Team Pin Drop
EITC, University of Manitoba
Winnipeg, Manitoba R3T 5V6

December 6, 2010

Dr. Paul Labossiere
Department of Mechanical Engineering, University of Manitoba
E1-546 EITC
Winnipeg, Manitoba R3T 5V6

Dear Dr. Labossiere,

Please find enclosed the Final Design Report prepared by Team 6 – Pin Drop and submitted December 6, 2010. The purpose of this final report is to present the team's results, and make our final design recommendations for the design of a tractor cab noise control system.

This report includes an overview of the measurement process, as well as results obtained during the testing phase. Several key problem noise areas were identified, and frequency signatures were used to trace the primary sound transmission paths. Since active noise control measures were found to be too costly and ineffective, alternative recommendations have been made. However, further testing is necessary to ensure the efficiency and applicability of these designs. Should you have any questions, comments, or concerns regarding our report, please contact our Team Leader, Jeffrey Leachman, by email at umleach2@cc.umanitoba.ca.

Sincerely,

Jeffrey Leachman
Team Leader and representative for:
Brendan Rempel (Secretary)
Sarby Gill
Peter Lacoursiere

Final Design Report:

TRACTOR CAB NOISE REDUCTION

MECH 4860 - Engineering Design
Prof. Paul Labossiere

Date of Submission: December 6th, 2010

Client: Buhler Versatile – Ed Lambert
Advisor: Dr. Vijay Chatoorgoon

Team 6 - **Pindrop**:

UNIVERSITY OF MANITOBA

Table of Contents

List of Figures

List of Tables

Glossary of Terms

1/3 Octave Band Level - An octave band is a range of frequencies which are defined by the center frequency of this range. The frequency range increases with increasing centered frequency. A 1/3 octave band simply has a smaller range from the listed center frequency, and therefore better resolution of which frequencies are creating the higher noise levels.

dBA (A-weighting) - The A-weighted sound level corresponds to a modified sound level where the sound levels at different frequencies are modified to imitate what is detected by the human ear. In this A-weighting the lower frequency sound is given less importance compared to the higher frequency sound.

Fast Fourier Transform (FFT) - Numerical method that converts time domain to frequency domain. Breaks up the signal into its frequency components.

Pure Tone - If a wave is undergoing simple harmonic motion and is composed of a single frequency this is referred to as a pure tone. If an octave band is at least 4 dB higher than the adjacent octave bands it man contains a pure tone [1].

Resonance - Occurs when an objects natural frequency is externally excited by another source. Natural frequency is a function of the objects mass and stiffness.

Shock Waves - When a flow abruptly changes from subsonic to supersonic motion. Usually involves an increase in pressure, temperature and density of the flow [2].

Sound attenuation - When sound energy experience a decrease per unit area of a wave. Usually occurs as distance increases from the source. Possible attenuation occurs through absorption and reflecting [3].

Structure-borne vibration – Vibrations that are transmitted through the structure.

Abstract

This report has been prepared as the final product of a noise reduction project for the Versatile 280 tractor cab. Team Pindrop, as requested by Versatile, looked into the acoustical noise problems with this tractor model and set out to measure and define the technical noise problems in the tractor. A measurement phase had to be completed before any designs that address the noise problems could be made. Measurements made by team Pindrop include sound pressure level readings of the tractor under load and no-load conditions, as well as accelerometer measurements of various areas. These measurements enabled the identification of problem noise sources, as well as the establishment of the sound transmission paths allowing for the design phase of the project to begin.

Through analysis of the measurements the muffler stack was found to be the leading source of noise. Other components in the tractor design which lead to high noise levels in the cab have also been found and addressed in this report. After conducting research and developing a thorough list of different design options available, the best options based on highest sound **attenuation** for lowest capital costs were selected. The selected designs include focusing on the noise source itself, by redesigning the muffler, as well as increase sound transmission losses from the exterior to interior of the cab by adding acoustic insulation and vibration damping. The muffler should be redesigned to exhaust at lower sound levels while the insulation added to the ceiling will help to attenuate the increased sound levels by the blower fan for the climate control system. Because of the complexity of the mechanical systems involved in a tractor, it is difficult to isolate and characterize the specific noise sources. This complexity makes it difficult to predict the affects of implementing a single design in the tractor, and thus, an overall noise level reduction for each option is not available. The effectiveness of various designs will only be known after implementing them and testing for the associated noise reduction. Therefore, team Pindrop recommends that Versatile implement and test the different design options to identify the most suitable combination for production.

1 Company Background

Buhler Industries Inc. has been evolving steadily over the past decade. In 2000, Buhler acquired Versatile from New Holland, and integrated the company into its corporate vision. In its current state, Buhler has established two major brands within the farm equipment sector. Farm King represents its small equipment offerings, which include pull-type sprayers, fertilizer applicators, flex-wing mowers, etc. Versatile, on the other hand, produces the 2WD and high-horsepower 4WD tractor series, as well as some more specialized tractors [4].

Versatile is interested in incorporating a prototype noise control system in one of its tractor models. This prototype system will be designed to attenuate the high noise levels that are associated with the operation of these tractors. With the implementation of this prototype system Buhler Versatile expects to achieve a significant reduction in the sound pressure levels in the tractor cab, specifically in the vicinity of the operator. Through the creation of a tractor cab with an acoustical option proven to attenuate sound to safe levels, Buhler Versatile hopes to gain an advantage over its competition in the agricultural industry [5]. In an age of safety-consciousness and comfort engineering, a good acoustical design is imperative to the marketability of the Versatile brand.

Versatile Buhler sponsored team 6 - Pindrop from the University of Manitoba to consult on the possibility of implementing an active noise control package in the Versatile 280 tractor. Although the preference for a state-of-the-art active noise control package was stated, the possibility of exploring passive measures and troubleshooting problems at the source was accepted. This report describes the measurements taken by team Pindrop, as well as the acoustical problem areas uncovered by testing procedures. At the heart of the report is an exploration of several sound reduction strategies that may be implemented by Versatile to reduce the in-cab sound pressure levels.

2 Design Problem

Buhler Versatile is interested in offering a noise reduction package for their tractor cabs. The package is to be implemented as an add-on feature which could be offered to customers as an option on the base tractor package. By offering a quiet tractor cab Buhler hopes to set them apart in the agriculture industry.

Buhler Versatile offers several different tractor models ranging from large four-wheel-drive tractors with engine sizes up to 575 horsepower, to smaller two-wheel-drive row crop tractors with a minimum of 190 horsepower. Team Pin Drop was asked to design a noise control system for the Versatile model 280 tractor, which sits in the middle of Versatile's two-wheel drive models with 280 horsepower [6]. It is hoped that the noise control solution designed for the model 280 tractor could be easily modified for implementation across Versatile's entire line of tractors [7].

The design of a tractor noise control system is a complicated design problem, due to the complex nature of tractor noise generation. As a result, this report focuses on the identification of noise sources and possible sound and vibration transmission paths. A description of the specific problems associated with controlling tractor noise and the objective of this design project are included in this report. Recommendations on how to deal with the primary noise sources and how to block possible transmission paths will also be addressed.

In order to define the design problem, the following sections will describe the safety hazards associated with prolonged noise exposure to highlight the importance of implementing a noise control solution. These safety issues form the basis for the importance of the current topic of in-cab noise reduction.

2.1 Noise Exposure Safety Issues

In the farming community, noise exposure is a serious issue. Farm equipment tends to be loud and extended exposure to high noise levels can cause hearing damage and other adverse health effects for farmers. According to part 12, section 2 of the Manitoba Workplace Health and Safety Regulation, if a worker is exposed to noise levels exceeding 80 **dBA** but lower than 85 dBA, the employer [8]:

- Must inform the worker about the hazards of the level of noise: and
- If the worker requests the employer must provide him or her with hearing protection and also any information on the selection of the hearing protection that complies with CAN/CSA Standard- Z94.2.02, Hearing Protection Devices- Performance Selection, Care and Use [8].

It should be noted that the above statement can be difficult to enforce on a farm, since many farmers are self-employed. For this reason the Manitoba Workplace Health and Safety Regulations are only used as a reference for the maximum allowable sound pressure levels to be reached in the tractor cab.

It is not only the magnitude of the sound pressure levels that must be considered, but also the amount of time that the operator is exposed to the noise levels. The permitted exposure times for different sound pressure levels is shown in Figure 1. The long hours typically spent in tractor cabs by farmers reinforces the idea that the tractor cab should be noise controlled.

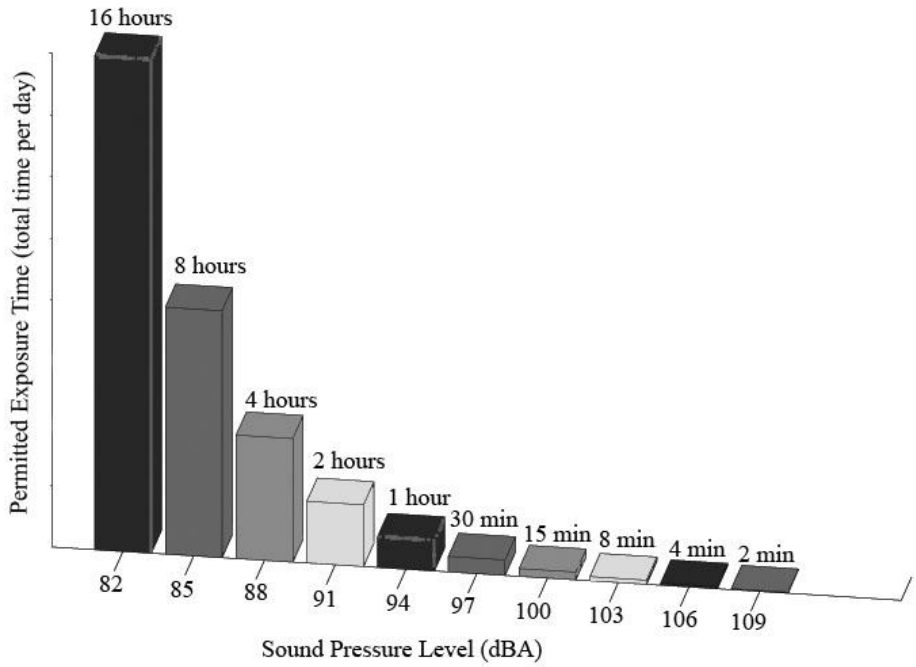

Figure 1 – Permitted exposure time per day [8].

Sound levels in the tractor cab must be controlled to avoid any major negative effects for the operator. Negative effects due to prolonged noise exposure include health problems, decreased worker performance and annoyance. The major effects on operator health are hearing loss and fatigue. Studies completed in the United States, by the Environmental Protection Agency, have shown that forty years of exposure to a steady daily noise level of 75 dBA can lead to permanent hearing damage. It is expected that the most operators will be in the farming profession for this time period [9, p. 4/8]. After this forty year period, the operator may experience a condition called Noise-Induced Permanent Threshold Shift. This threshold shift that is experienced is usually non reversible; it will remain throughout the entirety of the operator's life time and there is no possibility of further recovery. Permanent threshold shifts usually result due to acoustic trauma or may be produced by the cumulative repeated noise exposure over periods of many years. The majority of people experiencing permanent hearing loss from noise sustain such losses as a result of long periods of repeated noise exposure [10, pp. 18.12-18.19]. Non auditory health effects are another issue. Prolonged noise exposure can cause disorders such as hypertension and coronary heart disease. Noise can increase operator stress levels, leading to adverse physiological effects [11, pp. 25.1-25.19].

Performance of the operator is usually affected under continuous exposure to high sound levels. This is a problem because farming requires the operator to be alert for their safety as well as the safety of anyone that might be in the vicinity of the tractor or other farm equipment. Numerous studies have found several critical issues affecting the performance of workers that are continuously exposed to noise [12, p. 24.20]. It has been shown that a worker's response time, attention to detail and ability to interpret visual signals is detrimentally affected by noisy work environments.

Heavy equipment operators will be working in an environment that will require performing several tasks simultaneously. These tasks involve the observation of the digital displays and implements being used, while steering the tractor and operating the necessary controls. The efficiency of these tasks will be affected if the farmer is distracted by high noise levels. Throughout the day operator fatigue will further decrease the efficiency of completing these tasks. This will most likely lead to operator errors which could, in certain situations, cause harm to the operator or others.

In Versatile's model 280 tractor, sound pressure levels reaching 85 dBA were measured at the operator's position in the tractor cab. With sound pressure levels reaching 85 dBA it can be seen in Figure 1 that the maximum recommended exposure is eight hours per day. While the amount of time spent in a tractor will vary on a case by case basis, it would be beneficial to implement a means of reducing the noise levels in Versatile's model 280 tractor to increase operator safety and comfort.

2.2 Design Problem

Developing a noise control strategy is a complicated procedure, but can be broken down into three steps: finding potential noise sources, ranking the sources in terms of individual contribution to overall noise levels, and developing a noise control solution for the major sources [13]. After talking with Versatile and through some initial sound pressure level measurements, a list of possible noise sources was established. It was found that the predominant noise source on the tractor is the engine. Other noise sources include the hydraulic systems and cab HVAC equipment [7].

Given that the main source of noise on the tractor is the motor, this report will focus mainly on dealing with noise created by the engine. Diesel engines, like the 8.3L Cummins QSC used by Versatile on the model 280 tractor, create noise in a variety of ways. Typically, the majority of sound created by an engine is a result of the combustion process. It is difficult to identify what part of the combustion process is the main cause of noise. This is because as the engine moves through its combustion cycle the noise-causing vibration characteristics of each engine component will change, making it difficult to associate characteristic frequencies with a specific component. Diesel engines in particular, create a distinctive tone caused by the high cylinder pressures used to ignite the fuel. The forces created during combustion cause the engine surfaces to vibrate and radiate sound. Additionally, engine vibrations can be transmitted through the tractor chassis to other components, such as the cab or hood which will then radiate noise due to the forced vibrations [14, pp. 1024-1028].

Supporting systems for internal combustion engines, such as the radiator fan, fuel injection system, timing drive, turbocharger and exhaust system also create noise. In this project it was found that the exhaust system, which vents in close proximity to the cab was a predominant source of noise in the cab. Recommendations, for dealing with exhaust noise will be presented later in Section 3.2.1.

It should also be mentioned that changing any one system on the tractor can completely change the noise problem. It has come to team Pindrop's attention that the Versatile will be making updates to their tractor exhaust systems as required by new emissions standards [7]. Any changes made to the exhaust system could affect the effectiveness of the recommendations made in this report. In a recent study by Anderson and Baker, it was found that equations developed in 2005 for engine noise prediction based on stroke length, engine speed and cylinder bore size were no longer valid, even when compared to the engines used to develop the equations. After further study, it was found that changes made to the exhaust systems in order to meet improved emissions regulations, had changed the sound characteristics of the engine. The changes to the muffler resulted in a decrease in combustion noise and as a consequence, gear train rattle became the major noise source [14, p.1025].

3 Noise Measurement & Characterization

At the start of this project it was clear that in order to design the best solution to solve the noise problem in a 280 model tractor that a method to quantify the noise levels would be required. Measurements were taken to attain the overall sound pressure levels in the tractor cab and to find the characteristic frequencies associated with the noise. Sound pressure level measurements were taken using a Bruel & Kjaer 2250 sound level meter.

By taking measurements at different locations within the cab and around the tractor exterior, possible sound transmission paths can be determined. Sound transmission paths were traced by comparing the sound pressure levels in specific frequency bands in different measurement locations. The tractor components that caused the highest noise levels could also be traced by a similar method. For example, by conducting noise measurements close to the muffler and comparing these results to the measurements in the cab, it can be confirmed that the muffler is a large source of noise. This was confirmed by tracing what frequencies have the highest noise levels at the stack and correlating that to the measurements taken in the cab.

Once possible sound transmission paths and noise sources were identified, vibration measurements were used to find out more information about sound sources and transmission paths.

3.1 Measurement Apparatus & Procedure

Several different types of equipment were used in the design of a quieter tractor cab. The equipment ranged from simple devices such as a stethoscope which mechanically amplified vibrations, to a digital oscilloscope which can save and display outputs from transducers. A more thorough explanation of all the equipment used will be examined in this section of the report.

A Bruel & Kjaer 2250 sound level meter capable of averaging a sound measurement over a time interval and displaying the results in **1/3 octave bands** was used to obtain sound level readings. The Bruel & Kjaer 2250 sound level meter can be seen in Figure 2 below. A windscreen, also visible in Figure 2, was utilized when taking out of cab measurements to eliminate any interference caused by wind.

Figure 2 - Sound level meter & windscreen

It was important that the sound level meter used be capable of measuring sound pressure levels in 1/3 octave band centered frequencies. This is important because the 1/3 octave bands allow for a better resolution to allow for an easy method of determining which frequencies were responsible for the highest noise levels. The Bruel & Kjaer 2250 sound level meter met this requirement.

Sound is caused by the vibration of a surface. This means that any **pure tones** found in the sound level measurements can be matched to vibrating tractor components. If any tractor components are found to be significant contributors to the overall tractor cab noise, they can be specifically targeted by the noise control system. Vibration measurements were conducted using a tri-axial accelerometer transducer. This accelerometer is capable of measuring the amplitude of the acceleration of a part over time to determine how much the part is vibrating. The tri-axial output of the accelerometer means that every different direction that a surface can vibrate will be accounted for. The accelerometer was placed on different tractor components, such as the muffler, hood, different glass surfaces and frame components. An image of the accelerometer placed on a frame component can be found in Figure 3 below.

Figure 3 - Accelerometer on tractor frame

In all there were thirty three different surfaces that were measured for vibration. The output of the transducer was then amplified using pre-amplifiers to reduce line noise. After amplification the data was displayed and recorded using a digital oscilloscope which displayed an acceleration vs. time plot. The data was saved for a certain time interval so that analysis could be conducted after the measurements were taken. When recording measurements, care was taken to ensure that the acceleration was amplified as much as possible without overloading the system, which would have resulted in inaccurate data. Amplification was important in ensuring that the data was as clear and accurate as possible. An image of the pre-amplifiers, as well as the digital oscilloscope can be found in Figure 4 and Figure 5 below.

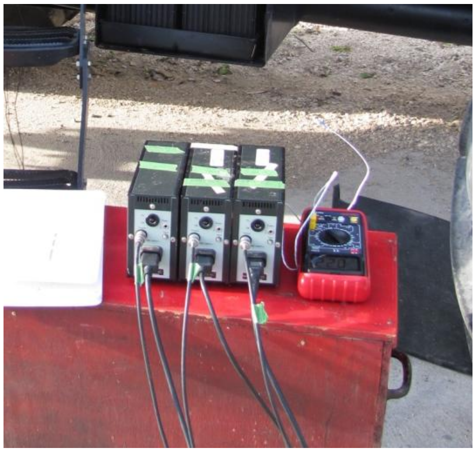

Figure 4 - Image of pre-amplifiers used

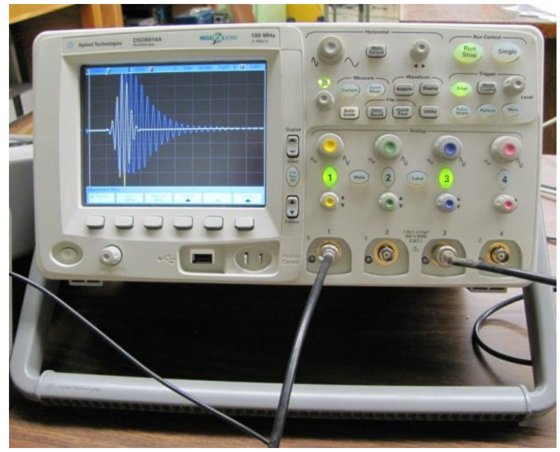

Figure 5 - Image of oscilloscope used

After the measurements were taken the data was post processed using an **FFT** in MATLAB to generate an acceleration amplitude vs. frequency plot. This plot can then be analysed to determine the main frequencies of vibration, linking the vibration measurements to noise measurements. All the measurement data can be found in Appendix A and B.

3.2 Noise Problem Areas and Recommendations

Several measurements were required in order to determine what changes were required to make for a quieter tractor cab. Only once enough measurements were taken to discover a trend in the data could design changes be suggested for this project. In finding this trend, data was taken using both the sound level meter and an accelerometer, as described in the previous section of this report.

After taking the measurements team Pindrop was able to discover several different things from analysing the data. The muffler stack was creating the highest noise levels out of all other tractor components. In an effort to make the largest impact on reducing noise, the muffler will be one of the main focuses in designing a quieter tractor cab. It was also noticed that turning on the air conditioning or heating systems raised the noise levels within the cab by approximately 3 dBA. Since this is a noticeable increase in sound pressure levels, the root of this sound must also be discovered. Because it is independent whether it is the heating or cooling system that makes the noise, it is obvious that it is the blower fan that it is the noise source for this system, as it is used to move air for both heating and cooling. A more in-depth analysis of this will follow.

The highest noise levels were measured consistently to be at 100 Hz and 300 Hz. In order to determine the transmission path for these frequencies, vibration measurements were made to find what components of the tractor vibrate at the 100 and 300 Hz frequencies. After taking thirty-three vibration measurements, many of which measured vibrations on all three possible directions, it was found that the component whose vibration most matched the noise frequencies heard by the operator was the windshield. This suggests that a lot of noise is being transmitted through the windshield of the tractor. In order to eliminate this transmission path the windshield design will be analysed in section 3.2.5. Other transmission paths found were the result of poor acoustic seals in the tractor. One such location of poor sealing was found in the floor of the tractor, and a discussion of this will follow.

The different design recommendations to the tractors cab will be summarized in the following sections of the report. The designs have been listed in order of the most significant noise reductions. The designs listed first will have the most significant affect on noise reduction, while the designs listed last will be the least feasible with very limited results. It should also be noted that team Pindrop attempted to focus on eliminating the noise source problems. This means that the designs that eliminate the noise sources are listed as more significant than designs that attempt to cover up any noise sources. Once the noise sources are limited as much as possible, focus will move to stopping noise from penetrating into the tractor cab. This will be followed by a method of cancelling any noise that has penetrated the tractor cab through active noise control methods.

3.2.1 Exhaust System

Throughout the measurement process, it was discovered that the tractor exhaust stack was one of the primary sources of noise, as perceived at the operator's level. The sound pressure levels at the tip of the stack were measured at 106 dBA. Furthermore, its primary frequency components, at approximately 100 Hz and 315 Hz are key frequencies in cab noise measurements. Figure 6 correlates the sound pressure level readings taken at the operator's position in the cab at the tip of the exhaust stack.

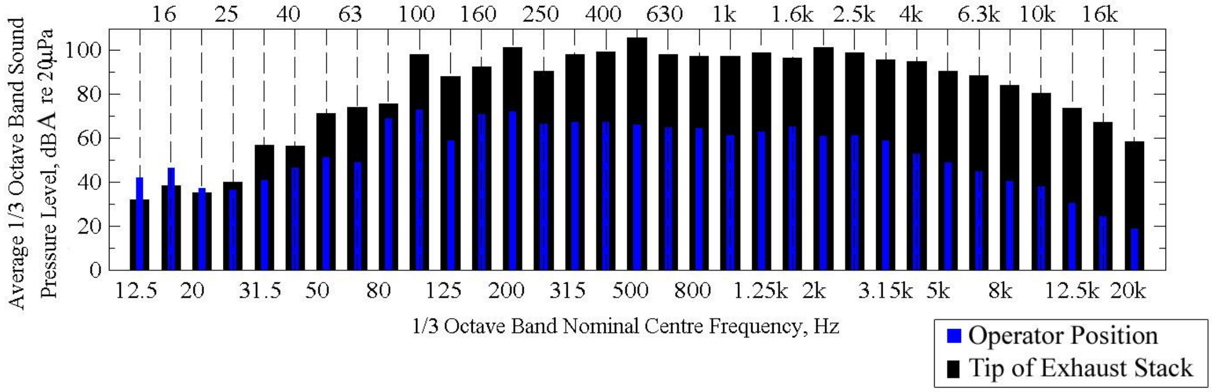

Figure 6 - SPL measurements at tip of exhaust stack and operator level

Exhaust stack noise can come from two sources: vibration of the stack, which is rigidly mounted to the tractor frame, and exhaust **shock waves** exiting the tip of the stack. The stack components can be seen in Figure 7.

Figure 7 – Exhaust stack components

Measurements by team Pindrop have correlated the main noise frequency components in the cab to the air exiting the stack, rather than the vibration of the exhaust stack and the surrounding heat safety shield. This is not to say that the vibration is not important, but rather that it does not constitute as great a noise contributor as the noise from the tip of the exhaust stack. The noise transmission path, as measured using accelerometers, most evidently goes from the tip of the stack to the main windshield, where it sets off two distinct resonant frequencies around 100 Hz and 315 Hz, and into the cab. For more information on the windshield, refer to section 3.2.5 in this report. Stack vibration and exhaust noise will be treated separately in this section.

3.2.1.1 Exhaust Shock Waves

Exhaust gases leaving the combustion chamber create acoustic (pressure) shock waves. Typically, perforated plates and baffles are placed strategically in a contiguous compartment, forming the "muffler". The muffler's job is to break up the shock waves and equalize the pressure waves so that when exhaust gases leave the stack, they do so quietly. Each engine system produces a signature set of shock waves, with vastly different frequency components, which need to be broken up in different ways. Thus, a "silent" muffler is engine-specific. As discussed previously, the main source of noise entering the tractor cab seems to be directly related to the exhaust stack. It is recommended that this problem have a high priority in noise reduction of the Versatile 280 tractor. Information was not available for the Versatile 280 exhaust stack. Since the required information is not available regarding the current exhaust stack, it is not possible to determine how effective the current stack is at reducing stack noise.

An appropriate engine exhaust is required to both reduce the outside noise pollution, as well as reduce the noise entering the cab. Since the current specifications are not known, a comparison of the old system and a new proposed system is not possible. However, conversations with Frank Gould from Cummins Filtration, the muffler arm of Cummins, suggested that the exhaust stack was redesigned within the past four years. According to Gould, muffler acoustics specialist at Cummins Filtration, they have worked with Versatile to develop a suitable exhaust stack. However, it is a hard problem to solve. He admits to knowing they have had vibration trouble over the past few years. However, other than very specific tuning of the muffler system to optimize sound reduction, the best way to reduce stack noise in the cab is to distance the tip of the stack from the cab. Otherwise, an increase in muffler body volume would also allow for greater sound attenuation. However, with the current footprint of the muffler, it is hard to increase performance [15]. Upon hearing a description of the problem, he also suspects that the Helmholtz resonator inside the muffler, tuned to reduce the "firing frequency" of 100 Hz, is not tuned closely enough to the target frequency.

After discussions with Versatile, team Pindrop became aware that Versatile will be transitioning to a different exhaust stack, to meet new emissions regulations [7]. It is recommended that acoustical performance be taken into consideration with the design of the new exhaust system. Further experimentation and design work are required to produce a suitable solution to the problem.

3.2.1.2 Stack Vibration

Although it is admittedly a smaller problem than the exhaust shock waves, after incorporating other priority measures, Buhler may decide to reduce noise emanating from the vibrating stack. Testing conducted at the Versatile factory showed that the vibrations of the exhaust stack were significant, and that the safety heat shield shown in Figure 7 was also vibrating.

Several approaches are available to reduce this vibration. First of all, there is significant vibration transmission to the stack itself, through the stack base. This is rigidly mounted to the rest of the tractor's structure. Isolation mounting would help reduce the magnitude of vibration of the stack. Secondly, vibration damping via a layer of high-temperature insulation may prove to be effective in reducing this vibration-induced noise. A high-temperature acoustic insulation product such as stone wool could be used. This product, of which Rockwool™ is one of the leading brands, has been used in the marine industry for its high environment-resistance and noise-absorptive properties. The use of this product could be implemented in a double-wall configuration to obtain good sound attenuation. In this construction, an insulation layer is sandwiched between two steel cylinders to form the exhaust stack. For acoustic information on this product, including sound absorption values, refer to the Rockwool™ published data available online [16].

Although a few approaches have been suggested for how to deal with the exhaust stack vibrations, it is not known by what amount this may reduce the noise levels. Further experimentation is necessary to determine the amount of noise reduction this would achieve, and whether or not it would be cost-beneficial.

3.2.2 Cab Floor

When conducting preliminary sound tests during a field test at Versatile Buhler, it was observed that the sound levels near the cab floor seemed to be quite high compared to the levels that were detected at the operators head level. This observation was confirmed analytically using a sound level meter to take a measurement at the operators head level and compare it to the sound pressure levels at the floor of the cab. By comparing the two sound pressure levels in 1/3 octave bands in Figure 8 shown below, it can be observed that overall, the floor position has high sound levels.

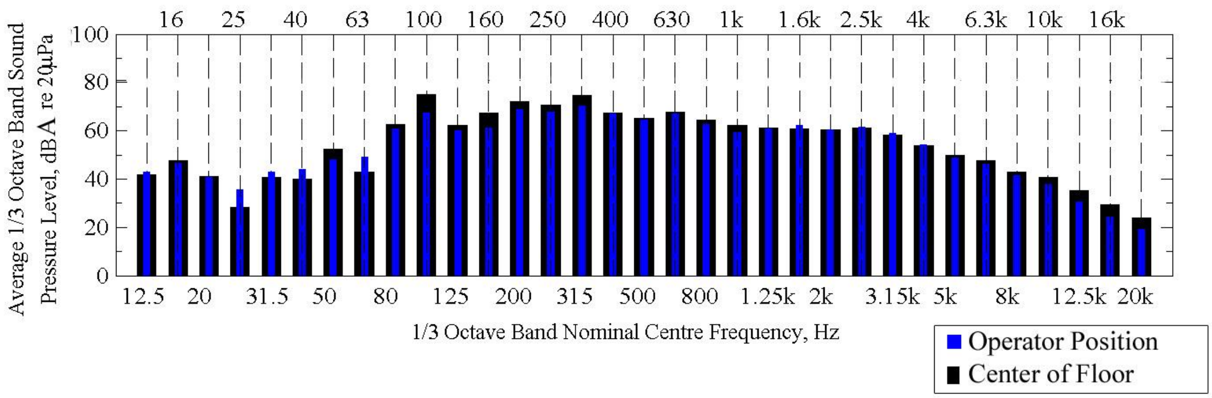

Figure 8 - Sound levels at floor compared to operators position

The calculated A-weighted sound pressure level at the operators head was found to be 77 dBA. This is 3 dBA lower than the 80 dBA that was measured at floor level between the operator's legs. This 3 dBA change in sound pressure levels is noticeable, and would be a distinguishable change in sound for the human ear when going from one location to the other [17].

Analysis of the data shown in Figure 8 has shown that one possible sound transmission path is through the floor of the cab. This was confirmed through measurements showing that the noise levels are higher at the floor level than the operators head level. After determining the floor of the cab as a possible transmission path, research will be focused on trying to establish what is allowing for the transmission of noise through the floor.

After conducting some preliminary research, it was found that the floor of the model 280 tractors has a removable thin metal plate. This plate is required for connecting hydraulic fittings during the installation of the cab to the tractor frame during the manufacturing process [7]. The plate is then bolted to the floor and covered with a rubber mat which provides a water proof floor for the operator. The rubber mat also acts as sound insulation, absorbing some of the noise that is transmitted through the floor. To get a better understanding of the dimensions of the plate and how it is fastened to the floor of the cab team Pindrop visited Buhler Versatile to watch the installation process and view some partially assembled cabs. The rubber floor barrier had also not been installed on the floor of the cab, allowing team Pindrop to observe the hydraulic access hole under the operator's feet. An image of this plate can be found in Figure 9 along with an image of the floor with the plate removed in Figure 10.


Figure 9 - Image of cab with floor plate installed


Figure 10 - Image of cab with floor plate removed

It is clear in Figure 9 and Figure 10 that when the plate is installed in the cab there is metal on metal contact between the plate and the cab floor. This metal on metal contact does not create a good seal to stop the transmission of noise from outside into the cab. In addition to a poor seal the contact between the plate and floor will allow for vibration transmission between the plate and the rest of the cab. To avoid metal on metal contact between the floor and the plate foam tape has been applied to the bottom of the removable plate. The foam tape is aligned to contact between the removable plate and the lip on the tractor floor that the plate is bolted to. The foam layer is intended to alleviate metal to metal contact, creating a better seal and stopping noise transmission. An image of the underside of this plate can be found in Figure 11.

Figure 11 - Image of underside of floor plate removed from tractor

The foam on the plate in Figure 11 did a very poor job of isolating the plate from the floor of the tractor. The insulation used is very thin and becomes highly compressed when the plate is fastened to the floor, eliminating most of the sound attenuation it created. The insulation also did a poor job isolating the plate, as there is no insulation on the edges of the plate where it contacts the floor, allowing for metal on metal contact. During vibration testing it was found that the plate did not vibrate as much as expected. This implies that a lot of the noise is coming through the floor because of a poor seal rather than from a highly vibrating floor plate. The vibration analysis of the floor plate can be found in Figure 12.

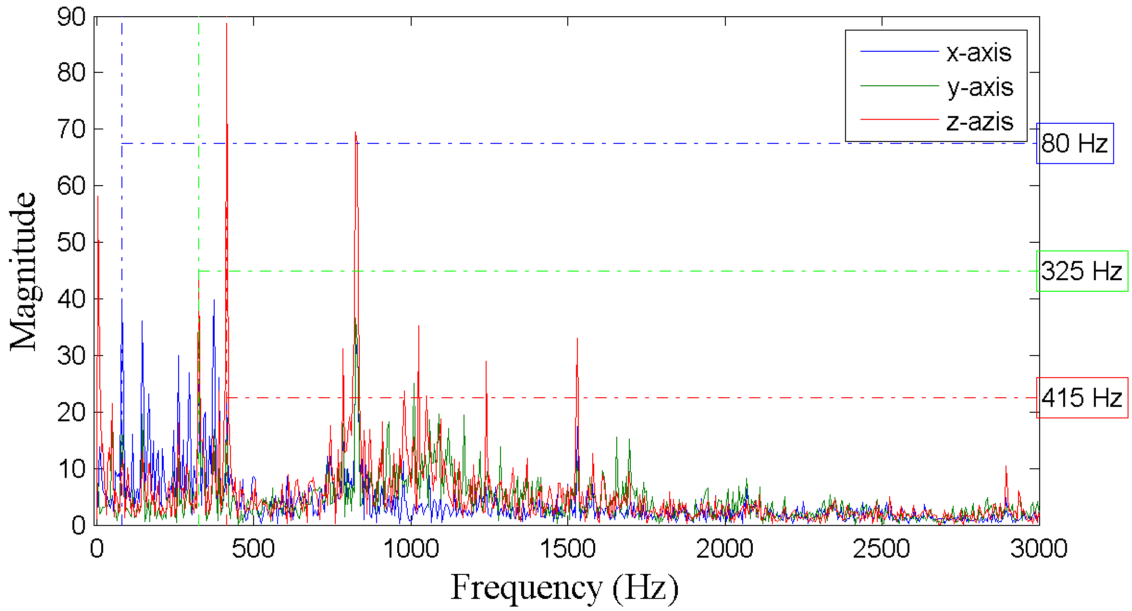

Figure 12 – Magnitude v. Vibration Frequency plot for floor plate

It should be noted that the values for the amplitude of the acceleration of this floor plate are low compared to other measurement locations. One such measurement location was the horizontal hydraulic mounting bar which supports the hydraulic lines that run underneath the tractor. This bar holds the hydraulic couplings that are connected underneath the removable floor plate when the cab is installed on the tractor and can be seen in Figure 10 and Figure 16 on page 23. More information on this mounting bar is discussed later in the report. However, to give an idea of the difference between the amplitude of vibrations between the floor plate and hydraulic mounting bar please refer to Figure 19 on page 25 for a plot of the vibration analysis of the horizontal hydraulic mounting bar.

A method of better insulting the cab from sound transmission will be explored after the confirmation from the vibration analysis that sound transmission was the main problem, rather than vibration transmission. To better insulate the floor from exterior noise it is suggested that a layer of insulation by applied between the metal cab floor and the rubber floor mat that is currently used to provide a water resistant grip for the operator in the cab. After conducted research on the different acoustical insulations available, it was decided that Barymat would be the best suited for this acoustic insulation for the application. Barymat is an acoustical composite that is well suited for absorbing both noise and vibrations. The sound transmission losses that can be reached by Barymat exceed what would be reached by any of the other acoustical insulations available for purchase that were researched for this purpose. A schematic of the Barymat composite can be found in Figure 13.

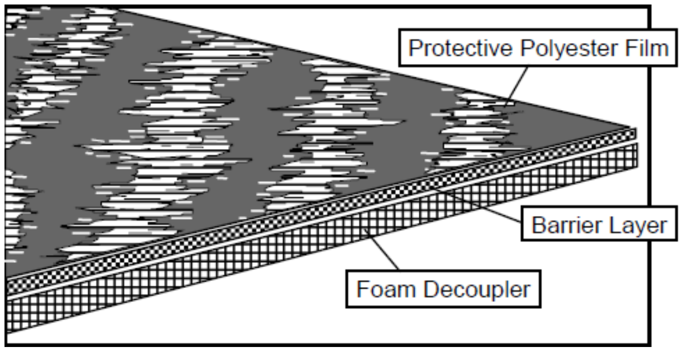

Figure 13 - Schematic of Barymat composite [18]

In Figure 13 the many layers of the Barymat composite can be observed. The protective polyester film will prevent moisture absorption into the foam decoupling layer. The barrier layer is a dense rubber layer that will absorb structure born vibrations and low frequency noise, while the foam decoupling layer will absorb higher frequency noise [18]. There are several different variations of Barymat available. The one chosen for the floor of a model 280 tractor is the M-600D model. This model achieves the highest transmission losses compared to the other Barymat products available. Please see TABLE I for the sound transmission losses provided by M-600D Barymat.

TABLE I - SOUND TRANSMISSION LOSSES [18]

Frequency (Hz)	Transmission Loss (dB) M-600D
80	25
100	25
125	24
160	25
200	25
250	27
315	27
400	28
500	28
630	29
800	32
1000	37
1250	43
1600	46
2000	47
2500	47
3150	51
4000	53
5000	56
6300	58
STC	**35**

The Barymat insulation has a high overall sound transmission class of 35 [18]. This is an impressive sound attenuation that can be realized with very little modifications to the current tractor cab design. It should be noted however, that the lower frequency noise is not attenuated nearly as much as the high frequency noise. This becomes obvious when the results of TABLE ITABLE are summarized in a plot as shown in Figure 14.

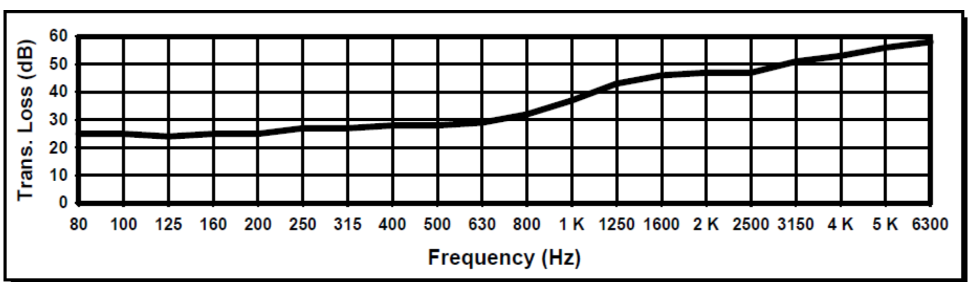

Figure 14 - Transmission losses of Barymat [18]

Although the low frequency sound attenuation is much less then what is achieved for high frequencies, the results are still impressive. For being only 0.56" thick and weighing 2.3 lb/ft^2 the Barymat can reduce sound levels inside the cab with very little added labour [18]. A proper design of how to install the Barymat insulation is imperative to ensure that it achieves the maximum sound attenuation possible. Barymat can be applied to almost any surface using an adhesive. The adhesive must be acrylic based to avoid the degradation of the Barymat composite over time, and to ensure that the composite is properly adhered to the surface [19]. It is recommended that 1099 plastic adhesive offered by Wilrep be used. This is a fast drying adhesive that bonds to all surfaces and is intended for use with Barymat [19]. This adhesive will be used to apply Barymat to the top of the floor on in the inside of the cab, and also to the bottom of the floor plate. The floor plate will have to be slightly enlarged so that there is a greater overhang onto the Barymat adhered to the cab floor, creating a better acoustic seal. When the plate is installed into the tractor the Barymat on the bottom of the plate will line up with the Barymat applied to the top of the cab floor, creating a uniform acoustic seal. In addition to applying the Barymat insulation it is recommended that the current bolts used to fasten the floor plate to the cab floor be replaced with bolts that have a rubber grommet to provide vibration isolation. This grommet will attenuate the vibrations travelling from the floor through the layer of Barymat into the top of the removable floor plate. Without the grommet, metal on metal contact between the floor, screw and removable plate will short out any vibration isolation provided by the Barymat. A cross section of the suggested design can be found in Figure 15. Figure 9 and Figure 10 on page 17 can also be referred to when comparing the proposed design to the existing installation of the floor plate.

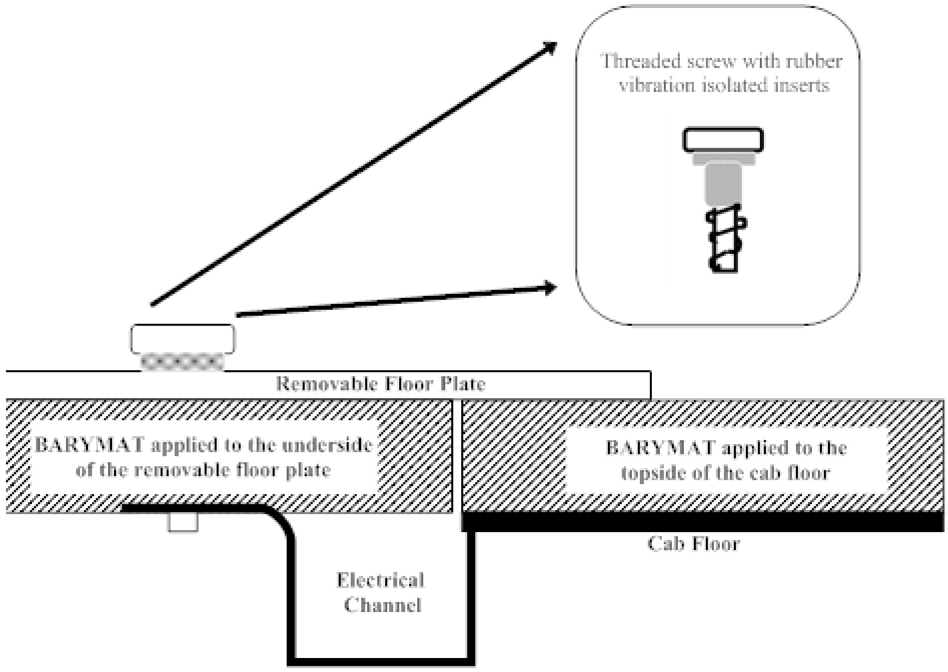

Figure 15 - Schematic of plate to floor attachment point

There are other tractor components other than the floor plate that can be adding to the noise levels in the cab. One of these components was discussed earlier in this section of the report. This component is the horizontal hydraulic mounting bar that runs directly under the removable floor plate of the cab. This bar can be seen in Figure 10 on page 17. A close up view of this bar can also be found in Figure 16.

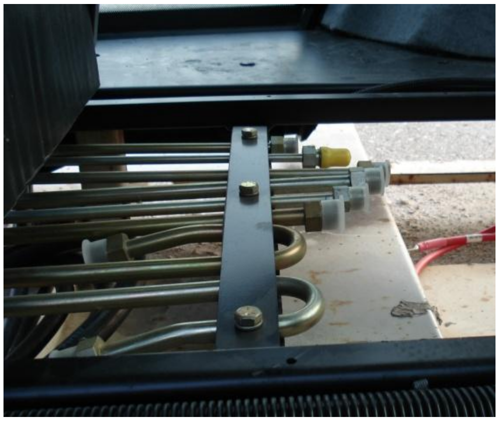

Figure 16 - Figure of horizontal hydraulic mounting bar

Figure 17 - Image of weld joint between hydraulic bar and cab

The horizontal bar is attached to the underside of the tractor cab by a weld on either side of the bar. This weld joint can be seen in Figure 17. This weld joint is important, because it does not give any vibration isolation between the horizontal bar and the cab. This vibration isolation is required because of the hydraulic piping that is supported in the bar. The hydraulic piping is mounted in the horizontal bar with no rubber or other vibration isolating materials to absorb any vibrations from being transmitted from the steel hydraulic hoses to the bar, then to the tractor cab. This non damped mounting of the steel hydraulic hoses in the bar can be seen in Figure 18.

Figure 18 – Image of hydraulic bar from underneath cab

It is recommended that Versatile Buhler add a vibration damping material between the hydraulic hoses and the metal bar to absorb any vibrations running through the hydraulic hoses. Although care was taken to ensure that the cab was separated from the tractor frame to isolate any vibrations resonating through the frame, the hydraulic hoses were overlooked and will transfer vibrations directly to the tractor cab through the horizontal bar at the welded joints. The high amplitude vibrations of the metal bar have been confirmed by analysing the acceleration data taken from the mounting bar. The data can be found in Figure 19.

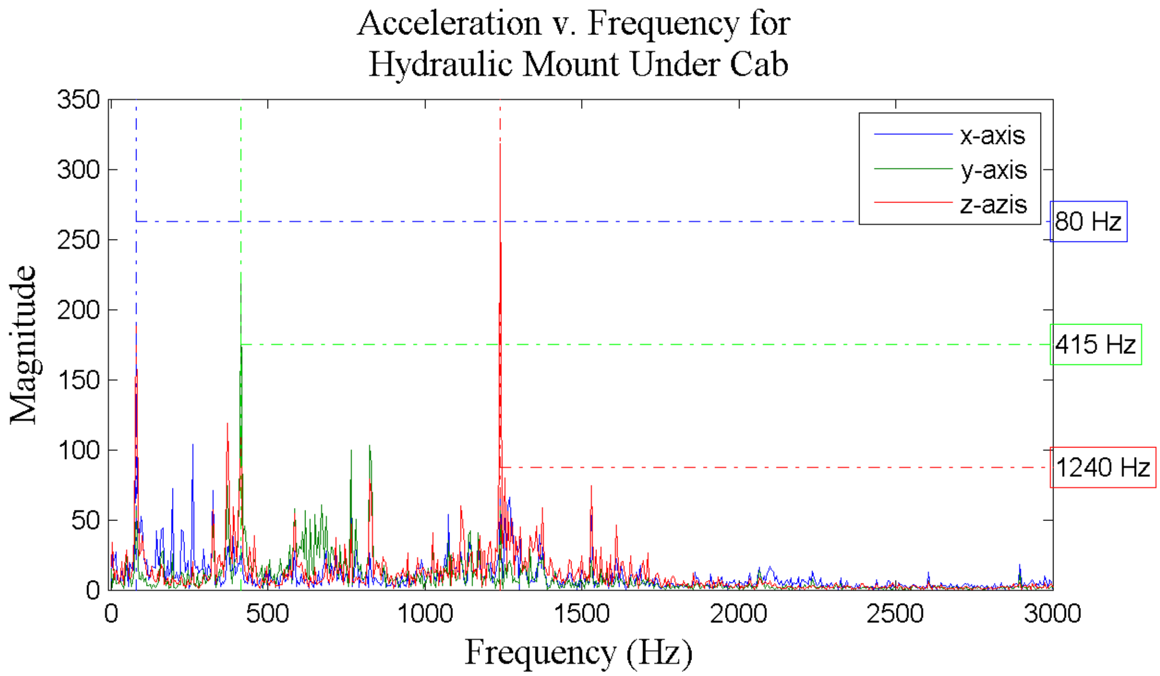

Figure 19 – Vibration analysis of horizontal hydraulic mounting bar

The amplitude of the peak vibrations for each axis should be compared to the peaks in Figure 12 on page 19. In Figure 12 the vibration magnitudes are about one quarter of what they are in Figure 19. The location of the horizontal bar and floor plate are within inches of each other. Because of the limited vibrations of the removable plate it is clear that it is the hoses contacting the bar, and not another source causing the severe vibrations in the bar, otherwise the removable plate would be vibrating as well.

In summary, it is recommended that the removable floor plate be slightly extended by roughly 1" to 2" on both sides of the electrical channel. It is also recommended that Barymat M-600D be applied to the cab floor and the underside of the floor plate. The Barymat will cost $234.00 for a 27 ft^2 roll [19]. The area of the rubber floor mat has been estimated to be roughly16 ft^2 from field measurements taken. The remaining 11 ft^2 can be used to insulate the wheel wells or underneath the operator seat where noise may also be penetrating through the floor. The remainder of the Barymat could also be split up for use on other tractors. Through the capital expenditure of $234 for a 27 ft^2 sheet of Barymat, $40.25 for the 1099 plastic adhesive that covers 27 ft^2, and roughly $10 for other materials such as rubber grommets for the fasteners and rubber to isolate the hydraulic hose vibrations, a large sound attenuation may be reached without requiring any major design modifications to the current tractor [19]. This total cost of all floor modifications is estimated at $284.25.

3.2.3 Roof

The roof of the model 280 tractor contains a large part of the heating and cooling system for the tractor cab. In this roof are the evaporator, heating coil, and blower fan, as well as a network of valves, hoses, and vents to control the flow of all fluids used. All of these components are located right above the operator's head, with only a thin roof panel separating the two. Out of all the components in the roof, it is only the blower fan that emits high noise levels. Fans typical release a lot of noise when operating because of their high rotational speed and the turbulence they create in the air during their operation. With such a thin barrier between the operator's ears and the blower fan, it is no surprise that the sound pressure levels increased inside the cab when the blower was turned onto full speed. Although the noise levels associated with the blower fan are small compared to the engine noise, the distance from the operator's ear must be taken into account. As sound travels it loses energy over the distance that it travels. The engine noise is located outside of the cab and must find transmission paths to travel to the operators ears. Going through these transmission paths results in a decrease in the acoustical energy that travels from the engine to the cab. However, the noise associated with the blower fan occurs right above the operator's head, and must only travel a short distance through the ceiling panel and ducting to reach the operator's ear. The combination of a short distance and little barriers makes the blower fan a noise problem in the tractor cab. See Figure 20 for a schematic of the blower fan location in the tractor cab compared to the engine and operators head level.

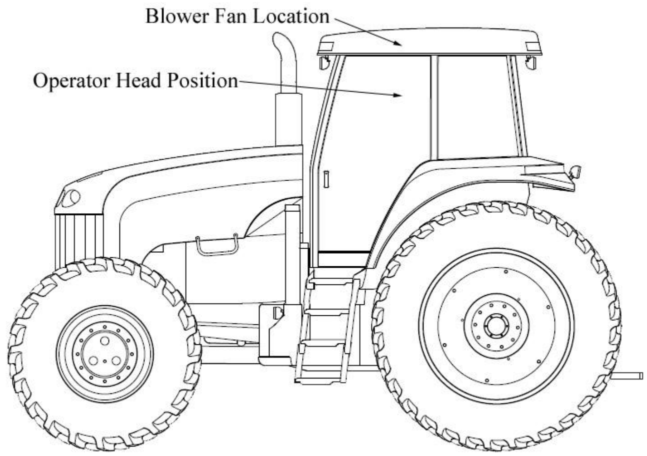

Figure 20 - Location of blower fan in Versatile 280 tractor [20, p. 22]

The proximity of the blower fan to the operators head can be seen in Figure 20. There are a few different approaches that can be used to reduce the blower fan noise heard by the operator. The most obvious approach is to alter the current climate control system. This can be done by finding a blower fan that meets the same flow and power requirements, but operates at lower sound levels. The system can also be altered by modifying the venting system that the air travels through. By changing the diffusers and vents to produce a more laminar flow, less noise will be created by the flow of air through the system. These approaches will be discussed in Section 3.2.4 of this report.

A second method to minimize the sound levels reaching the operator is to adopt an approach similar to what was discussed in Section 3.2.2. This approach will use a material to provide acoustic insulation to attenuate some of the sound emitted from the blower fan. This will only work for noise traveling from the fan, through the ceiling panel to the operator. It will not work for noise travelling through the air vents into the cab. The acoustical insulation recommended for this process is Barymat M-100D. This is an acoustical insulation made by the same company as what was used in the floor. Barymat 100D is very similar to Barymat 600D. They are both mass loaded vinyl acoustical insulations with a foam decoupling layer. It provides similar fire resistance to the 600D model, but weighs and costs less while taking up much less space [21]. A summary of Barymat 100D, which includes a schematic, table and plot of sound transmission losses at different frequencies has been summarized below.

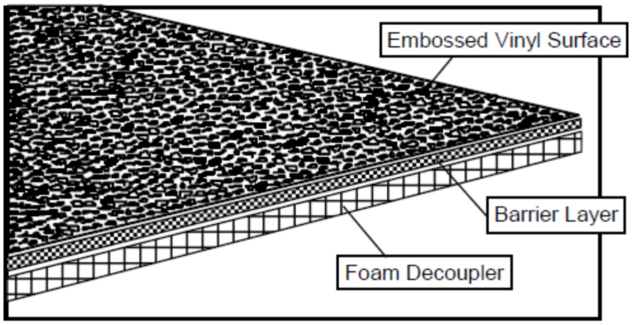

Figure 21 - Schematic of Barymat 100D [21]

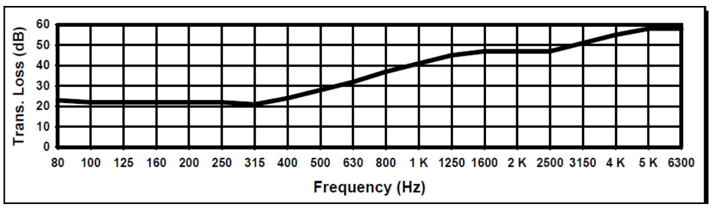

Figure 22 - Plot of transmission losses vs. frequency for Barymat 5 [21]

TABLE II- TRANSMISSION LOSSES [21]

Frequency (Hz)	Transmission Loss (dB) M -100D
80	23
100	22
125	22
160	22
200	22
250	22
315	21
400	24
500	28
630	32
800	37
1000	41
1250	45
1600	47
2000	47
2500	47
3150	51
4000	55
5000	58
6300	58
STC	**33**

Barymat 100D is only .375" thick [21]. This is important because the ceiling cavity is a small space with a lot of climate control equipment located in it. This leaves very little room in the ceiling to add an insulation layer. However, because of how thin Barymat 100D is, there should be enough room to accommodate it. Another benefit of adding this insulation layer is the mass added to the ceiling panel. Right now the ceiling panel is a large thin panel that spans across the ceiling of the cab. This panel acts similar to a speaker, vibrating, and transmitting noise through the ceiling. By adding the mass to the roof it is expected that it will dampen the roof, lowering the amount it is vibrating.

Barymat 100D can be purchased in 27 ft^2 squares for $141.90. This 27 ft^2 is more than sufficient to insulate the entire ceiling cavity. The same adhesive as described in Section 3.2.2 will also be required for a cost of $40.25 for a 1 litre can capable of adhering 27ft^2 of Barymat to a surface. The total capital cost for roof modifications is estimated as $182.15 [19]. This is a relatively low investment, and it is recommended that it be applied to the ceiling to test how well it attenuates blower noise levels. Installing this layer of insulation would be more cost effective than reengineering the air vents that run through the tractor, or implementing a quieter blower fan. For this reason adding Barymat 100D to the roof should be the first step in attempting to reduce blower fan noise to help reduce overall sound levels in the tractor cab.

3.2.4 HVAC

Another major contributor to the noise levels within the tractor cab is the air conditioning (AC) system. Since AC systems are desired by operators to maintain their comfort level, sound level measurements were completed to determine how running this system will affect the overall noise spectrum. It should be noted that all measurements are taken when the AC is set at its maximum. Even though the AC will not necessarily be at this level the entire time, it is important to design for the worst case noise scenario. The noise in AC systems is usually produced by the diffuser vent / blower combination which moves the cooled air to the operator's position from the evaporator.

Sound level measurements were completed at Buhler Versatile with the tractor under load. Putting the tractor under load simulated more realistic operating conditions. Figure 23 shows the sound pressure levels for the 1/3 octave band frequencies after they have been adjusted for A-weighting. By comparing the measurement conditions at each 1/3 octave band, it is clear that turning on the AC increases the sound pressure level at each of the 1/3 octave bands. This increase in each 1/3 octave band will account for an increase in total sound pressure level from 77 dBA at the operators position for no AC on to 84 dBA at the operators position at the maximum AC setting. This is a substantial increase in A-weighted sound pressure levels.

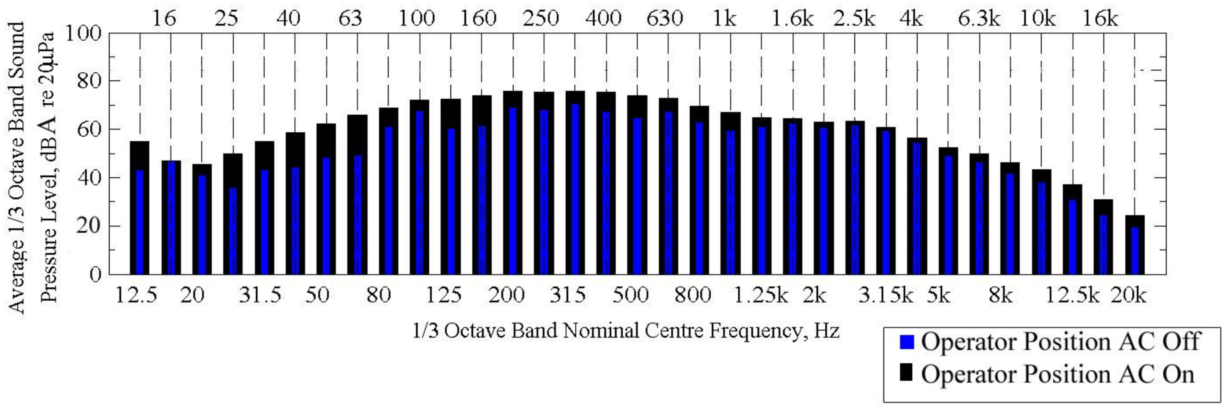

Figure 23 - Average 1/3 octave band sound pressure levels re µ20 Pa

It can be determined that the AC system adds broadband noise to the noise levels in the tractor. Broadband noise involves an increase in sound pressure levels at all 1/3 octave bands, not just at a specific frequency. Broadband noise from the AC system can be confirmed by observing that the levels increase for each 1/3 octave band in Figure 23 [22]. After analyzing the sound data obtained from the measurements, different methods of controlling the high noise levels associated with running the AC system will be explored. Detailed analyses of the available options are listed in the following sections of this report.

3.4.2.1 Blower Fan

In order to move air through the evaporator of the AC system to the operator in the cab a blower fan is used. Blower fans are typical associated with high broadband noise levels produced by turbulent velocity fluctuation and pressure fluctuations on the surface of the blade. Small blower fans usually have a broad peak in the noise spectrum between 250-1000Hz [23, pp. 44.6-44.9]. By observing Figure 23 it can be seen from the sound level measurements taken with the AC system running that there is a broad peak in the 250-1000Hz range, roughly at 315 Hz . This confirms that an increase in noise levels is associated with the blower fan.

Another pattern that should be seen for a blower is a 5 dB per octave decrease at the higher frequencies [23, p. 44.6]. This drop is not seen but a drop of 1.5 to 2 dB per octave is found at the higher frequencies. One reason for this could be due to the presence of six diffusers and the air being blown through a duct system which could be most likely reflecting sound back to the source, rather than emitting it through the tractor cab.

The following steps could be taken to reduce the sound created by the blower.

- Design the blower to have a lower static pressure because this allows the device to operate at a lower tip speed. Low static pressure indicates that there is less resistance in the path of the airflow. If unnecessary sources of resistance can be eliminated then the airflow will increase and the fan diameter or speed could be reduced allowing for a lower noise level to be achieved. Tip speed relates to the speed at the blade tip [23, p.44.8]. Every time a blade passes a point in the air, that point receives an impulse. The repetition rate of this impulse is called the blade frequency, which allows for the determination of the fundamental tone that is being produced. Doubling of the number of blades of a fan, or doubling the rotation rate usually doubles the fundamental frequency [24, p.41.4-41.6]. Since a higher frequency is easier to attenuate using passive methods when compared to low frequency noise. This may be desirable for managing fan noise levels.

- The blower should operate near its point of maximum static efficiency because this allows for optimal airflow through the blades to be achieved. Operating at maximum efficiency also creates minimum noise levels produced by the blower. Static efficiency is important in selecting a suitable operating point. Static efficiency of a blower is the volumetric flow rate multiplied by the static pressure divided by the electric power that is inputted [24, p.44.8].

- Design of the blower should be done so that it operates away from its best efficiency point (BEP), which is the point where maximum efficiency is achieved. Small blowers tend to be very unstable when they operate near the BEP, producing a lot of noise. This instability is due to the BEP having a high static pressure and a low airflow. The blower is required to operate at a point which is found by developing two curves. The first of these curves is called the system resistance curve which is a plot of the rise in static pressure across the ventilating system versus the volumetric airflow that is passes through it. The second curve is the performance curve which gives values of total pressure, static pressure, total efficiency, static efficiency and power against the volume flow rate of the blower. The intersection of these two curves gives the optimal operating point for which the design of the blower should be completed [24, p.44.8].

- When selecting a blower, avoid blowers which contain sharp peaks in its 1/3 octave band power spectrum, as this peak usually indicates that there is a discrete frequency component. This component tends to be produced by impulses created by the blades as they pass any given point. Discrete frequency peaks are not desirable since the human ear has the ability to distinguish pure tones in a noise spectrum [25, pp.29.1-29.10].

According to the Buhler Versatile climate control manual the blower is always running at its minimum speed when the key switch is on so that the cab remains pressurized. The pressurized cab is important to ensure that no dust infiltrates the cab. This is not believed to be a noise issue because the blower is operating at such a low speed that the noise produced will have very minimal affect on the overall noise in the cab. It is, however, important for any future considerations to take this into account when selecting a blower. Figure 24 provides the locations of the blower within the cab roof of the tractor.

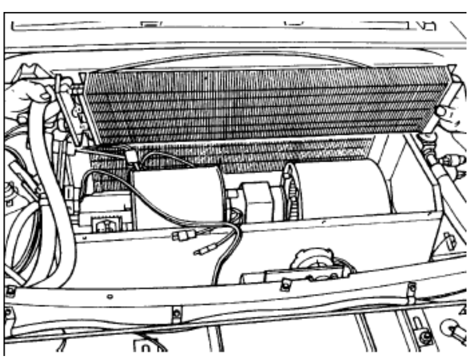

Figure 24 - Blower fan location in cab roof [26].

1) Blower Fan
2) Heater Core
3) Evaporator

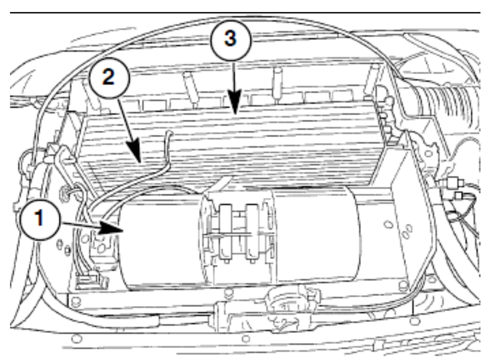

Figure 25 - Components of AC system [26].

Looking at the layout of the three components within the roof of the cab in Figure 25, it is possible that the evaporator could be contributing to noise within the cab. As air is moved through the evaporator it can increase in turbulence, creating higher noise levels as the air flows through the ducts. This could become a problem due to the ability of this noise to travel through the diffusers and into the cab. Therefore, lining of the roof with absorptive material described in greater detail in section 3.2.3 of this report should be considered.

3.4.2.2 Diffuser

Diffusers usually contain air deflectors that can be adjusted to help distribute air evenly or to different locations within the tractor cab. These deflectors are a source of noise due the disruption they cause in the airstream as they change the air flow. The sound increases with the deflections that occur. If the velocity of the air is doubled, a 16 dB increase in the sound power for octave bands centered at 500 Hz and below can be seen. An 18 dB – 24 dB increase is observed for octave bands centered at 1000Hz and above [27, pp.42.4-42.7]. It is because of this that a low speed blower is crucial for providing the best sound attenuation. Figure 26 shows the air distribution by the diffusers within the cab.

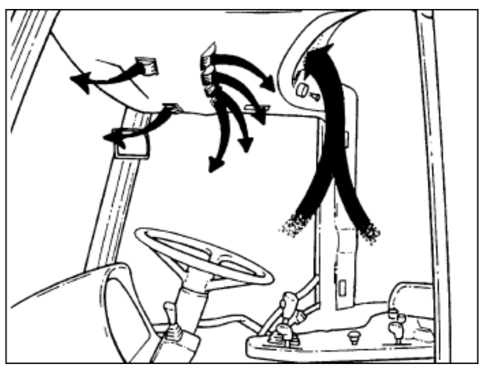

Figure 26 - Diffuser air distribution within the cab [26].

3.4.2.3 Duct / Roof

The ducting system in the roof of the cab is another area that could be looked at to attenuate sound. The best solution would be to line the duct with sound-absorptive insulation. Attenuation can also be obtained by using 90° elbows to reflect sound back to the source. If the velocity of the airflow is greater than 10 m/s then using 90° elbows would not be recommended since the turbulent flow will actually be a source of noise [27, pp. 42.7-42.14]. The pressure drop through the fan should be calculated to determine how much lining is needed. The roof space could be lined with sound absorptive material to provide some additional attenuation. Refer to the section 3.2.3 for more detail. The blower is determined to be the largest source of noise in regards to the AC system, so considerations should be made to line the duct directly before or after this component. Figure 27 show the layout of the roof of the cab and how the air is re-circulated and distributed. Any of these air paths could be targeted to provide absorption of the sound. It is recommended that focus be made for the path after the air has passed through the blower, as it is the blower that will add sound to the airstream. Putting insulation after the blower will absorb some of this added noise.

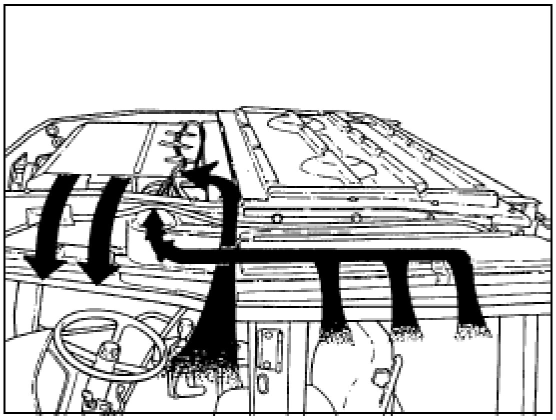

Figure 27 - Roof of the tractor [26].

3.2.5 Windshield

One of the most direct paths for noise to travel through into the tractor cab (in the absence of exposed openings in the cab) is the windshield. Windshields can transmit both structure-borne and air borne vibration. From measurements acquired over the last months, team Pindrop suspects that **structure-borne vibration** in the windshield (which could then act as a diaphragm, emitting acoustic noise) is not a significant component of the noise. The vibration isolation between the frame and the cab provides very good vibration damping. It is more probable that the windshield is transmitting air-borne noise to the inside of the cab.

For the Versatile model 280 tractor, air-borne noise transmission seems to be acting in two distinct manners. First of all, general sound transmission occurs from acoustic energy travelling through the windshield and into the cab. The amount of sound transmitted can be characterized by a material's sound transmission loss. A change in the glass density or the use of laminated glass could greatly increase sound transmission loss from the exterior of the cab. The second way in which noise transmission is occurring has to do with the phenomenon of **resonance**. Resonance occurs when a physical object's natural frequency, a function of its stiffness and mass, is excited by another sound source. For the tractor, measurements found that the two predominant frequencies from the stack, in the one third octave bands centred around 100 Hz and 315 Hz, corresponded with the main vibration frequency components in the main frontal windshield. Figure 28 and Figure 29, are two accelerometer readings done on the main frontal windshield. They show different acceleration magnitudes, as they were taken in two separate positions on the windshield. However, they both show maximum peaks at 100 Hz and 305 Hz respectively.

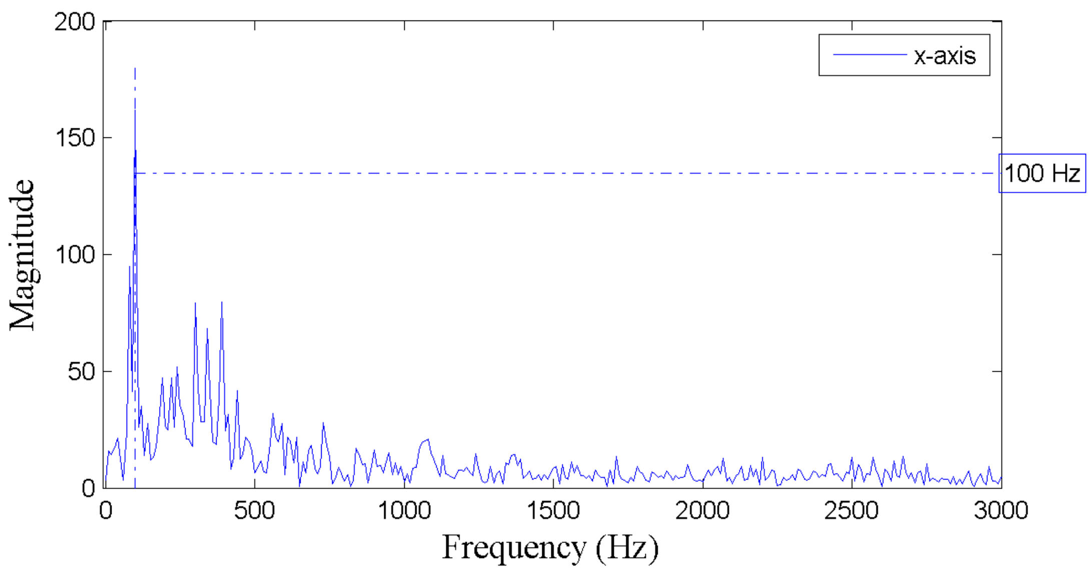

Figure 28 - Acceleration vs. Frequency for centre of windshield

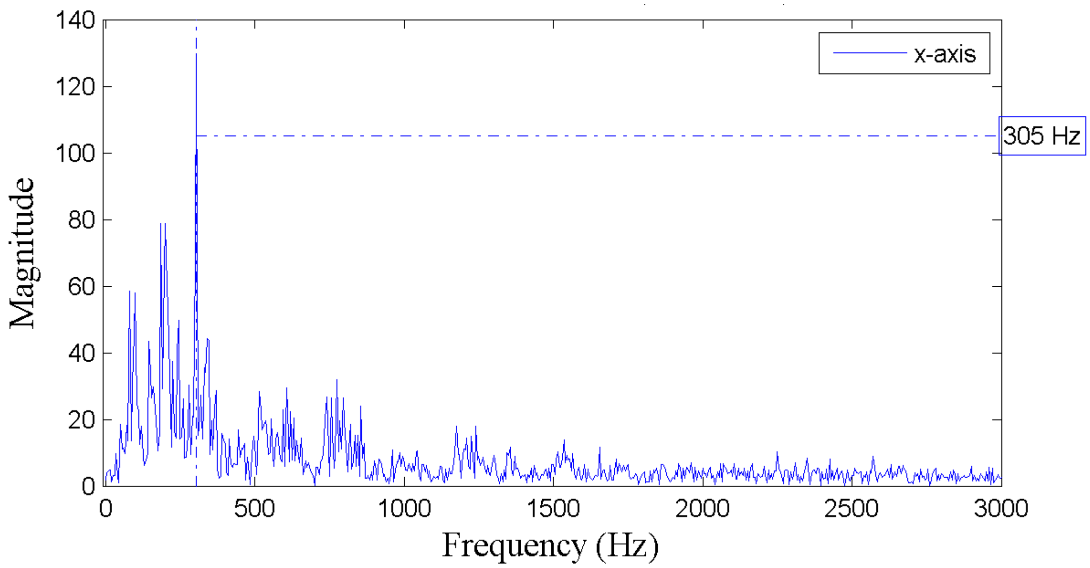

Figure 29 - Acceleration vs. Frequency off the centre of the windshield

This makes it probable that the two loudest exhaust stack frequencies are actually inducing a resonant condition in the windshield. This would allow sound to propagate into the cab, and the two frequencies to be amplified by the windshield. Measurements in the cab support sound pressure levels in both of these frequency ranges, so the transmission path seems to be aided by this windshield resonance, causing higher sound pressure levels in both the 100Hz and 315 Hz frequency centered one third octave bands.

The optimal way to treat windshield noise transmission would be to analyze the windshield mounts (which provide vibration damping) for efficiency, and then to change the windshield glass. From measurements taken by team Pindrop, it seems that the most important glass surface to treat would be the windshield. It is not only directly situated between the operator and the exhaust stack, but as described previously it seems to have natural frequencies that correspond with the two main frequency components of the exhaust noise output. A higher transmission loss and better resonance frequency management could be achieved by using a noise-insulating composite glass for the front windshield.

3.2.6 Active Control

Active control systems are a highly technical method in which unwanted sound and vibrations can be controlled through destructive interference. As the name implies active control systems are dynamic and react to changing environments. This is achieved through the use of transducers capable of taking measurements which are in turn post processed. Software creates an out of phase signal which destructively interferes with the incoming signal measured with the transducer [28]. The two different types of active control explored in this experiment are active noise control and active vibration control. An overview of each method is available in the following sections of this report.

3.2.6.1 Active Noise Control

Active noise control (ANC) is achieved using destructive interference created by a speaker to cancel out noise causing sound waves. In order to create a sound wave capable of destructively interfering with the noise causing sound waves, a microphone is used to record the incoming sound. The real time sound recording is then processed to create an output single for broadcast by the loud speaker. A schematic showing a basic ANC system is found in Figure 30.

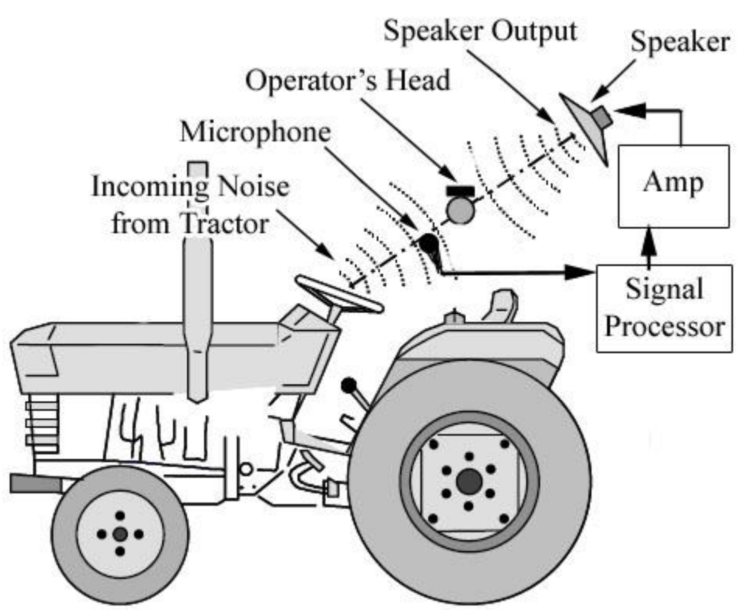

Figure 30 - Active noise cancellation setup [29, p. 449]

The incoming noise from the tractor is detected by the microphone and a corresponding signal is sent to the processing unit. Both digital and analogue processing units are available. However, inexpensive yet powerful digital signal processing units are a good option. The signal processing unit shifts the phase of the recorded sound waves and outputs the signal to an amplifier which powers the speaker. By shifting the phase of the output signal the right amount, the sound waves from the speaker will interfere with the noise to cancel out the acoustic energy. The destructive interference between the speaker sound waves and noise source is for the set up shown in Figure 30 is depicted in Figure 31.

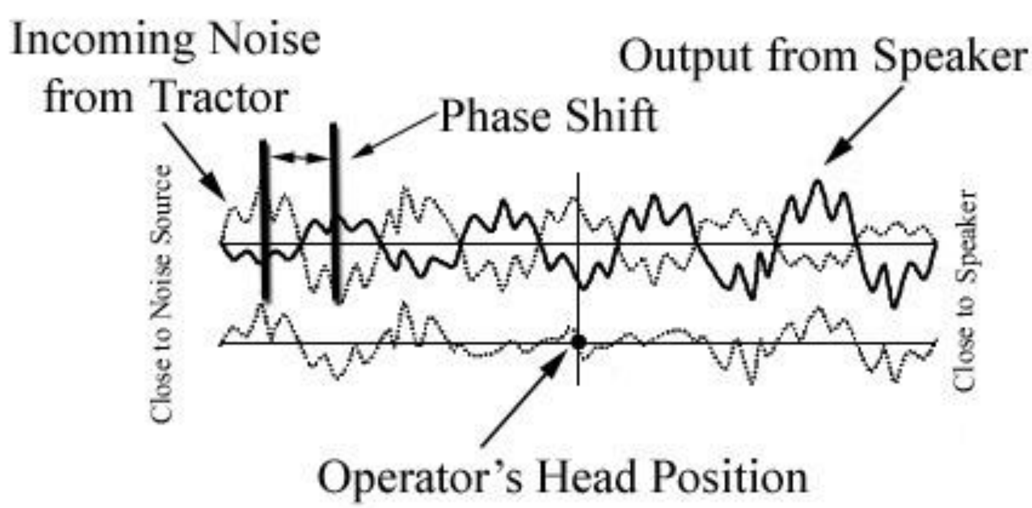

Figure 31 - Destructive interference of sound waves [29, p. 449]

There are two types of ANC strategies for enclosures like the model 280 tractor cab, local and global. In a global ANC strategy the goal is to reduce the amount of acoustic energy in the entire enclosure. Unfortunately, as the target sound wave increases in frequency the number of possible resonance modes also increases. In other words, high frequency sound waves have the ability to reflect off of enclosure surfaces and propagate in a large number of directions in the enclosure. As a result, the sound pressure levels of higher frequency noise will vary significantly over the volume of the cab. For example, the sound pressure level for a 1000 Hz tone will change over the distance from the operator's typical head position to the front windshield. Due to the increased complexity of sound distribution for higher frequency noise in enclosures, a single speaker ANC system is only capable of attenuating frequencies up to 100 Hz. Adding more speakers and additional microphones to the cab will increase the range of the system to decrease sound pressure levels for noise up to 250 Hz. While a global ANC system could be used to attenuate the low frequency noise associated with the muffler, the space, cost and power requirements of the system would be prohibitive [30].

Another approach to ANC in enclosures is localized cancellation, where a quite zone is created in the enclosure. A quiet zone can typically be created using a single microphone, which greatly decreases the complexity and cost of the ANC set up when compared to a global system. The ANC set up shown in Figure 30 employs a localized approach. In Figure 31, it can be seen that the sound waves completely cancel at the operator's head position and then the noise levels increase moving away from the operator's position. Using a single microphone it is possible to create a zone of silence about the size of a grapefruit, with good noise attenuation up to several hundred hertz [31, p. 62]. Given the small size of the quiet zone, two separate speaker and microphone systems would have to be set up for the tractor operator, one for each ear.

While ANC system complexity is greatly reduced in a localized system compared to a global ANC system, there are some short falls. For one, tractor operators are constantly moving their head from the typical driving position to monitor implements and system controls. Given the small size of the quiet zone, it is easy for the operator to leave the quieted area during typical tractor operation. When the operator's head is outside of the quiet zone a localized ANC system will provide no benefit to the operator. However, it is unlikely that waves will constructively interfere and make some areas of the cab interior louder [32, p. 795].

Given the limitations of both local and global ANC solutions, an active noise control system should only be considered as a last resort solution for controlling noise in the tractor cab. First, cab noise should be attenuated as much as possible using the passive attenuation methods outlined in this report. If passive means of reducing noise are not found to be adequate, an active solution could be implemented to attenuate low frequency noise.

One additional ANC method that could be explored is noise cancelling headsets, as seen in Figure 32.

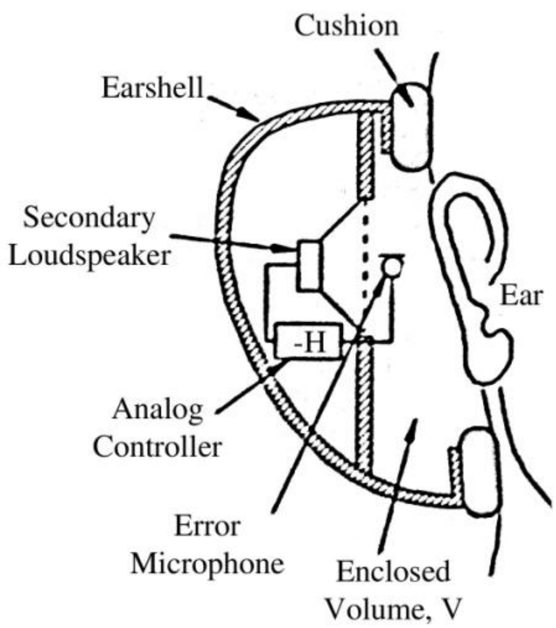

Figure 32 - Active noise cancellation headset [32, p. 768]

In an ANC headset, the microphone and speaker are very close to the ideal quite zone and as a result effective active noise cancellation can be provided up to 1000 Hz. An added benefit of the NC headsets is that they move the quiet zone with the operator's head, making them a good solution for tasks requiring mobility. The earshell surrounding the operator's ear also provides good attenuation for frequencies above 1000 Hz that cannot be suppressed using ANC methods [32, p. 768].

It is not feasible to implement an ANC system in the tractor cab for the target budget of $1500. In addition, an ANC system would only help to deal with the low frequency noise inside the cab, which would not do much to reduce the overall noise levels. However, partnering with a manufacturer to tailor a set of noise cancelling headphones for use in Buhler Versatile's tractor cab is a viable option.

3.2.6.2 Active Vibration Control

It was found through analysing the vibration and sound measurements that one major transmission path for noise is through the windshield of the tractor. The exhaust stack of the tractor causes the windshield to resonate at 100 Hz and 305 Hz. These were the frequencies which were found to have the highest noise levels when measurements were taken at the operators head level inside the cab. It is the believed that if the vibrations of the window can be controlled, it will allow for control of the amount of noise that is transmitted into the cab through the windshield. This is where the active vibration windshield system can be used to control noise levels in the cab.

An active vibration system uses a mechanical actuator to induce vibrations into a flat plate object, or in the case of this project, a windshield. The actuator will have to cause the windshield to vibrate in such a way as to cancel out the 100 Hz and 305 Hz frequencies that it is predominantly vibrating at. The actuator must vibrate shifted 180° out of phase with what the windshield is vibrating at to cancel out all vibrations. To reach this phase shift will require the system to measure the vibrations with a transducer, and then to process the readings from the excitation. The transducer readings will be processed using a mathematical algorithm that will create an output signal which causes another equal vibration in the windshield 180° out of phase with original vibration, cancelling out vibrations in the windshield. In order to properly design the algorithm, several factors must be taken into consideration. These factors include, but are not limited to the distance of the windshield from the noise source, the inflection angle the sound waves contact the windshield, and the processing speed of the system [28]. It becomes obvious fairly quickly that this will be a complex system to implement in a tractor.

It was decided by team Pindrop that this technology would not be the best fit for the project. Although it has potential for greatly reducing the vibrations that travel through the windshield, the technology is still relatively undeveloped. It would also be difficult to find all the proper amplifiers and transducers that meet the electrical and space requirements of the tractor. Also, because of all the electrical components required for such a system, it is expected that the budget would be well above the $1500 limit specified by Versatile Buhler. However, aside from all other limitations, the major fallback of this system is that it would only work for cancelling noise travelling through the glass surfaces of the tractor, and not through other components. It is suggested that efforts be focused to solve the noise problem at the source, rather than to try and attenuate the vibrations as they travel into the tractor.

4 Design Recommendations and Conclusion

After establishing the primary noise sources and transmission paths on the model 280 Versatile tractor by taking sound and vibration measurements, a series of designs to eliminate these noise sources or transmission paths has been developed. Each of these different designs has been fully explained and justified in order of importance in previous sections of this report. The designs have been listed in order of most feasible to implement. This means that the designs that can be implemented at an acceptable cost while still providing high transmission losses. Because each design focuses on changing a different system of the tractor it is not known how the changes will affect the overall sound pressure levels in the tractor cab. To properly evaluate the effectiveness of each design it is recommended that one design be implemented at a time, with testing done after each implementation to see how it affects the sound pressure levels inside the cab. If implementing one recommendation does not provide sufficient noise attenuation for the cab, the next best design should also be implemented and the process repeated until adequate sound levels are reached.

The first design to implement should be a change in the muffler system. Changing this system will address the noise problem at its source, which was found to be the muffler tip, after analysing the measurement data. In one meeting with Versatile, it was mentioned that in the near future they will be modifying their engine and exhaust system as they change over from a Tier 3 engine to a Tier 4 engine to meet new, more strict emission standards [7]. This change over period would be an excellent time to consider the design recommendations and be more conscientious of acoustical performance when selecting a new exhaust system.

If a change in the muffler system is not an option that Versatile wants to explore than it is recommended that they move on to the next best design, which would be modifications to the floor. This is a relatively cheap option that can be easily implemented on a tractor to test its effectiveness. The material cost to implement this design change is estimated at $285 per tractor. This method will not decrease the sound pressure levels created by the tractor, but will help to keep the noise from penetrating into the tractor cab.

To attenuate added noise levels from the climate control system it is recommended to first add a layer of acoustic insulation to the ceiling panel. This can be done at an estimated cost of $183. If this does not reach the desired levels of sound attenuation then other options can be explored. These options include, changing the ducting, or adding a perforated lining with acoustically absorbent material to the duct work to absorb noise caused by the blower fan.

In summary, there are several different options listed in this report that will help decrease sound levels inside the tractor cab. Each option has both its benefits and drawbacks and which option or combinations of options to select is at the discretion of Versatile Buhler. An effort has been made to list the different options in order of best expected sound attenuation for the amount of capital expenditure required. However, isolating and characterising specific noise sources on the complex mechanical systems of a tractor is a difficult problem. Furthermore, establishing the relationship between noise in the cab and a specific noise source adds to the complexity of the problem. As a result, an overall noise level reduction for each option is not available and will have to be obtained through implementation and further testing.

List of References

[1] C.M Harris, "Introduction," in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 1.5-1.6.

[2] Your Dictionary (nd). [Online]. Available: http://www.yourdictionary.com/shock-wave [Dec. 5, 2010]

[3] Dictionary.com (n.d). [Online]. Available: http://dictionary.reference.com/browse/attenuation [Dec. 10, 2010]

[4] Buhler Industries Inc, "*Buhler Industries 2009 Annual Report*." Winnipeg, MB: Buhler, 2009.

[5] E. Lambert (private communication), Sept 16. 2010.

[6] Buhler Industries Inc, (2009) "*Versatile – Tractor Ranges*" Available: http://www.versatile-ag.ca/tractor_ranges/index.html [Dec. 2, 2010].

[7] E. Lambert (private communication), Oct 29. 2010.

[8] Safe Work Manitoba, *Guideline for Hearing Conservation and Noise Control*. (2007, January). Manitoba Workplace Safety and Health Division, Winnipeg, MB [Online]. Available: http://safemanitoba.com/uploads/guidelines/hearing.pdf [Dec. 1, 2010].

[9] S.M. Taylor and P.W. Wilkins, *"Health Effects,"*in Transportation Noise Reference Book, 1st Edition, P.M Nelson, Ed. Crowthorne, England: Butterworth & Co., 1987, pp. 4/3-4/12.

[10] W. Melnick, "*Hearing Loss from Noise Exposure*," in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 18.1-18.19.

[11] G. Jansen, "*Physiological Effects of Noise*," in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 25.1-25.19.

[12] D. M. Jones and D. E. Broadbent, "*Human Performance and Noise*," in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 24.1-24.21.

[13] Health and Safety Executive. (nd) *"Noise Control: Determining the Best Option"* Available: http://www.hse.gov.uk/pubns/noisesources.pdf [Nov 23, 2010]

[14] T. Reinhart. "Internal Combustion Engine Noise Prediction and Control – Diesel and Gasoline Engines Handbook of Noise and Vibration Control," in Handbook of Noise and Vibration Control. M. J. Crocker, Ed. Hoboken NJ: John Wiley & Sons, 2007, pp.1024 - 1032

[15] F. Gould (private phone communication), Nov. 30, 2010.

[16] Rockwool (2010). *Sound Measurements* [Online]. Available: http://www.international.rockwool-marine.com/applications/sound+insulation/sound+measurements [Oct. 20, 2010]

[17] EH Price (nd), Fundamentals of Air Distribution" [Online]. Available: http://www.price-hvac.com/content/flash/ptm/ptm.asp?Section=Noise Control Fundamentals [Dec 4, 2010].

[18] Wilrep Ltd. (nd). "*Barymat M-600D"* [Online]. Available: http://www.wilrep.com/pdf format/3505.pdf [Nov. 20, 2010].

[19] Dale from *Wilrep Ltd*. (private communication), Nov. 25, 2010.

[20] Buhler Industries Inc. (2010). *Row Crop Tractors - 250 to 305hp* [Online]. Available: http://www.versatile-ag.ca/news_and_media/downloads/Versatile-RC-brochure.pdf [Oct 03, 2010]

[21] Wilrep Ltd. (nd). "*Barymat M-100D"* [Online]. Available: http://www.wilrep.com/pdfformat/3504.pdf [Nov. 23, 2010].

[22] Introduction to Noise Removal. (n/a). [Online]. Available: http://www.cedar-audio.com/intro/dehiss_intro.html [Oct. 23, 2010].

[23] G.C. Maling and A.L Boggess, "Ventilating Systems for Small Equipment," in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 44.1-44.17.

[24] J.B. Graham and R.M. Hoover, "Fan Noise," in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 41.1-44.22.

[25] G.C. Maling, “Ventilating Systems for Small Equipment,” in Handbook of Acoustical Measurements and Noise Control, 2nd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1979, pp. 29.1-29.10.

[26] Buhler Versatile Inc., *“Repair Manual: Climate Control.”* Winnipeg, MB: Buhler Versatile, (nd)

[27] R.M. Hoover and W.E. Blazier, “Noise Control in Heating, Ventilating, and Air Conditioning Systems,” in Handbook of Acoustical Measurements and Noise Control, 3rd edition. C.M. Harris, Ed. Columbia, NY: McGraw-Hill, 1991, pp. 42.1-42.31.

[28] H. Zhu, X. Yu, and R. Rajamani. (2004). *Active control of glass panels for reduction of sound transmission through windows*. Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN. [Online]. Available: Elsevier ScienceDirect [Nov. 29, 2010]

[29] Y. Peng, A. Sasao, S. Shibusawa. (2001). *Active noise control in proximity of a tractor operator’s head.* [Online], vol. 44 (2), pp. 447-455. Available: ASAE [Nov. 12, 2010]

[30] N. Popplewell (private communication), Sept 16. 2010

[31] S. D. Snyder, Active Noise Control Primer.Springer, 2000.

[32] S. J. Elliot, "Active Noise Control," in Handbook of Noise and Vibration Control. M. J. Crocker, Ed. Hoboken NJ: John Wiley & Sons, 2007, pp.761-796

List of Figures

List of Tables

Appendix A

Data from all the sound level measurements made over the course of the project will be included in this Appendix. A diagram highlighting how the sound level measurements are displayed is shown in Figure 1. Each plot is given a measurement position and a description of the position as seen on the left of Figure 1.

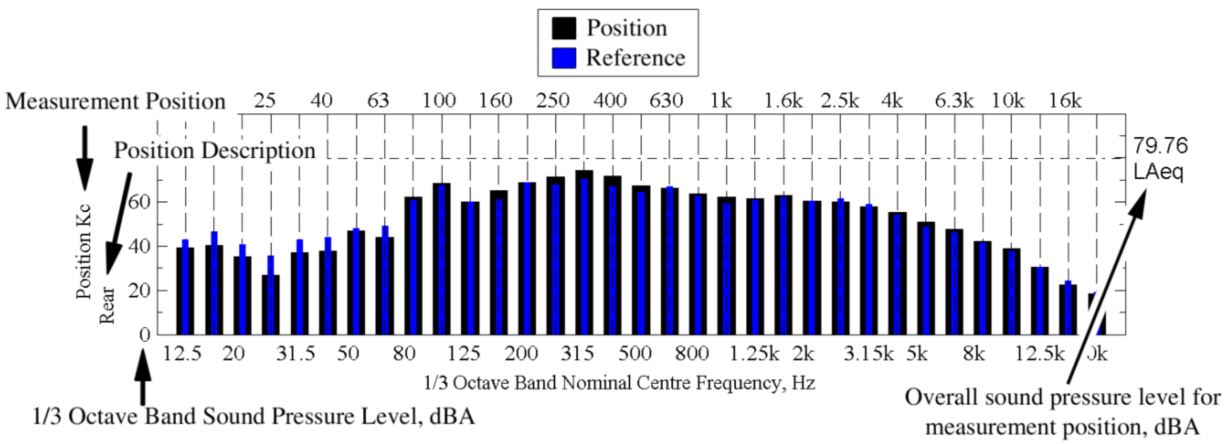

Figure 1 - Measurement data schematic

All sound pressure levels, unless otherwise noted have been A-Weighted, meaning the measurements reflect the human ear's response to sound pressure. The sound level meter used to make the measurement is an electronic device and has a nearly flat response to sound pressure levels at all frequencies. However, the human ear perceives low frequency sound waves as less loud when compared to higher frequencies of the same sound pressure level [1]. A chart of the A-Weighting placed on each octave band is shown in Figure 2, mapping the human ear's response to different frequency centered 1/3 octave bands. The overall sound pressure level is given on the left top corner, as shown in Figure 1.

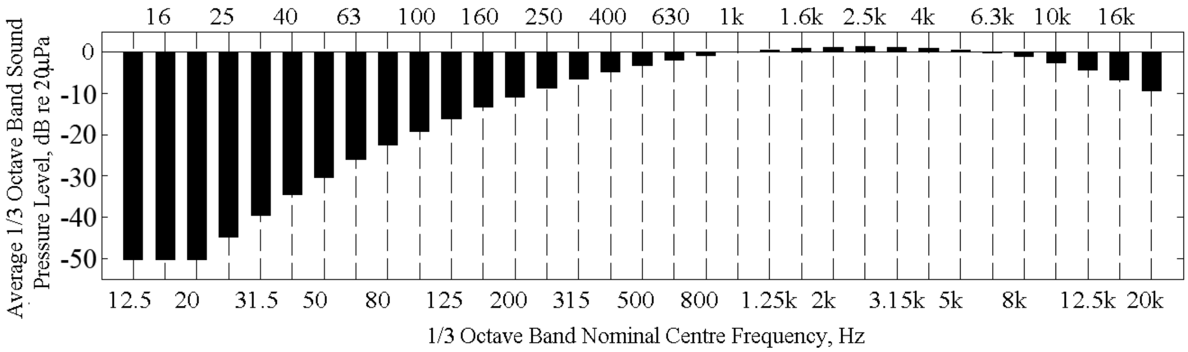

Figure 2 – A-Weighting scale [1]

The measurement positions for each location are described in each figure; they can also be matched with the locations labelled on Figure 3. The capital letter corresponds to the location in the cab from a side profile, with the lower case letter denoting left, right or center of the cab. For example, the operator position which is roughly in the center of the cab is described as Ec.

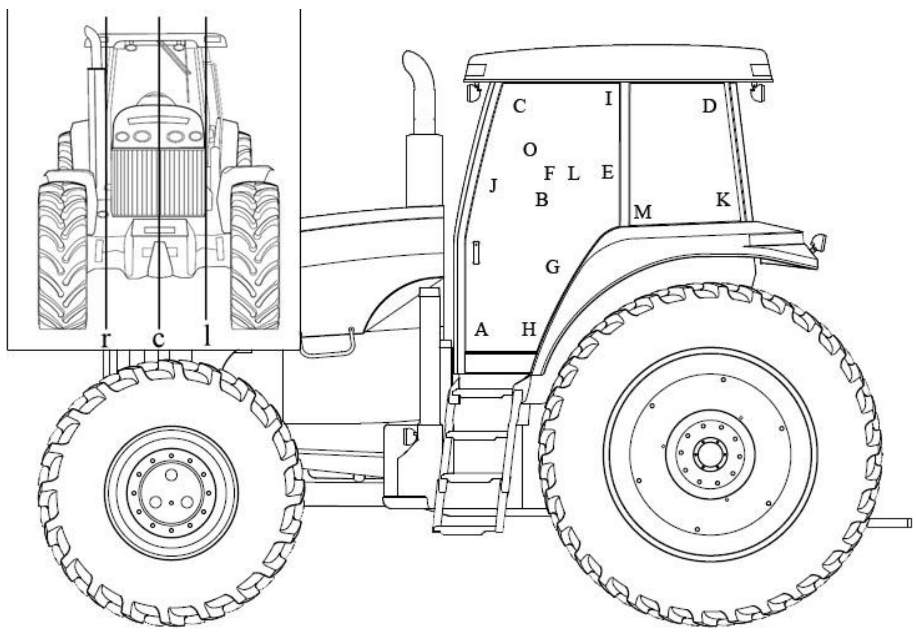

Figure 3 - Measurement positions [2 ,p. 22]

All sound pressure level measurements are made from the operator position with the microphone facing the measurement position. So, for the measurement near the center of the left side door (Bl) the microphone is facing the class door.

A.1 Initial Sound Pressure Level Measurements

With no specific information about the acoustic properties of the cab or the characteristics of the noise produced during tractor operation, initial measurements were made to get a feel for the noise problem. Analyzing the preliminary measurements revealed areas to focus future research on. These measurements showed the exhaust stack to be an important noise producing component. In addition, it looks like the tractor cab floor is one of the main sound transmission paths into the cab.

Information about the measurement equipment and testing conditions can be found in TABLE I. The averaging time given in TABLE I is the duration over which each sound level measurement was taken. The presented data is the average sound pressure levels over this time. The reference position for the sound pressure level measurements in Figure 4 through Figure 9 is the operator position, Ec, and can be found in Figure 4. The reference position for the sound pressure level measurements in Figure 10 is also the operator position but for an engine speed of 900 RPM and can be found in Figure 10.

TABLE I – MEASUREMENT CONDITIONS INITIAL TEST

Date/Time	September 29th 2010	8:50 to 10:00 am
Location	Buhler Versatile Plant	1260 Clarence Avenue, Winnipeg, MB
Tractor	Buhler Versatile model 280	
Engine Speed	See figure	RPM
Tractor Speed	0	
Load	0	
Equipment	Bruel & Kjaer 2250 sound level meter	
Ambient Air Temp.	13°C	
Averaging Time	10 seconds	

*The sampling time for this measurement day was insufficient to properly capture sound pressure levels in the 1/3 octave band center frequencies from 12.5 to 40 Hz. Data in these low frequency 1/3 octave bands should be ignored.

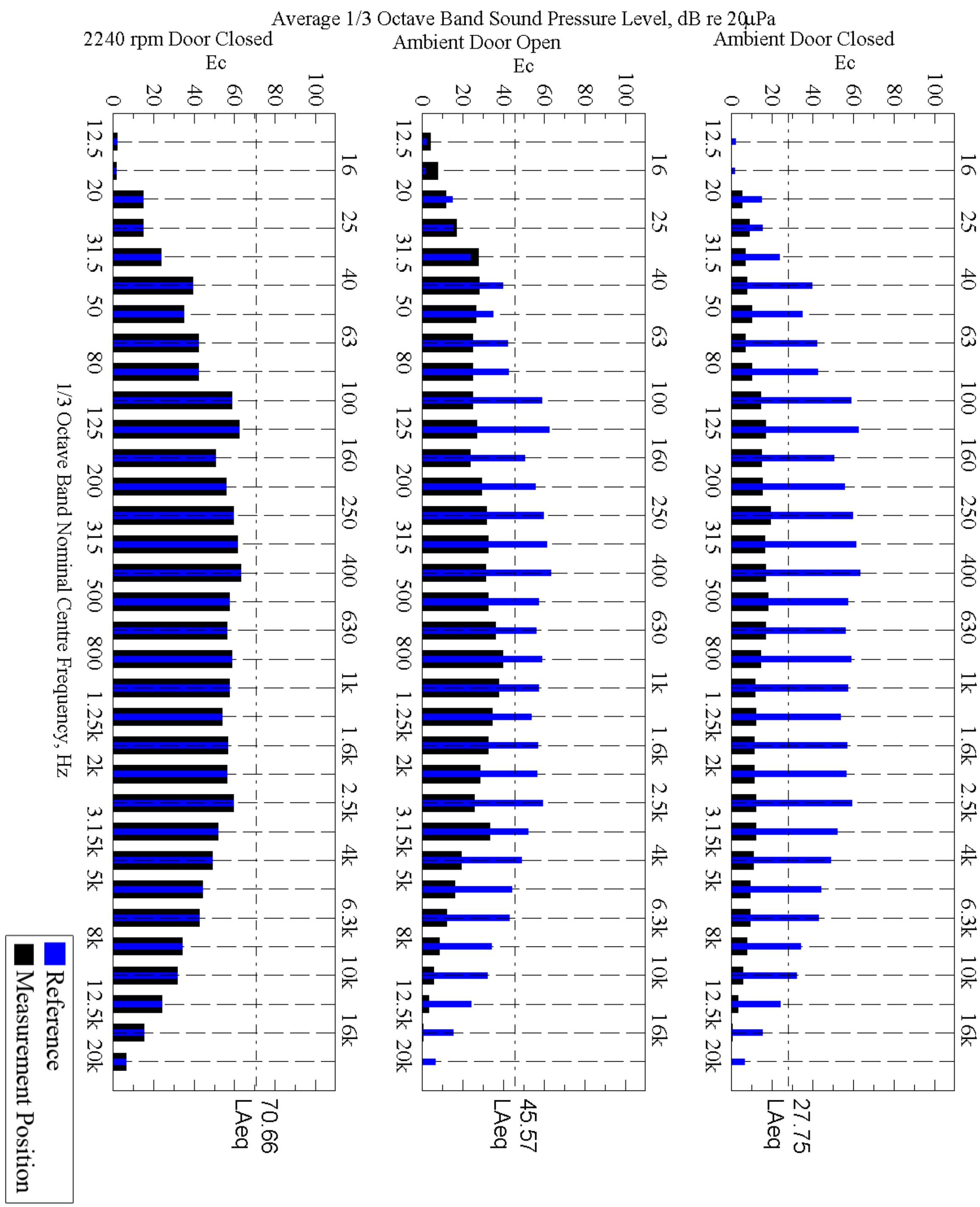

Figure 4 - Initial sound pressure level measurements A

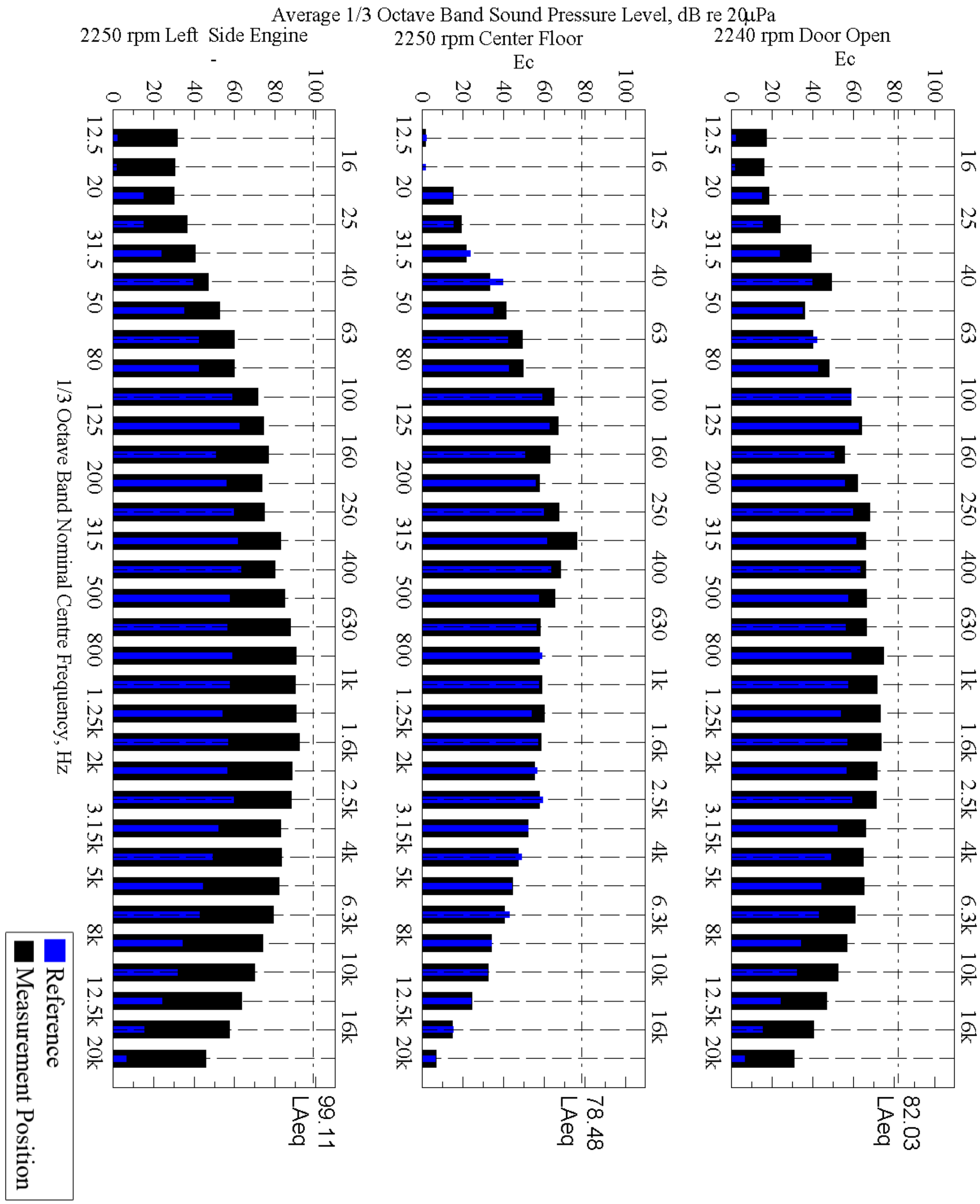

Figure 5. Initial sound pressure level measurements B

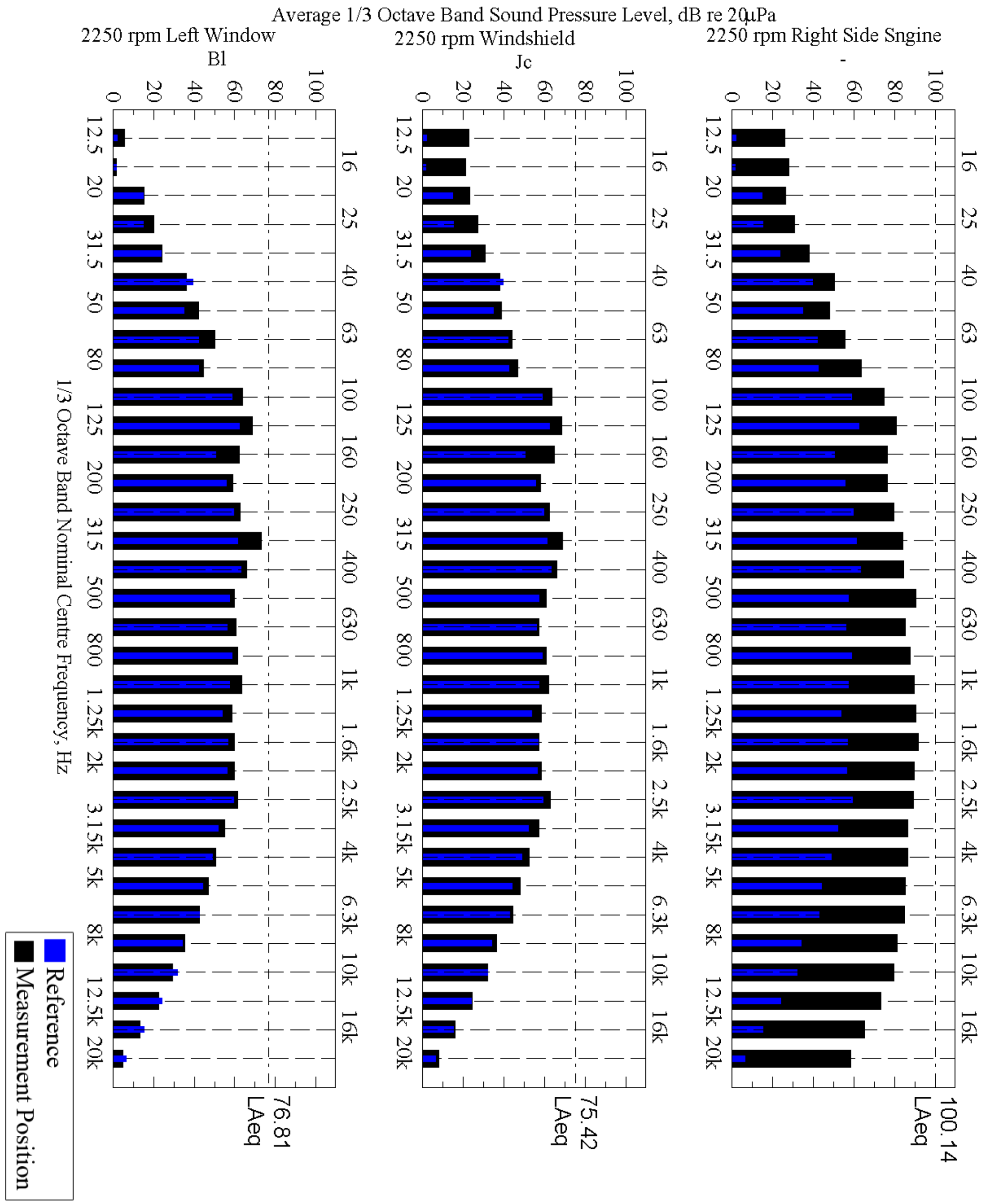

Figure 6 - Initial sound pressure level measurements C

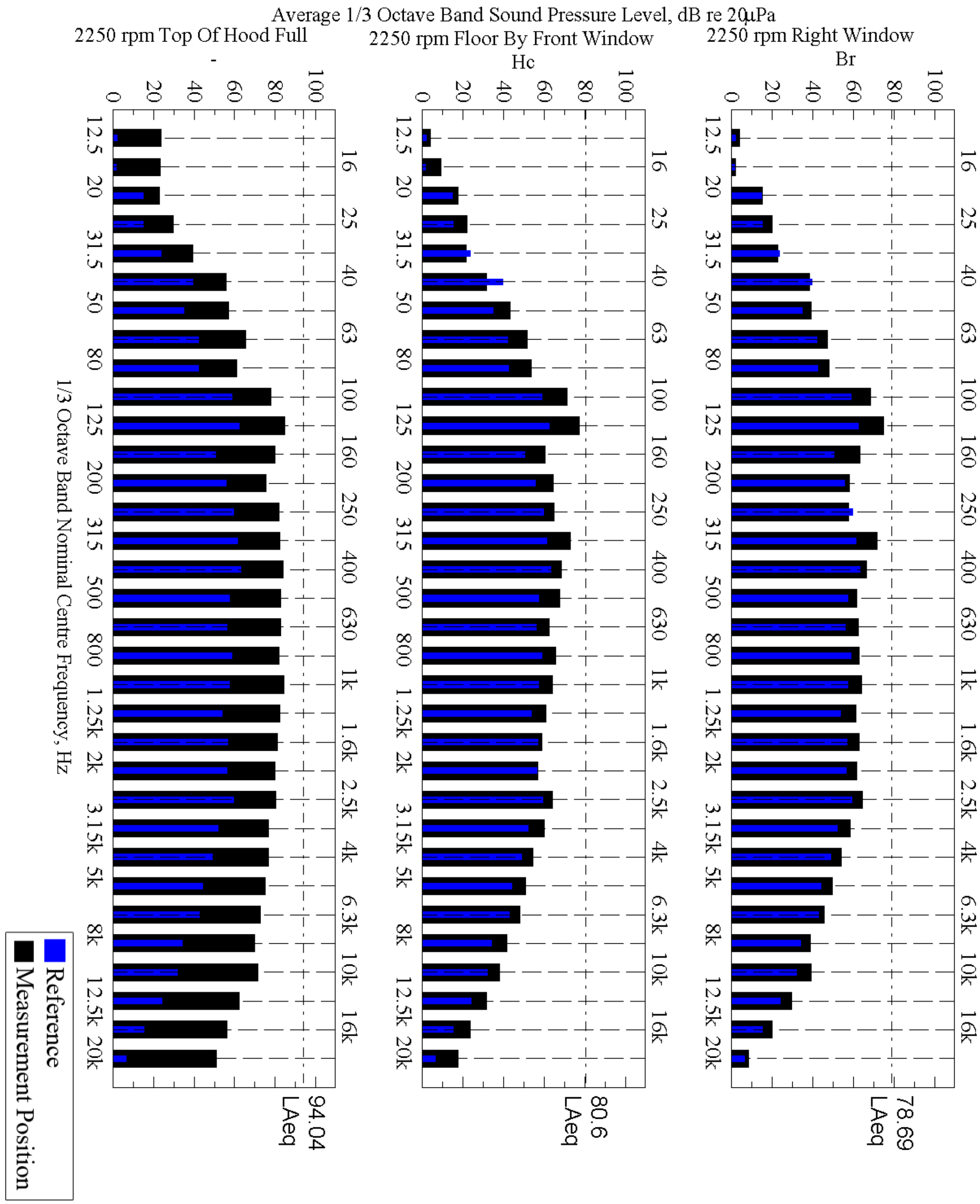

Figure 7 - Initial sound pressure level measurements D

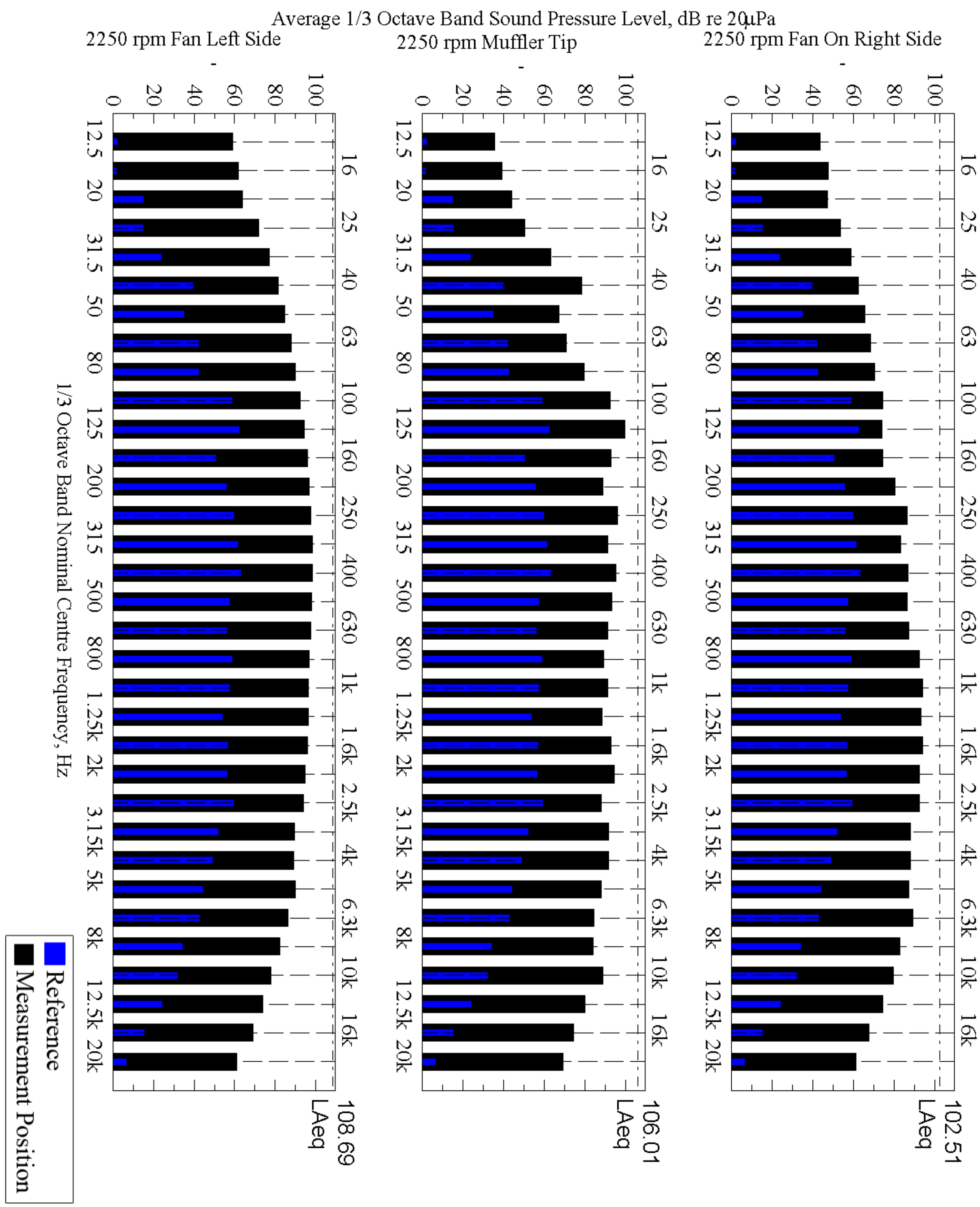

Figure 8 - Initial sound pressure level measurements E

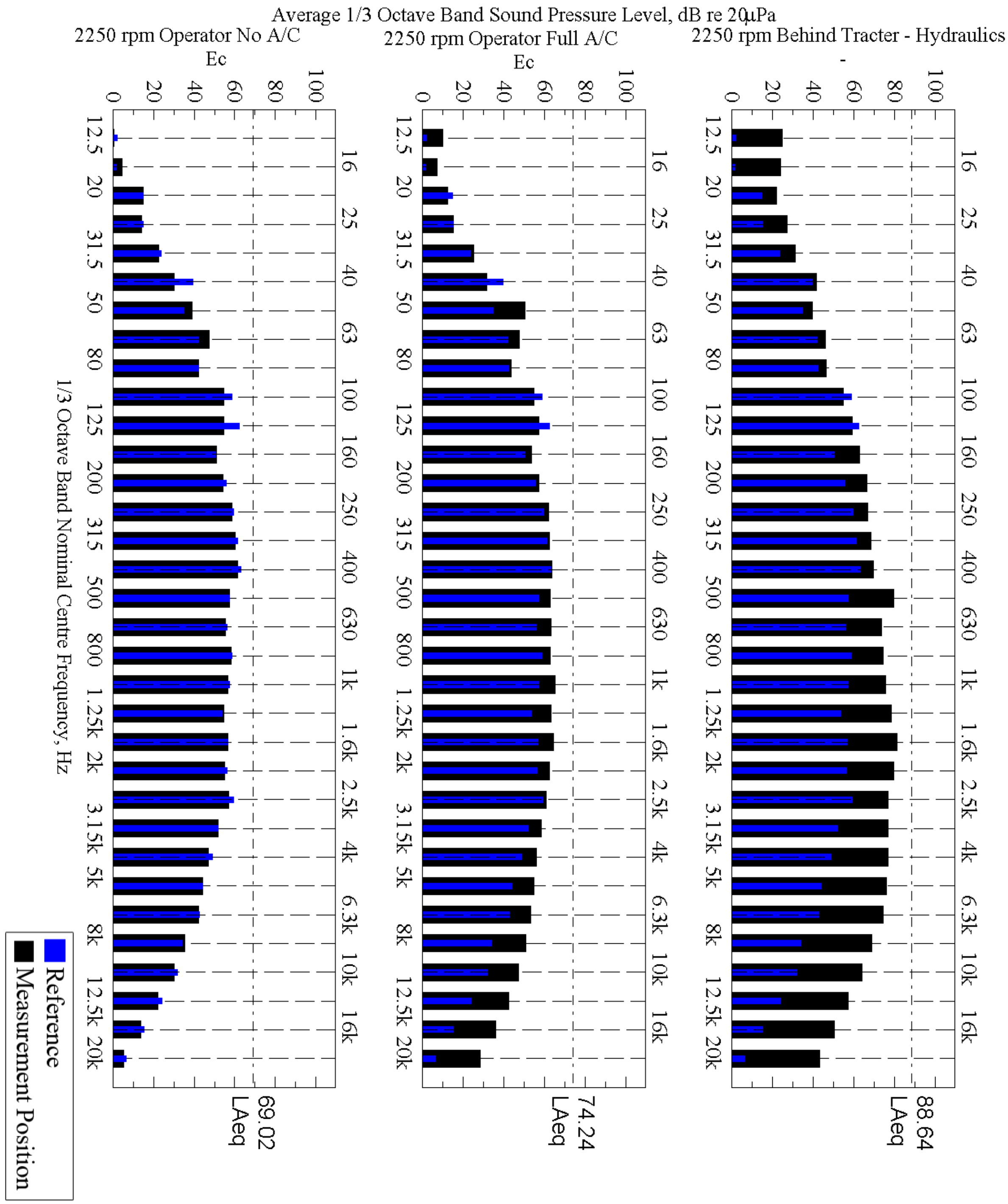

Figure 9 - Initial sound pressure level measurements F

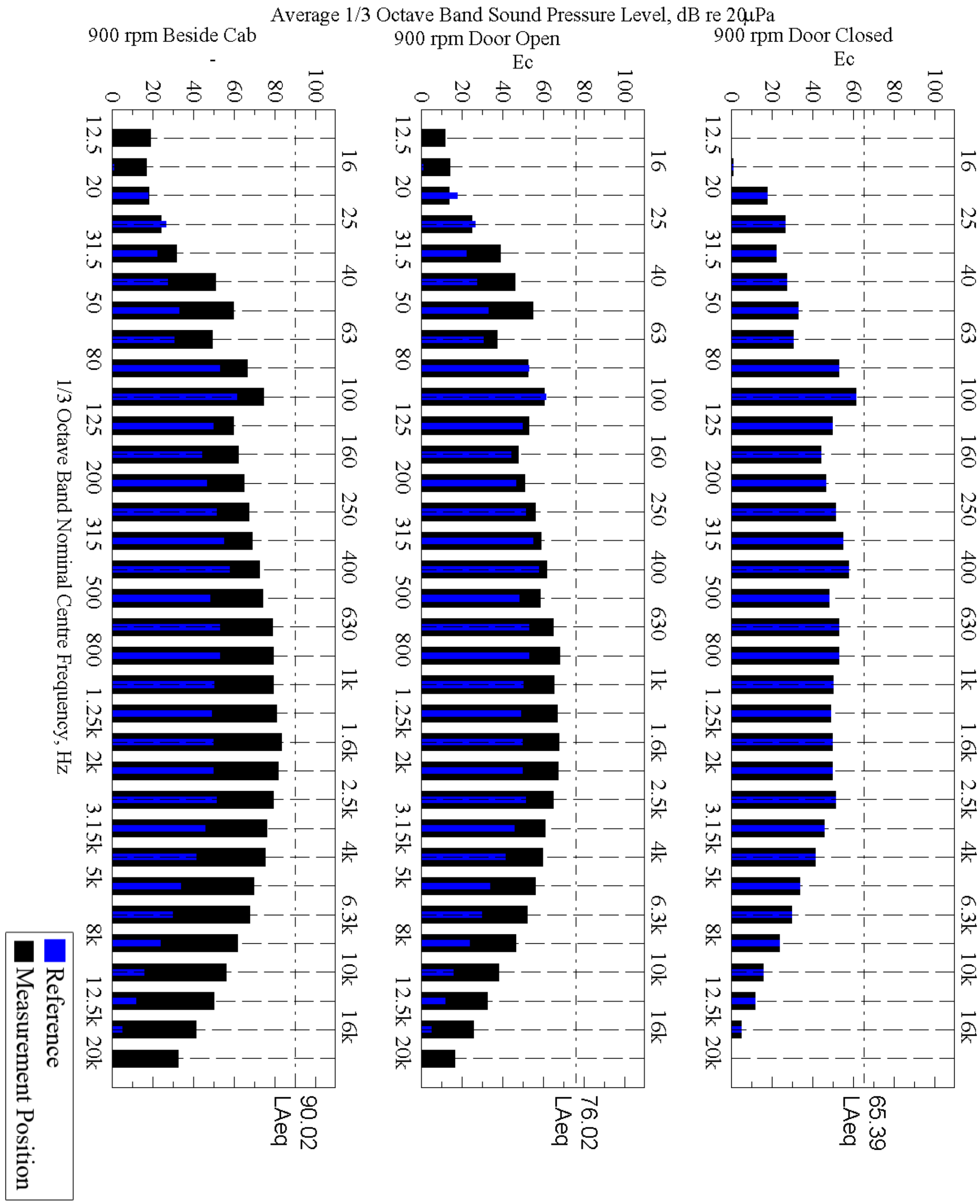

Figure 10 - Initial sound pressure level measurements G

A.2 Dynamic Sound Level Measurements Under Load

After some problem areas were established in the initial measurements, dynamic measurements were made under load, focusing on the problem areas. Three separate measurement phases were done under different operating conditions.

A.2.1 Run 1

Measurement conditions for Run 1 can be found in TABLE II. The reference position for these measurements is the operator position and can be seen in Figure 13.

TABLE II – MEASUREMENT CINDITIONS UNDER LOAD RUN 1

Date/Time	October 14th, 2010	2:10 to 2:40 pm
Location	Buhler Versatile Test Facility	Sanford, MB
Tractor	Buhler Versatile model 280	2 set of tires
Engine Speed	1800 RPM	7th Gear
Tractor Speed	4.2 MPH	
Load	full load	
Equipment	Bruel & Kjaer 2250 sound level meter	
Ambient Air Temp.	10°C	
Averaging Time	20 seconds	

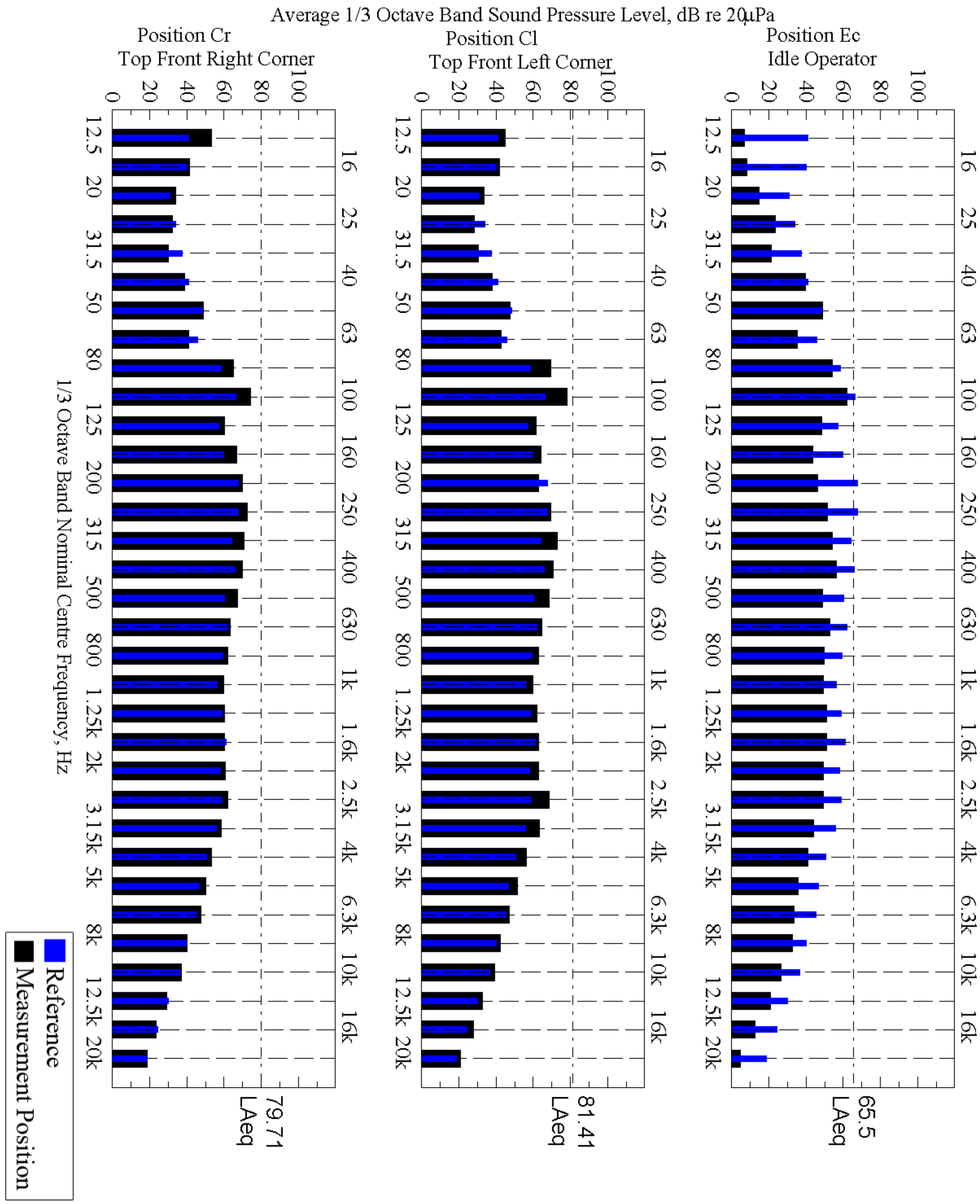

Figure 11 - Dynamic sound pressure level measurements run 1 A

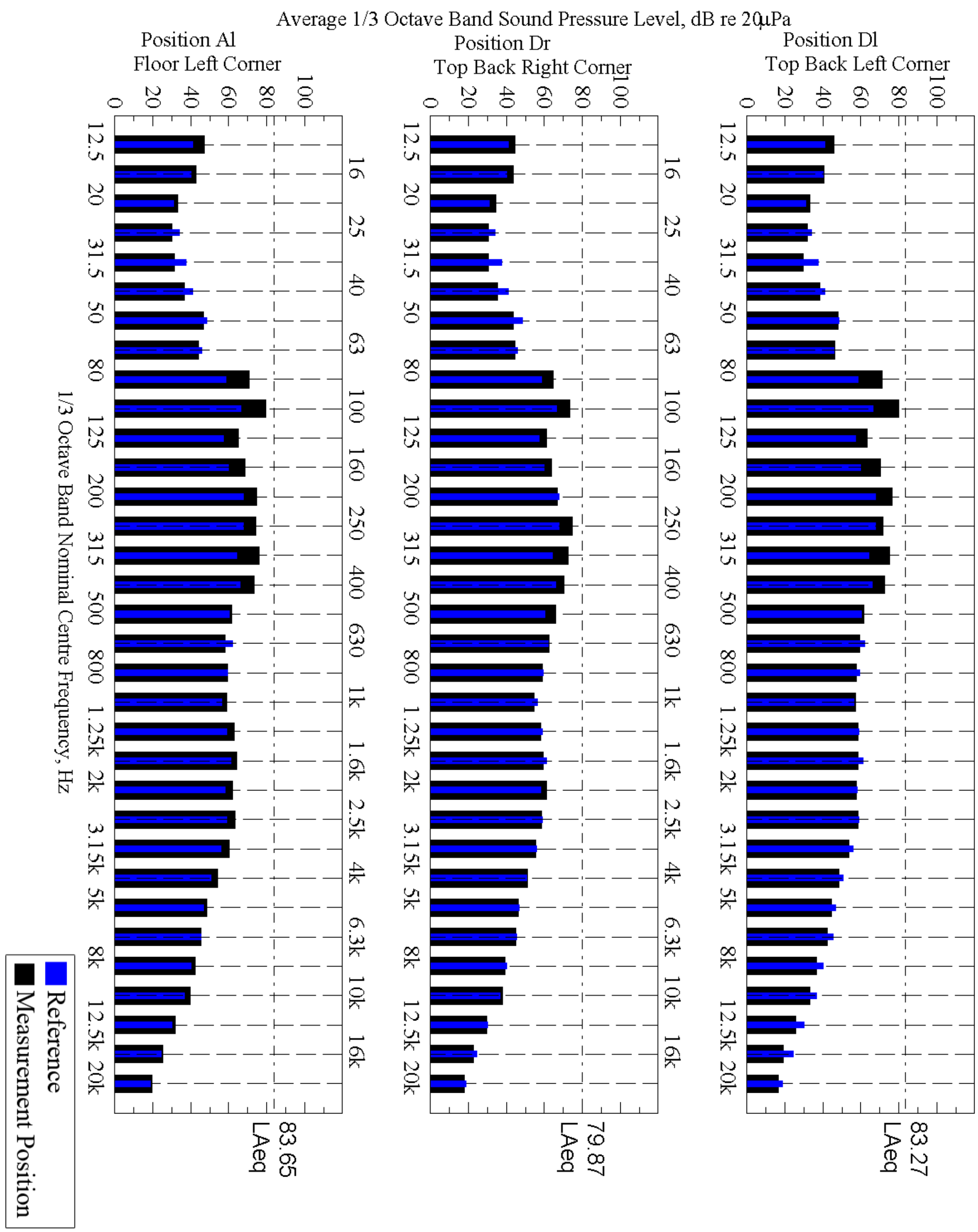

Figure 12 - Dynamic sound pressure level measurements run 1 B

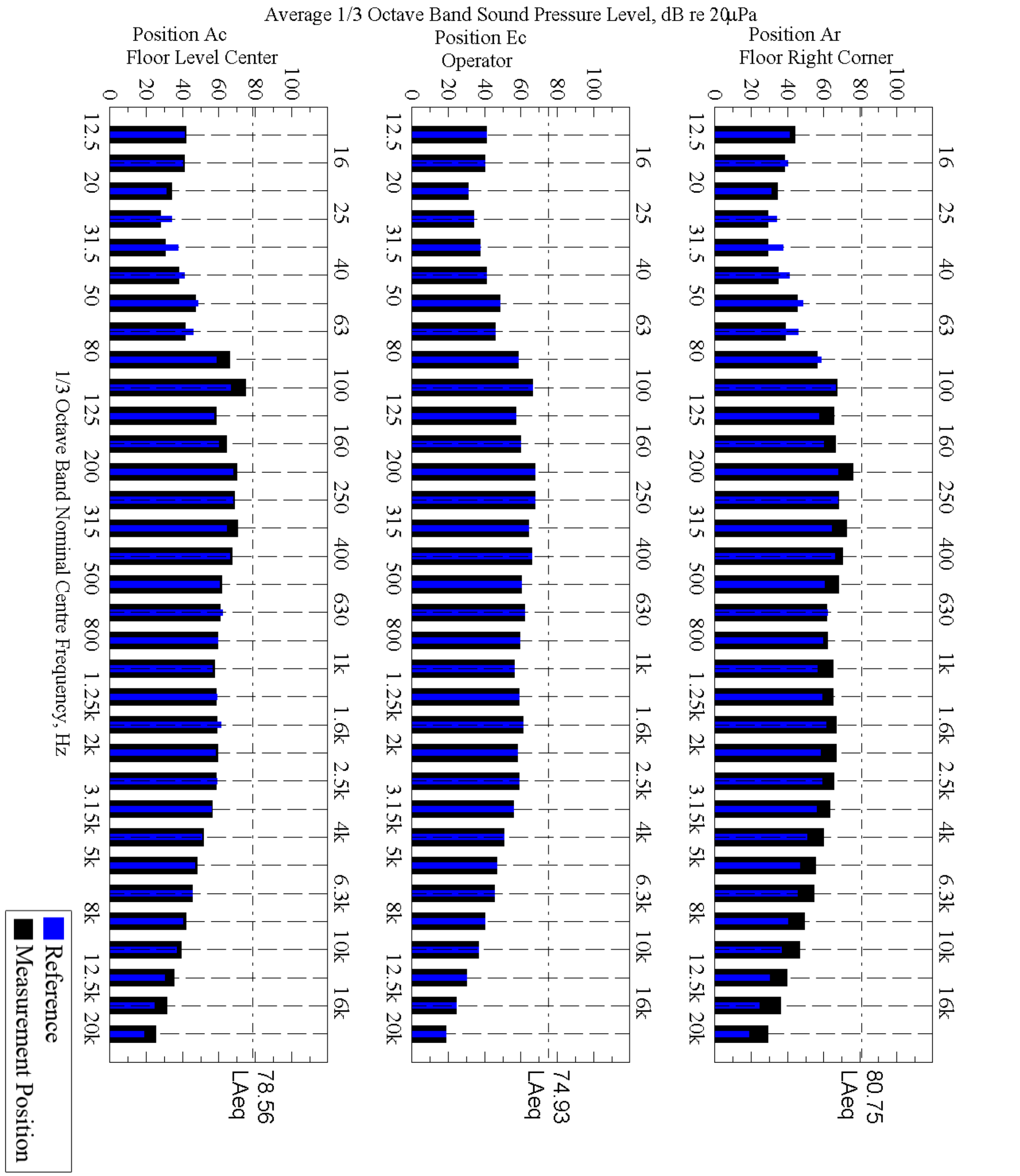

Figure 13 - Dynamic sound pressure level measurements run 1 C

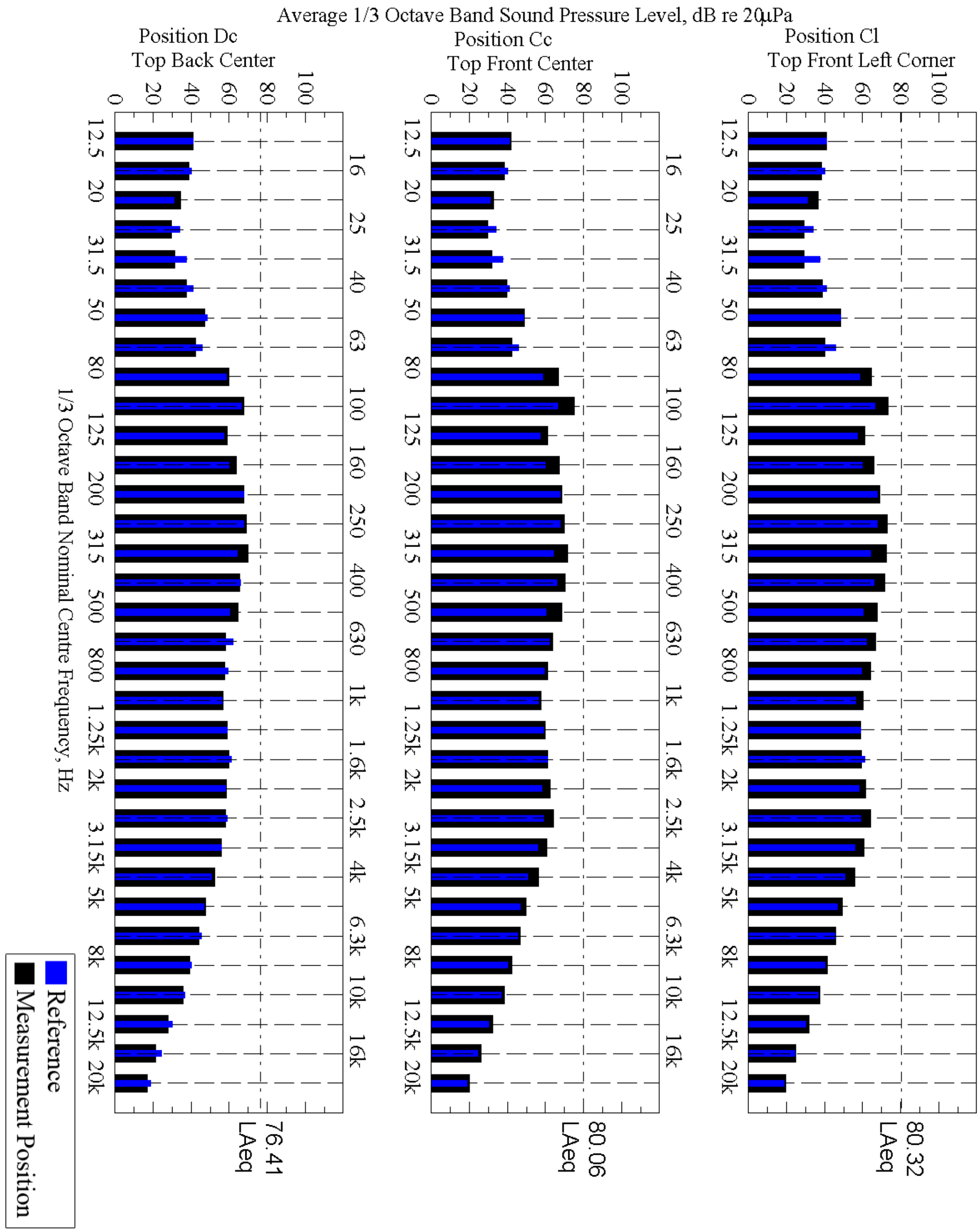

Figure 14 - Dynamic sound pressure level measurements run 1 D

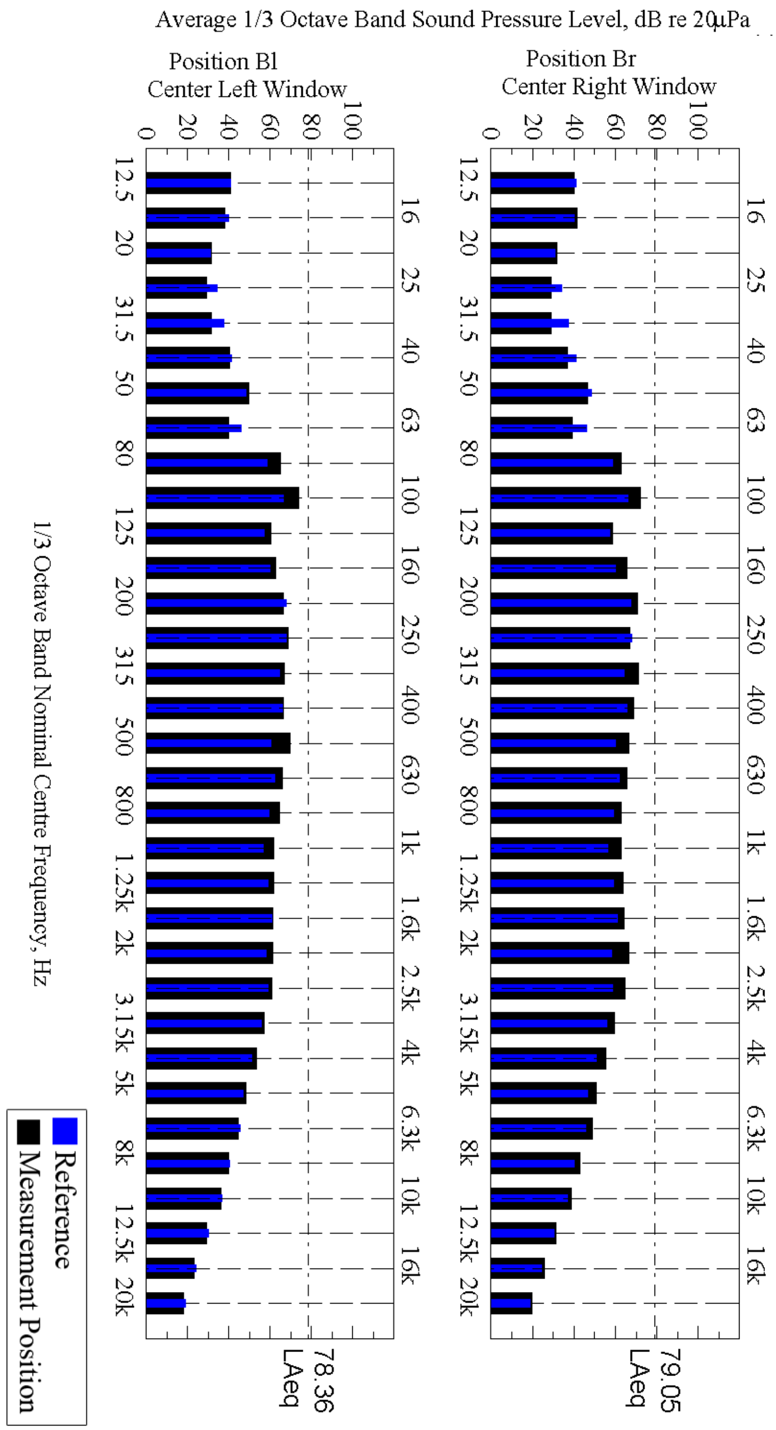

Figure 15 - Dynamic sound pressure level measurements run 1 E

A.2.2 Run 2

Measurement conditions for Run 2 can be found in TABLE III. The reference position for these measurements is the operator position and can be seen in Figure 20.

TABLE III – MEASUREMENT CONDITIONS UNDER LOAD RUN 2

Date/Time	October 14th, 2010	2:45 to 3:18 pm
Location	Buhler Versatile Test Facility	Sanford, MB
Tractor	Buhler Versatile model 280	2 set of tires
Engine Speed	2040 RPM	7th Gear
Tractor Speed	-	
Load	full load	
Equipment	Bruel & Kjaer 2250 sound level meter	
Ambient Air Temp.	10°C	
Averaging Time	20 seconds	

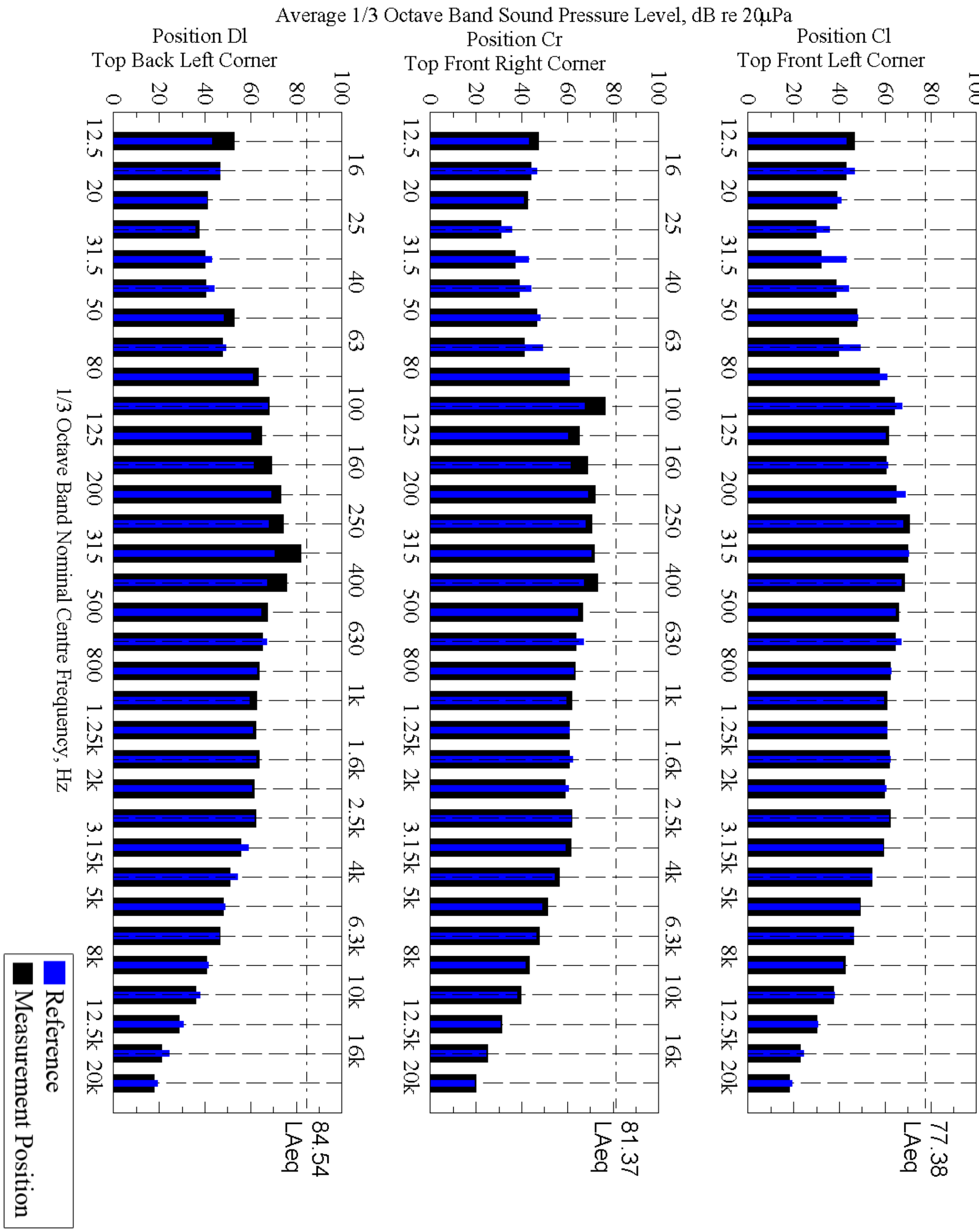

Figure 16 - Dynamic sound pressure level measurements run 2 A

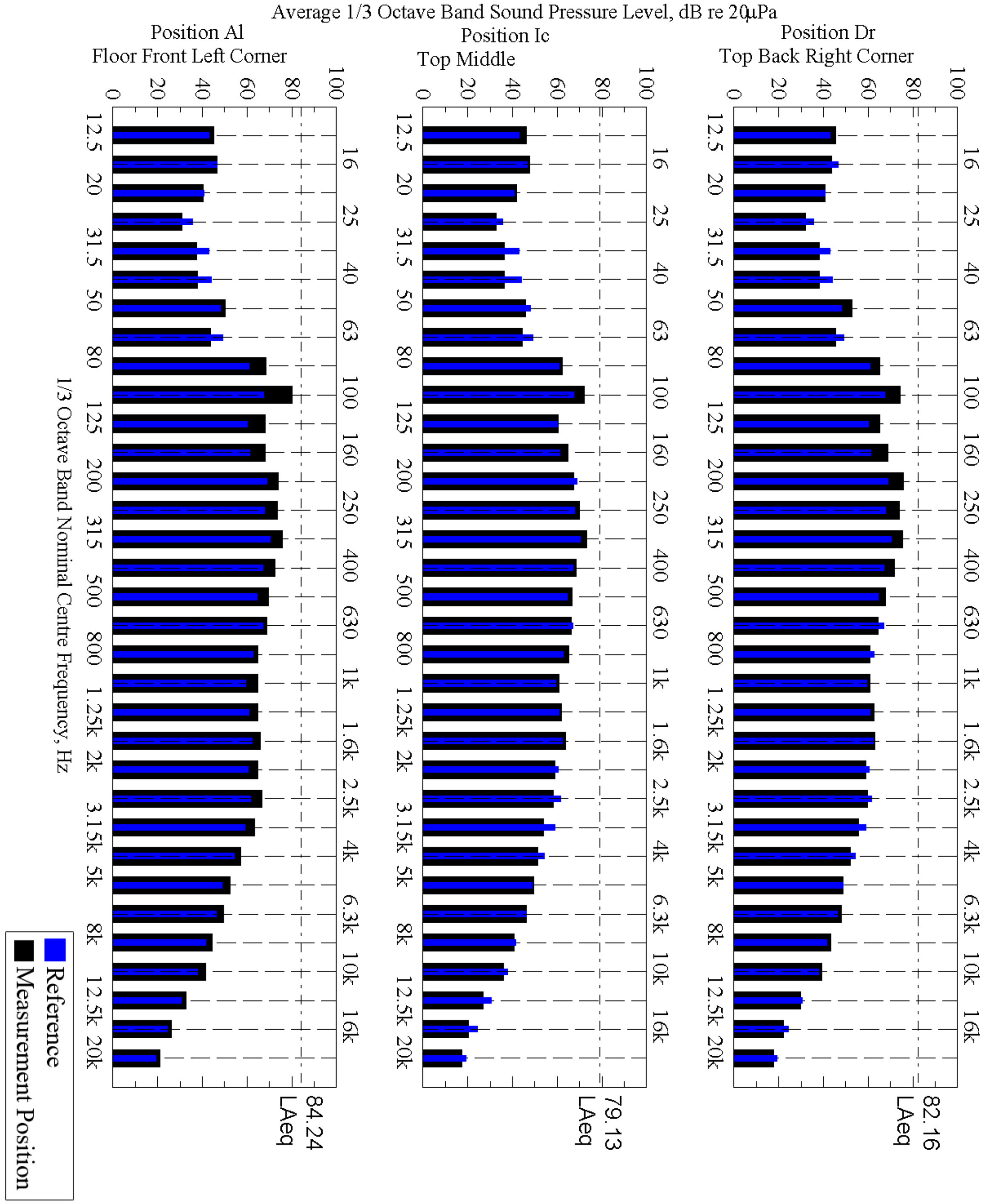

Figure 17 - Dynamic sound pressure level measurements run 2 B

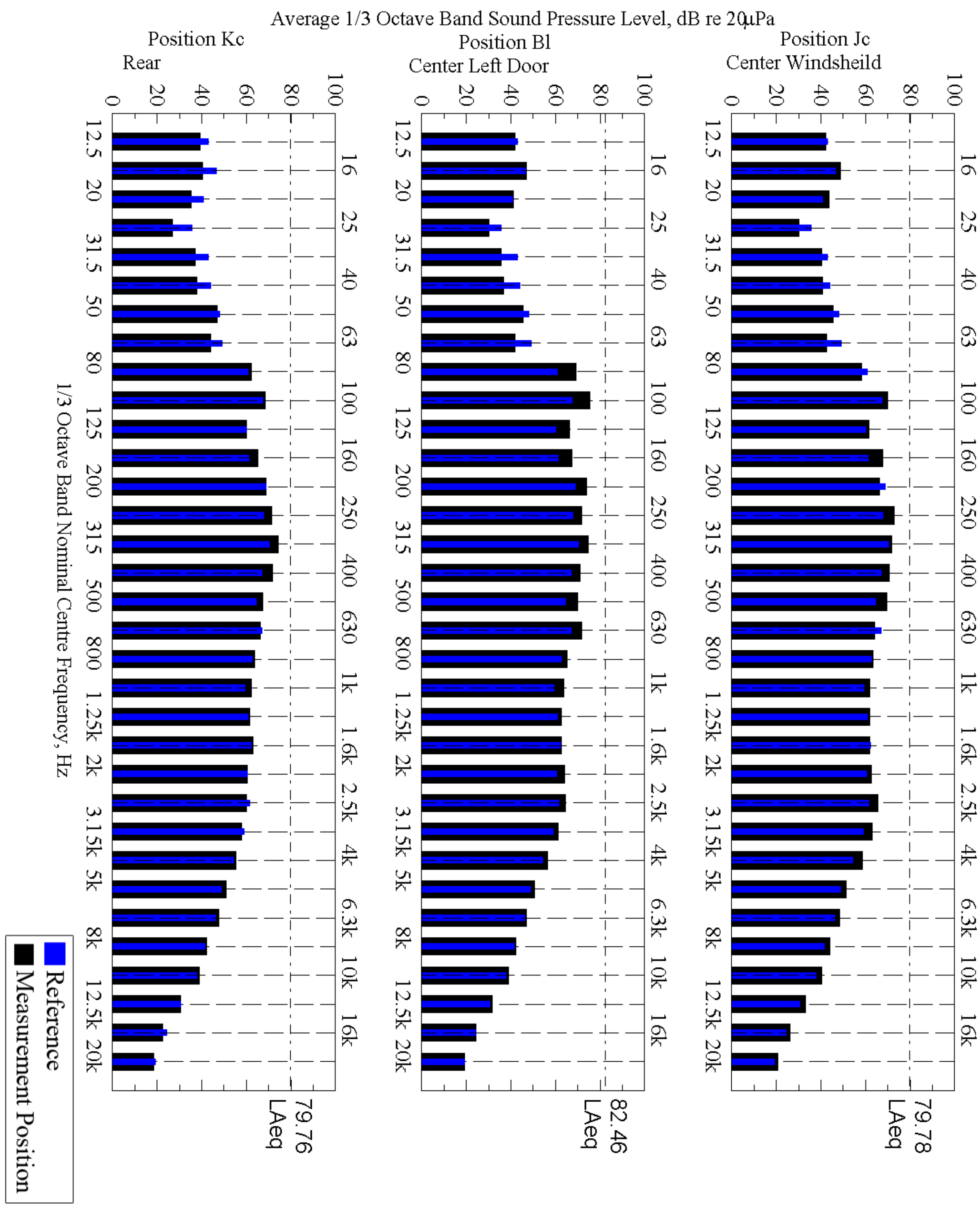

Figure 18 - Dynamic sound pressure level measurements run 2 C

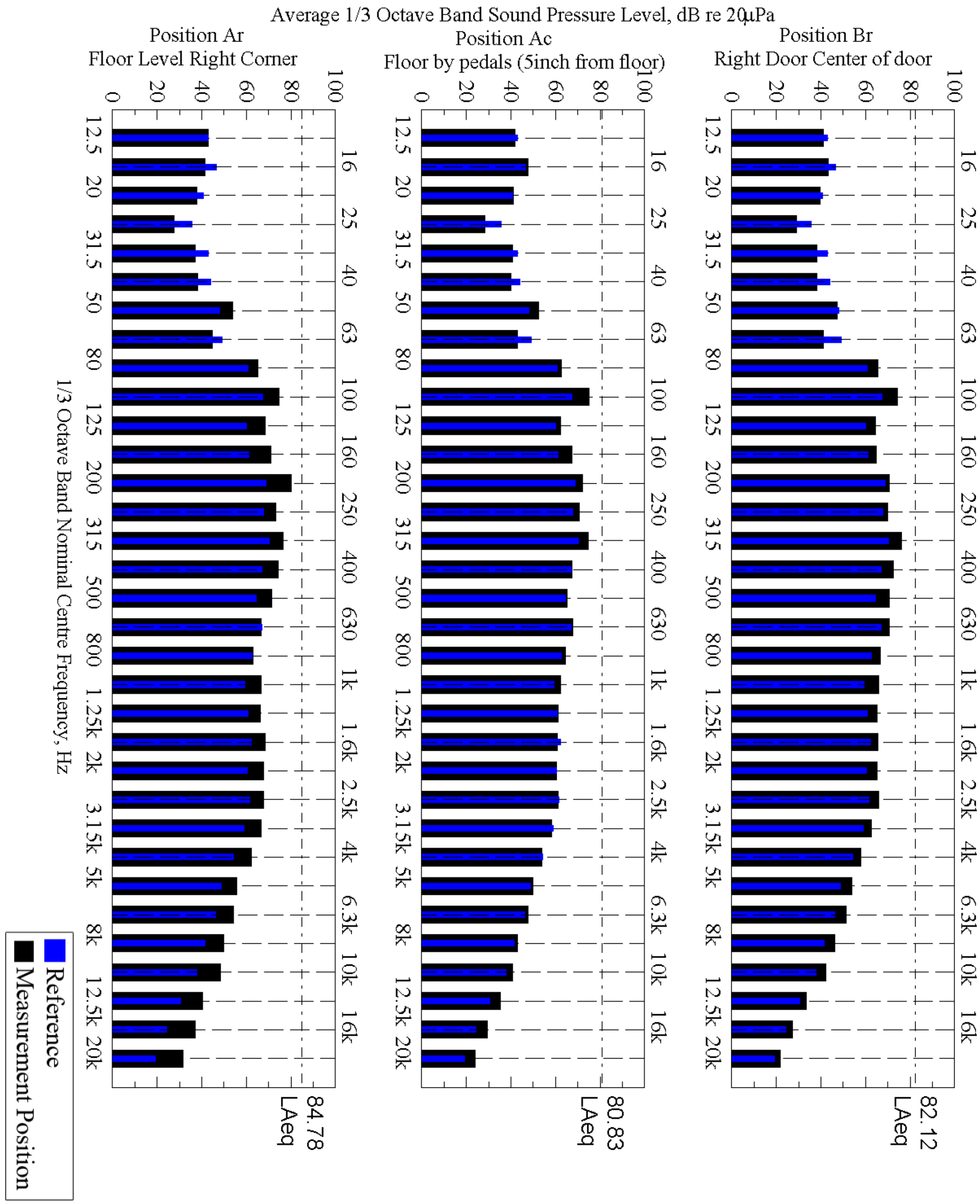

Figure 19 - Dynamic sound pressure level measurements run 2 D

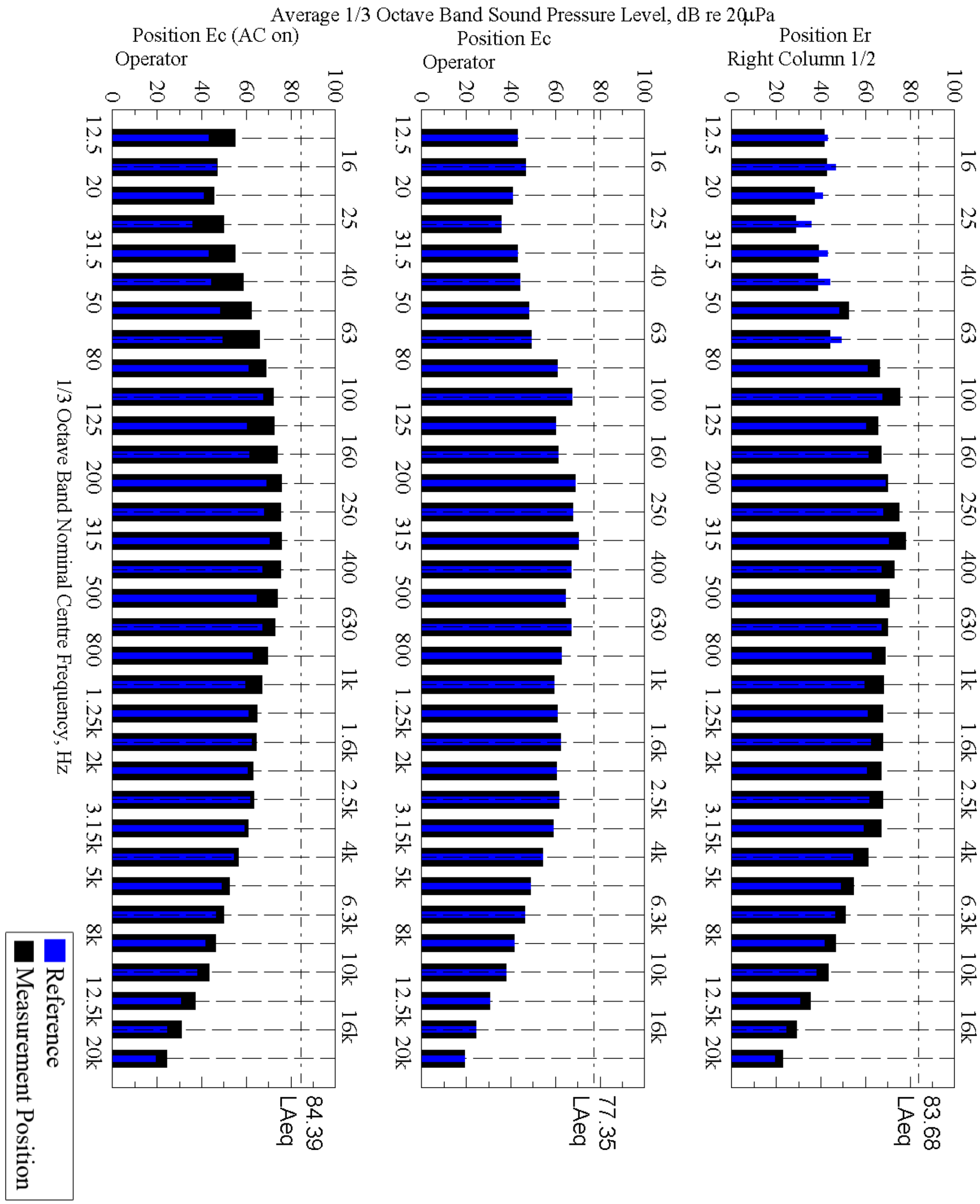

Figure 20 - Dynamic sound pressure level measurements run 2 E

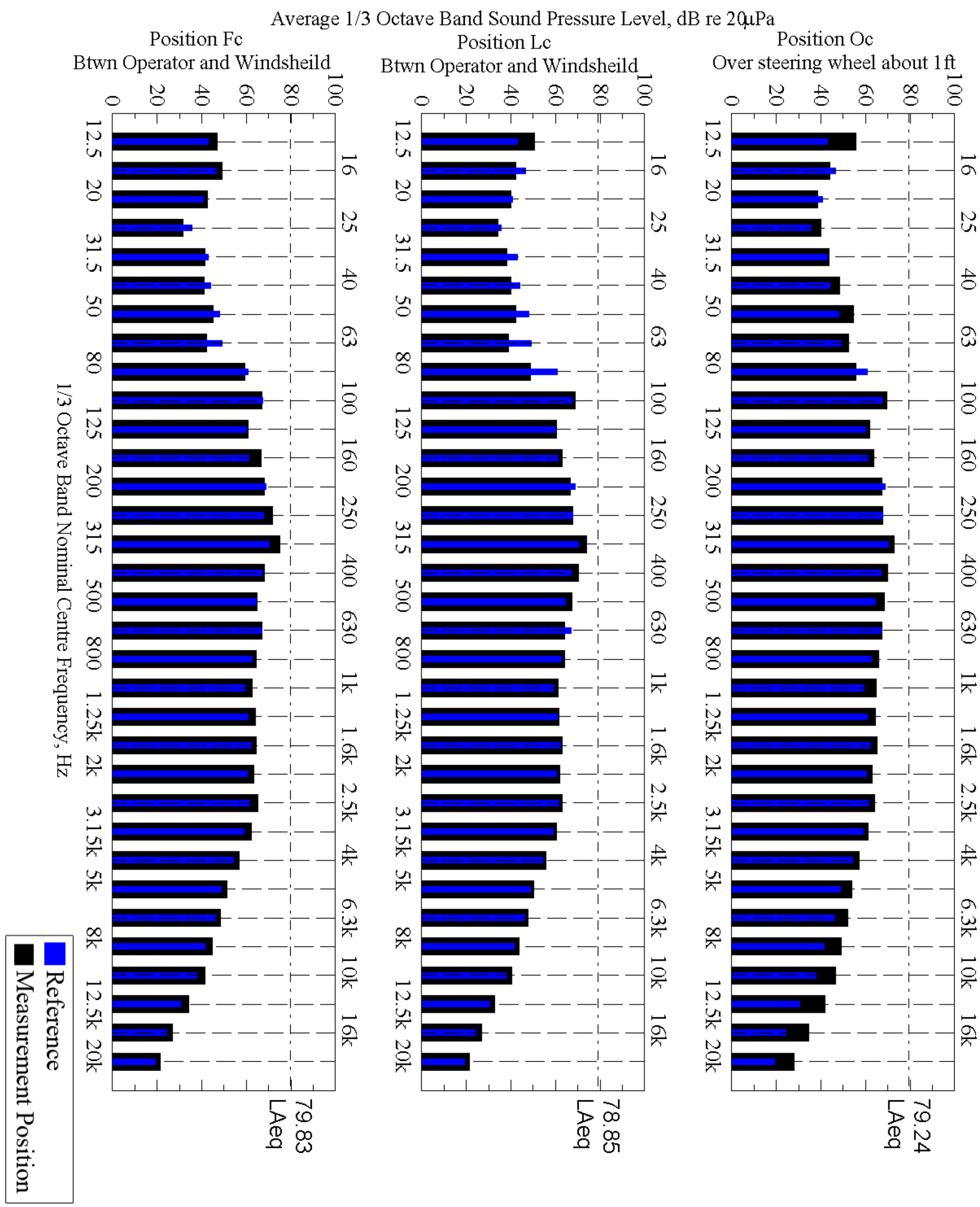

Figure 21 - Dynamic sound pressure level measurements run 2 F

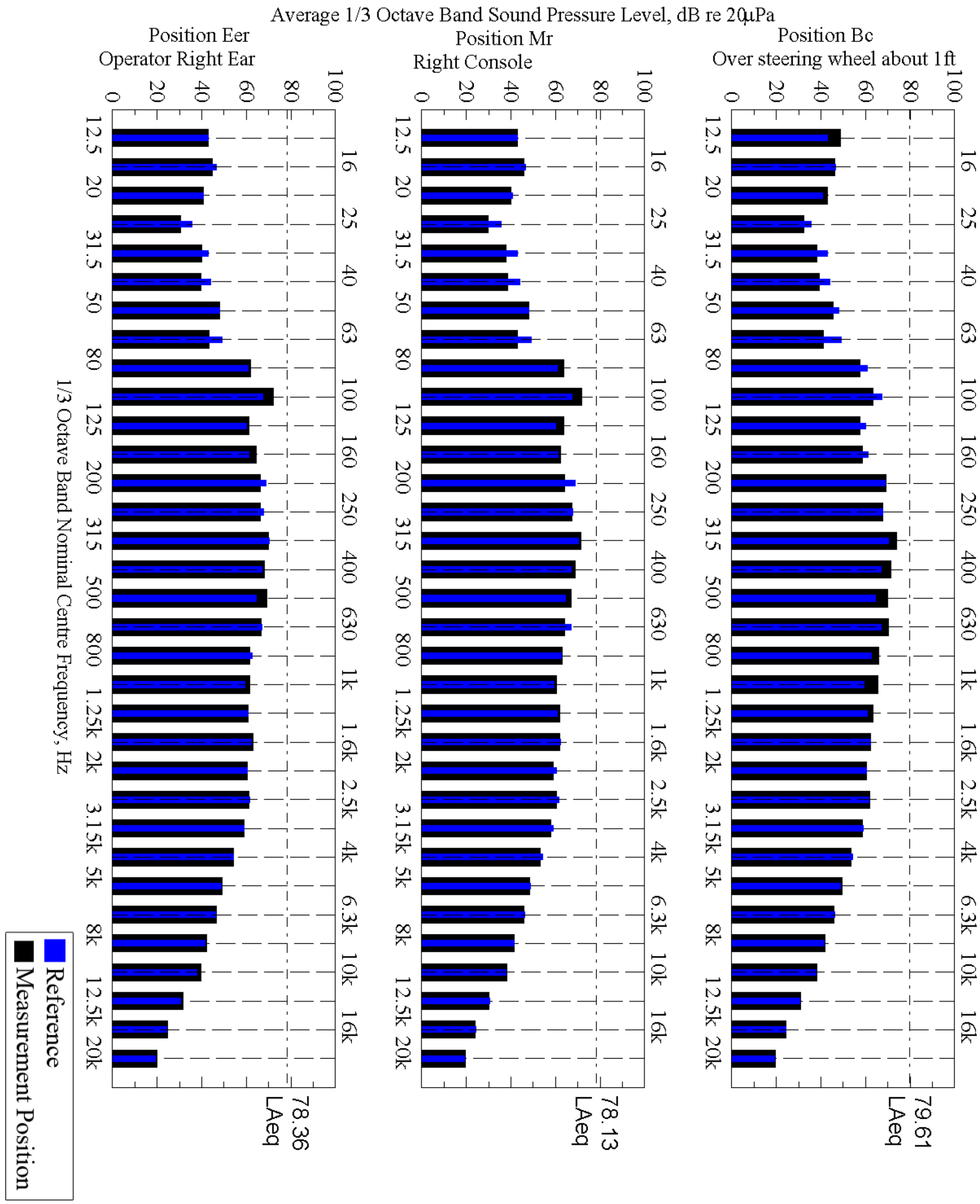

Figure 22 - Dynamic sound pressure level measurements run 2 G

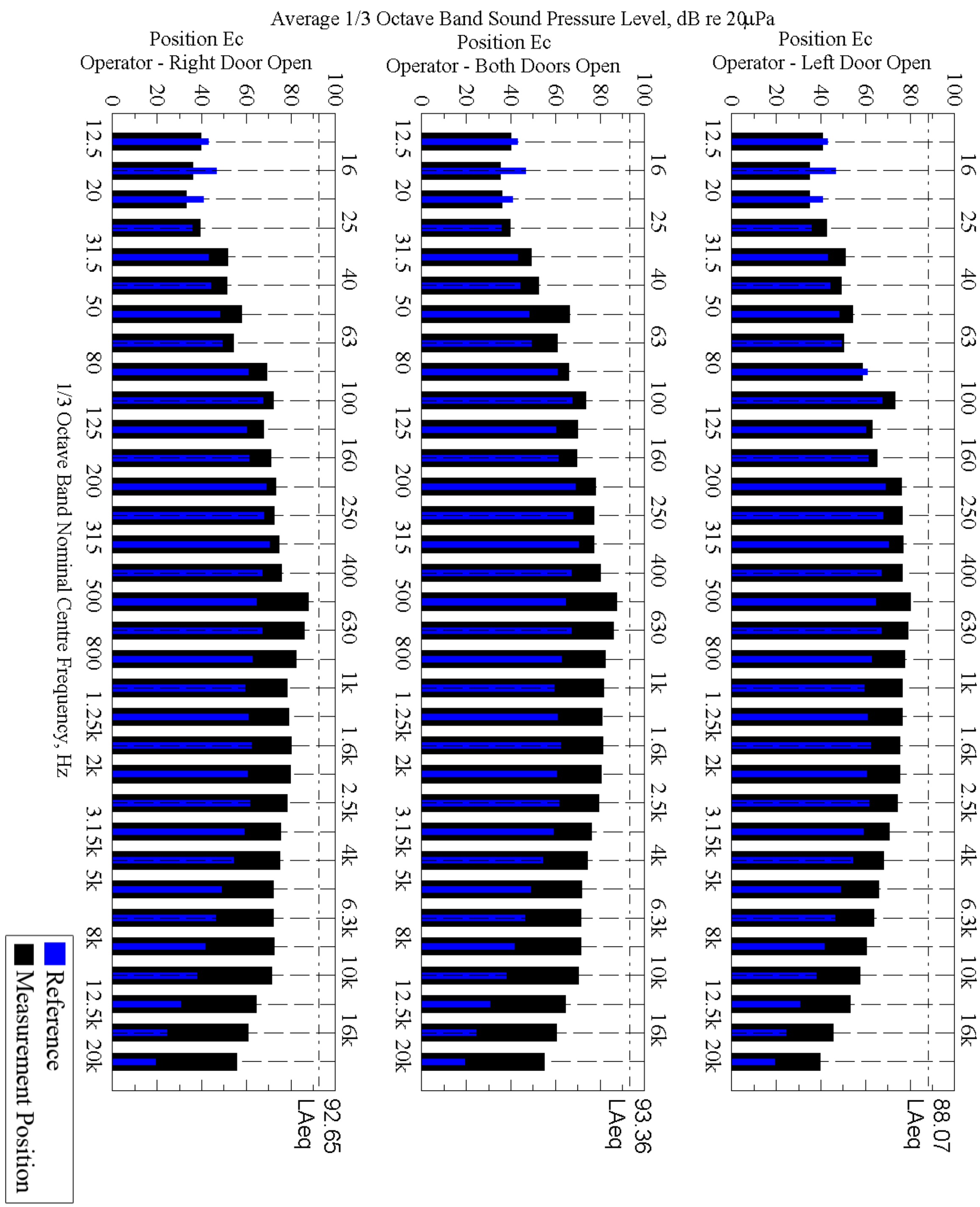

Figure 23 - Dynamic sound pressure level measurements run 2 H

A.2.3 Run 3

Measurement conditions for Run 3 can be found in TABLE IV. The reference position for these measurements is the operator position and can be seen in Figure 24.

TABLE IV – MEASUREMENT CONDITIONS UNDER LOAD RUN 3

Date/Time	October 14th, 2010	3:18 to 3:45 pm
Location	Buhler Versatile Test Facility	Sanford, MB
Tractor	Buhler Versatile model 280	2 set of tires
Engine Speed	1870 RPM	8th Gear
Tractor Speed	-	
Load	full load	
Equipment	Bruel & Kjaer 2250 sound level meter	
Ambient Air Temp.	10°C	
Averaging Time	20 seconds	

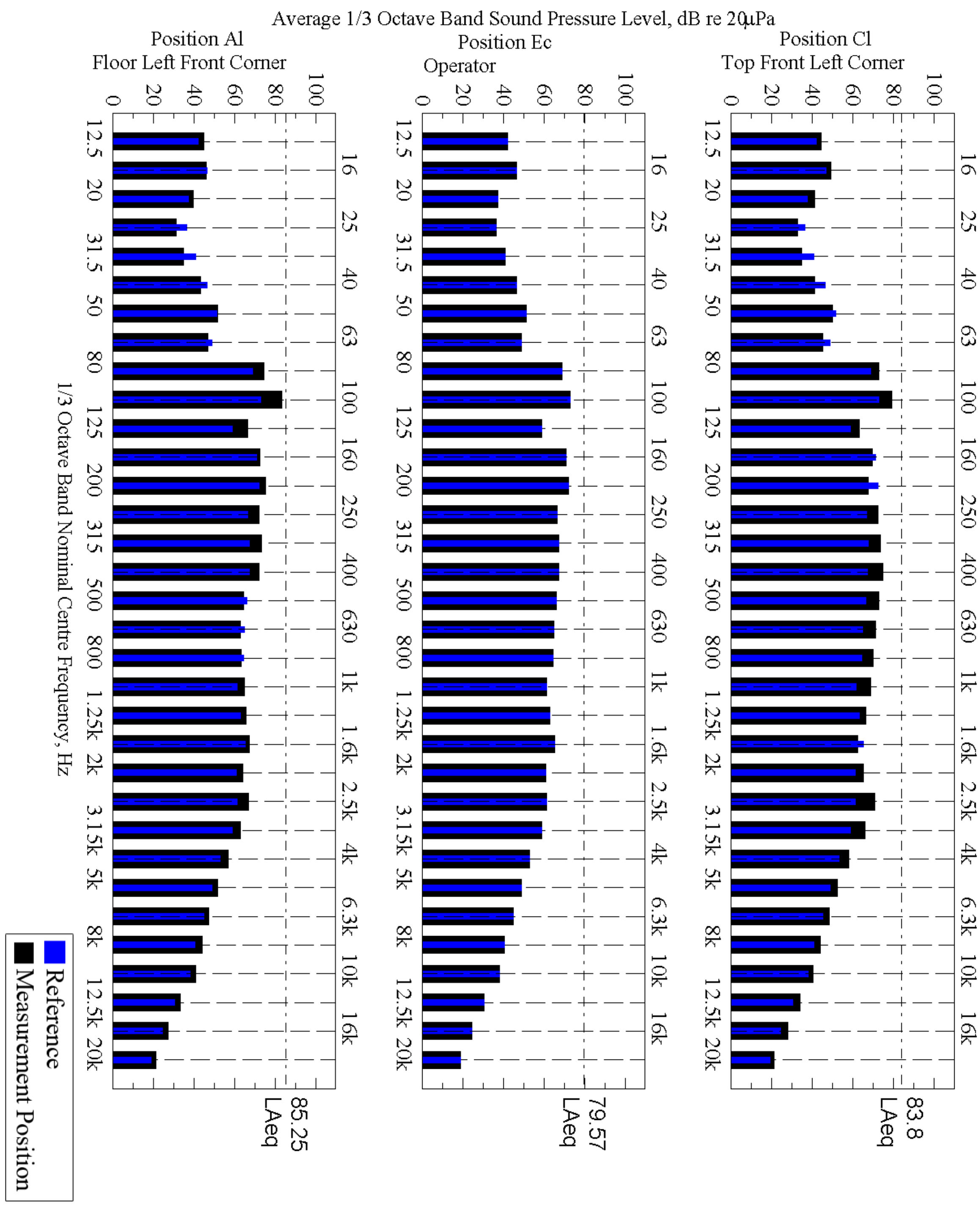

Figure 24 - Dynamic sound pressure level measurements run 3 A

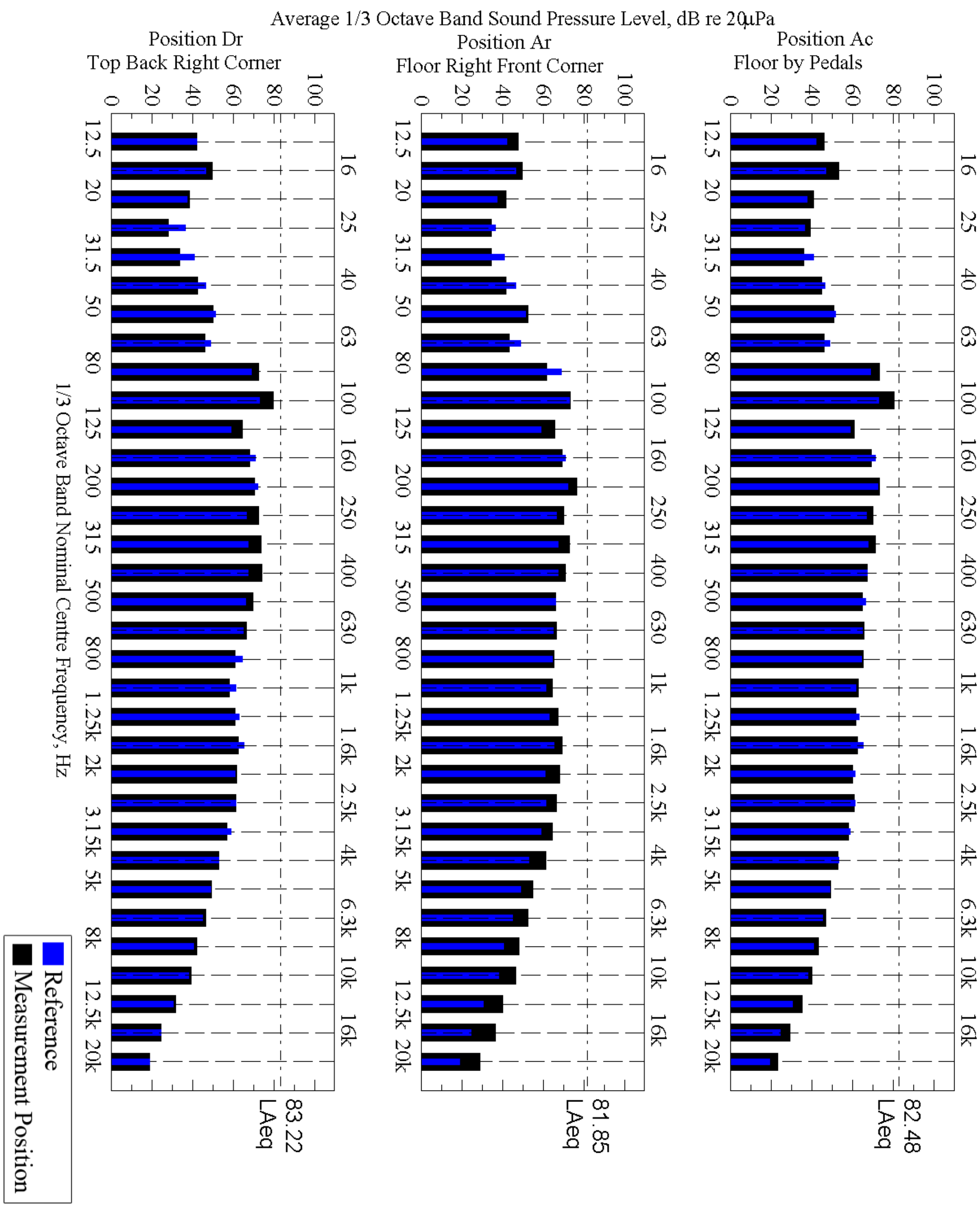

Figure 25 - Dynamic sound pressure level measurements run 3 B

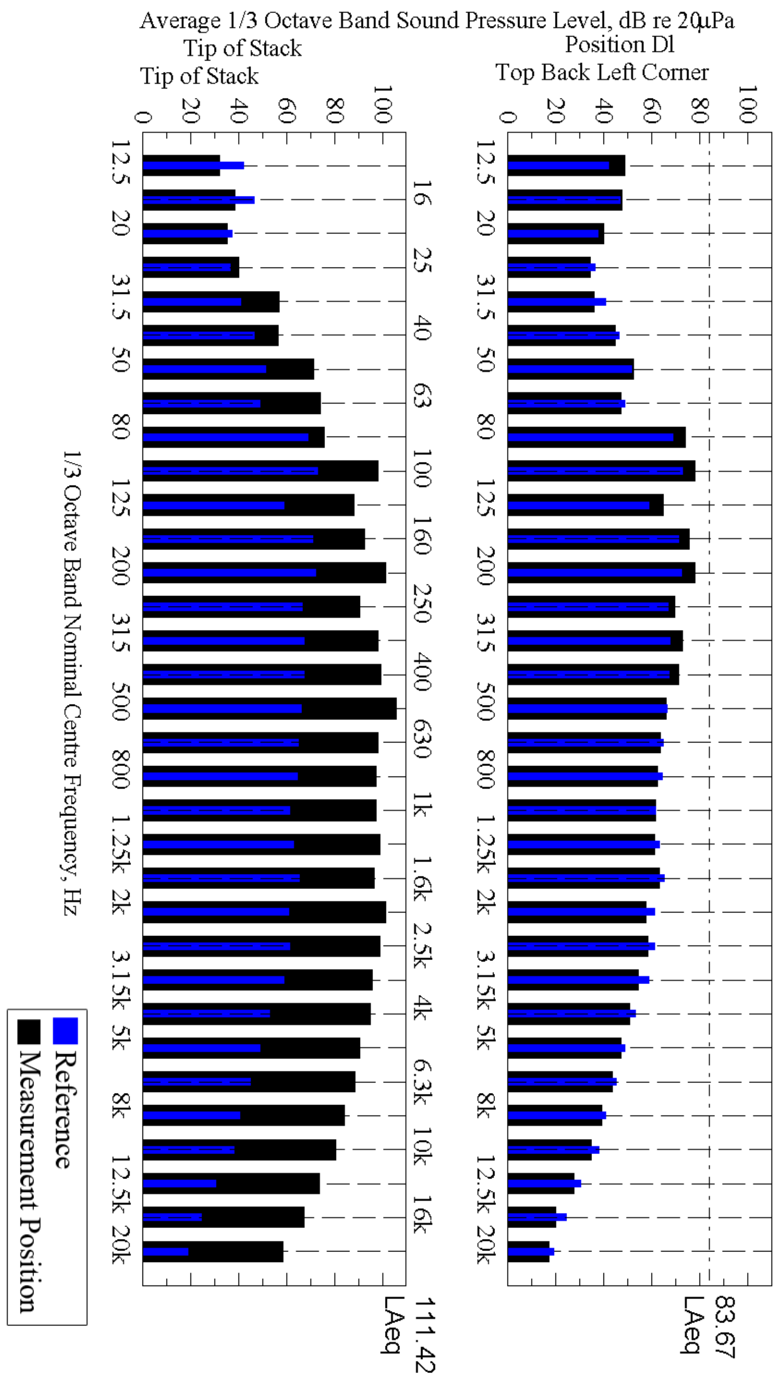

Figure 26 - Dynamic sound pressure level measurements run 3 C

A.3 Static Sound Level Measurements

The final measurements were made primarily to gain more information about the noise generated by the heating and cooling systems in the tractor cab. Three measurements were made in each position and the averaged results are shown in the following figures. For each position the measurements were within 3 dBA of each other indicating good agreement. In addition to sound level measurements, vibration measurements were also done and are summarized in Appendix B.

Measurement conditions for the final measurements can be found in TABLE V. The reference position for these measurements is the operator position and can be seen in Figure 27.

TABLE V – HVAC MEASUREMENTS

Date/Time	November 7th, 2010	8:30 to 11:00 am
Location	Buhler Versatile Plant	1260 Clarence Avenue, Winnipeg, MB
Tractor	Buhler Versatile model 305	
Engine Speed	1950 RPM	
Tractor Speed	0	
Load	0	
Equipment	Bruel & Kjaer 2250 sound level meter	
Ambient Air Temp.	10°C	
Averaging Time	20 seconds	

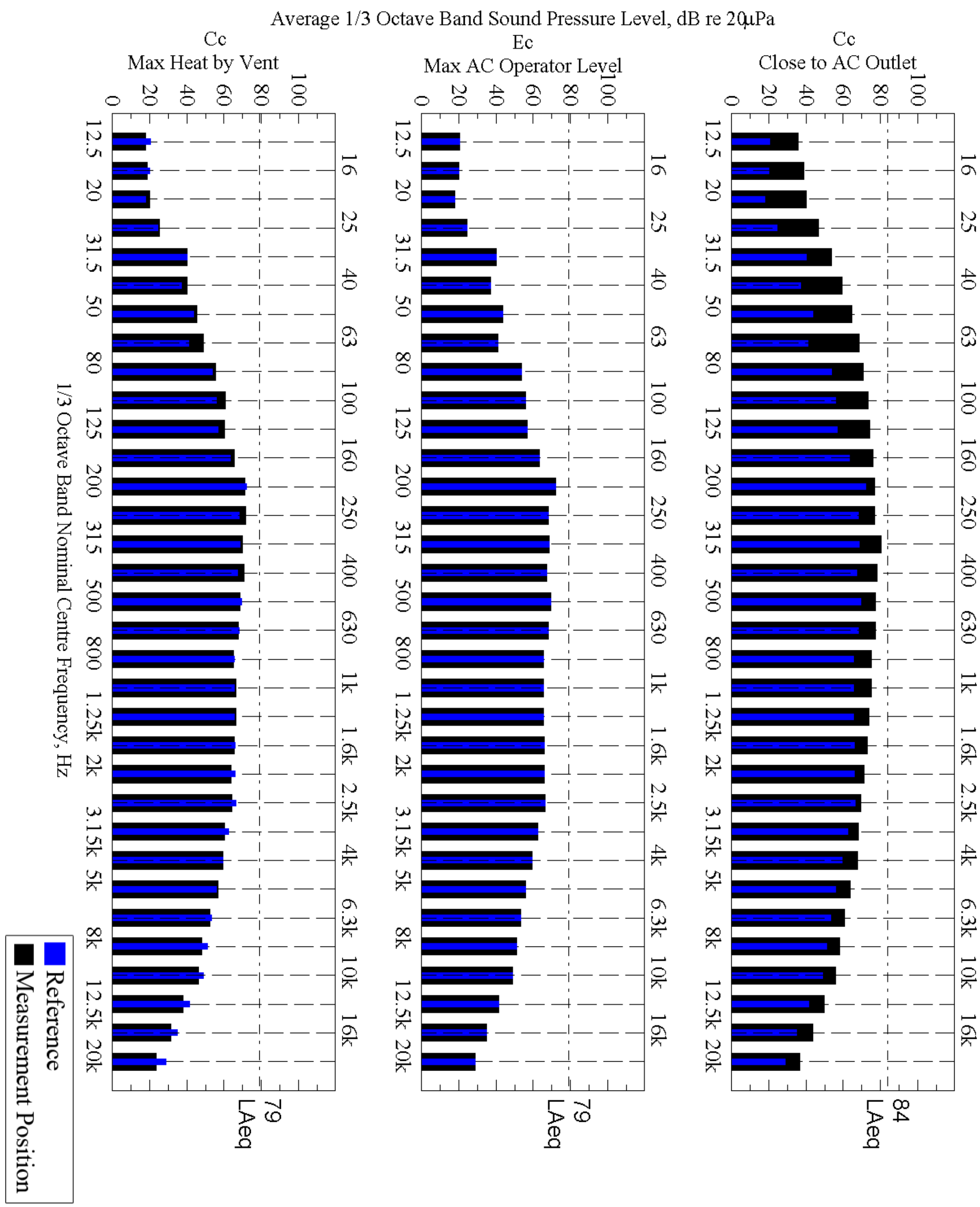

Figure 27 - Static sound pressure level measurements A

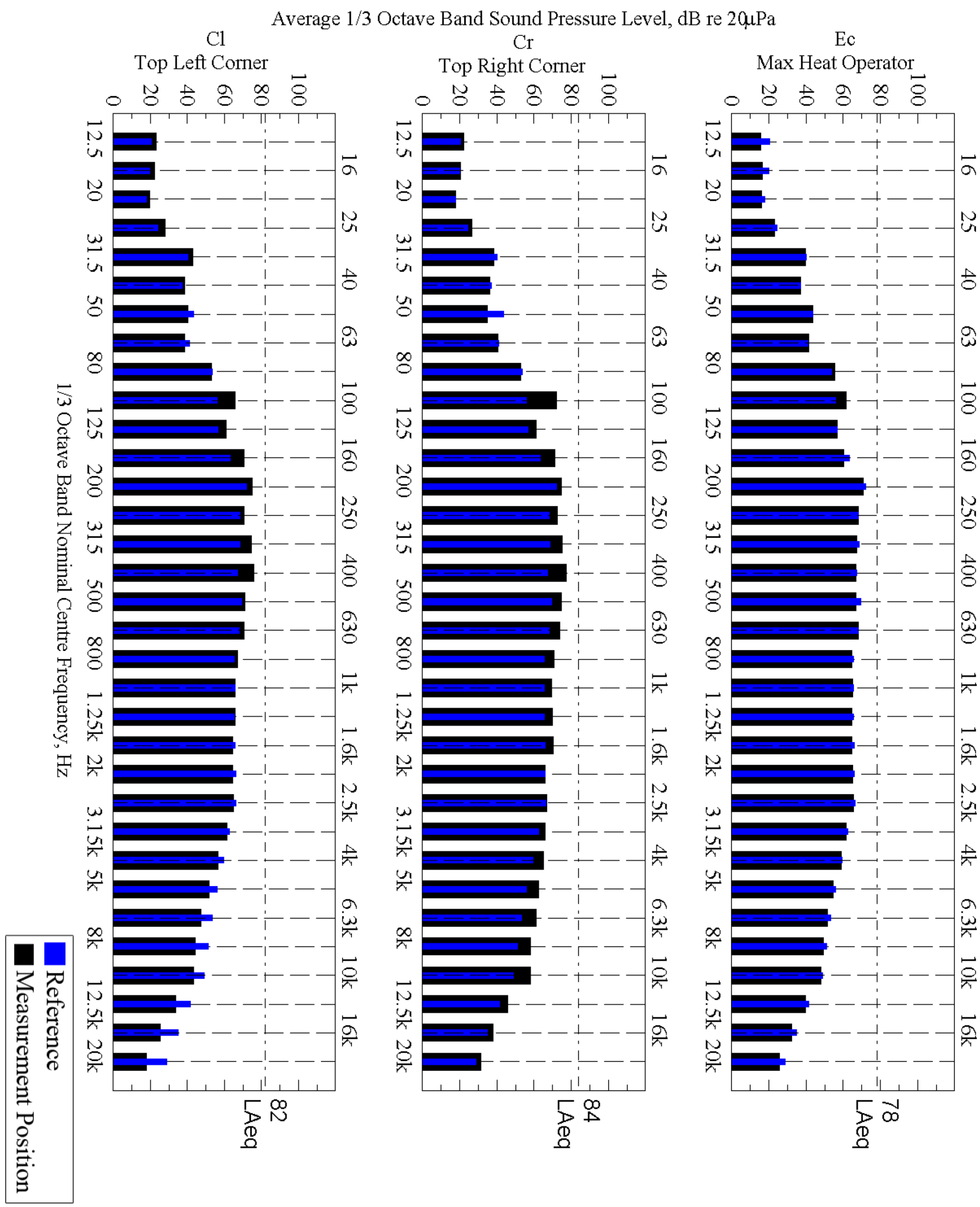

Figure 28 - Static sound pressure level measurements B

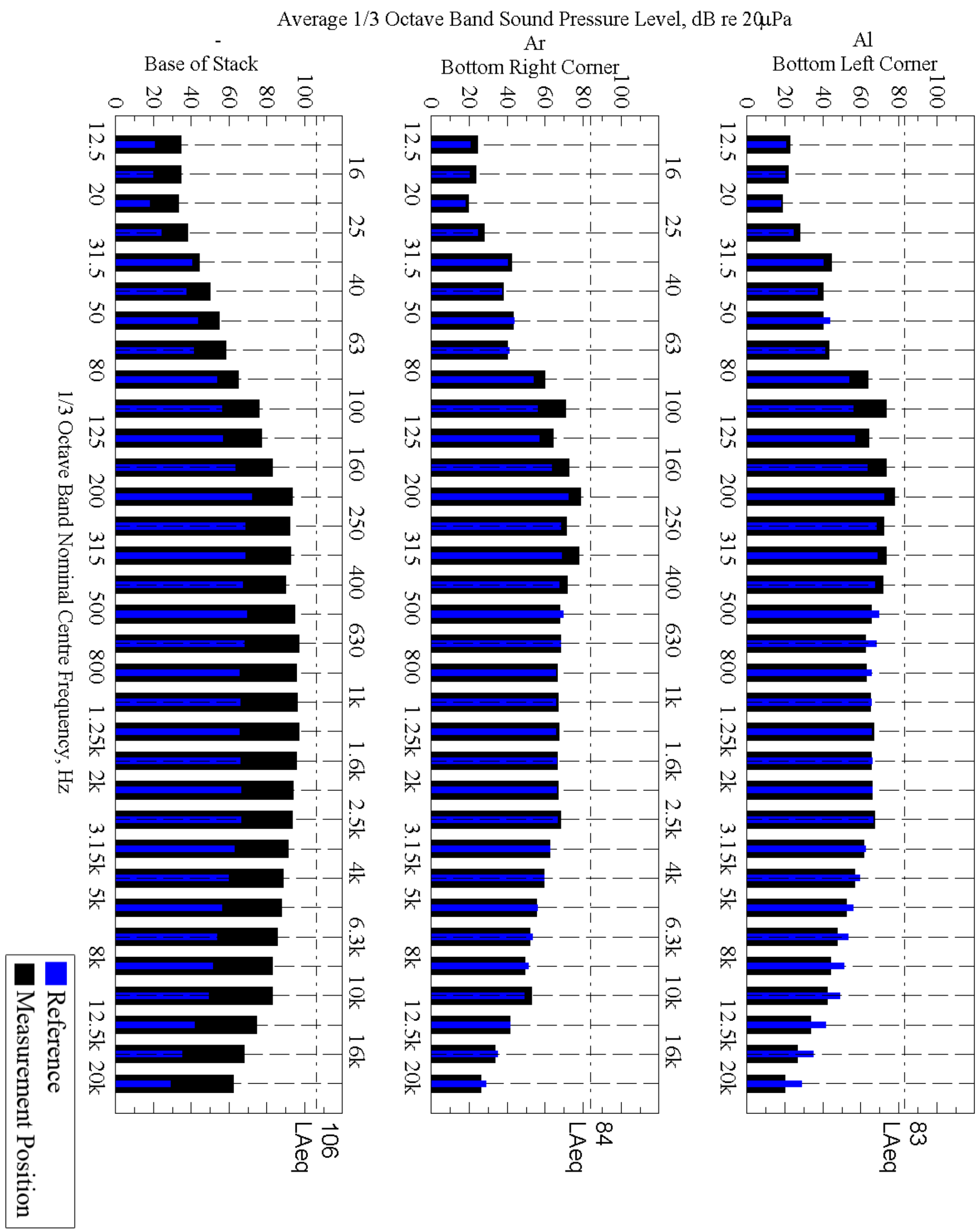

Figure 29 - Static sound pressure level measurements C

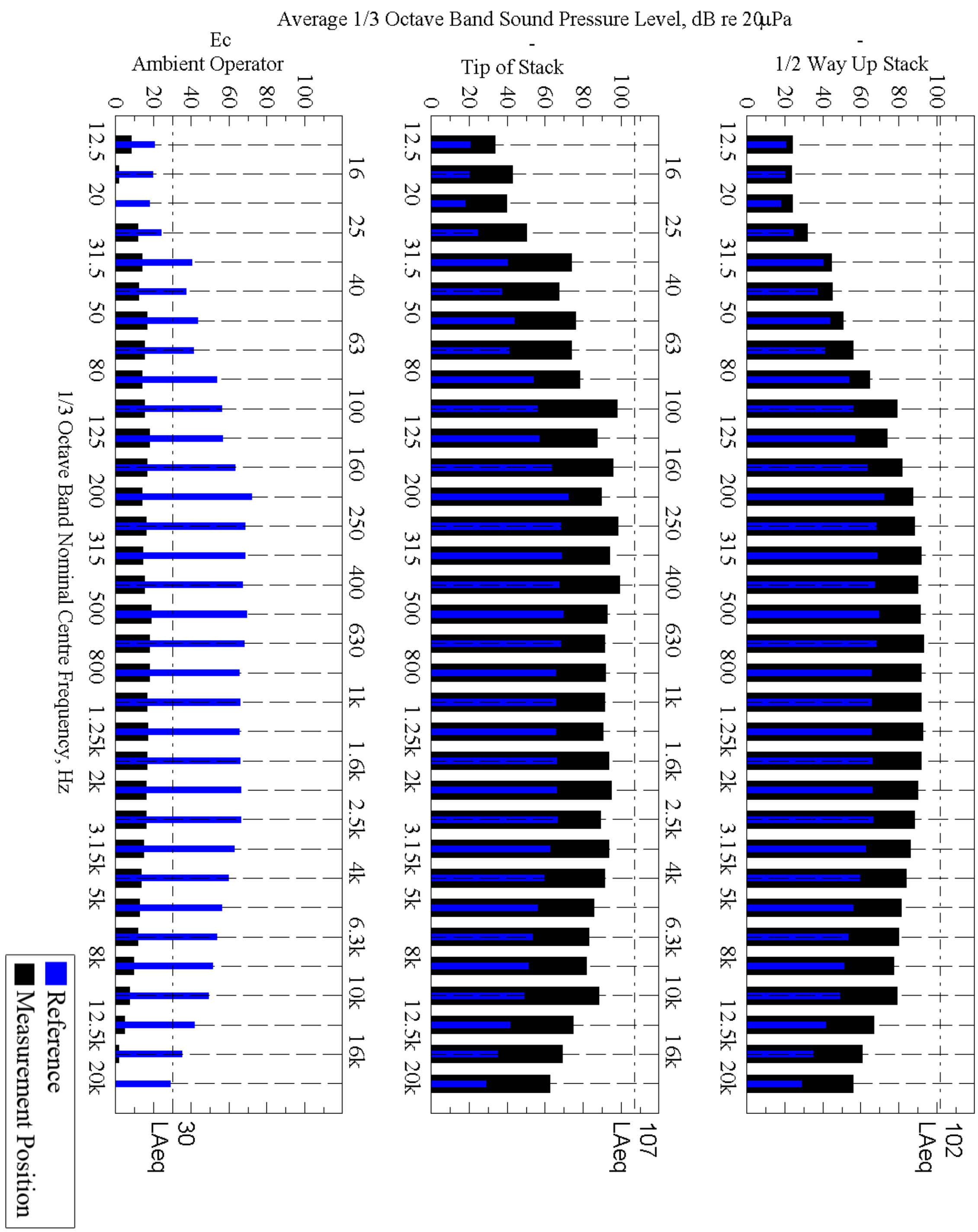

Figure 30 - Static sound pressure level measurements D

Appendix B

Noise is created by the vibration of a surface. One way to confirm an object as a noise source is to compare the frequency of noise measured to the frequency at which the object is vibrating. Team Pindrop utilized this approach when tracing the noise back to its source and finding possible noise transmission paths. The noise measurements were first taken in order to find the 1/3 centered octave bands which had the highest sound pressure levels. This helped to find the range of frequencies which had the highest noise levels. Any one third octave band centered frequencies that had a distinguishably high sound level most likely represented a pure tone in the measurements. These pure tones are what should be targeted for noise reduction. Next a set of acceleration measurements was taken on different components of the tractor. In all thirty three different measurements were taken. In order to determine the main frequency that the component is vibrating at the Acceleration vs. Time measurement is transformed into an Acceleration vs. Frequency plot using an FFT. The main frequency that each component is vibrating at can then be matched to the frequencies that had the loudest noise levels. By matching the frequencies the source of the noise can be determined. It will also show the transmission paths, as they will also be vibrating at the same frequencies as the frequencies found in the noise measurements.

A summary of the measurement conditions can be found in TABLE V. A tri-axial accelerometer was used to take these measurements. The tri-axial accelerometer was capable of measuring the acceleration in all directions. In all of the measurements shown in Appendix B, except for measurements taken on the frame, the blue line, which representing the x-axis on the plots is perpendicular to the surface that the accelerometer is placed on. In measurements where this was not the case has the direction of the x-axis labelled in the title of the plot. The x-axis, perpendicular to the plate is typically the direction that experiences the highest vibration measurements. In some measurements only the x-axis was measured. This was done because of the equipment restrictions that did not allow for cables to reach the amplifiers for all three channels. Also, different measurements required different levels of amplification in order to make the data as clear and accurate as possible. This meant that the magnitude of the vibrations needed to be adjusted for the level of amplification used. In all figures used in the main body of the report this was done, however, because it is a very tedious task to make all the required adjustments, this was not done in this Appendix. The frequency at which the components being tested vibrate at was the main concern for doing the vibration testing, rather than the magnitudes at which they vibrate. Therefore adjusting for proper amplification was not necessary and would not have provided anything extra to the data being analysed.

When viewing the following figures in this report there are a few things to observe. The frequency at which the object had its highest vibrations is listed on the right hand side of the graph. This is done for each axis that the vibration was measured in. This frequency generally coincides with the main frequency that the object vibrated at, either by forced or resonance vibrating conditions. Each measurement location has been listed in the title of the plot. Figure 50 thru Figure 52 show the modal analysis that was conducted on the safety shield that surrounds the muffler. This shroud was believed to be vibrating significantly. The modal analysis was conducted to calculate the resonance frequency of this shroud to see if it matched the peak frequencies heard in the cab. The resonance frequencies did not match what was expected and it was determined that it was the muffler itself that was creating the most noise, rather than the safety shield. Also, when viewing the figures, it can be noted that the majority of the components measured are vibrating at low frequencies, generally below 1000 Hz.

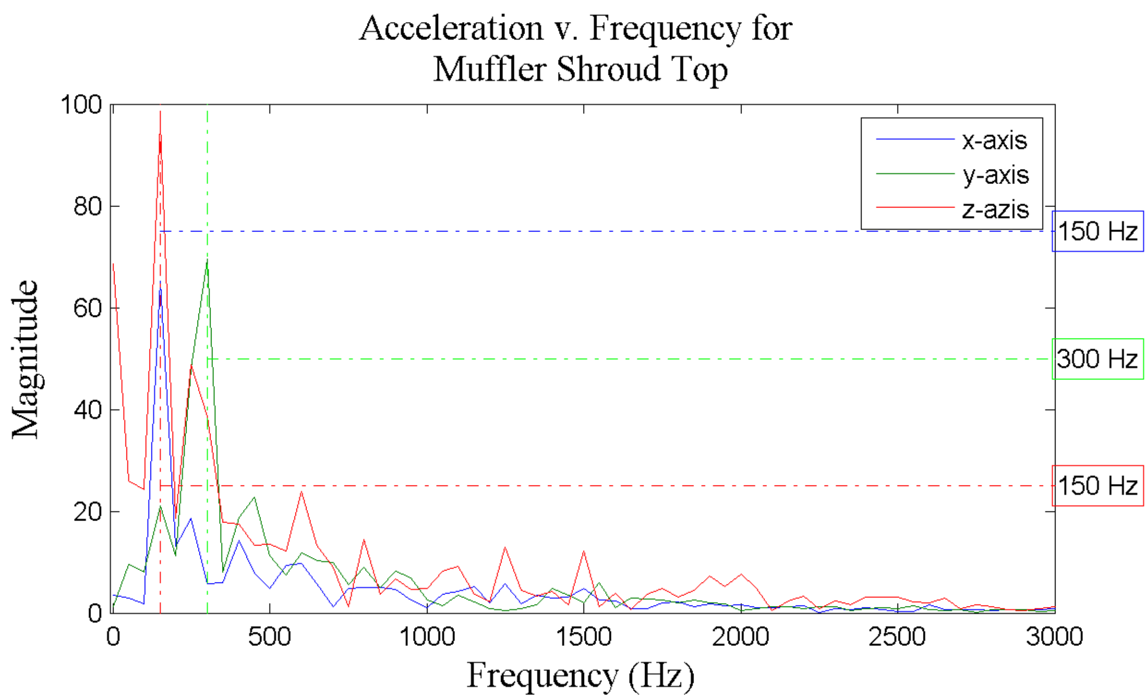

Figure 31 – Vibration measurement A

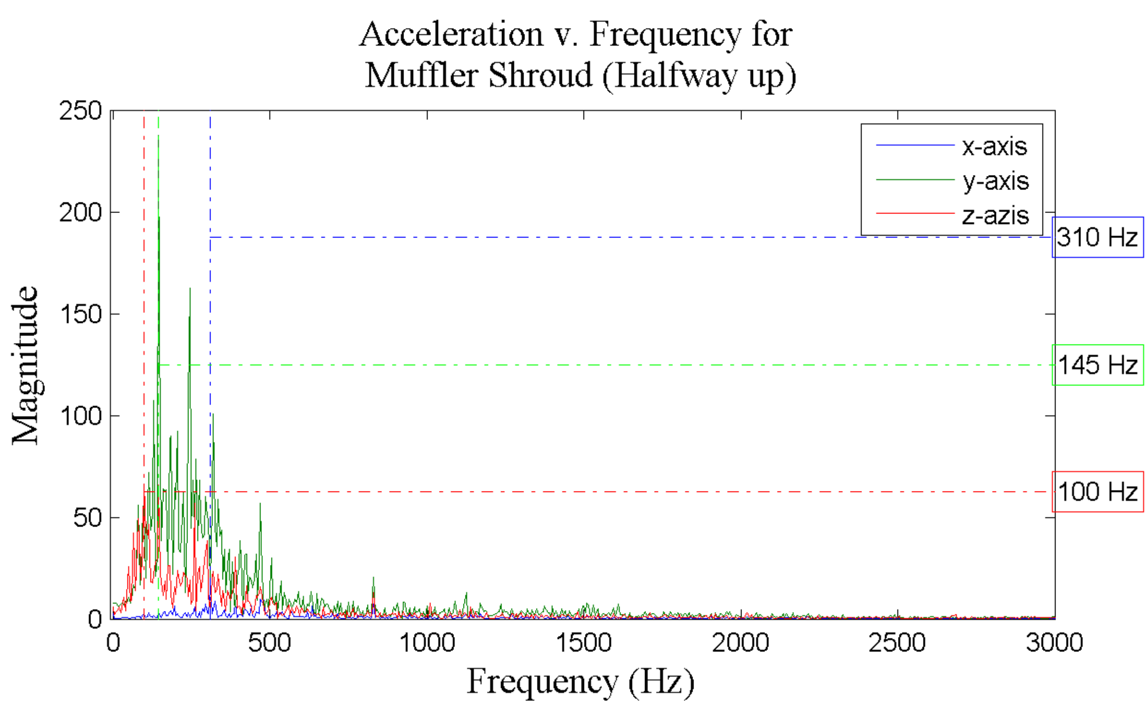

Figure 32 – Vibration measurement B

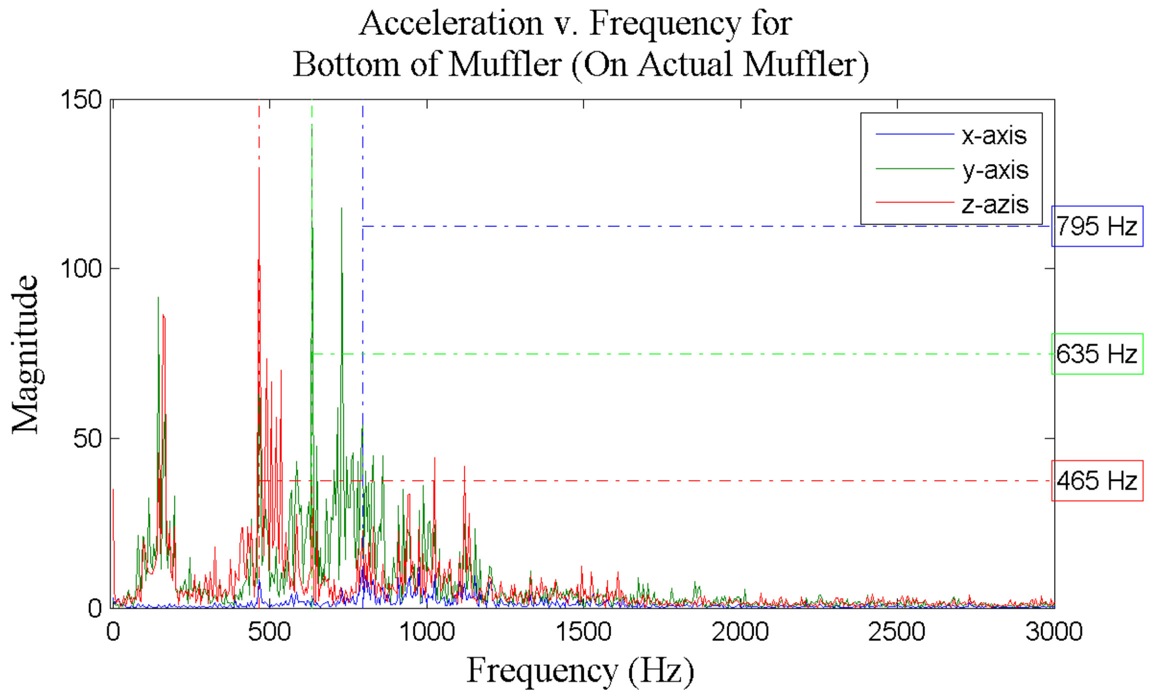

Figure 33 – Vibration measurement C

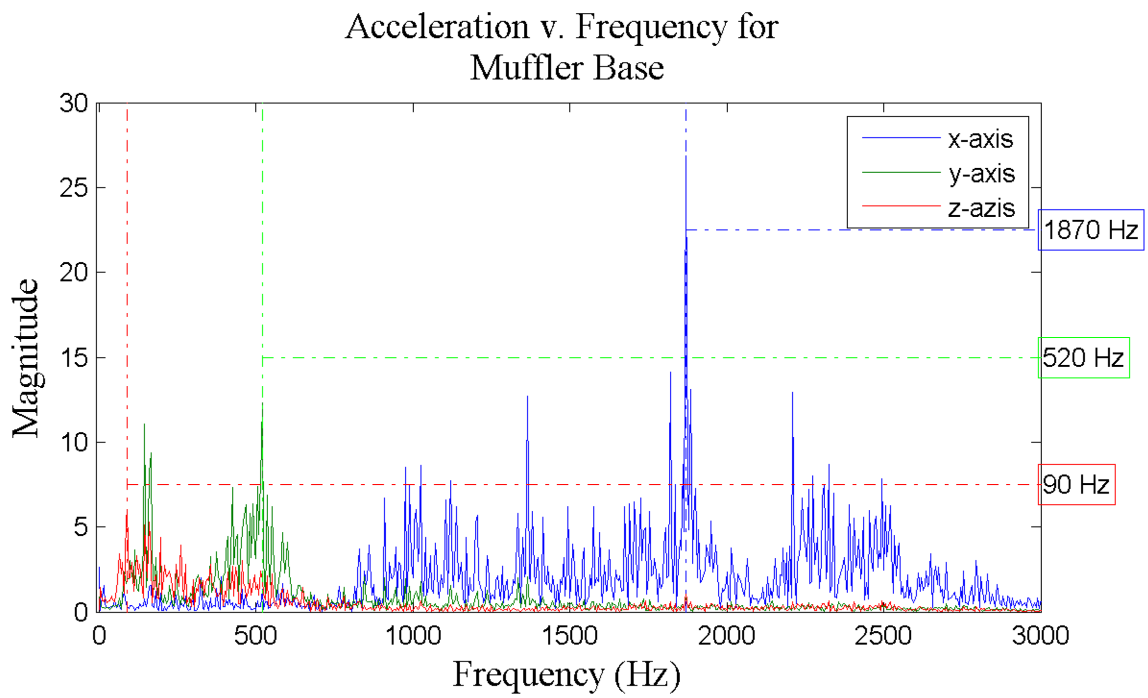

Figure 34 – Vibration measurement D

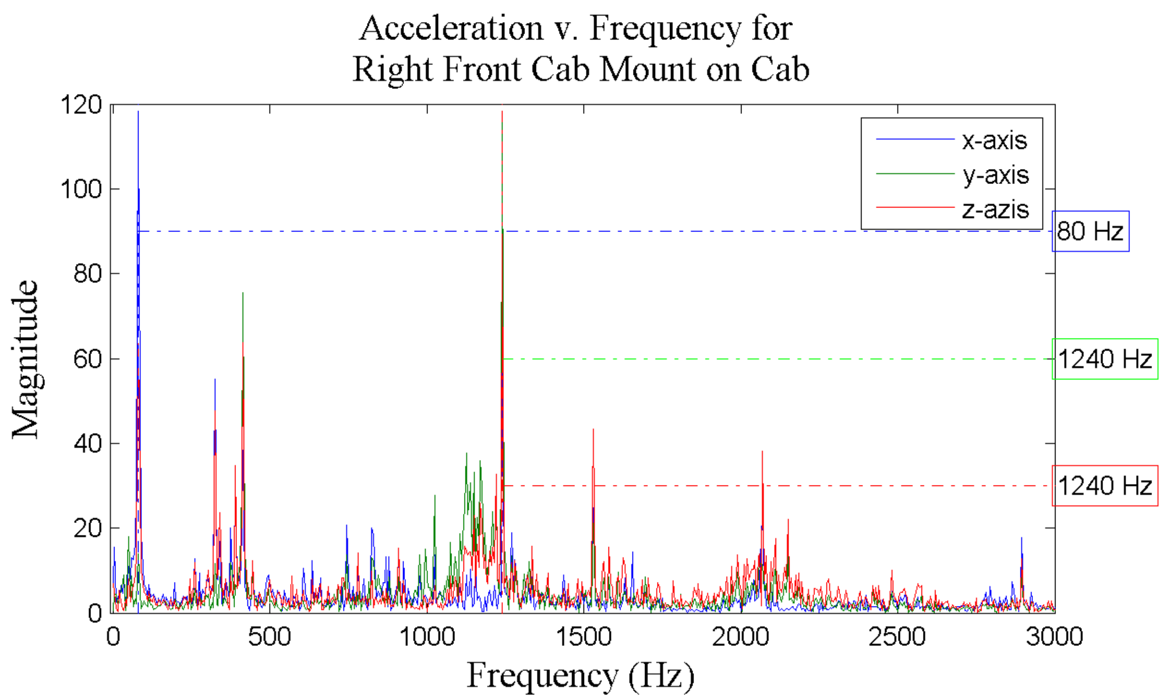

Figure 35 – Vibration measurement E

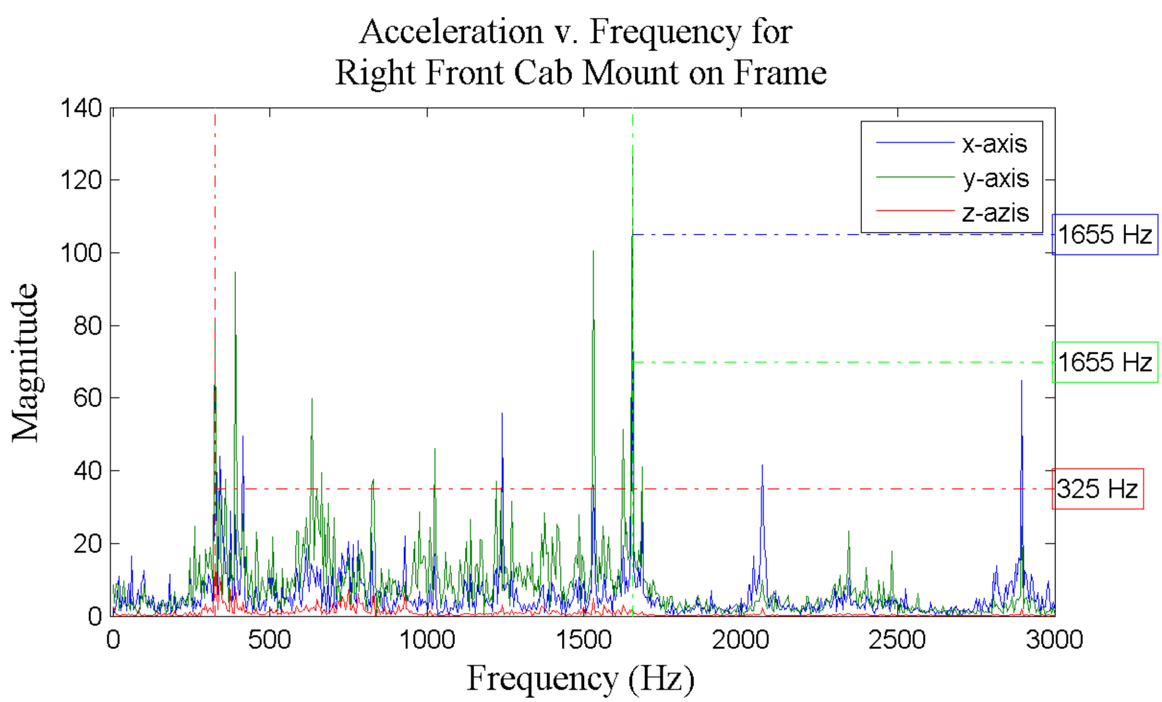

Figure 36 – Vibration measurement F

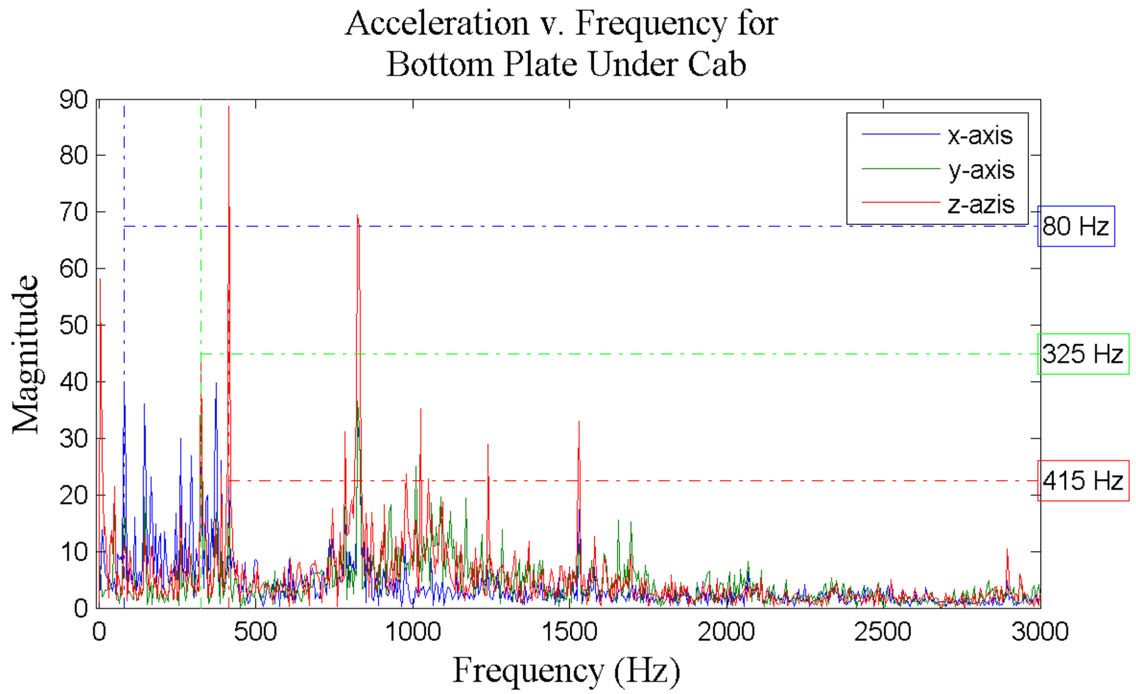

Figure 37 – Vibration measurement G

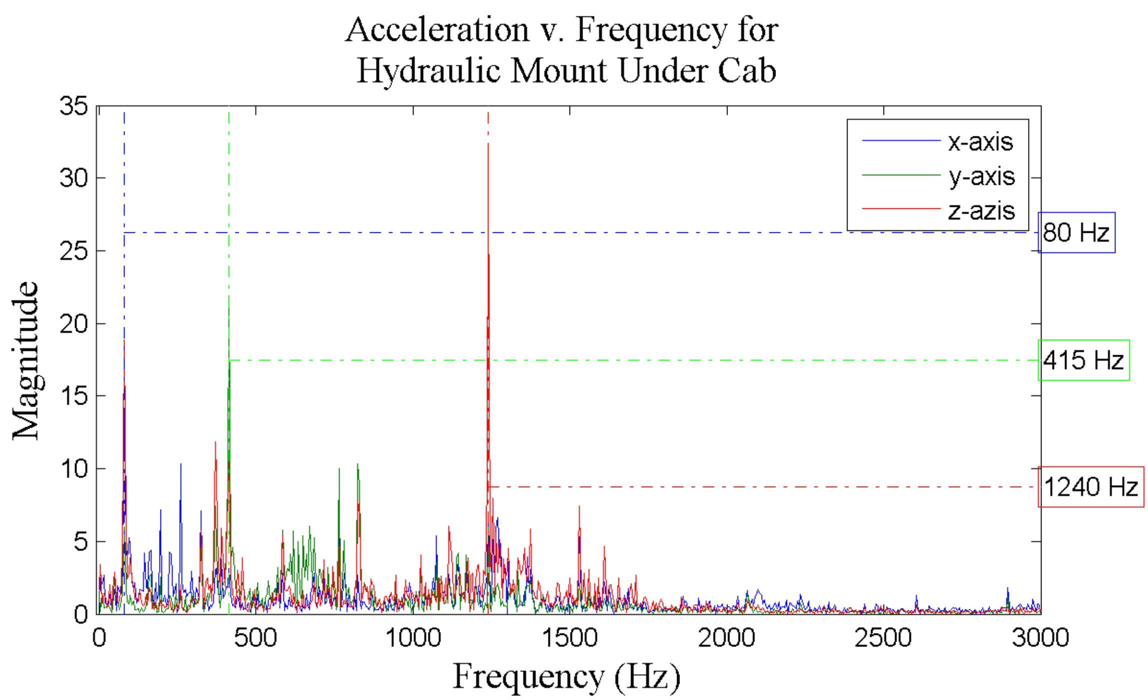

Figure 38 – Vibration measurement H

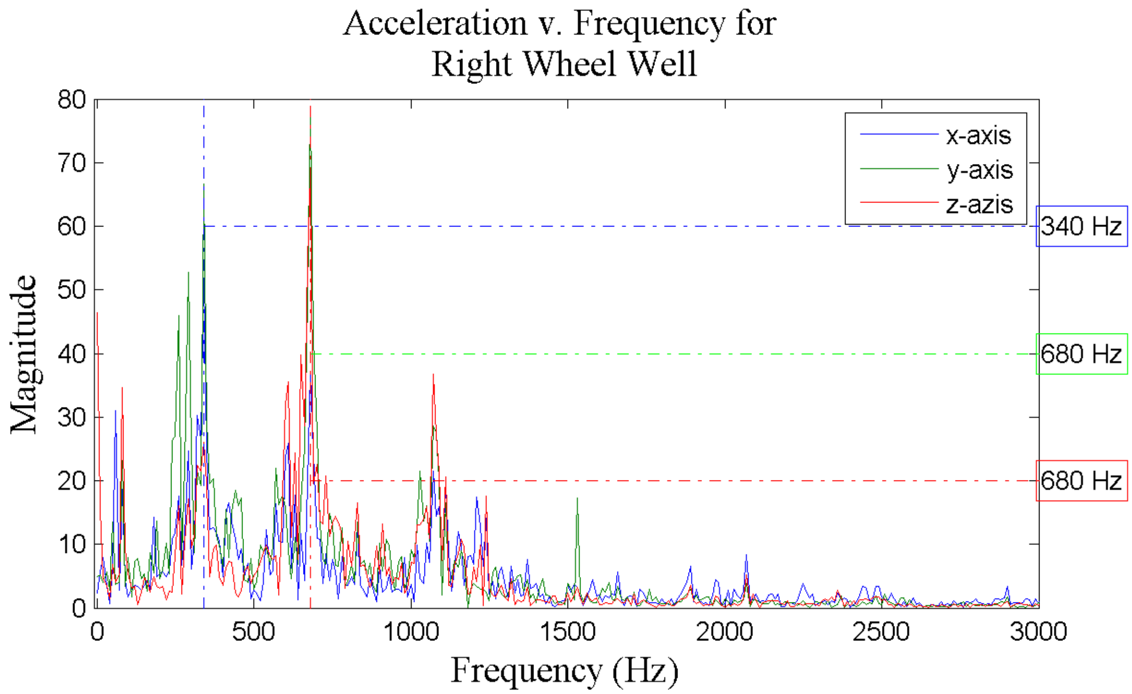

Figure 39 – Vibration measurement I

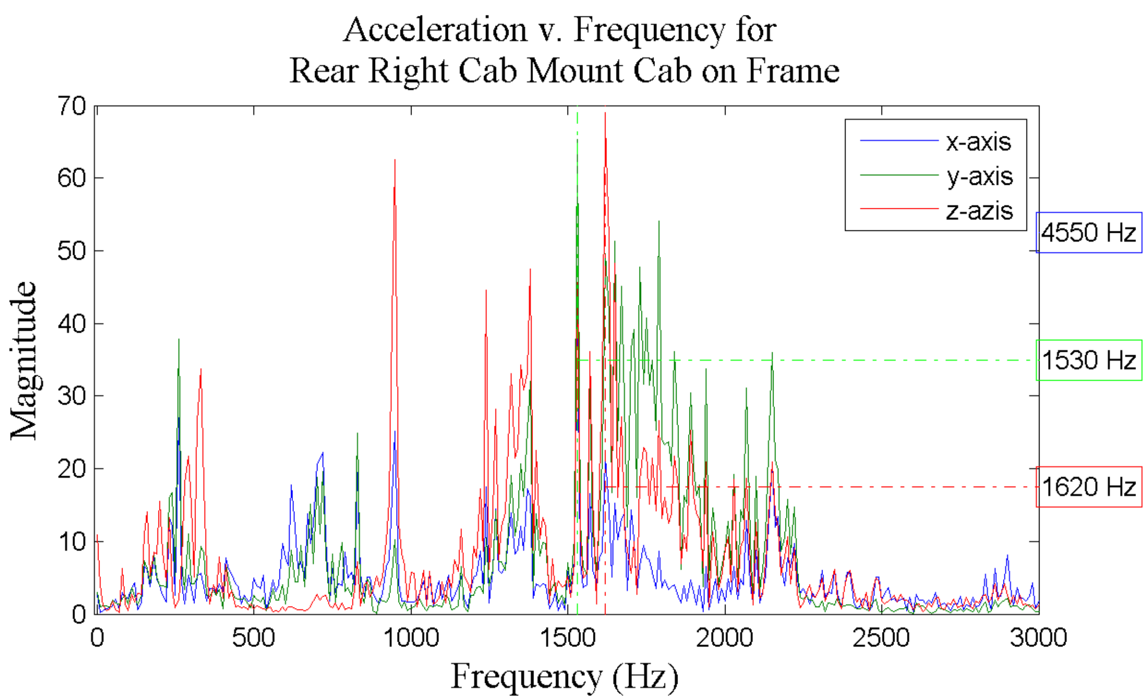

Figure 40 – Vibration measurement J

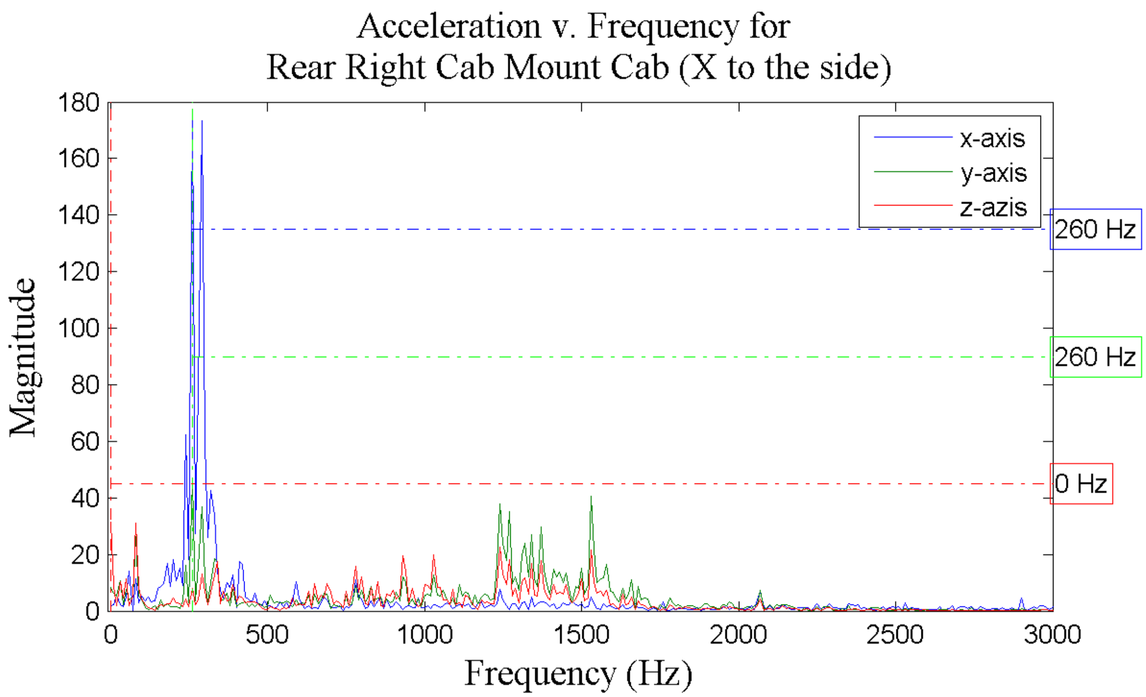

Figure 41 – Vibration measurement K

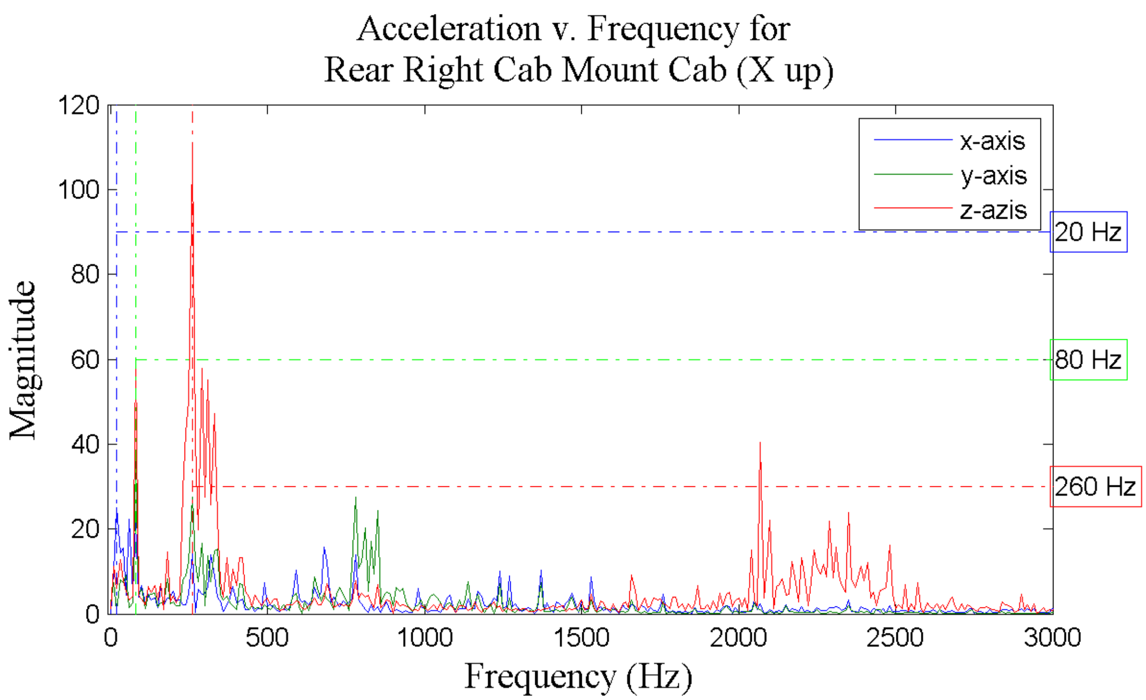

Figure 42 – Vibration measurement L

Acceleration v. Frequency for
Right Door

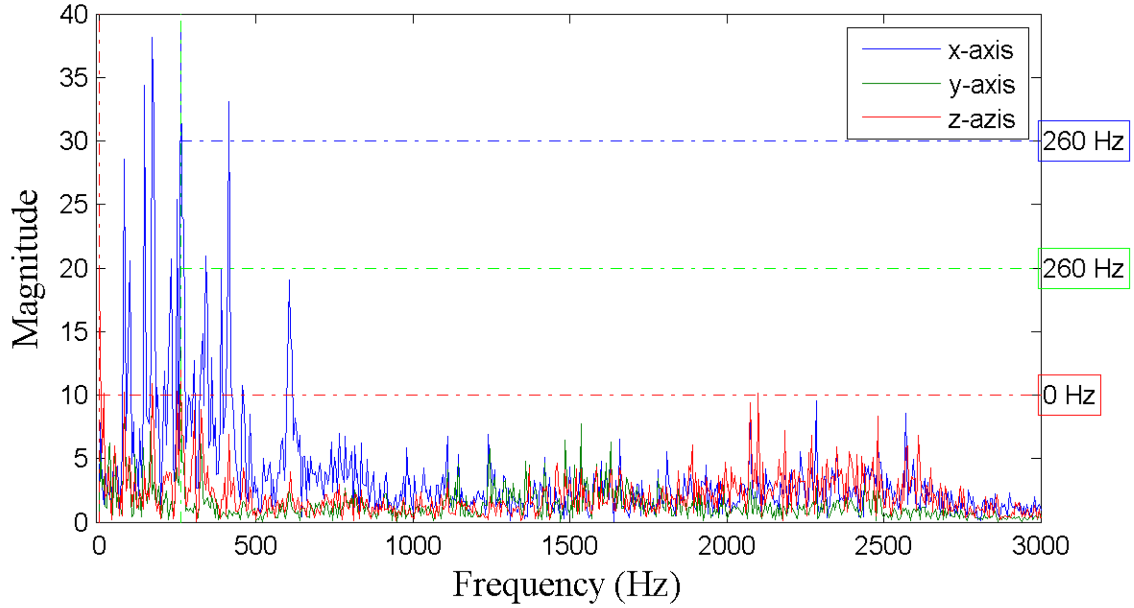

Figure 43 – Vibration measurement M

Acceleration v. Frequency for
Right Bottom Windshield

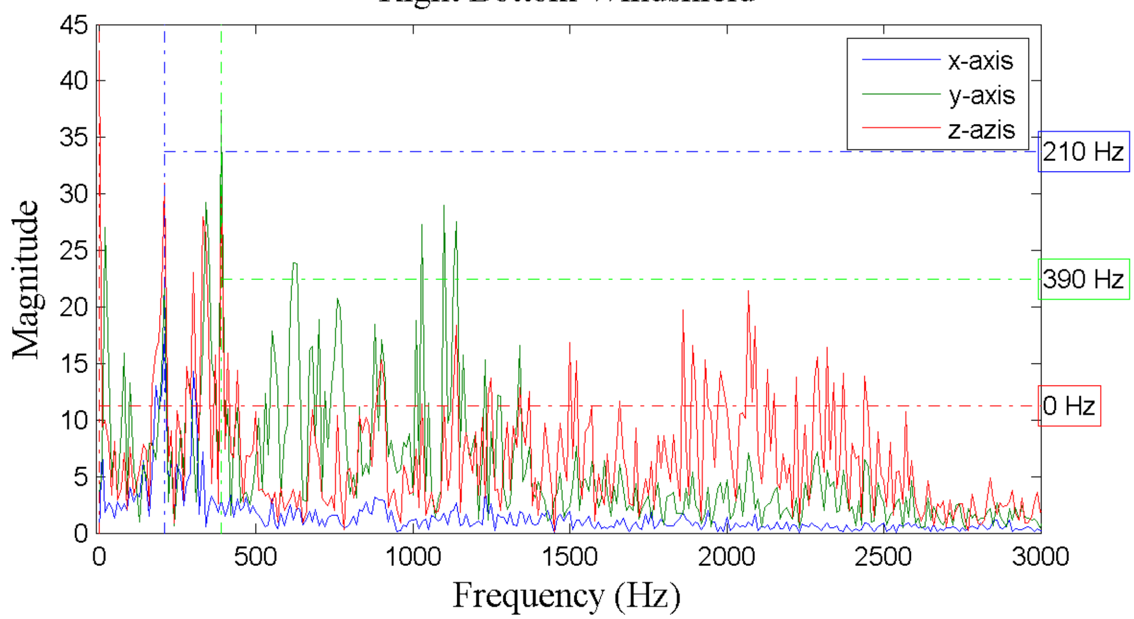

Figure 44 – Vibration measurement N

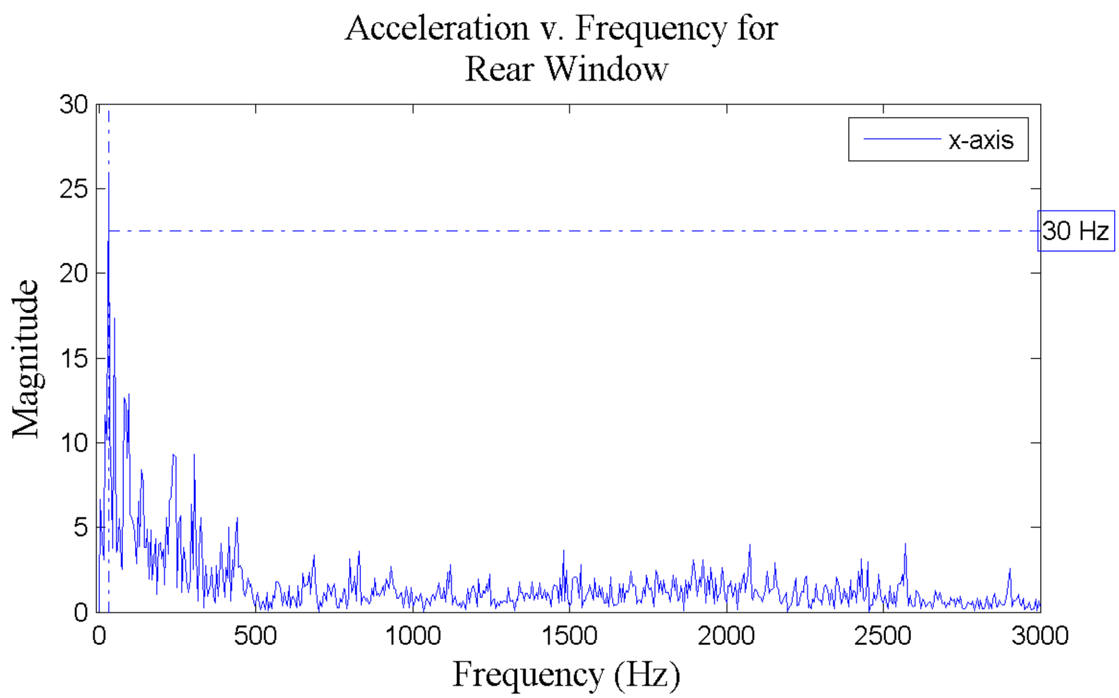

Figure 45 – Vibration measurement O

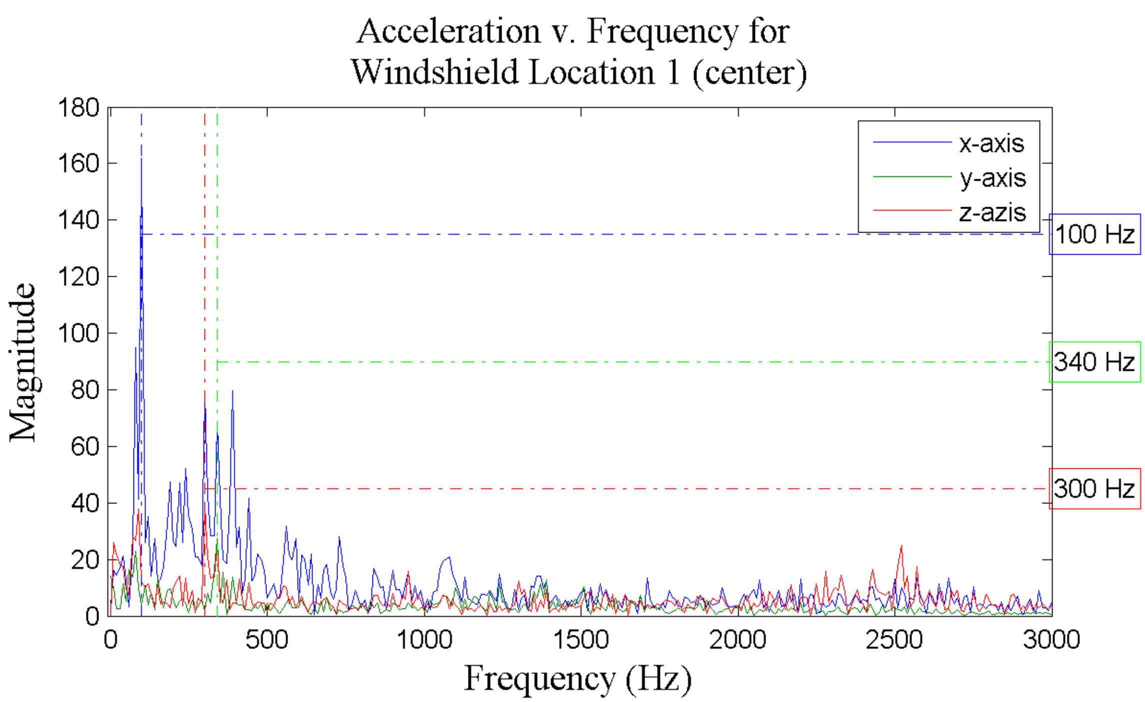

Figure 46 – Vibration measurement P

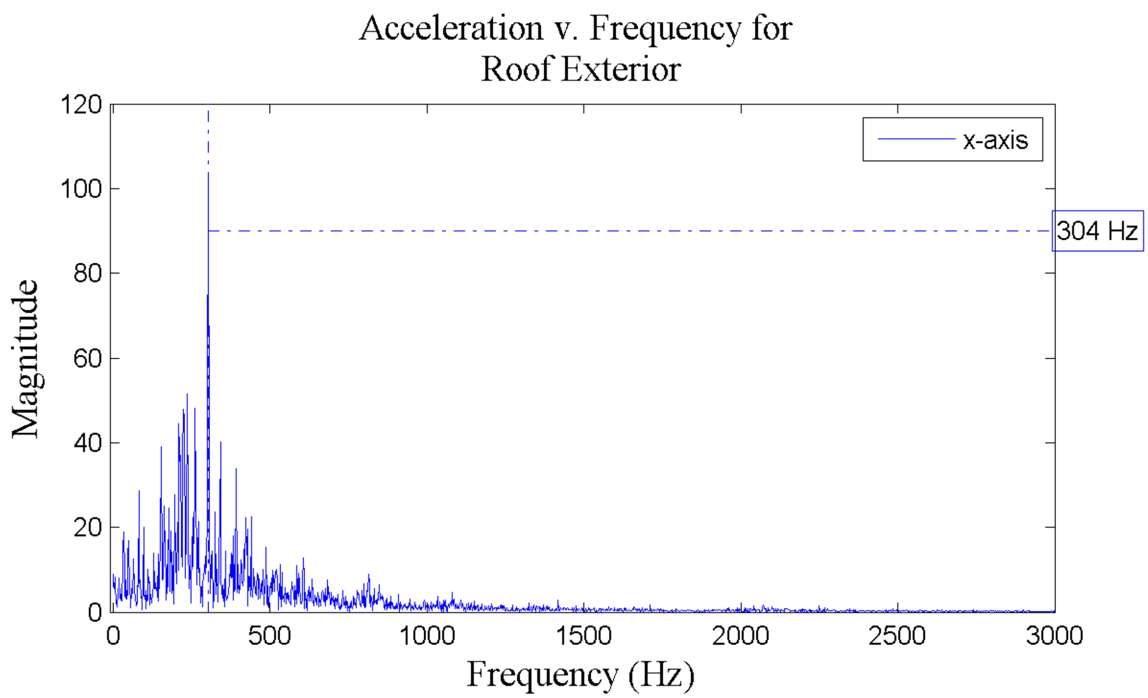

Figure 47 – Vibration measurement Q

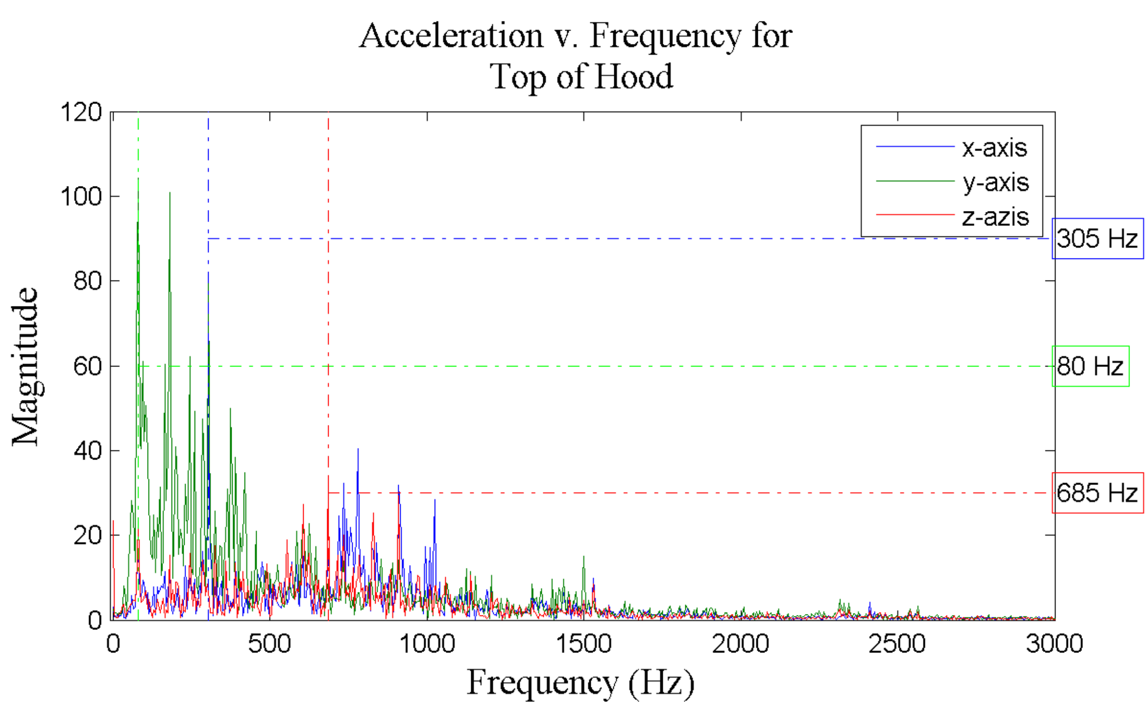

Figure 48 – Vibration measurement R

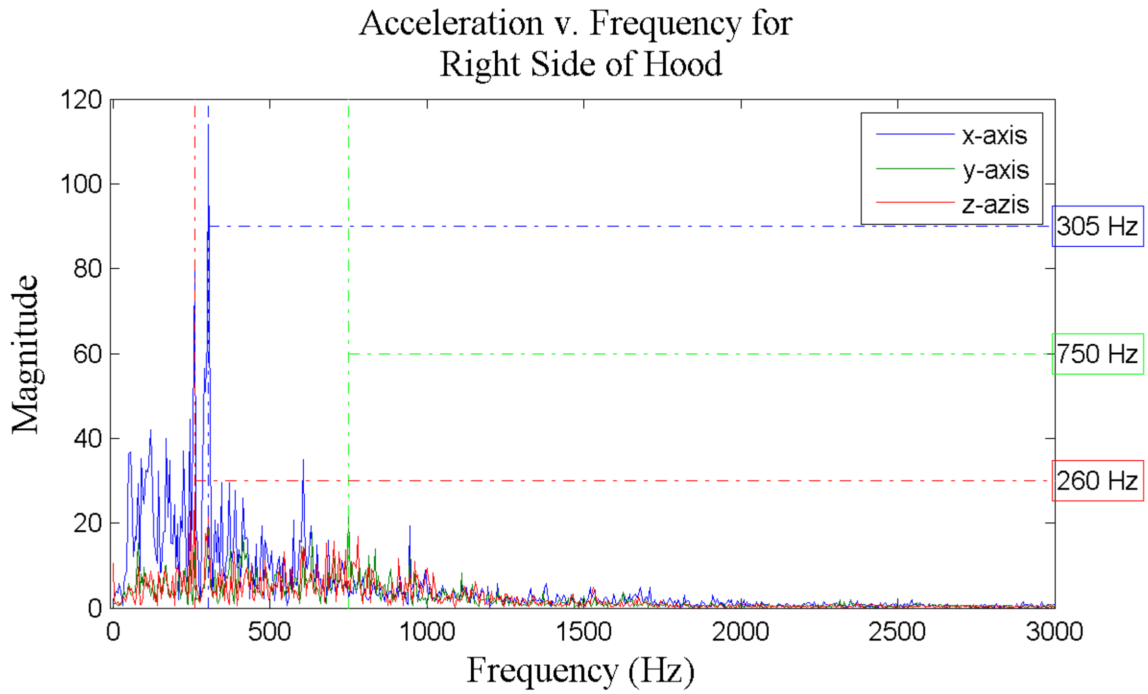

Figure 49 – Vibration measurement S

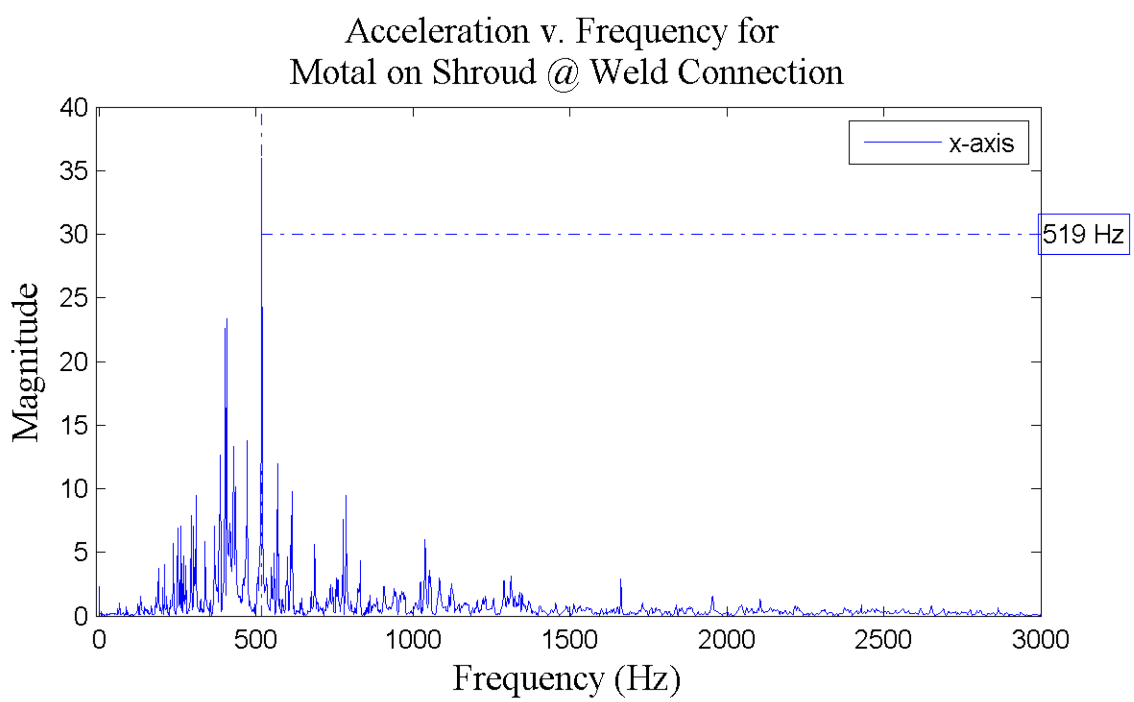

Figure 50 – Vibration measurement T

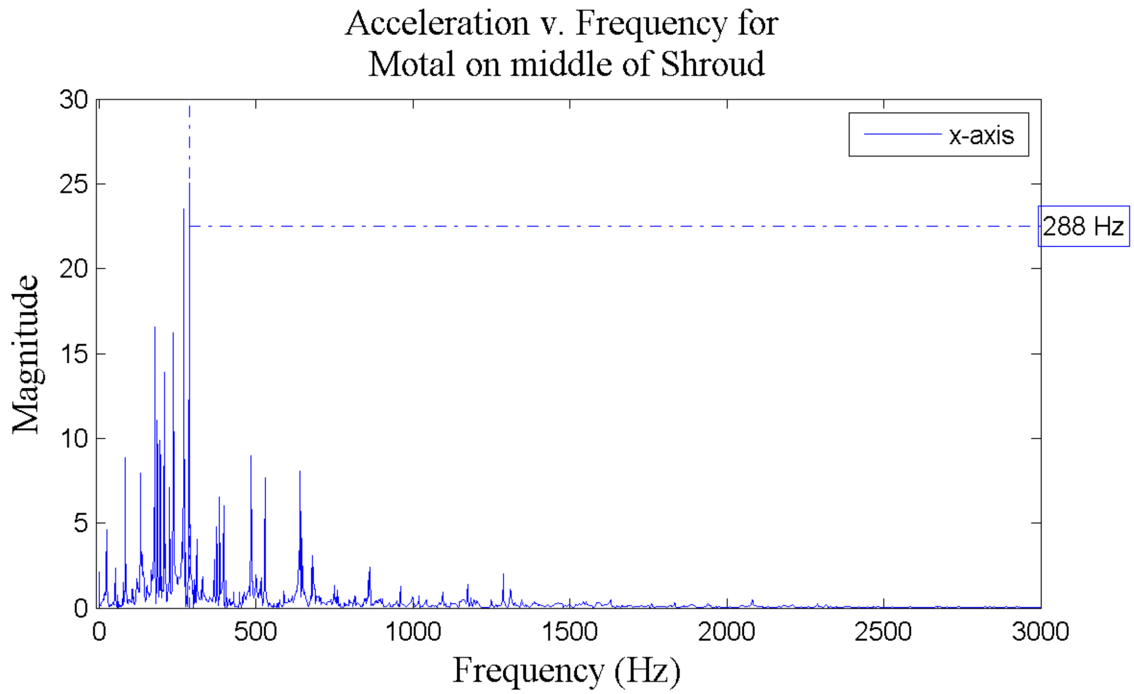

Figure 51 – Vibration measurement U

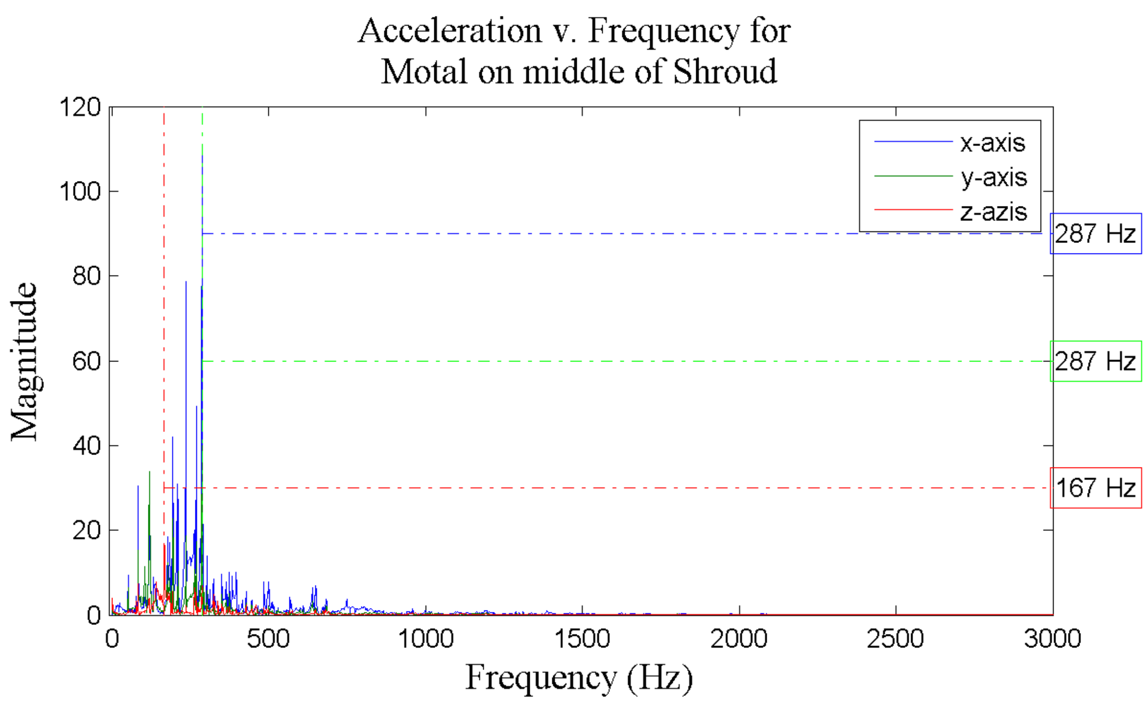

Figure 52 – Vibration measurement V

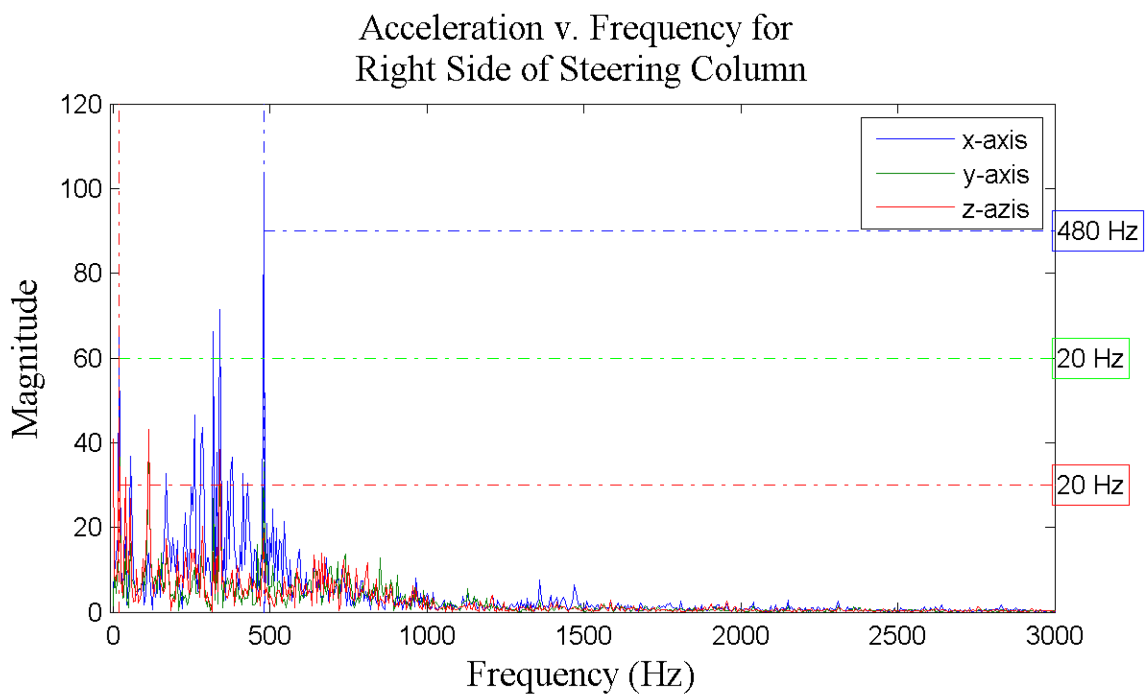

Figure 53 – Vibration measurement W

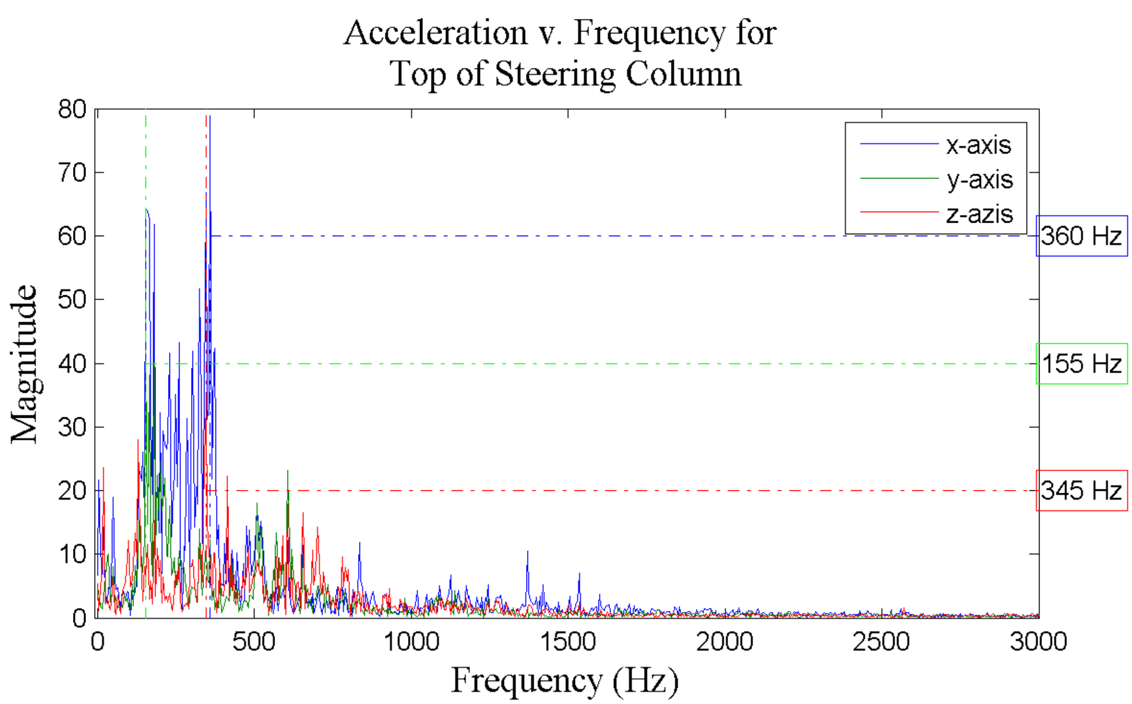

Figure 54 – Vibration measurement X

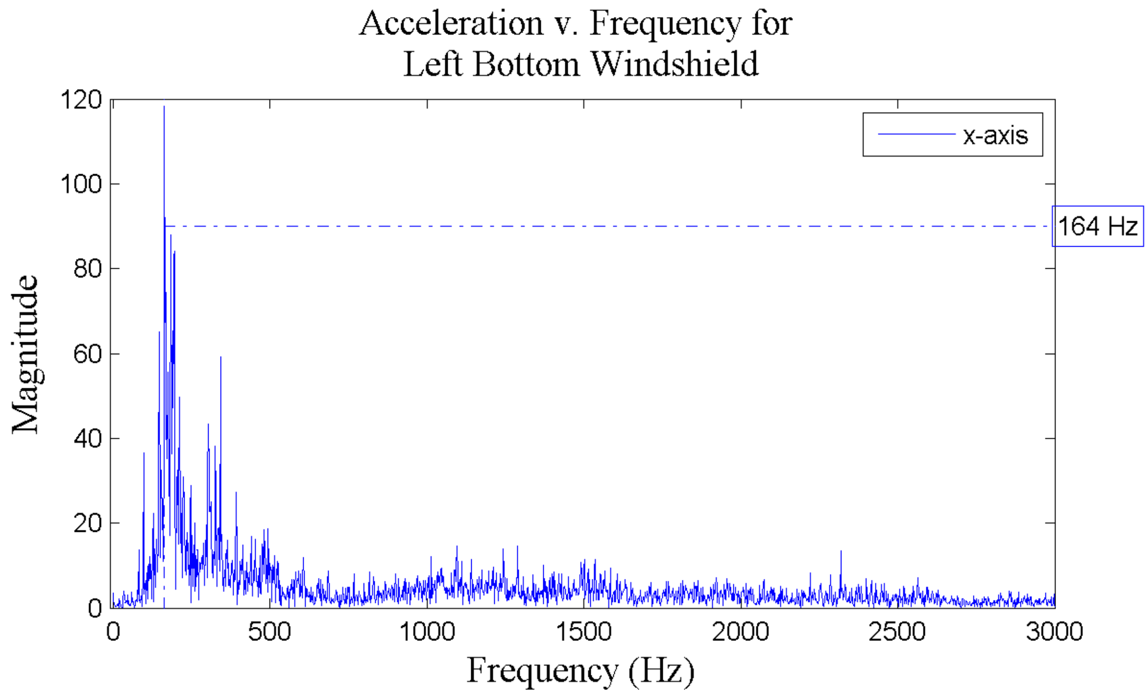

Figure 55 – Vibration measurement Y

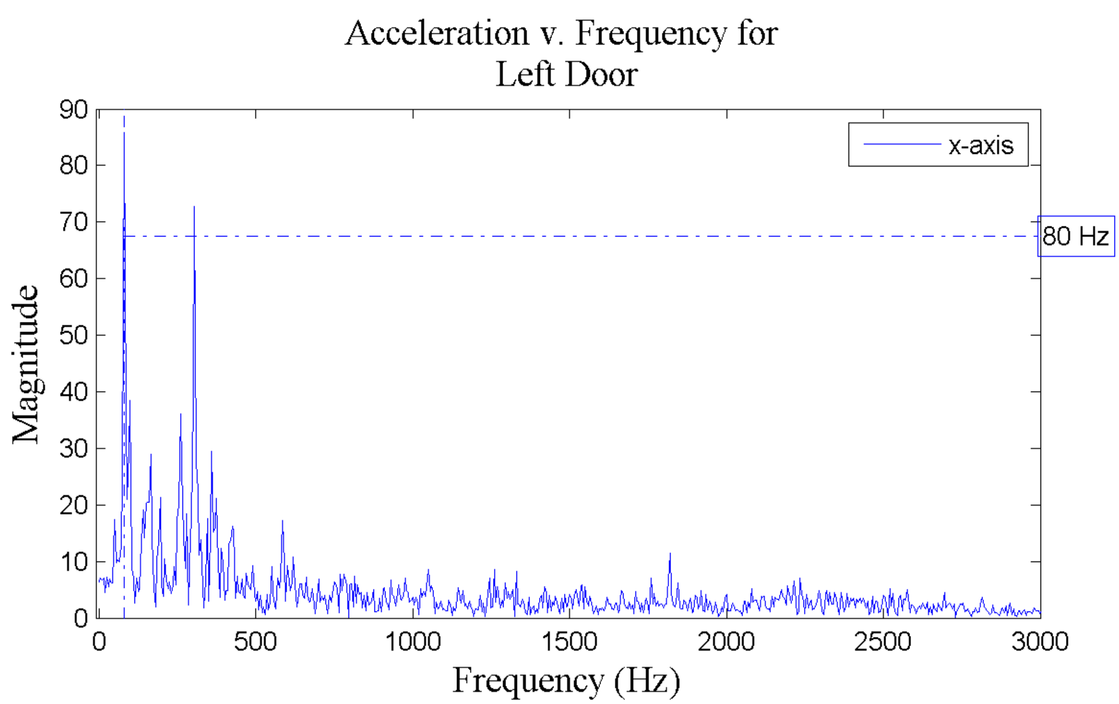

Figure 56 – Vibration measurement Z

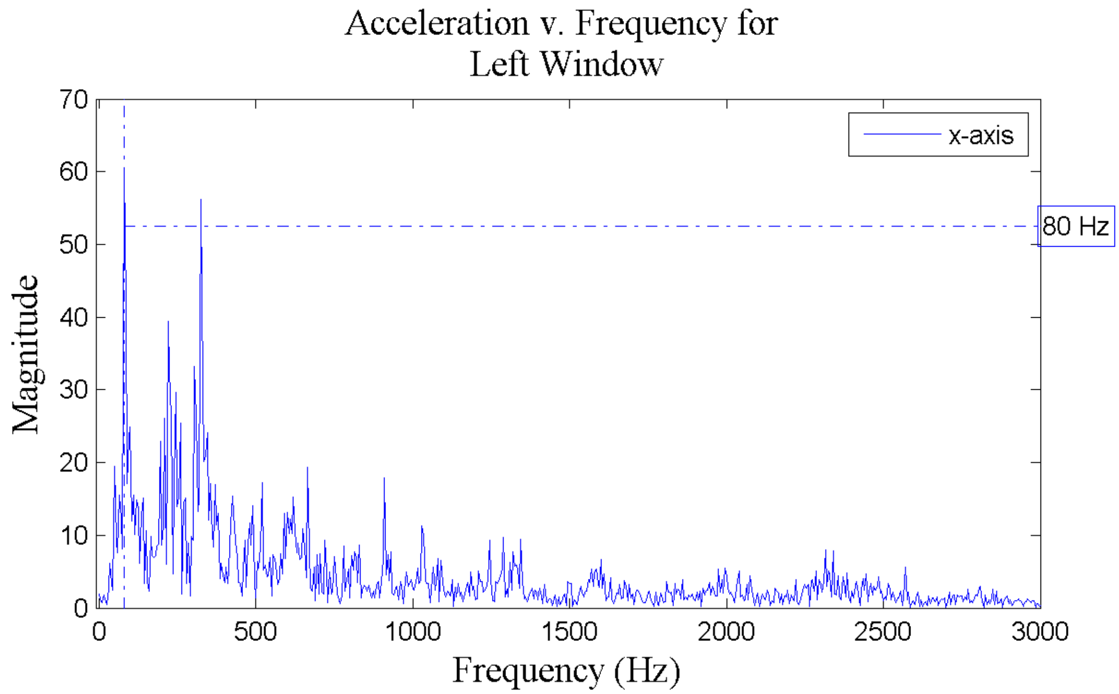

Figure 57 – Vibration measurement AA

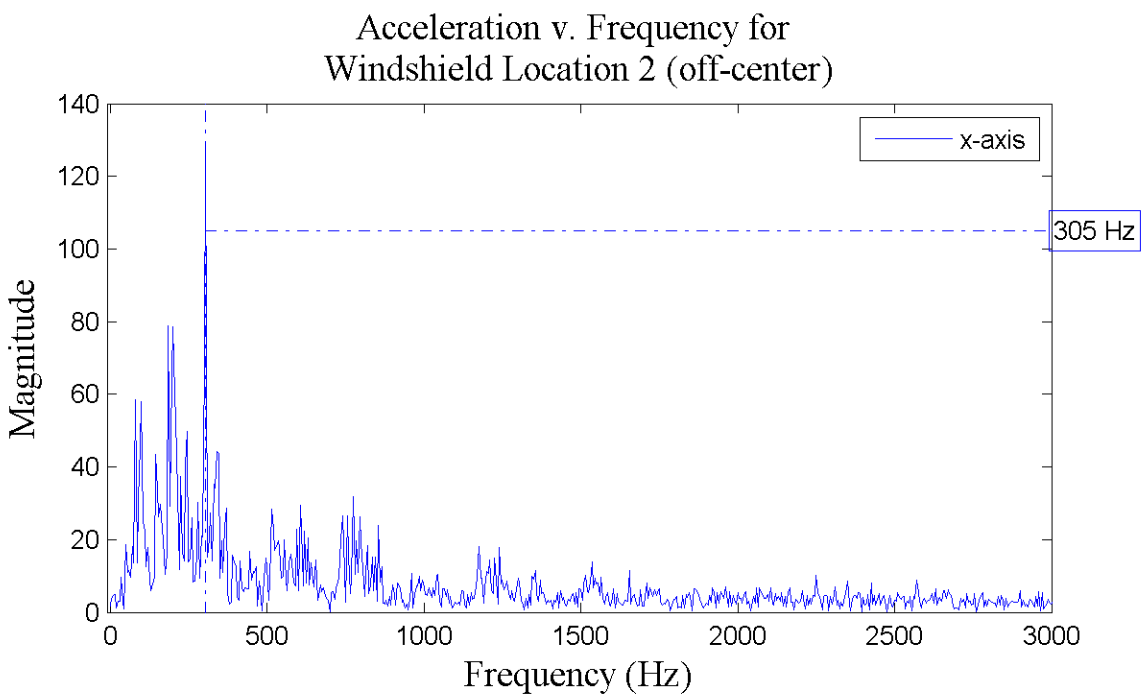

Figure 58 – Vibration measurement AB

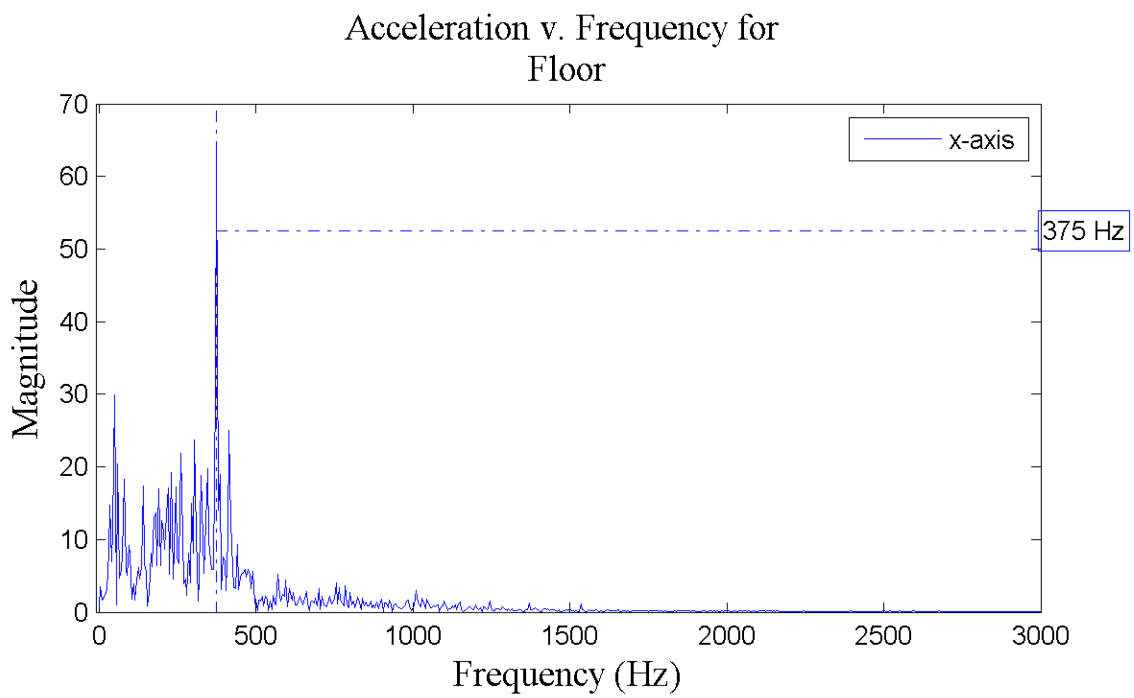

Figure 59 – Vibration measurement AC

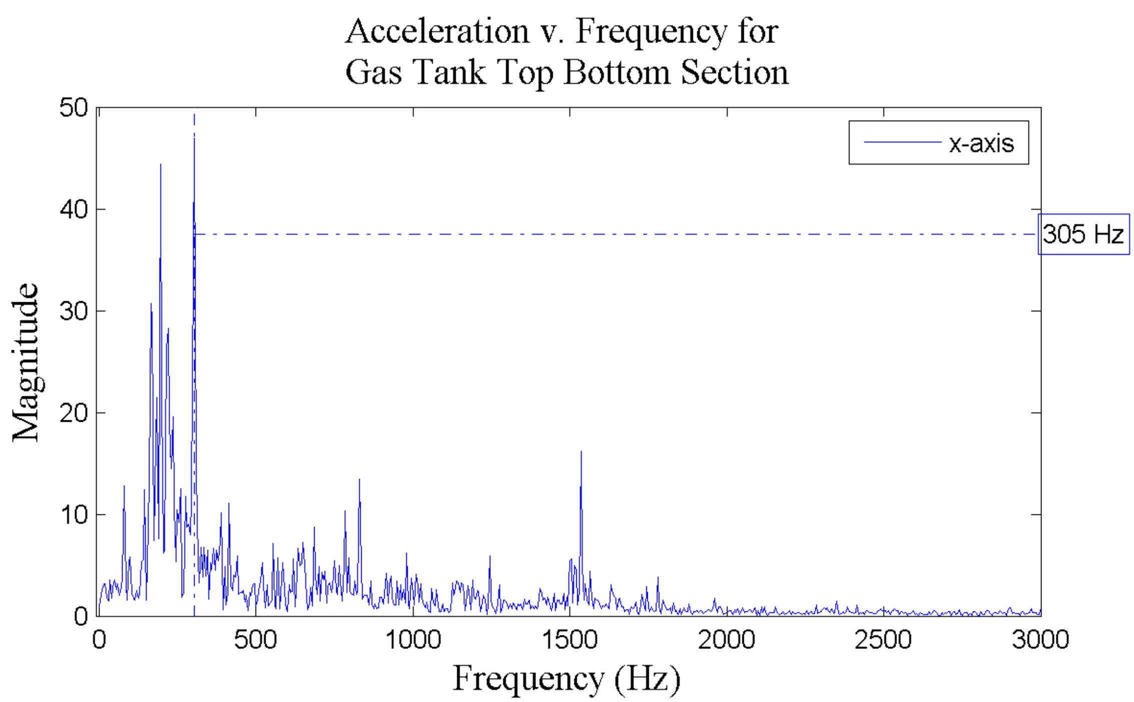

Figure 60 – Vibration measurement AD

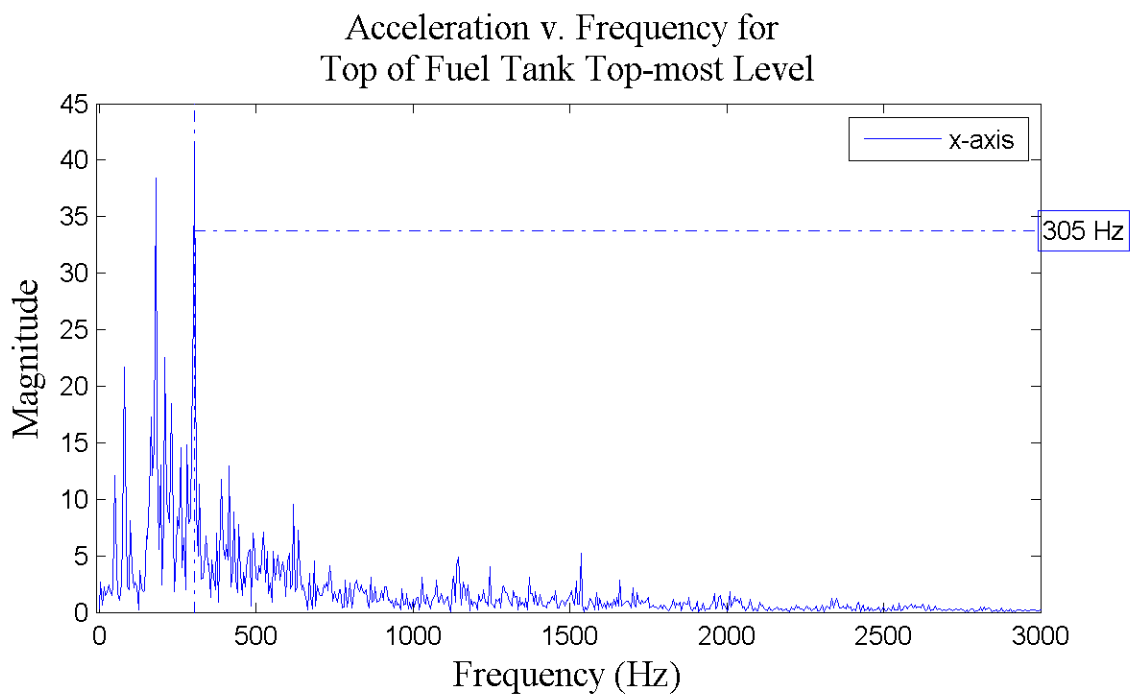

Figure 61 – Vibration measurement AE

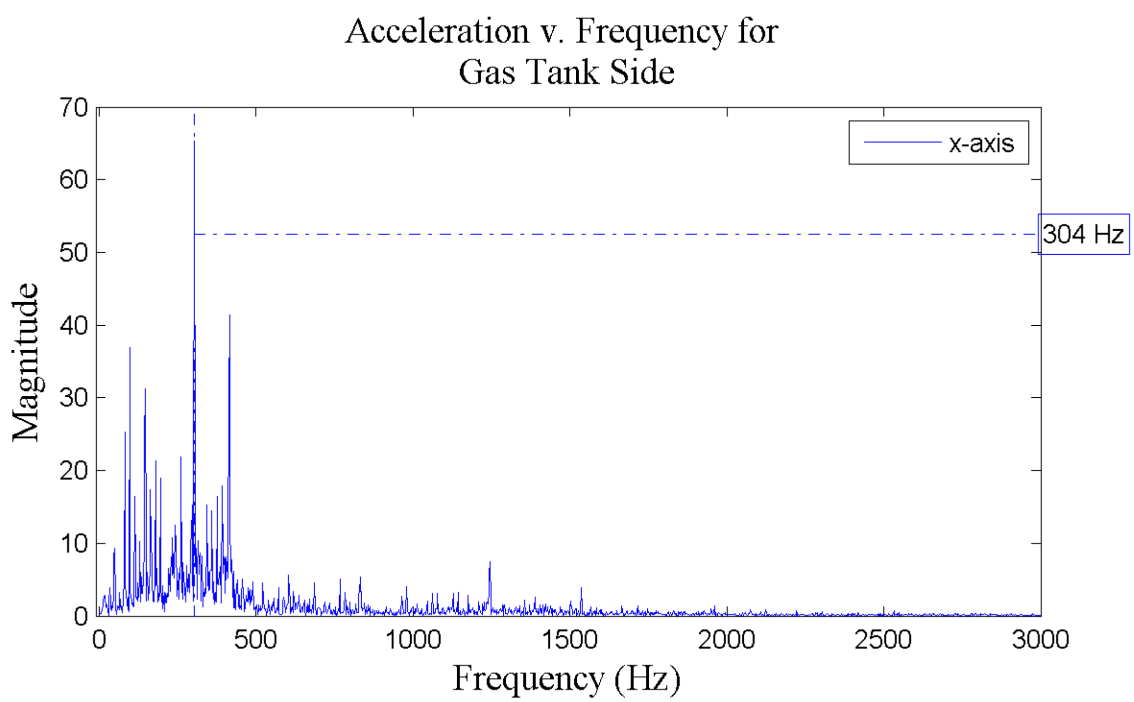

Figure 62 – Vibration measurement AF

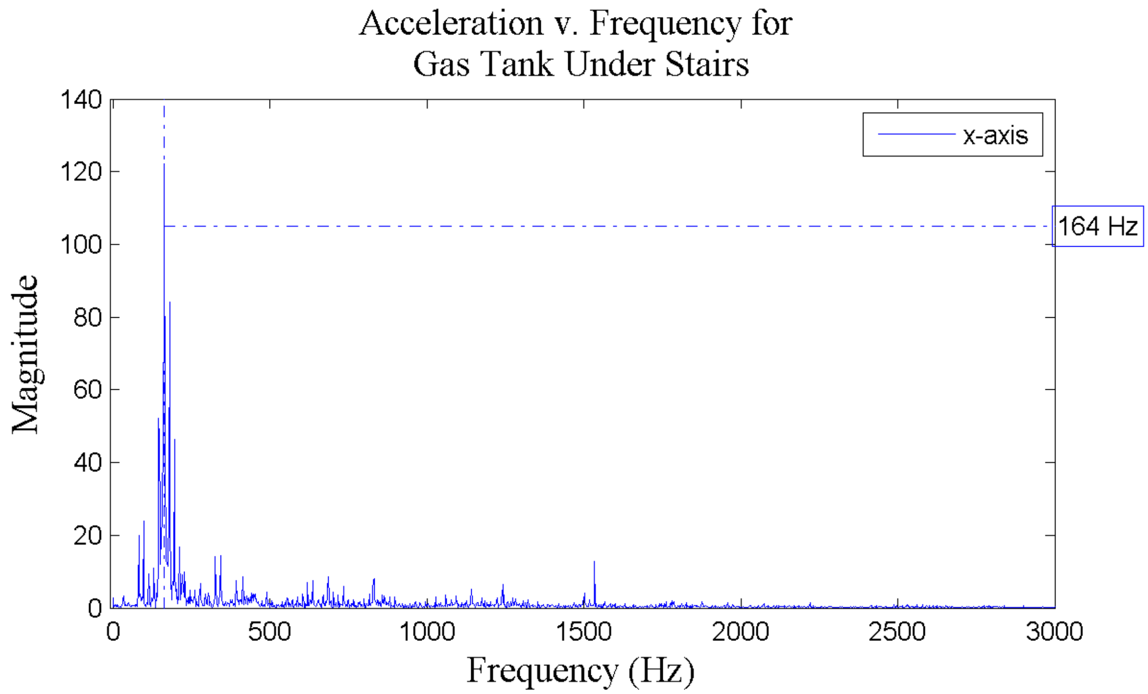

Figure 63 – Vibration measurement AG

List of References

[1] Dirac Delta. (2010). "*A-weighting*" [Online]. Available: http://www.diracdelta.co.uk/science/ source/a/w/aweighting/source.html [Dec 1, 2010].

[2] Buhler Industries Inc. (2010). *Row Crop Tractors - 250 to 305hp* [Online]. Available: http://www.versatile-ag.ca/news_and_media/downloads/Versatile-RC-brochure.pdf [Oct 03, 2010]