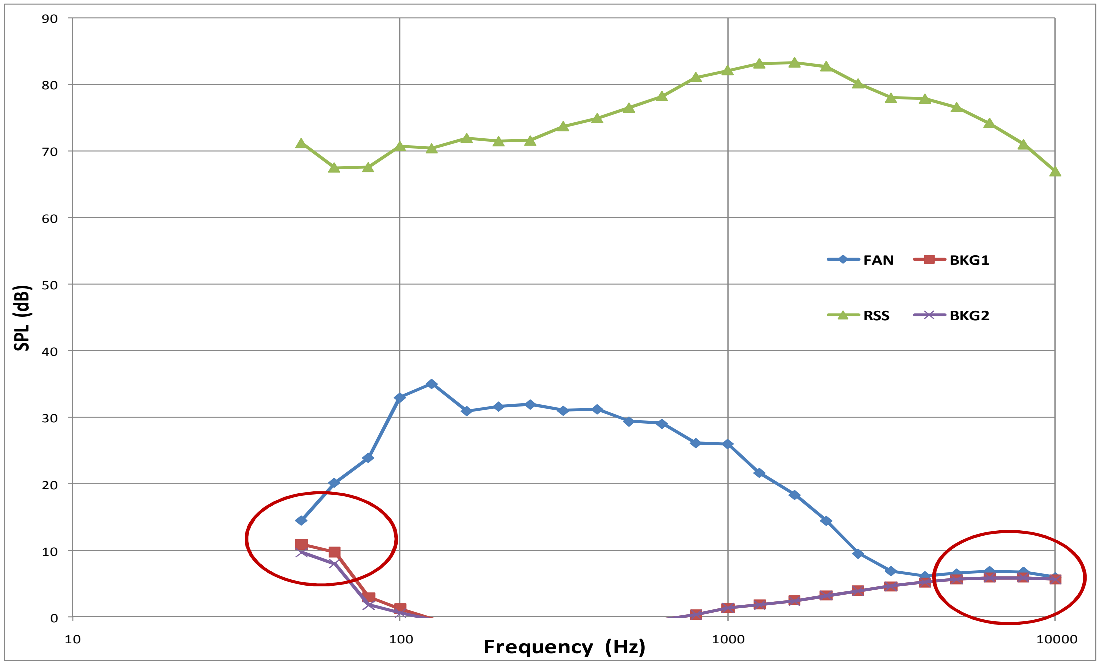


Figure 21 Low Sone Fan Spectrum

A typical low sone fan spectrum (less than 1 sone) is shown in Figure 21 above . The separation criteria is not met at very low frequencies (below 63 Hz) and at very high frequencies (above 5 kHz). At frequencies below 63 Hz, the chamber BKG levels are close to that of the fan noise levels, and hence the separation is not met. However, in the frequency range of 0-63 Hz, the minimum audible loudness level is very high. For example, the lowest audible SPL at 50Hz is 42 dB.

Figure 22 shows the minimum perceived loudness level in the various frequency bands based on the equal loudness index table (HVI 2009). All SPLs below the curve are assigned a sone value of zero.

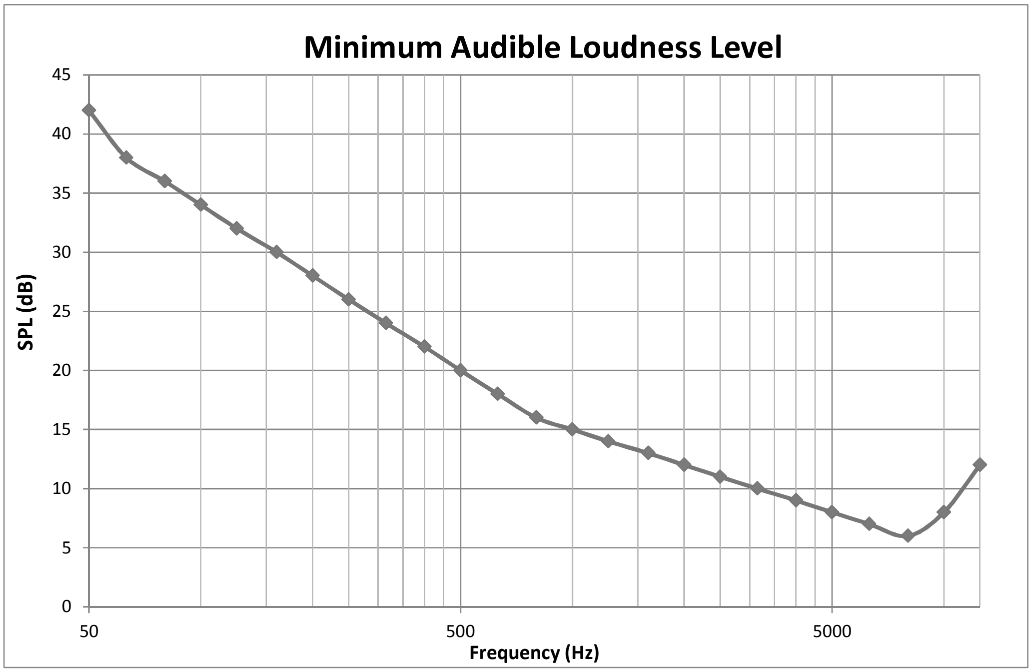


Figure 22 Minimum Audible Loudness Level

The effect of separation on the loudness rating of the fan for the low frequency range is illustrated through a simple calculation as follows.

<u>Case 1</u>: At 50 Hz,

FAN + BKG = 15 dB

BKG 1 = 11 dB

Then SPL for FAN only at 8 ft = 10 $^{\mathrm{LOG10(10\^{}A1 - 10\^{}A2)}}$ = 13 dB

Room characteristic Ratio at 50 Hz = 10 dB

Rating Distance Correction for 5ft = -14.65 dB

SPL for FAN @ 50 Hz , 5ft = 13+ 10 -14.65 = 8.35 dB < 42 dB,

Sone Rating @ 50 Hz = 0

<u>Case 2</u>: If the separation was met

Assume BKG1 = 9 dB,

then SPL for FAN @ 50 Hz , 5ft = 9.375 dB < 42 dB

Sone Rating @ 50 Hz = 0

The loudness rating for the fan does not change and the signal-to-noise ratio is considered sufficient.

In the high frequency range (above 5 kHz), the fan makes almost no noise and hence the SPL for BKG is recorded for the fan also.

Hence, while considering the separation requirement during the qualification of a reverberant chamber for low sone testing, it is essential to take into account the minimum perceived loudness levels for that frequency.

10. CONCLUSION

The six microphones array system is an upgrade to the rotating boom microphone setup. The array system provides spatially averaged SPL without any transient peaks. It is now possible to test low-loudness rating fans.

A spectral analysis of the BKG levels reveals adequate sound attenuation by the walls of the chamber. Structure borne vibrations are observed, but these vibrations are outside the range of fan test frequencies and hence can be ignored. It is also established that it is possible to test a low sone fan during the daytime. However, care should be taken to ensure that transient events, such as firing range noise, airplane/train passage are not recorded during the measurement.

For a low-sone fan, the fan and the BKG level separation is not maintained at very high frequencies (greater than 5 kHz) and at very low frequencies (below 63 Hz). The reverberation chamber can be still be qualified to test low-sone fans despite inadequate separation as the minimum perceived loudness in frequencies in which the fan makes noise is high and will not result in a change in the loudness rating.

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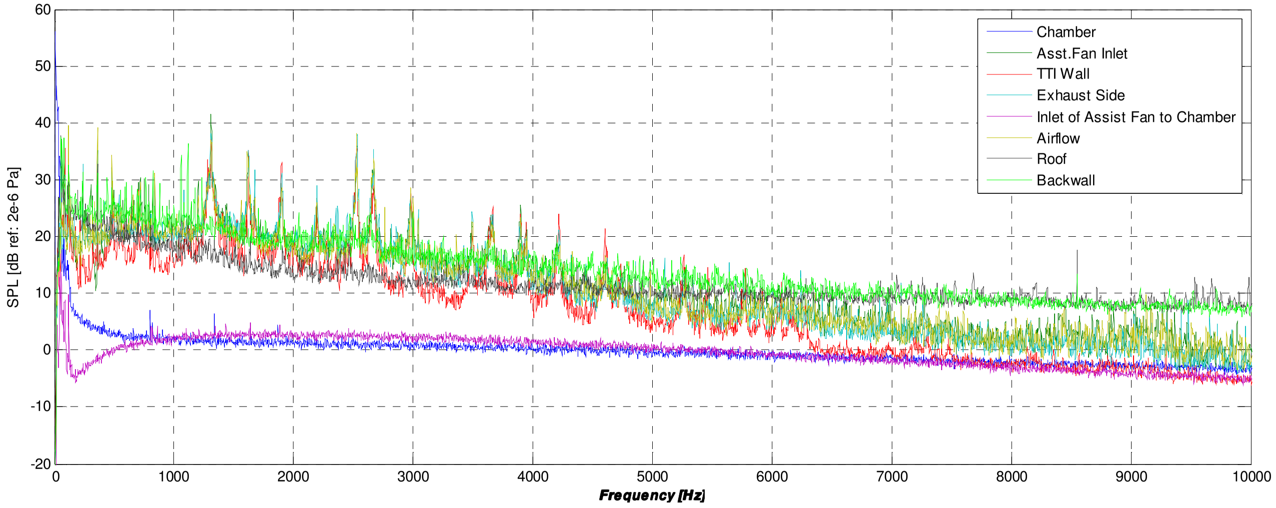
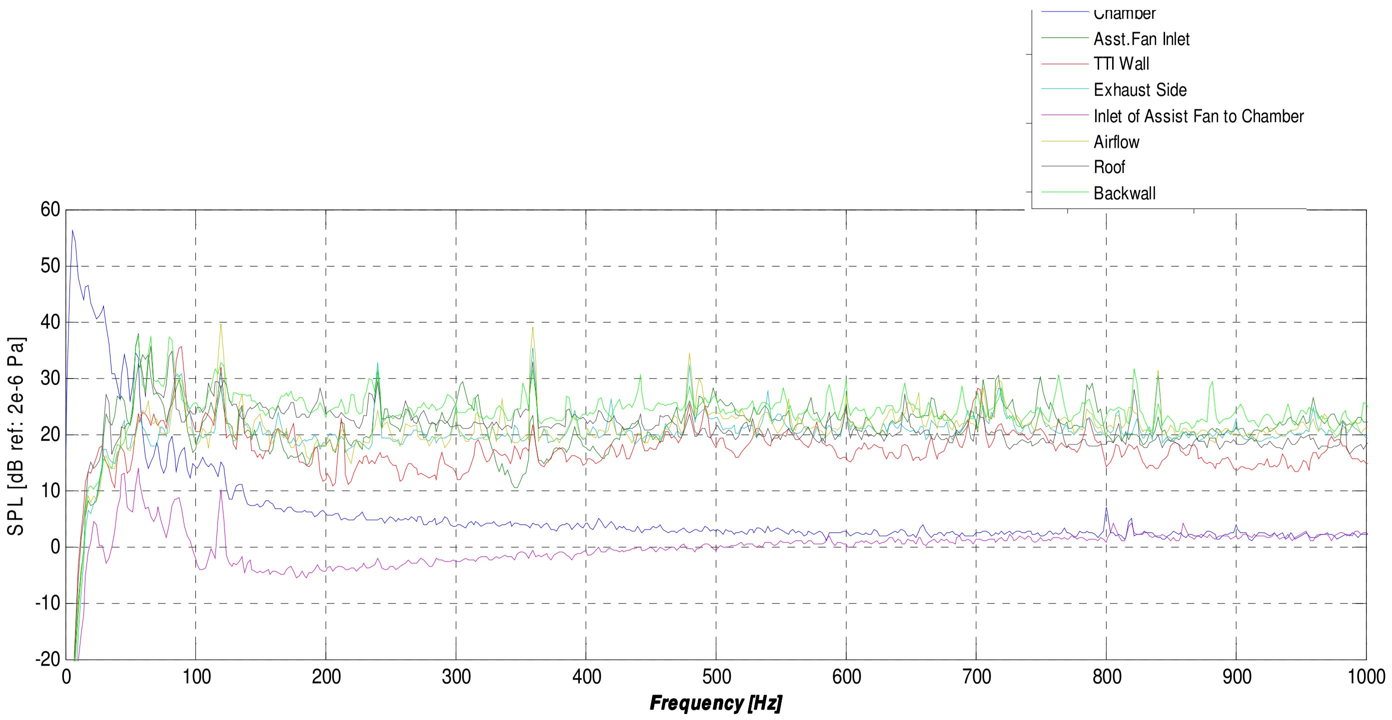
APPENDIX

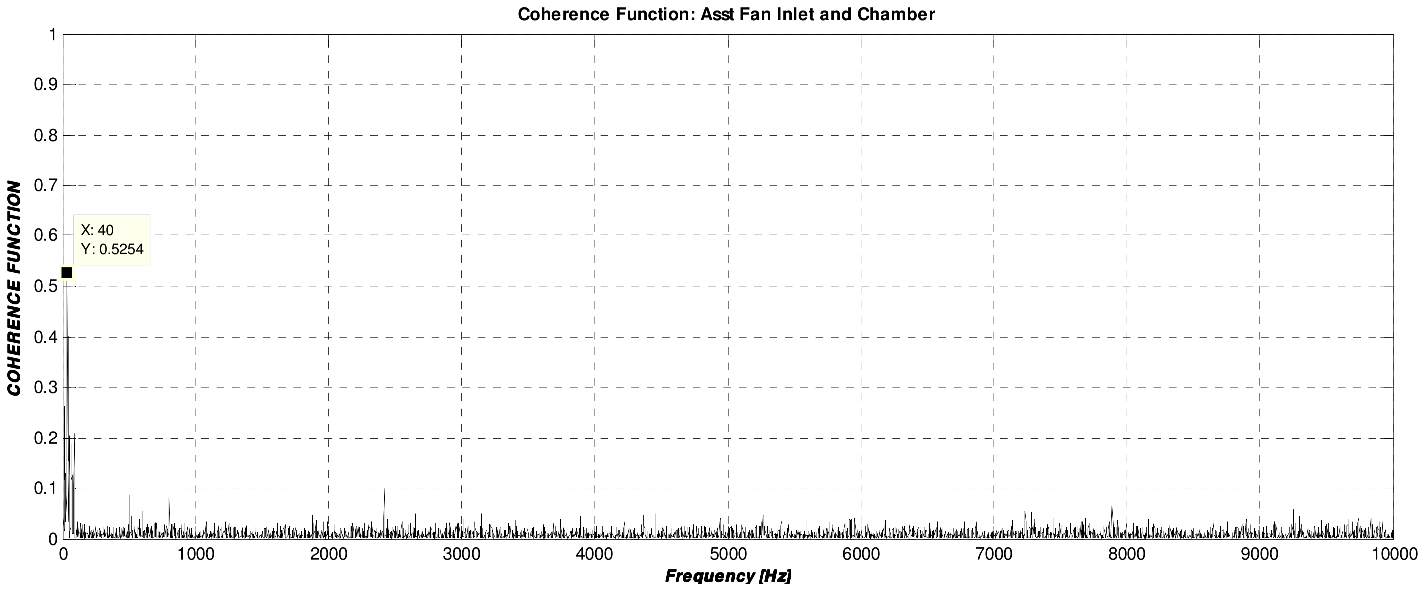
Auto-Spectra of All Microphones (0-10kHz)



Auto-Spectra of All Microphones (0-1kHz)



Coherence Function for Mic 2 & Mic 1



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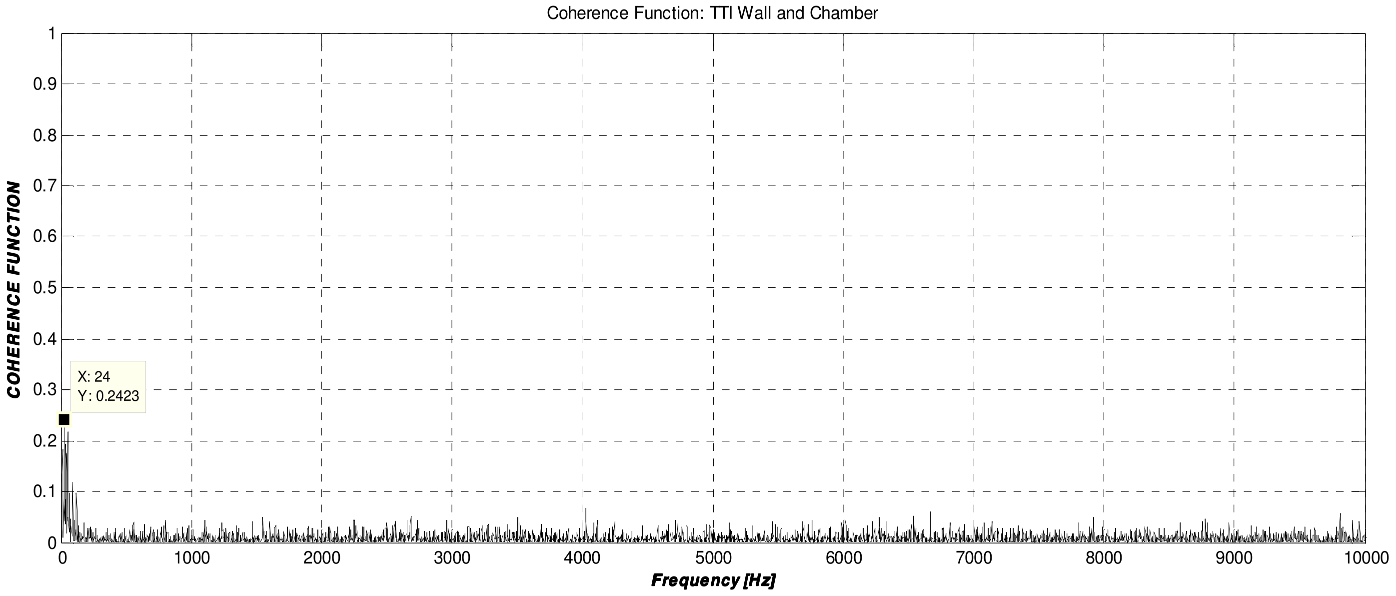
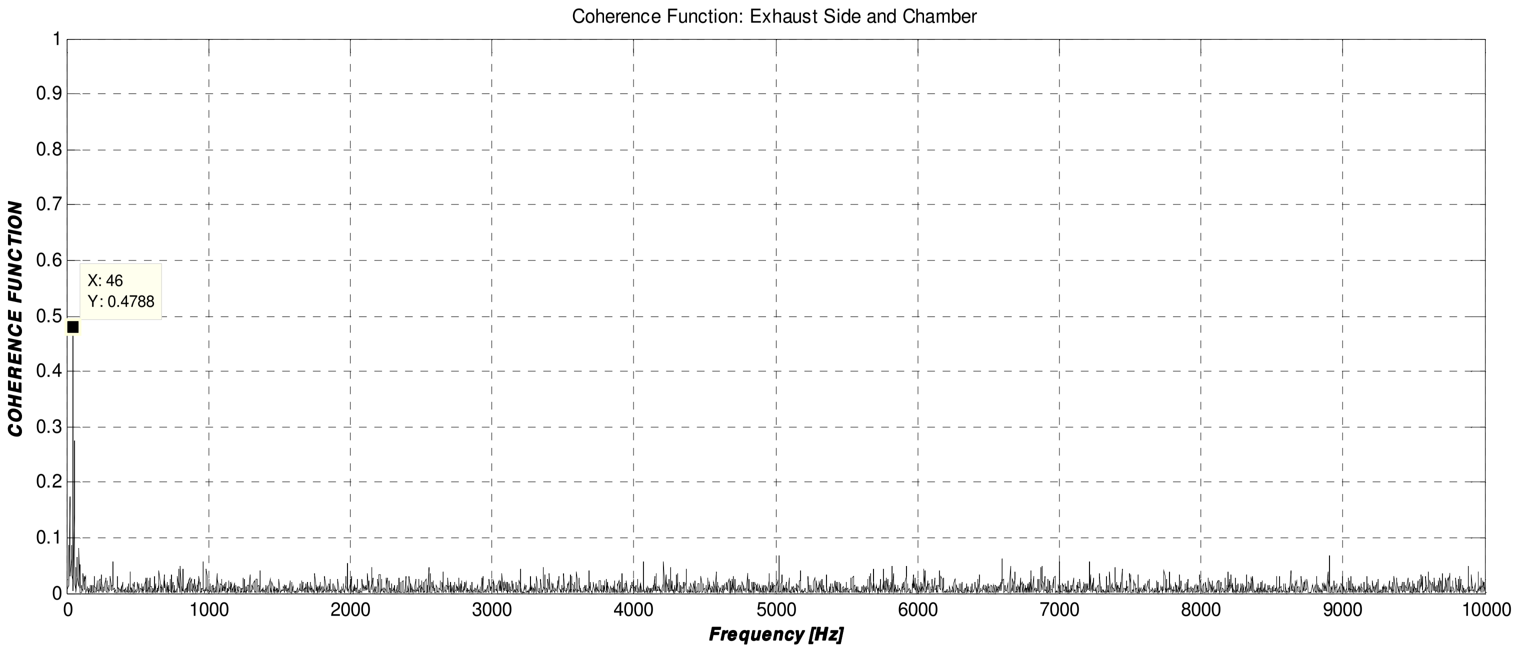
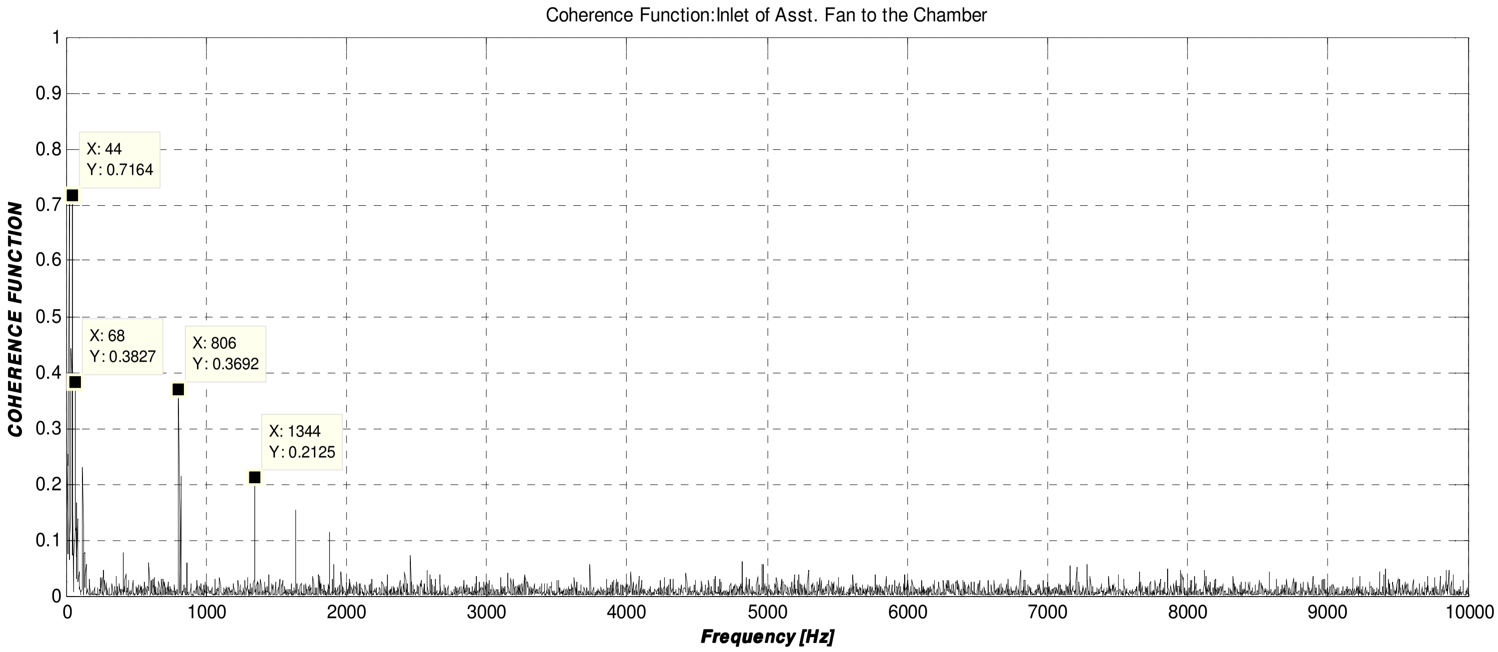


Coherence Function for Mic 4 & Mic 1



Coherence Function for Mic 5 & Mic 1



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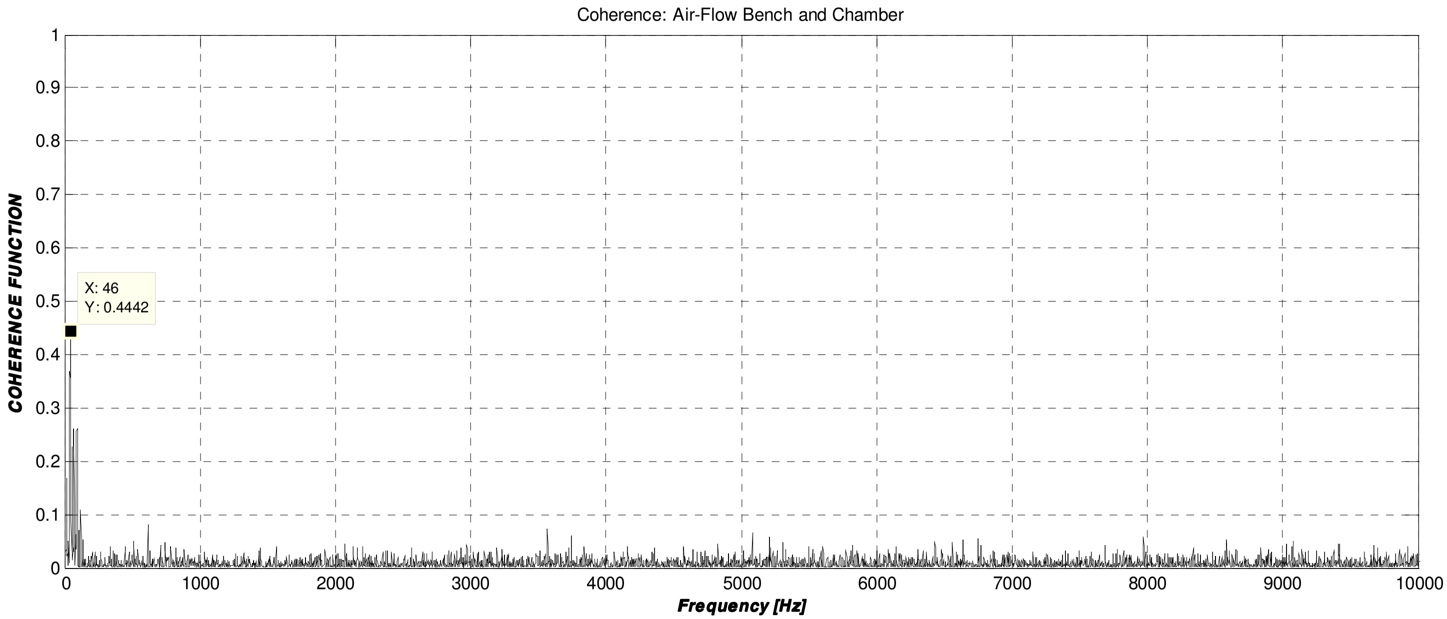

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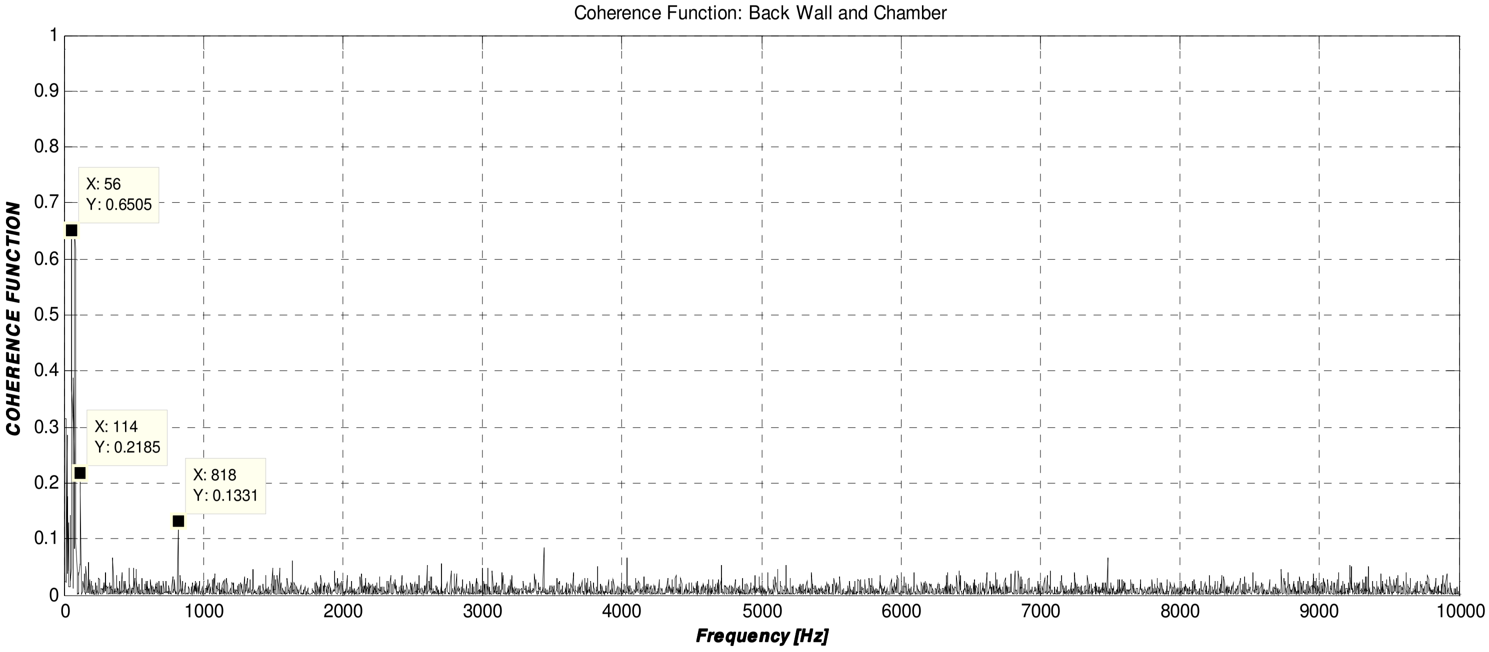
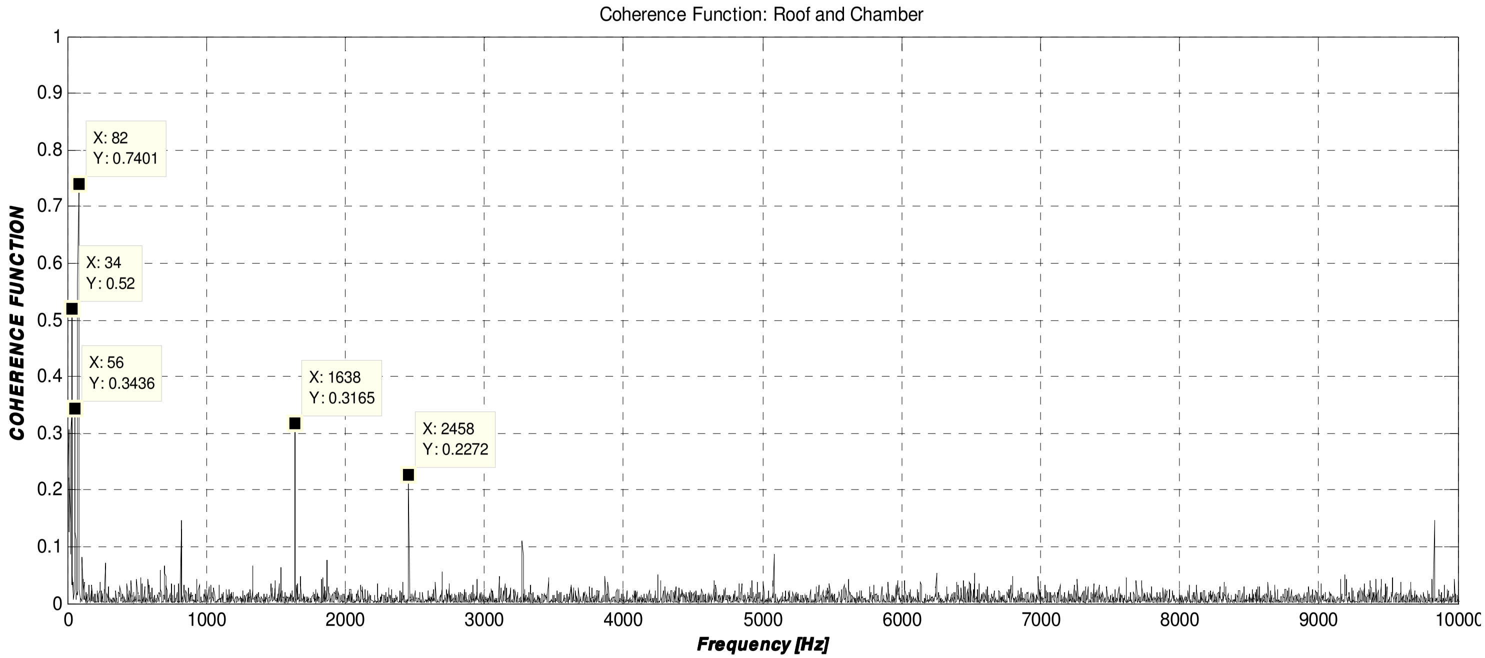


Coherence Function for Mic 8 & Mic1



VITA

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