Objective Predictor metric of Annoyance for Hydraulic Engine Mount Cavitation

John Powell

OBJECTIVE PREDICTOR METRIC OF ANNOYANCE FOR HYDRAULIC ENGINE MOUNT CAVITATION

By

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(Under the Direction of Brian L Vlcek, PhD)

ABSTRACT

Vehicle acoustics has been found to have a direct impact on customer experience. Unexpected noises play a role in this experience. Hydraulic engine mount cavitation, the noise heard from the collapse of vapor bubbles in the mount, is considered one of those unexpected noises. During the design phase of a vehicle when an unexpected noise is found there is a need for a method to quantify how much of the noise is too much. Subjective evaluations alone are not enough due to variability from engineer to engineer. An objective way needed to be developed in order to evaluate the cavitation noise. To address this issue, an objective predictor metric of annoyance was developed. The model was developed by comparing psychoacoustic metrics to subjective ratings by means of regression analysis. Once the psychoacoustic metrics were chosen multiple regression analysis was used to develop the predictor metric.

INDEX WORDS: hydraulic engine mount, cavitation, psychoacoustic metrics, regression analysis

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by

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DEDICATION

I would like to dedicate this thesis to all of friends, family, professors, and co-workers that never stopped believing in me and continuously pushing me to achieve this goal. The phrase “You got that thesis done yet?” will continue to haunt my dreams.

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I would also like to thank my committee members Aniruddha Mitra and Biswanath Samanta for assisting me in my time of need, during a quickly approaching deadline.

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CHAPTER 1

INTRODUCTION

1.1 Purpose of Study

The purpose of this project is to develop an objective predictor annoyance metric for hydraulic engine mount cavitation.

1.2 Statement of Needs for Study

There are many factors that change the way a customer perceives comfort-level within a vehicle. Around the top of that list is the vehicle acoustics. The perception of the vehicle acoustics has a direct impact on the customer experience as seen in Figure 1.1 (Zeller 2009).

Figure 1.1 The attributes that contribute to a customer's experience (Zeller 2009)

With acoustics impacting customer's perception so highly there is a need to know how much of a noise is too much. Hydraulic engine mount cavitation, the noise heard from the collapse of vapor bubbles in the mount, can be heard in the vehicle with variability from car to car. With this variability it is hard for different engineers to subjectively evaluate the noise. Since subjective evaluations can be inconsistent at quantifying such events there is a need for an objective metric to rate the noise. This metric would evaluate the noise and apply a rating to it. Once an objective rating is achieved a cutoff number can be given. The cutoff number would provide the answer to how much is too much. This research focused on the development of the objective predictor annoyance metric for hydraulic engine mount cavitation.

1.3 Hydraulic Engine Mounts

A vehicles engine is one of the largest sources of vibration due to the inherent unbalance of its moving part. The vibrations created by those moving parts are transferred from the engine to a mount where they are then transmitted through the body structure resulting in noise, typically below 1000Hz, in the vehicle interior. In order to diminish the transferred vibrations, an engine mount plays a very important role in vehicle sound quality. There are a few different types of engine mounts such as elastomeric mounts, hydraulic engine mounts, and active engine mounts but the most prominent is the hydraulic engine mount.

Hydraulic engine mounts are used for their ability to be tuned for two damping characteristics. Two damping characteristics are needed due to the different vibration sources exciting the engine. One of the sources is from the road and wheel inputs acting in the vertical direction as well as idle shake. This source requires the mount to be stiff and highly damped to control those sources, usually over 5-30Hz range (Singh, Kim and Ravindra 1992). The other source is related to the unbalanced engine 2nd order forces in the frequency range of 25-200Hz (Wang and Denker 1997). This range requires the mount to be low dynamic stiffness and low damping (Lee, Choi and Hong 1994). The device provides the desired damping characteristics via the implementation of a mechanical switching mechanism known as the decoupler in conjunction with a narrow, highly restrictive fluid path known as the inertia track as seen in Figure 1.2 (J. Christopherson 2012).

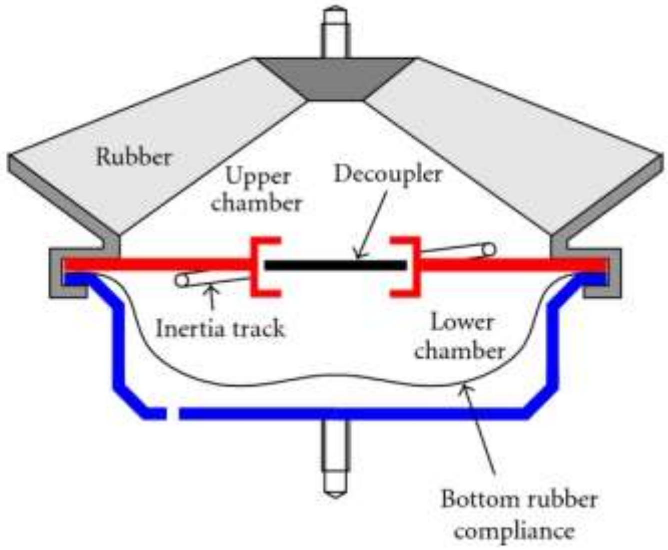


Figure 1.2 Typical hydraulic engine mount construction (J. Christopherson 2012)

When the engine experiences vibrations induced from the road it creates a large pressure differential to the fluid chambers, forcing the decoupler to bottom. Increased damping coefficient to the engine mount occurs as the inertia track dimensions decreases. However, when the external vibrations are low in intensity, or at increased frequency, the decoupler does not bottom out, and hence the inertia track is effectively short-circuited; therefore, due to the decoupler's large dimensions, the system provides a low damping coefficient (J. Christopherson 2012). The fluid is usually a glycol based fluid.

A properly tuned hydraulic engine mount is required otherwise there will be abnormal noise due to cavitation effect (Hazra 2011). Cavitation noise, due to vibrations caused by the collapse of vapor bubbles in the mount, is such a noise which is very difficult to identify in initial vehicle development stage. The effects of cavitation in the hydraulic engine mount become increasingly important for noise and performance goals (Hazra 2011).

1.4 Cavitation

A properly designed hydraulic engine mount does its job by isolating the vibrations coming from the engine; though it does have the ability to add vibrations to the structure from its own components. These added vibrations are due to cavitation. Cavitation is the dynamic process of gas cavity growth and collapse in a liquid (Totten, et al. 1998). These cavities are due to the presence of dissolved gases or volatile liquids, and they are formed at the point where the pressure is less than the saturation pressure of the gas (gaseous cavitation) or vapor pressure (vaporous cavitation) as seen in Figure 1.3.

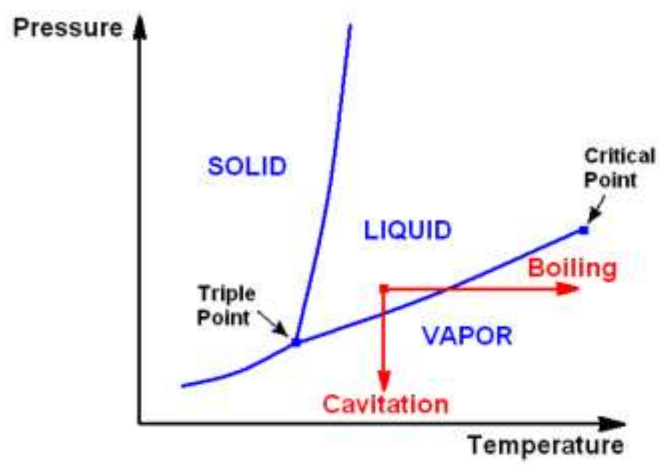


Figure 1.3 When pressure drops below the saturation line bubbles are formed and cavitation occurs. This effect can happen due to the increase of temperature as well. (Brennen 2011)

In hydraulic engine mounts, the vapor bubbles are created by the decrease in pressure inside the mount by the engine oscillating up and down due to road inputs. Since the engine is moving up and down the pressure in the mount decreases then subsequently increases. When this happens the bubbles that are formed are forced against a surface and implode due to the pressure, creating a shockwave through the mount (Figure 1.4). That shockwave produces vibrations that become structural and airborne noise inside the cabin of the vehicle. Collapsing bubbles can produce pressure as high as 60,000 psi (Ahmad 2006)

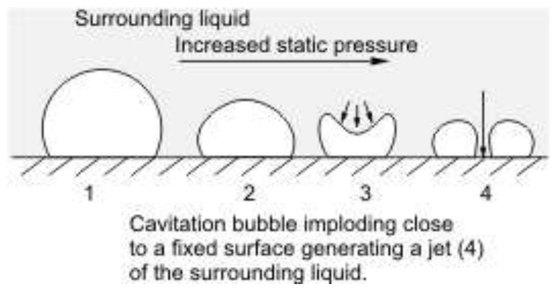


Figure 1.4 Bubble collapsing due to increasing pressure causing a high speed jet of fluid impacting a surface (lidingo 2007)

The greater propensity for cavitation of water and water containing hydraulic fluids compared to mineral oil is due to the higher density and vapor pressure of water (Totten and Negri 2012).

1.5 Goals

The goal of this research was:

- To develop an objective predictor annoyance metric for hydraulic engine mount cavitation, through a combination of subjective and objective analysis. This would allow an engineer to specify a cutoff point for how much cavitation noise is too much.

In order to achieve this goal the following was completed:

1. Obtain suitable engine mounts for analysis
2. Install required equipment for Cabin noise analysis
3. Setup vehicle on 4 poster, run road profile, and subjectively rate the noise
4. Record objective data
5. Perform a correlation study of psychoacoustic metrics to subjective ratings in order to find best predictor variables
6. Develop a predictor annoyance metric through multiple regression analysis

1.6 Hypothesis

By using various psychoacoustic metrics with multiple linear regression, an accurate predictor metric can be produced that predicts the annoyance of hydraulic engine mount cavitation.

1.7 Gantt Chart

The research was started and completed during spring and summer semesters. In order to manage the limited time a schedule was developed to understand the required progression of the research. A gantt chart was used to visualize the schedule per week seen in Figure 1.5.

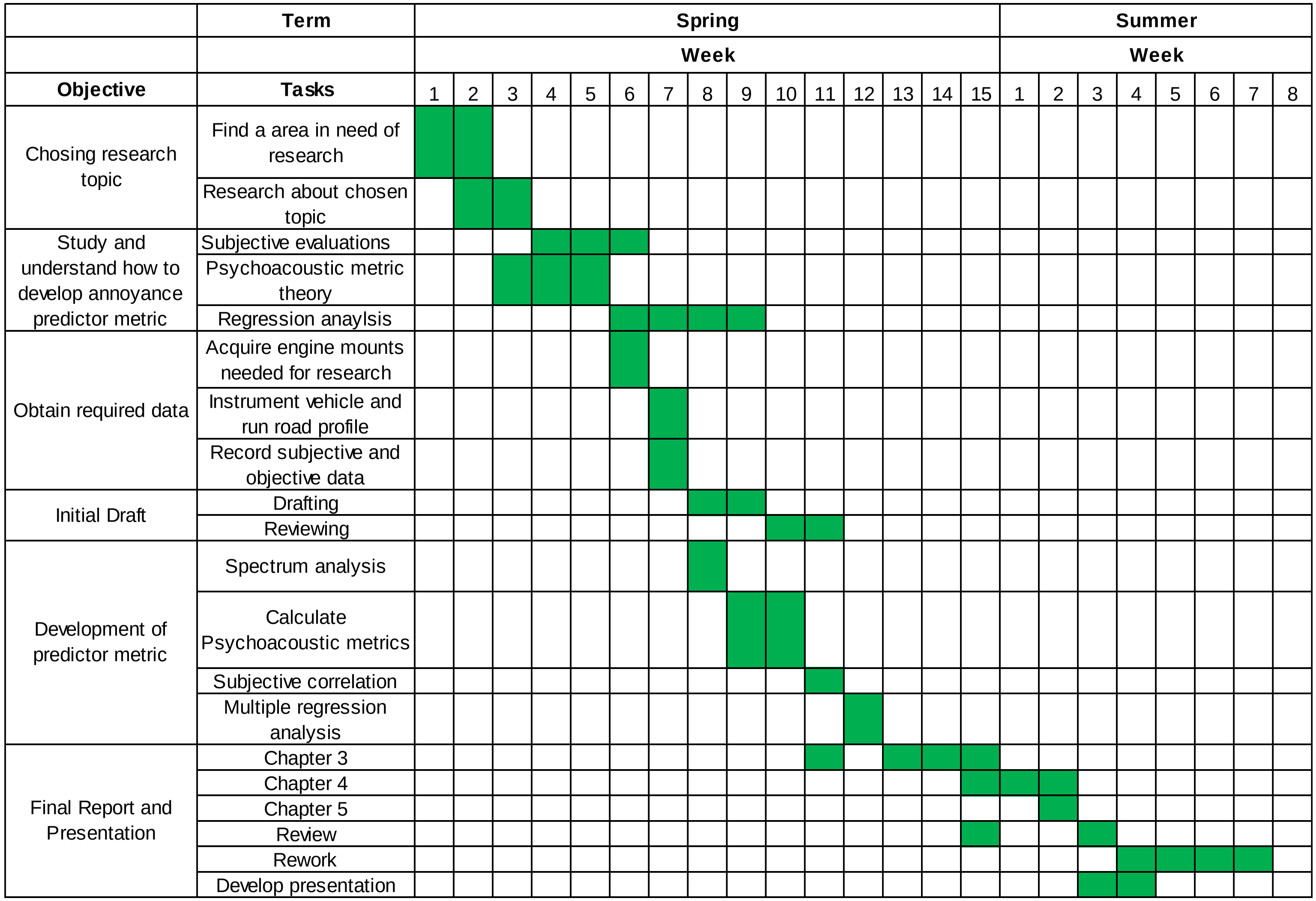


Figure 1.5. Time Management Task Schedule

CHAPTER 2

REVIEW OF RELATED LITERATURE

2.1 Introduction

It is common practice to predict perceived noise annoyance by means of regression models using instrumental psychoacoustic metrics as predictors (Ellermeiera, Zeitler and Fastl 2004). This type of work is applied to all types of consumer items such as cars, refrigerators, washing machines, and even hairdryers (E. Altmsoy 1999) (Sobhi and Ladegaard 1999). In order to develop this model, two analysis need to done a subjective and objective. Subjective analysis is usually done with a large group of people referred to in many papers as jury based tests. The people listen to the sounds and fill out a questionnaire that is intended to rate the annoyance of the noise. Objective analysis uses just a microphone to record the noise in question and different psychoacoustic metrics are applied such as loudness, sharpness, prominence ratio, tonality, roughness, fluctuation strength and tone to noise. Regression analysis is then used to find the best fit singular value that correlates with the subjective rating. These best fit singular values from the psychoacoustic metrics are then used in multiple regression analysis to develop a model that can predict the way a consumer reacts to the sound of the product. This process of model development can be seen in the following papers.

Lipar, Prezelj, Steblaj, Rejec, and Cudina (2012) developed a model of sound pleasantness of vacuum cleaners and suction units. Their study included seven suction units of the same type and five different vacuum cleaners. A jury based test was used for this study. 10 second long samples were given to the jury. All of the listeners used the same pairs of headphones and listened to the same recordings several times. They relatively evaluated sound quality with points from 1 (less pleasant) to 5 (more pleasant). Objective data was recorded using an artificial head with microphones in the ears. Loudness, sharpness, tonality, and roughness was used to develop their model seen below through multiple regression analysis.

$$P = \left[R + SFM + \frac{100}{N} + \frac{100}{S} \right] \cdot K$$

______equation 2.1

Where P denotes pleasantness, N represents loudness, S sharpness, SFM tonality, F fluctuation strength, R roughness, and K offset factor.

Ellermeiera, Zeitler, & Fastl (2004) used the same process in their research but what they wanted to know was how non-sensory variables such as the meaning of the sound effected the ability to develop a predictive model. This paper took audio recording of everyday sounds such toilet flushing or a door closing and modified them as to reduce the identifiablility of the sound source. Their subjective analysis included two independent groups of 25 participants. One group had the original sound and the other had the modified. Each group rated the sound on a 0-50 scale with 50 being unbearably annoying. They were also asked to identify the sound. During their objective analysis multiple linear regression was used and found that 5^{th} percentile loudness, median sharpness, and roughness predicted the overall annoyance ratings fairly well with the model seen below.

$$CSA = 8.07 + 0.563 * N_5 + 3.022 * S_{50} + 2.175 * R$$

____equation 2.2

This model correlated well with the modified sounds but dropped 15% when applied to the original sounds.

Gauduina, Noel, Meillier, & Boussard (2008) used multiple regression to develop a model for predicting rattle noise in cars. Rattle caused by the suspension system is the main focus of the paper. For the subjective analysis a jury was not used. Only one trained expert was used to evaluate 19 suspenion systems. The expert rated each system on a scale of 0 to 10 in 0.5 increments with 10 being best; while driving the car on a test track with different surfaces. Objective analysis was performed using a binaural headset and the car on a 4 poster shaker in order to precisley control the road profiles. A filter analyis was performed to localize the rattle phenomenon. Three spectral metrics were proposed based on the frequency ranges found to represent the phenomenon. Five temporal metrics were proposed, along with three time-frequency metric. All eleven metric could not be used to predict the rattle because of the high number of predictors (11) to the number of observations (19). Multiple linear regression was used in many of combinations to find the best model with the highest goodness of fit and correlation coefficient. Six metric out of the eleven were chosen to build the model.

In order to develop a predictive model for hydraulic engine mount cavitation the same process found in works of Gauduina, Noel, Meillier, & Boussard (2008) , Ellermeiera, Zeitler, & Fastl (2004), and Lipar, Prezelj, Steblaj, Rejec, and Cudina (2012) was followed. A subjective analysis was performed. This subjective analysis used the ratings of one expert evaluator instead of a jury and utilizing a scale of 1-10 at 0.25 increments with 10 being the best. Objective analysis utilized 2 microphones to record the data. Psychoacoustic metrics were then used to develop the model. The metrics investigated were prominence ratio, sharpness, loudness, fluctuation strength, and tone to nosie.

2.2 Psychoacoustics

Psychoacoustics is the study of the subjective human perception of sounds (Surhone, Timpledon and Marseken 2009). It connects the physical world of sound vibrations in the air to the perceptual world of things actually heard when listening to sounds (Jehan 2005). It incorporates the subjective attributes of sound, such as loudness, sharpness, roughness, fluctuation strength and tonality; and how they relate to physically measurable quantities such as sound level, frequency, duration and spectrum of the sound (Kadlaskar 2010).

2.3 Psychoacoustic Metrics

Many psychoacoustic metrics have been developed to quantify the subjective perception of particular sound characteristics (Willemsen and Rao 2010). These metrics were developed through extensive subjective evaluations and are meant to mimic the sound processing of the human hearing system (Willemsen and Rao 2010). Some common psychoacoustic metrics include loudness, sharpness, roughness, fluctuation strength, and tonality (Zwicker and Fastl 1999).

2.4 Loudness

Sound loudness is the perceived intensity of the sound waves when it reaches the ear. The intensity is related to the volume of the sound, which can be expressed in sones (Beranek, et al. 1951) (Stevens 1955). Based on countless hearing tests, Zwicker developed a model for loudness measured in sone. One sone is equal to the sensation caused by a 1KHz tone at 40dB (Zwicker and Fastl 1999). Perceived loudness changes with frequency. At lower frequencies sound pressure must be higher in order to keep the same loudness. This can be seen by the equal loudness contours in Figure 2.1. The sound pressure level is constantly changing with frequency in order to stay at the same loudness level.

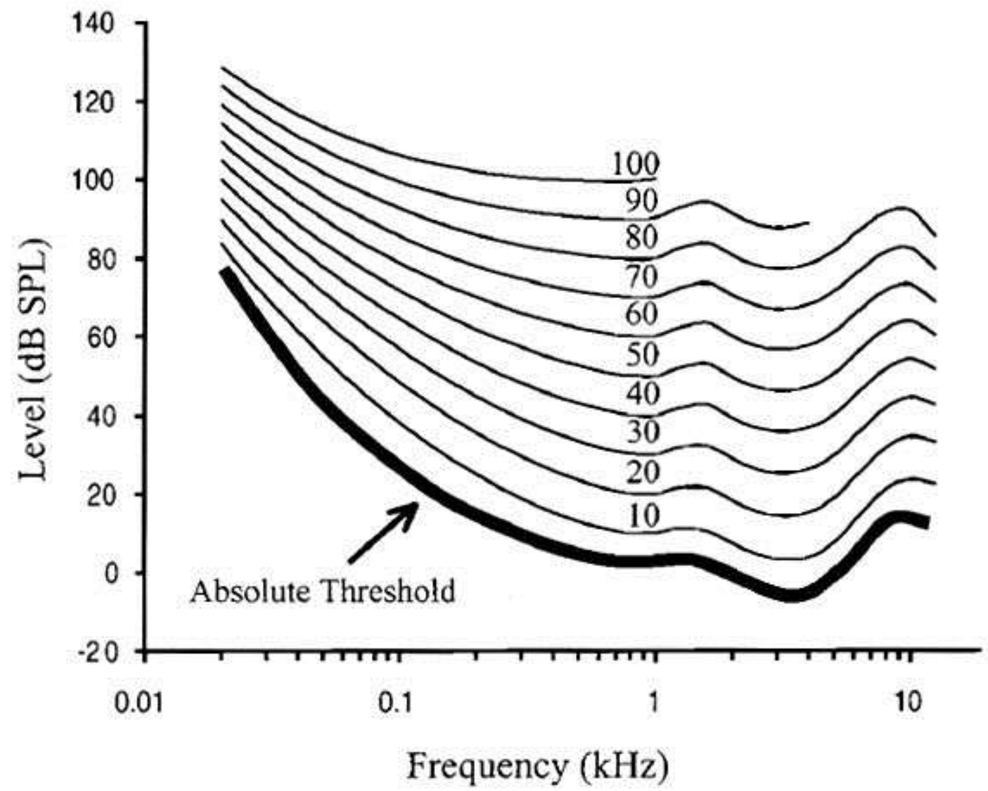


Figure 2.1. Equal loudness contours. Each curve represents the levels and frequencies of pure tones of equal loudness. (Fletcher and Munson 1933)

Since humans perceive sound loudness over different frequencies non-linearly when recording sound with a microphone the data needs to be weighted in order to mimic the way the ear processes the sound at different loudness levels. This is because the microphone has a flat frequency response, meaning it will produce the same electrical output level, for any sound frequency input. The most common weightings are A, B, C, and D (Figure 2.2).

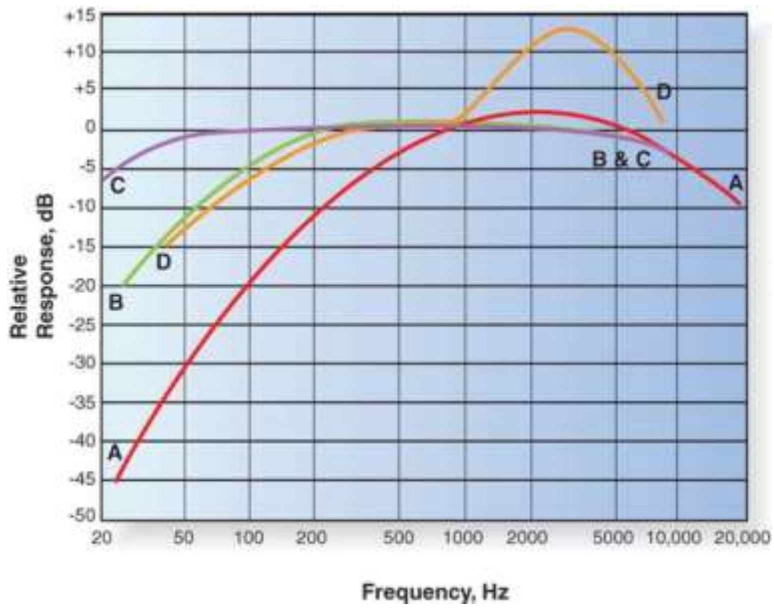


Figure 2.2. Weighted Filter Response Curves (Somers n.d.)

A-weight is the most common (Lamancusa 2000). This is because it correlates reasonably well with hearing damage, it is easily implemented in a filter network, it is a simple measure, overall level is one number, and it is used in most regulations.

Zwicker has established a procedure to calculate loudness and sound pressure level which now has been standardized by ISO norm (ISO 532 B). The same method is described in the German standard as well (Deutsche Norm, DIN 45631).

2.5 Sharpness

Sharpness is a measure of the high frequency content of a sound, the greater the proportion of high frequencies the ‘sharper’ the sound (Manchester 2015). If the loudness pattern of a sound is available, its sharpness can be relatively easily calculated. There is no standardization for the calculation of sharpness. Most software uses the same equation of Aures (1985) to determine sharpness from specific loudenss:

$$\frac{S}{acum} = 0.11 \frac{\int_0^{24 Bark} N'(z) g(z) z dz}{\ln\left(\frac{N}{sone \times 20} + 1\right)}$$ equation 2.3

where:

$$g(z) = e^{0.171z}$$

This term causes the higher weighting of high-frequency components, which produce the sensation of sharpness.

2.6 Roughness

Roughness is a complex effect which quantifies the subjective perception of rapid (15-300 Hz) amplitude modulation of a sound. The unit of measure is the asper. One asper is defined as the roughness produced by a 1000Hz tone of 60dB which is 100% amplitude modulated at 70Hz (Zwicker and Fastl 1999). Maximal roughness is found to be at increasingly lower modulation frequencies when the carrier frequency is below 1000Hz.

$$R = cal \cdot \int_0^{24Bark} f_{mod} \cdot \Delta L \cdot dz$$ equation 2.4

Where cal is a calibration factor, f_{mod} is the frequency of modulation and ΔL is the perceived masking depth as seen in Figure 2.3.

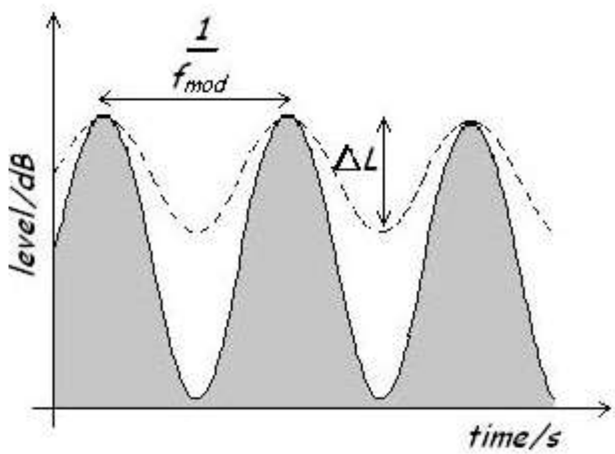


Figure 2.3. The effect of subjective duration on rapid amplitude modulated noise: (i) the modulation depth (unbroken line) and (ii) the perceived masking depth (dashed line).

2.7 Fluctuation Strength

Fluctuation strength is similar in principle to roughness except it quantifies subjective perception of slower (up to 20Hz) amplitude modulation of a sound. The sensation of fluctuation strength persists up to 20Hz then at this point the sensation of roughness takes over. The unit of measure for fluctuation strength is the vacil. One vacil is defined as the fluctuation strength produced by a 1000Hz tone of 60dB which is 100% amplitude modulated at 4Hz. Zwicker & Fastl (1999) developed the equation seen below using the same variables from roughness.

$$F = \frac{0.008 \cdot \int_0^{24Bark} \Delta L \cdot dz}{\left(\frac{f_{mod}}{4Hz}\right) + \left(\frac{4Hz}{f_{mod}}\right)}$$

equation 2.5

2.8 Prominence Ratio and Tone to Noise Ratio

When discrete tones appear in broadband noise, the signal is perceived as being more annoying than the broadband noise signal itself, in absence of the tones (Nobile and Bienvanue 1991). The psychological percept for this sticking-out of a tone is called prominence. The Prominence Ratio is defined as the ratio of the power in the critical band centered on the tone under investigation to the mean power of the two adjacent critical bands. A tone is classified as prominent when the prominence ratio exceeds 7 dB (Sirkka 2007). Tone to noise ratio is a measure describing the amount of pure tones in the signal (Zhang and Shrestha 2003).

CHAPTER 3

METHODOLOGY

3.1 Introduction

The purpose of this study was to develop an objective predictive metric to rate the annoyance of hydraulic engine mount cavitation. To this end, experimental data was collected in a mid-sized sedan. Acoustic measurements were made for three different hydraulic engine mount types in the same vehicle. A four poser test rig was used to simulate repeatable road profiles. Instrumentation included 2 microphones, 2 triaxial accelerometers and a 16 channel data acquisition system. With this equipment, it was possible to input simulated road profiles to the vehicle and acquire the pressure changes inside the cabin and vibrations of each engine mount type. A process diagram can be seen for this below.

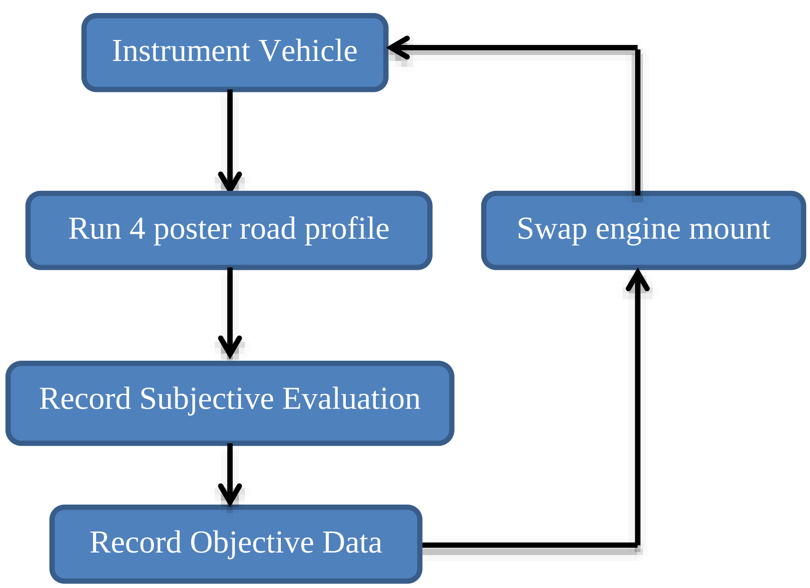


Figure 3.1. Process for obtaining data on each engine mount

A subjective analysis was performed during the process. This subjective analysis used the ratings of one expert evaluator instead of a jury and utilizing a scale of 1-10 at 0.25

increments with 10 being the best. Utilizing the microphone data obtained, psychoacoustic metrics were then used to develop the model. The metrics investigated were prominence ratio, sharpness, loudness, fluctuation strength, and tone to nosie.

3.2 Sensors

The sensors in Table 3.1 are required in order to collect the measurements which are needed for analysis. A brief description of each sensor follows.

Table 3.1 Sensors used during testing

Sensor	Data Collected	Unit of Measure
Triaxial Accelerometers	Vibration	m/s^2
Microphones	Sound	Pa

3.2.1. Triaxial Accelerometers

In order to measure the vibrations, ceramic shear piezoelectric accelerometers with an integrated microelectronic amplifier were used. These accelerometers function using the piezoelectric effect. The piezoelectric effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress (Nanomotion n.d.). This effect is an inherent property of quartz and an induced property of certain manufactured ceramic crystals (PCB Group, Sensing Geometries for Piezoelectric Accelerometers 2015). When force is applied to the crystal, negative and positive ions will accumulate onto the opposed surface of the crystal in an amount that is propositional to the applied force as illustrated in Figure 3.2.

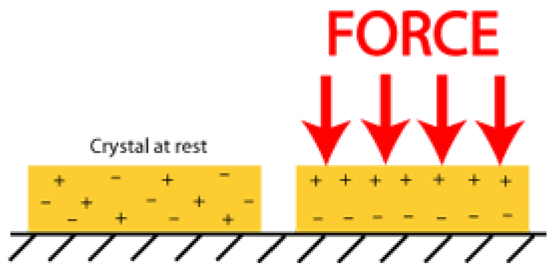


Figure 3.1. Illustration detailing how the positive and negative ions move to opposite sides when force is applied (PCB Group, Sensing Geometries for Piezoelectric Accelerometers 2015)

In order to measure acceleration a mass is coupled to the crystal. When the combined unit is experiencing acceleration, the mass causes a force to act upon the crystal and thus generating a proportional electric charge. There are three main methods for inducing stress on the crystal which include compression, shear, and flexural. For this experiment a triaxial, high sensitivity, ceramic shear piezoelectric accelerometer with an integrated microelectronic amplifier was used. Specifications for this sensor can be found in appendix A. Shear mode accelerometers were chosen due to their ability to be less susceptible to base strain and thermal transient effects than compression mode and being more robust than the flexural design. By having an integrated microelectronic amplifier the need to have a charge amplifier and the need to use short low-noise cables was eliminated (Figure 3.3).

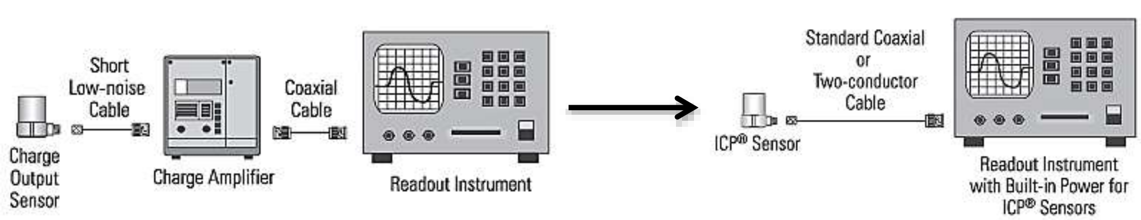


Figure 3.2. The difference in equipment needed using charge output sensor vs. integrated circuit piezoelectric sensor (PCB Group, Signal Conditioning Basics for ICP® & Charge Output Sensors 2015)

Triaxial accelerometers were used in order to fully measure the force directions involved on the measurement locations (Figure 3.4).

Figure 3.3. Triaxial Accelerometer

Accelerometers were glued to the active and passive side of engine mount seen in Figure 3.5. Mounting of the transducer is as important as the selection of the transducer in many applications. If the motion of the test structure is not accurately transmitted to the transducer, it cannot be accurately measured.

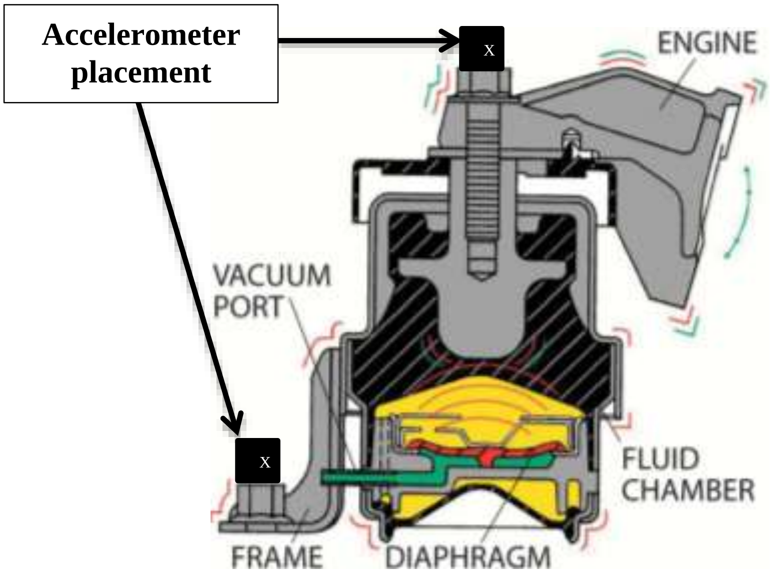


Figure 3.4. Placement of accelerometers on engine mount (Freudenberger 2006)

In many cases accelerometers can only be mounted using an adhesive. The cured adhesive stiffness is important in order to get quality data that is not degraded by the low transmissibility of the adhesive. The more space in between the test structure and the accelerometer, the greater the degradation of transmissibility. Dental cement was used to attach the accelerometers to the structure. Additional options include cyanoacrylate (super glue), petro-wax, 2 sided tape, and hot glue (glue gun)

Dental cement is very similar to cyanoacrylate in its transmissibility over a wide range of frequencies. It is important not to have a thick layer of adhesive below the accelerometer. The thick layer of adhesive is actually a spring and has the effect of creating a new spring mass system, which degrades recorded data. The frequency response of the common adhesives can be seen in Figure 3.6.

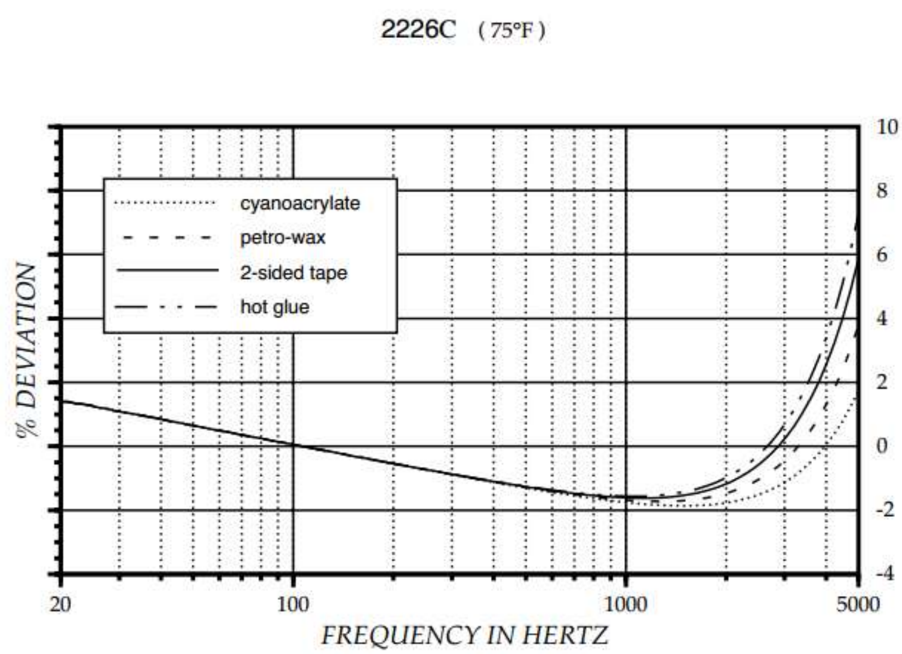


Figure 3.5. Frequency Response Curves for Common Accelerometer Mounting Adhesives (Endevco 2009)

The only problem with dental cement lies with its tenacity. It is considered by Gatti and Ferrari (1999) to be a permanent method of bonding. Even though it is considered by some to be a permanent method of bonding it can be removed, but there is a high likelihood that the transducer will be damaged.

Accelerometer placement orientation is important. Each side of the block is labeled with its respective positive axis location as seen in Figure 3.3. Direction is important because the direction needs to be inputted correctly into the LMS software.

3.2.2 Microphones

To measure noise inside the cabin of the vehicle a diffuse field condenser microphone is used. For recording there are three main types of microphones dynamic, condenser, and ribbon (Karney 2007). A condenser microphone was used in this experiment because it has a wider, flat frequency response as compared to other options (Utz 2003). Condenser microphones work by having a conductive diaphragm that is separated by air between another conductive plate. When sound waves vibrate one of the plates, the capacitance change between the plates creates a small electrical signal (Karney 2007). The layout of a condenser microphone can be seen in Figure 3.6.

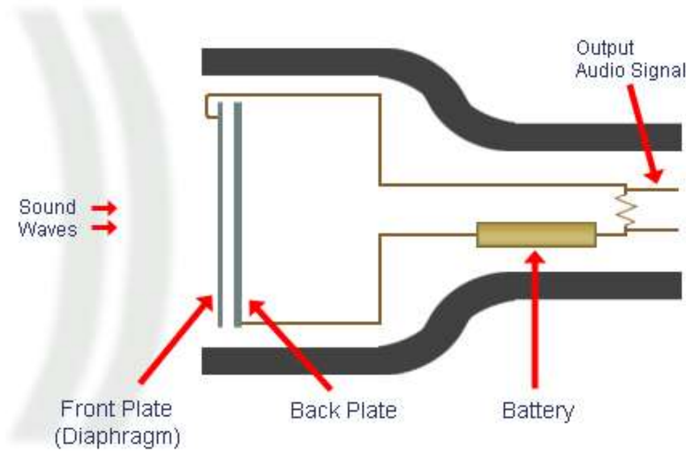


Figure 3.6. Cross-Section of a Typical Condenser Microphone (Media 1995-2012)

In order to measure the sound levels correctly, the characteristics of the microphones chosen need to be suitable for the type of acoustic field it is in. There are two main types of acoustic field, the free field where sound arrives from a known direction and the diffuse field where sounds arrive from all directions (Templeton and Saunders 1987). Diffuse field microphones were used.

3.2.2.1 Diffuse field Microphone

This type of microphone is used for in car measurements due to the sound source not coming from a single area but reflected around the vehicle cabin. It is designed to account for the reflections and diffractions caused by it being in the sound field. For a ½” diameter microphone the effect is highest around 26.9 KHz, where the wavelength of the sound (λ=342 m*s^{-1}/26.9 KHz=12.7mm=0.5in) coincides with the diameter of the microphone (Webster and Eren 2014) The microphone is designed to output a flat response curve for sound waves that arrive simultaneously from all directions (Templeton and Saunders

1987). A Diffuse-field microphone over-estimates the pressure in a sound wave when arriving normal to the diaphragm (NI 2013).

One half inch pre-polarized diffuse-field microphones with Type 2671 preamplifiers were used for this experiment as seen in Figure 3.7. The specifications for both the microphone and the pre-amplifier can be found in appendix B.

Figure 3.7. 4942-A-021 - ½-inch diffuse-field microphone with Type 2671 preamplifier (Kjær, 4942-A-021 n.d.)

3.2.2.2 Microphone Calibration

In order to make reliable measurement, all of the microphones used were calibrated before each measurement. The calibration establishes the output signal of the microphone for a given acoustic signal at a specific frequency. A sound calibrator type 4231 by Brüel & Kjær was used for calibrating the microphones and can be seen in Figure 3.8.

Figure 3.8. Microphone inserted in to calibrator (Kjær, Sound Calibrator Type 4231 n.d.)

The calibration frequency is 1000 Hz, so the same calibration value is obtained for all weighting networks (A, B, C, D and Linear) (Kjær, Sound Calibrator Type 4231 n.d.). The calibration pressure is 94 ± 0.2 dB. A table with the devices specifications can be seen in Table 3.2. The test conforms to ANSI S1.40-1984 which is the standard for acoustical calibrators.

Table 3.2 Specifications of type 4231 sound calibrator

Standards	IEC 942 (1998) Class 1
Calibration Pressure	94 and 114 dB SPL
Calibration Frequencies	1000 Hz
Calibration Accuracy	± 0.2 dB
Transducer	1-inch and 1/2-inch

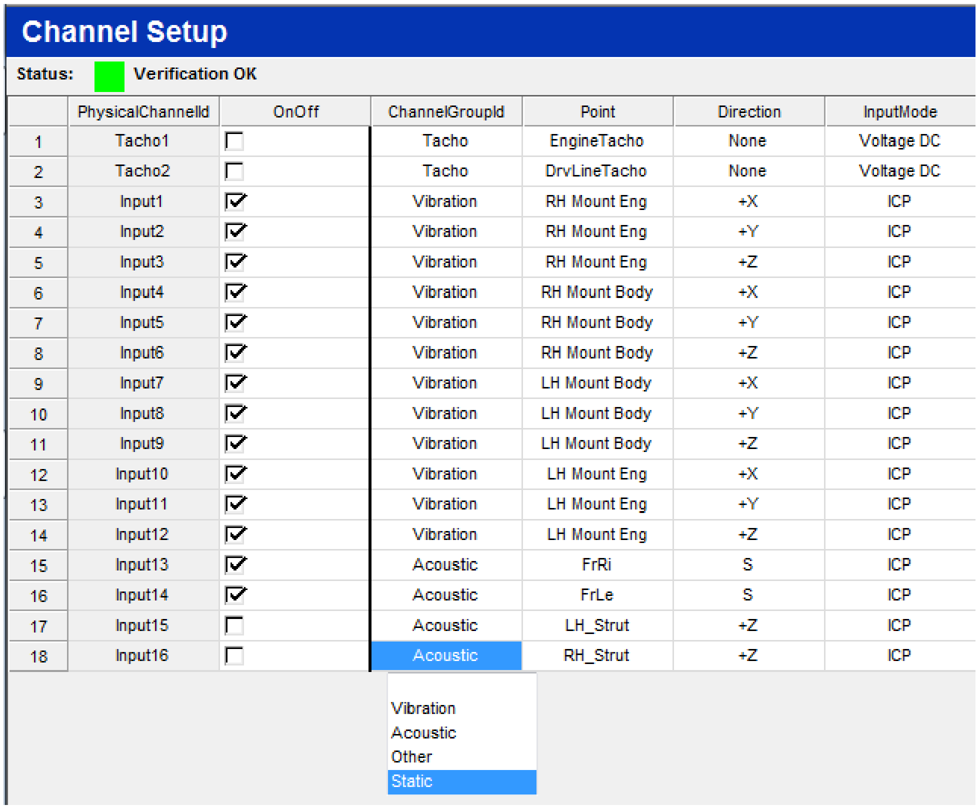
3.3 Data Acquisition System

In order to acquire a signal from the sensors used during the experiment a LMS SCADAS Mobile frontend was used, seen in Figure 3.9. By using 2 triaxial accelerometers and 2 microphones 8 channels were needed to acquire all of the data simultaneously.

Figure 3.9. LMS SCADAS mobile DAQ system with BNC connectors attached

3.3.1 Acquisition software setup

With the hardware selected for the experiment the software needs to be setup to be able to accurately record for post-processing. The first step is specifying the channel and transducer characteristics that will be used for the test. There are three main identification fields that need to be selected which are the channel definition, transducer, and signal conditioning fields. All of the details for each field can be seen in appendix C-E. There are six main options that need to be reviewed in the channel definition field which are physical channel Id, On/Off, channel group Id, point, direction, and input mode as seen in Figure 3.10. The physical channel Id reflects which channel the sensor is plugged into. A triaxial accelerometer was plugged into the first three inputs, always in x, y, and z order. By clicking the check mark under On/Off the software will know to record that channel. Under channel group id the correct measured data group was selected so if the input is an accelerometer, vibration was chosen and if microphone then acoustic was chosen.



Channel Setup

Status: Verification OK

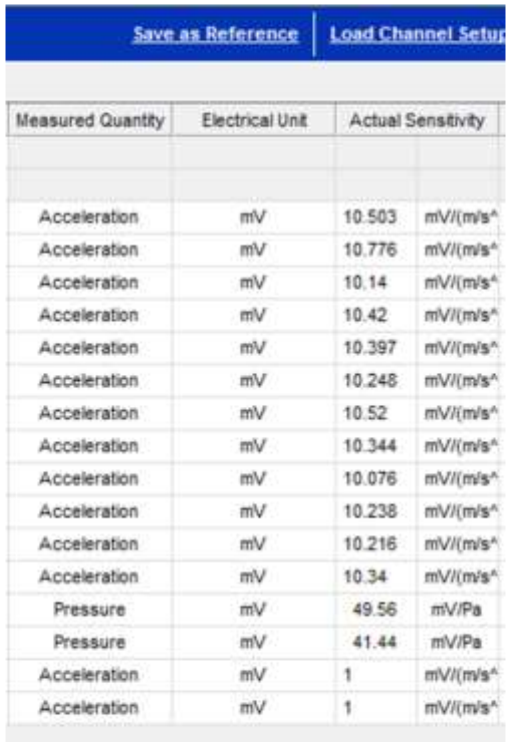
	PhysicalChannelId	OnOff	ChannelGroupId	Point	Direction	InputMode
1	Tacho1	☐	Tacho	EngineTacho	None	Voltage DC
2	Tacho2	☐	Tacho	DrvLineTacho	None	Voltage DC
3	Input1	☑	Vibration	RH Mount Eng	+X	ICP
4	Input2	☑	Vibration	RH Mount Eng	+Y	ICP
5	Input3	☑	Vibration	RH Mount Eng	+Z	ICP
6	Input4	☑	Vibration	RH Mount Body	+X	ICP
7	Input5	☑	Vibration	RH Mount Body	+Y	ICP
8	Input6	☑	Vibration	RH Mount Body	+Z	ICP
9	Input7	☑	Vibration	LH Mount Body	+X	ICP
10	Input8	☑	Vibration	LH Mount Body	+Y	ICP
11	Input9	☑	Vibration	LH Mount Body	+Z	ICP
12	Input10	☑	Vibration	LH Mount Eng	+X	ICP
13	Input11	☑	Vibration	LH Mount Eng	+Y	ICP
14	Input12	☑	Vibration	LH Mount Eng	+Z	ICP
15	Input13	☑	Acoustic	FrRi	S	ICP
16	Input14	☑	Acoustic	FrLe	S	ICP
17	Input15	☐	Acoustic	LH_Strut	+Z	ICP
18	Input16	☐	Acoustic	RH_Strut	+Z	ICP

Vibration
Acoustic
Other
Static

Figure 3.10. Sections that need to be updated in the channel identification group

Under the column labelled “Point” (Figure 3.10) a description of where the sensor was attached was inputted. For example, for the accelerometer attached to the body side of the engine mount, RH Mount Body was inputted. Direction needs to reflect what axis of the accelerometer is plugged into that input and the orientation of the accelerometer on the vehicle. The software was configured so that positive x always faces the rear of the vehicle, positive y faces the right hand side, and z faces up. If the accelerometer was mounted any other way then it needs to be changed in the direction section to reflect that change. All of the sensors used were integrated circuit piezoelectric(ICP) sensors so under input mode ICP was chosen.

There were four main selections needed for the transducer group, measured quantity, electrical unit, actual sensitivity, and the units of the actual sensitivity as seen in Figure 3.11.



Measured Quantity	Electrical Unit	Actual Sensitivity	
Acceleration	mV	10.503	mV/(m/s^
Acceleration	mV	10.776	mV/(m/s^
Acceleration	mV	10.14	mV/(m/s^
Acceleration	mV	10.42	mV/(m/s^
Acceleration	mV	10.397	mV/(m/s^
Acceleration	mV	10.248	mV/(m/s^
Acceleration	mV	10.52	mV/(m/s^
Acceleration	mV	10.344	mV/(m/s^
Acceleration	mV	10.076	mV/(m/s^
Acceleration	mV	10.238	mV/(m/s^
Acceleration	mV	10.216	mV/(m/s^
Acceleration	mV	10.34	mV/(m/s^
Pressure	mV	49.56	mV/Pa
Pressure	mV	41.44	mV/Pa
Acceleration	mV	1	mV/(m/s^
Acceleration	mV	1	mV/(m/s^

Figure 3.11. Selections needed from the transducer group

For this experiment accelerometers and microphones were used, which measure acceleration and pressure. The other three sections are based on the specifications of the sensor. The units that the sensors output electrically and what the calibration is for all inputs with the correct units for the calibration numbers was inputted into the rest of the options for the transducer field. Options for the signal conditioning field were left as default settings. The microphones were calibrated using the settings seen in Figure 3.12.

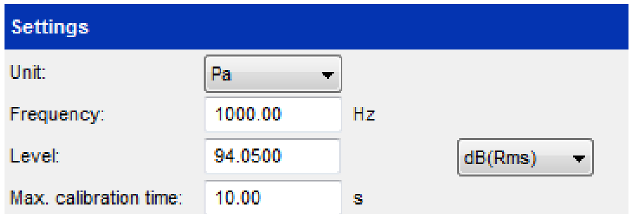


Figure 3.12. Calibration setting for microphones

Since the magnitude of acceleration each accelerometer will experience is unknown, all of the accelerometers went through a process of adjusting the window that will be recorded before the test. This is necessary to amplify the incoming signals before digitizing them. The gain should be such that the optimum (maximum) number of ADC bits is being used (Software n.d.). LMS Test.Lab has an integrated autorange function to accomplish this task. The accelerometers were autoranged for each road profile tested.

3.4 4-Poster Test Rig

To create vehicle responses nearly identical to those generated by real road surfaces, a 4 poster test rig was used to apply vertical forces through the tire of a vehicle. An example can be seen in Figure 3.13.

Figure 3.13. A hydraulic 4 poster test rig

These systems simulate a diverse number of road conditions, from small road surface vibrations to high-velocity pothole strikes. The machines are used to perform validation, durability, buzz, squeak and rattle (BSR), and noise, vibration and harshness (NVH) testing. A block road profile was used similar to the one seen in Figure 3.14. The profile was 28 seconds long. This profile was chosen due to its continuous input. Continuous input was needed in order to induce more instances of the cavitation noise.

Figure 3.14. Example of block layout

3.5 Subjective Evaluation Rating

With the objective measurements recorded there is a need to be able to compare that to what the subjective annoyance perception of the cavitation noise is in the cabin of the vehicle. In order to do that a 1-10 rating scale is used similar to SAE J1060 seen in Figure 3.15. The SAE standard is used as a rating scale for subjective evaluations of noise and discomfort in motor vehicles. In this part of the test an expert evaluator sits in the vehicle and listens while the vehicle goes over the simulated road surfaces and rates the sound in the cabin based on the rating scale. The rating procedure is performed in three steps of progressive refinement. The first step concerns the estimated class of various raters. At this point this procedure selects a broad range of numerical categories. The next step of the rating procedure is choosing the customers perception, leads to narrowed numerical categories. The final step is the judgment of whether the disturbance is unacceptable, poor, borderline, acceptable, fair, and various degrees of good.

	1	2	3	4	5	6	7	8	9	10
Attribute Performance	Not Acceptable		Poor		Borderline	Acceptable	Fair	Good	Very Good	Excellent
Customer Perception	Very Dissatisfied				Somewhat Dissatisfied	Fairly Well Dissatisfied		Very Satisfied	Completely Satisfied	
Perceptible By	All Customers			Average Customer		Critical Customer		Trained Observer		Not Perceptible

Figure 3.15. Subjective Annoyance Rating Scale

3.6 Process of Experiment

A mid-size sedan was used as the test vehicle. Three hydraulic engine mounts were tested, and they are henceforth labeled as A, B, and C. The characteristics of each of the mounts are summarized in Table 3.3.

Table 3.3 Background of mounts used in experiment

Mount	Background of Mount
A	Mount was returned due to complaint Unusual Engine Noise while Driving
B	Mount was modified from original design to reduce the effects of cavitation
C	As built mount with no complaints

Engine mount A was installed in the test vehicle. Two triaxial accelerometers were fixed to the mount, one on the engine side and one on the body attachment side as seen in Figure 3.4. Two microphones were placed in the vehicles cabin; one by the driver's left ear and one by the passenger's right ear as seen in Figure 3.16.

Using the 4 poster test rig, the road profile was simulated on the test vehicle. An expert evaluator sat inside the vehicle and gave a subjective evaluation score for the noise heard from inside the cabin during the run. Data from two test runs for each type of mount was acquired. After the data was acquired, the accelerometers were removed and mount B was installed in the test vehicle. Once mount B was installed the accelerometers were then reattached to the mount and the test was repeated in the same fashion as before.

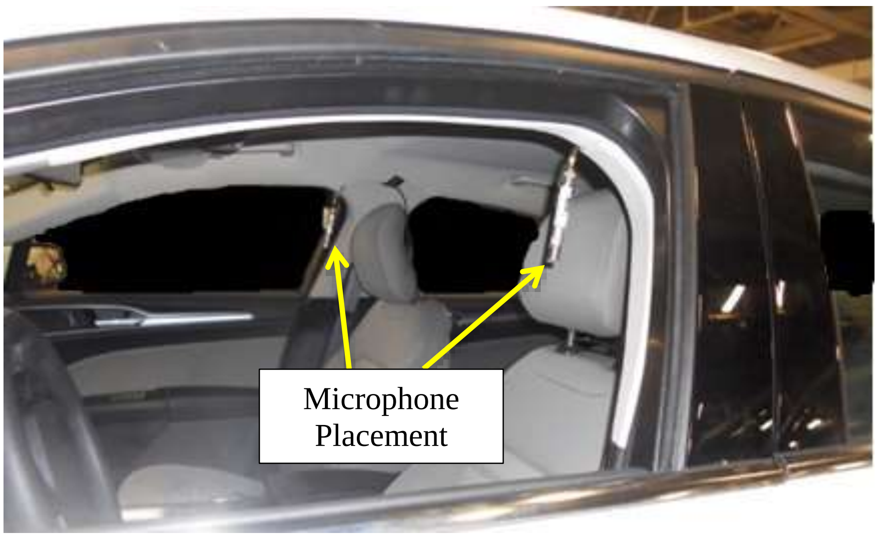


Figure 3.16. Microphone placement in cabin

Mount C was then tested in the same way as mount A and B. Using LMS Test.Labs the sound pressure that was acquired from inside the cabin was evaluated by psychoacoustic metrics loudness, sharpness, roughness, fluctuation strength, tonality.

3.7 Pearson's coefficient

The Pearson product-moment correlation coefficient is a measure of the strength of the linear relationship between two variables (LeBlanc 2004). It is referred to as Pearson's correlation or simply as the correlation coefficient. If the relationship between the variables is not linear, then the correlation coefficient does not adequately represent the strength of the relationship between the variables (Lane n.d.).

Pearson's r can range from -1 to 1. An r of -1 indicates a perfect negative linear relationship between variables, an r of 0 indicates no linear relationship between variables, and an r of 1 indicates a perfect positive linear relationship between variables. The equation can seen below.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \qquad \text{equation 3.1}$$

Where r = Pearson r correlation coefficient, n = number of value in each data set, $\sum xy$ = sum of the products of paired scores, $\sum x$ = sum of x scores, $\sum y$ = sum of y scores, $\sum x^2$= sum of squared x scores, $\sum y^2$= sum of squared y scores.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

A road profile was simulated under the vehicle with a 4 poster shaker. The data collected from the accelerometers and microphones were then used to develop an objective annoyance predictor metric of hydraulic engine mount cavitation using psychoacoustic metrics.

4.2 Filter Analysis

Various filters such as bandstop, bandpass, low pass, and highpass were used to isolate the cavitation noise in the acoustic data. Headphones were used to listen for the suspect noise while applying filters in order to isolate the noise to a certain frequency range. Graphic user interface of this operation can be seen in Figure 4.1.

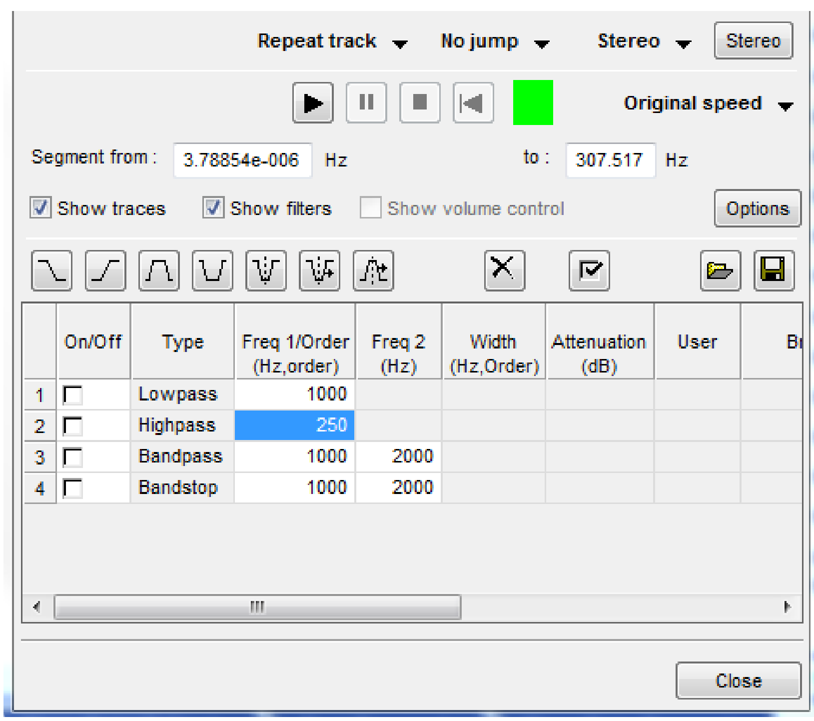


Figure 4.1. Audio playback filter analysis

It was found that the noise was around 300-600Hz range. Using a portion of the sound that encompasses two impacts an A-weighted power spectral density color map was processed with a resolution of 5Hz seen in Figure 4.2.

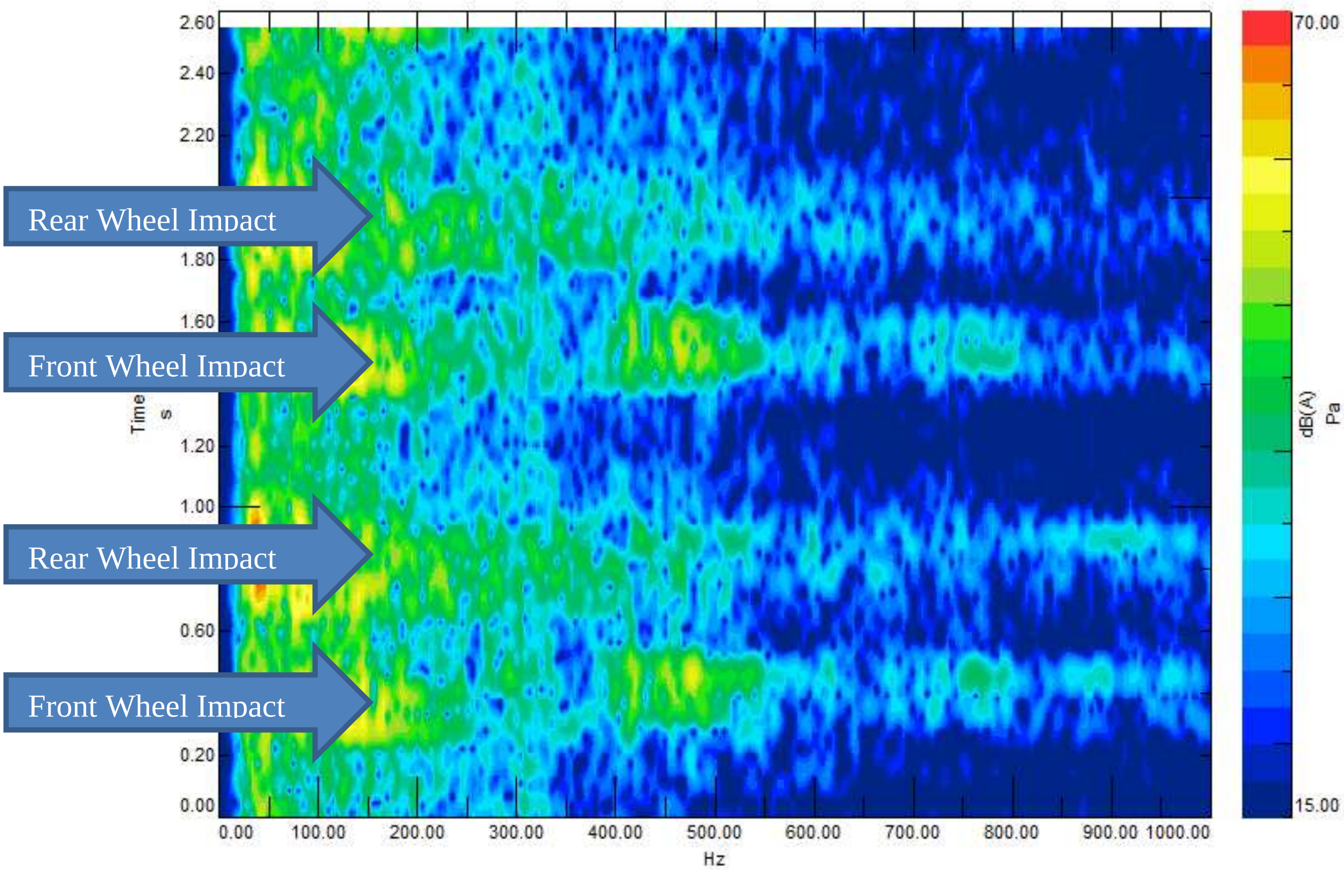


Figure 4.2. Spectrum color map of vehicle going over two impacts

Since cavitation occurs when the engine oscillates, the cavitation noise should be heard when the front of the vehicle goes over an impact and not when the rear does. By viewing the color map in Figure 4.3 there is a noise that is only prevalent on front wheel impact and not on rear wheel impact.

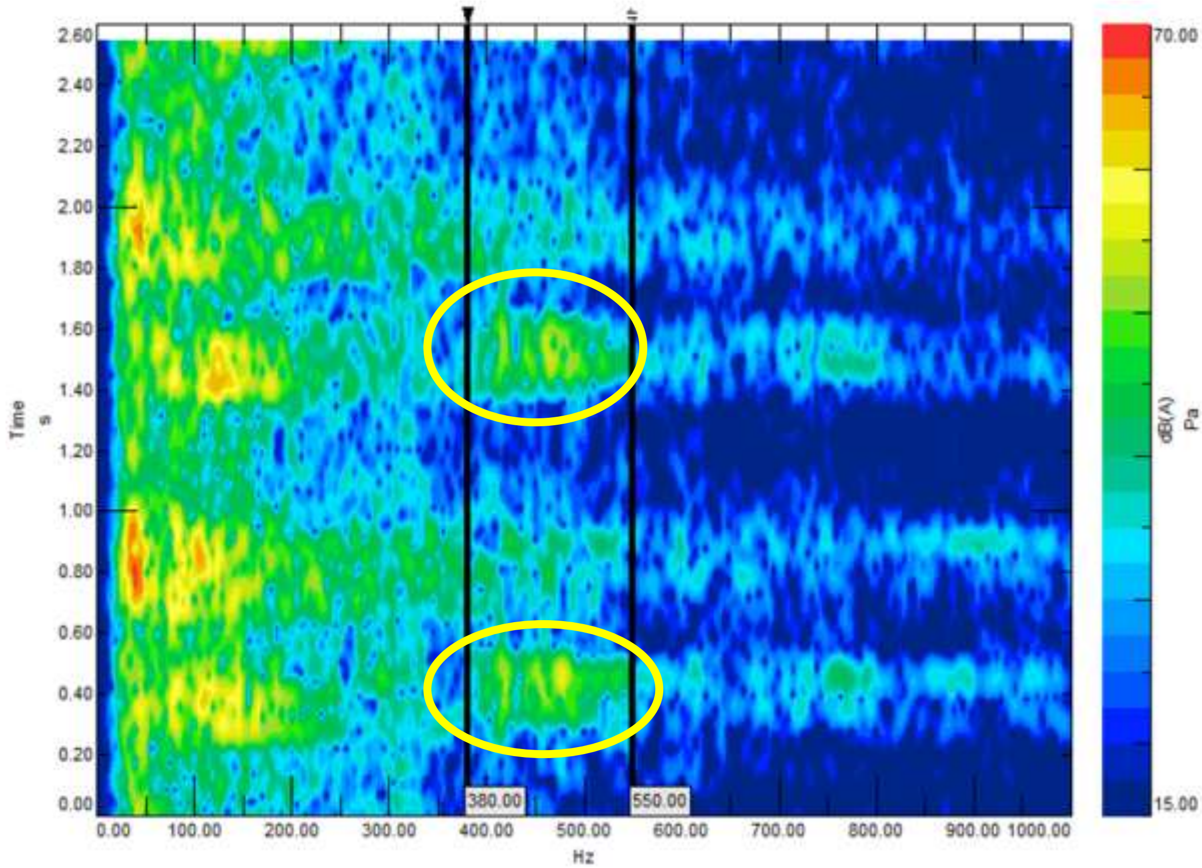


Figure 4.3. Cavitation noise on color map

A moving average power spectral density was calculated at 6 averages per second with a 1 Hz resolution in order to compare all 3 mounts (Figure 4.4).

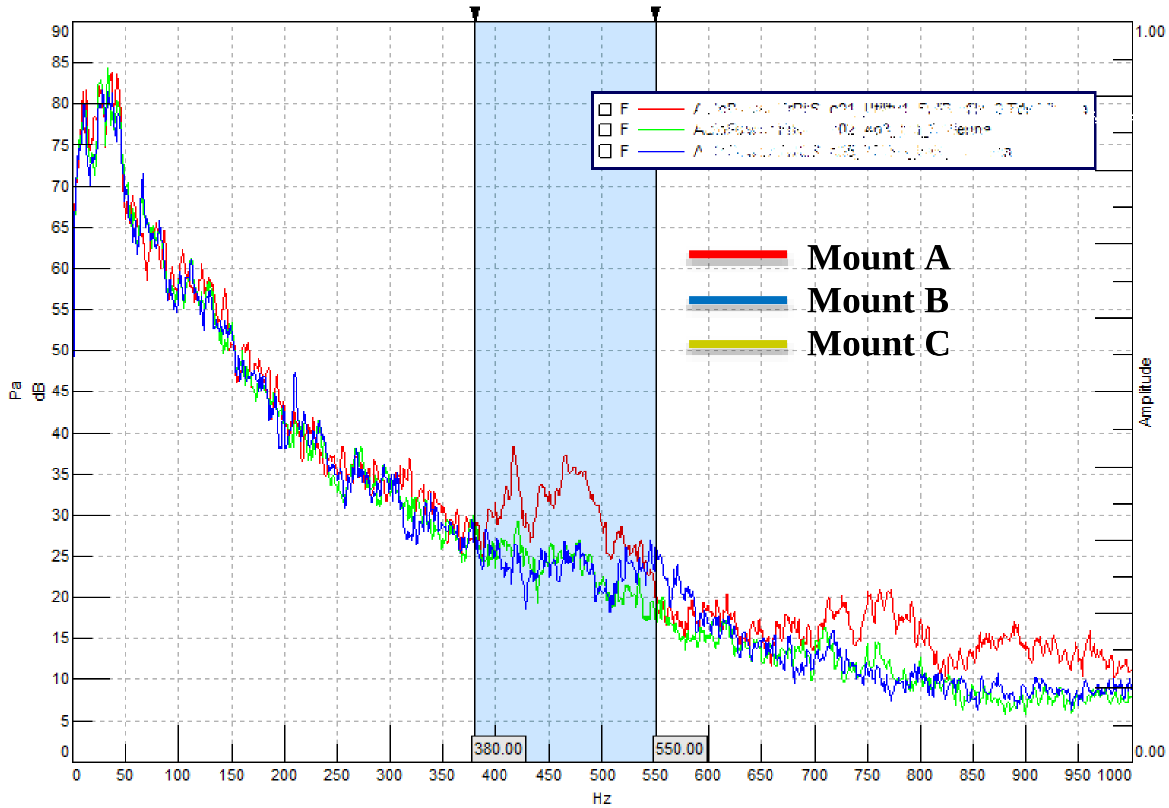


Figure 4.4 Frequency response of each mount

With the frequency range found, the microphone frequency response curve was compared to the accelerometer data to validate that the accelerometers were reading the same range. The comparison of all three mount's body mounted accelerometer x, y, and z can be seen figures 4.5 to 4.7.

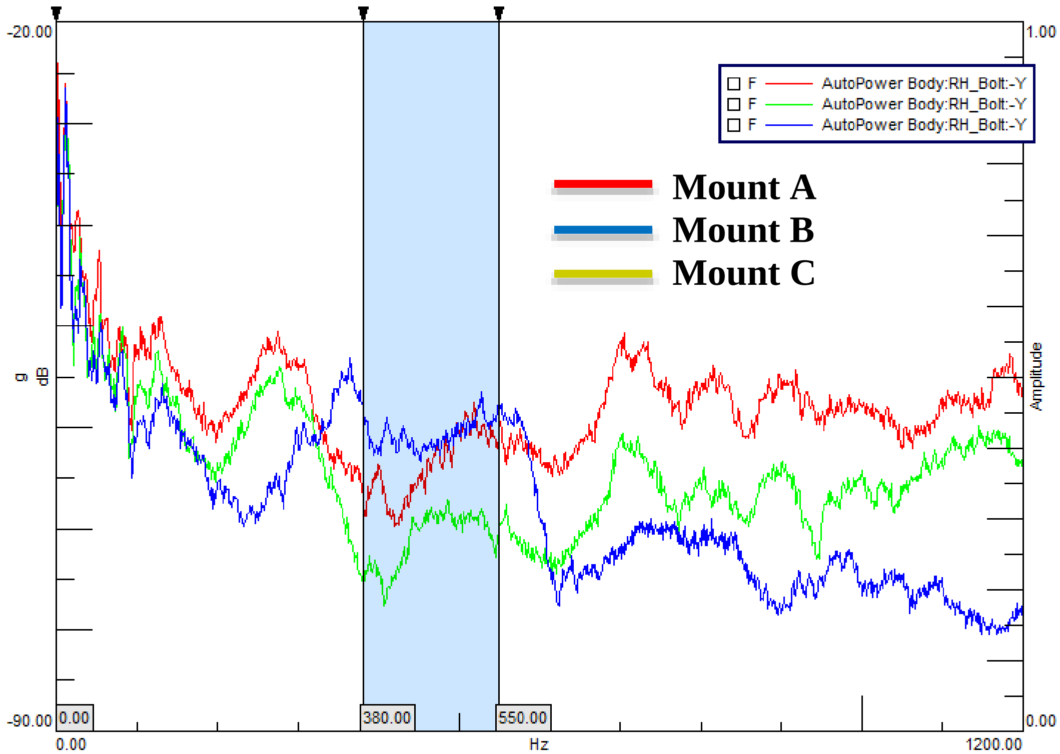


Figure 4.5 Acceleration in Y axis on the body side bolt for all three mounts

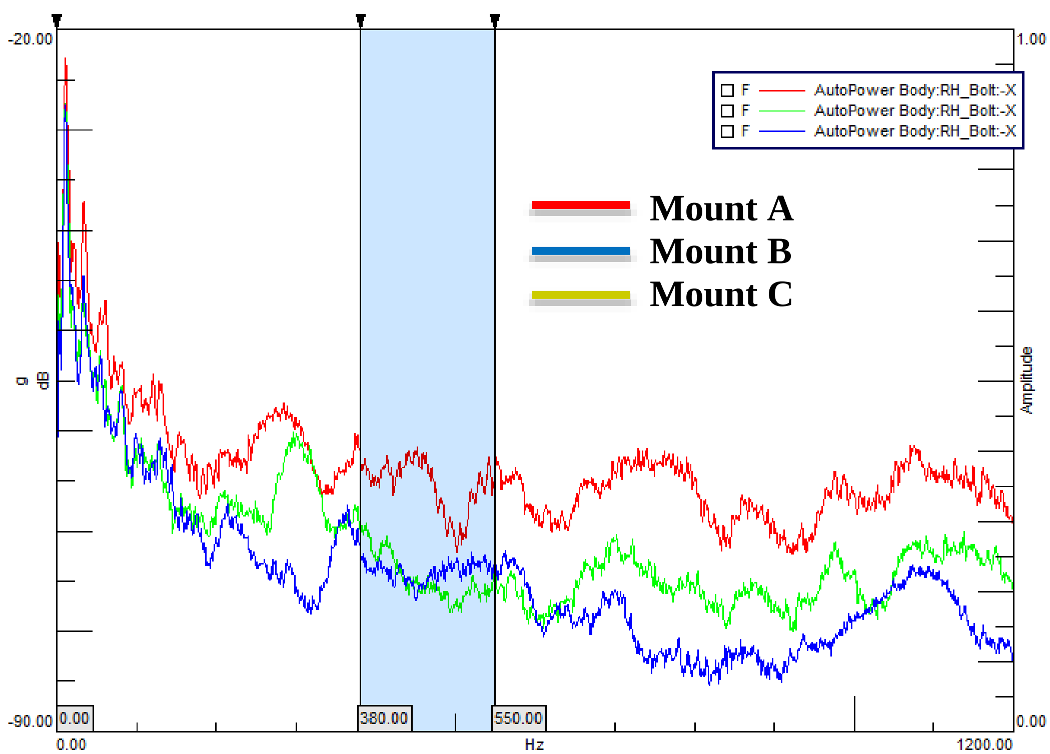


Figure 4.6 Acceleration in X axis on the body side bolt for all three mounts

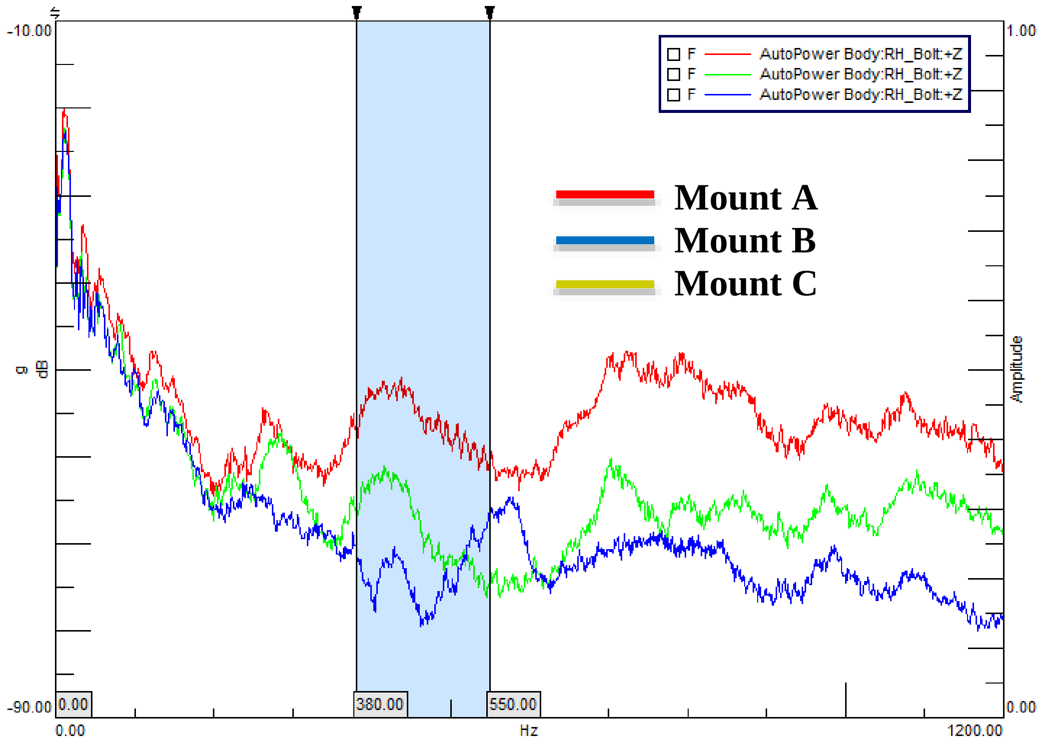


Figure 4.7 Acceleration in Z axis on the body side bolt for all three mounts

X and Z axis correlate well to the microphone data though the Y axis does not. The Y axis vibrations are less of a contributor to the noise.

4.3 Psychoacoustic Analysis

The results of the subjective evaluation were used to obtain a set of ratings for the three engine mounts. During the process of analyzing the objective data they all were compared to the subjective ratings. The subjective ratings from each of the mounts can be seen in Table 4.4.

Table 4.1 Subjective Rating of each Mount

Mount	Subjective Rating
A	6.25
B	6.5
C	7

Before developing the objective predictor metric, the individual relationships between each of the calculated psychoacoustic metrics and the subjective ratings were examined. These relationships were derived from simple linear regression, using the psychoacoustic metric singular values as predictor variables. The strength and significance of each regression model were then analyzed to determine which metrics correlate best to the subjective ratings. The strength of each model was determined based on: Coefficient of determination (R^2) and Pearson's rank correlation coefficient (*r*). During this process the metrics evaluated were prominence ratio, roughness, loudness, fluctuation strength, and tone to noise ratio. The correlation of each of the metrics can be seen in Table 4.5.

Table 4.2 Determination of psychoacoustic metric singular values

Prominence Ratio (Pr)						
Mount	Average	5% percentile	10% percentile	50% percentile	90% percentile	95% percentile
A	2.33	1.47	1.55	1.96	3.47	4.32
B	2.04	1.56	1.65	1.94	2.45	2.53
C	1.75	1.4	1.46	1.71	2.11	2.18
R^2=	0.964	0.358	0.399	0.933	0.794	0.717
r=	-0.982	-0.599	-0.631	-0.966	-0.891	-0.847

Tone-to-Noise Ratio (Tn)						
Mount	Average	5% percentile	10% percentile	50% percentile	90% percentile	95% percentile
A	0.37	0.28	0.28	0.34	0.48	0.54
B	0.37	0.29	0.31	0.36	0.45	0.49
C	0.31	0.25	0.26	0.3	0.36	0.38
R^2=	0.893	0.703	0.318	0.617	0.992	0.999
r=	-0.945	-0.839	-0.564	-0.786	-0.996	-1.000

Roughness (R)						
Mount	Average	5% percentile	10% percentile	50% percentile	90% percentile	95% percentile
A	0.72	0.33	0.38	0.68	1.08	1.3
B	0.5	0.22	0.23	0.41	0.84	1.22
C	0.43	0.23	0.26	0.41	0.59	0.65
R^2=	0.786	0.489	0.383	0.571	0.969	0.952
r=	-0.887	-0.700	-0.619	-0.756	-0.984	-0.976

Loudness (N)						
Mount	Average	5% percentile	10% percentile	50% percentile	90% percentile	95% percentile
A	18.12	10.71	11.95	18.29	23.85	24.94
B	12.64	8.54	9.15	12.72	15.96	16.9
C	12.18	8.27	8.91	12.27	15.28	15.71
R^2=	0.639	0.669	0.641	0.637	0.641	0.686
r=	-0.800	-0.818	-0.801	-0.798	-0.801	-0.828

Fluctuation Strength (F)						
Mount	Average	5% percentile	10% percentile	50% percentile	90% percentile	95% percentile
A	1.67	1.41	1.47	1.67	1.9	1.95
B	1.56	1.28	1.35	1.55	1.79	1.82
C	1.47	1.24	1.28	1.45	1.66	1.71
R^2=	0.940	0.781	0.888	0.942	0.980	0.944
r=	-0.969	-0.884	-0.942	-0.971	-0.990	-0.972

Based on the correlation study, the best correlations are highlighted in grey as seen in Table 4.5. The highest correlated values to use as predictor variables were mean prominence ratio, 90th percentile tone-to-noise, 90th percentile roughness, 95th percentile loudness, and 90th percentile fluctuation strength. Most of the metrics were highly correlated, which can be seen in Table 4.6. It was also observed that loudness was the least correlated metric highlighted in grey in Table 4.6. Based on these results, only mean prominence ratio, 9th percentile tone-to-noise, 90th percentile roughness, and 90th percentile fluctuation strength were considered for inclusion in the objective predictor metric for hydraulic engine mount cavitation.

Table 4.3 Estimated model parameters and measures of model strength for each psychoacoustic metric

Predictor Variable	A	B	C	R^2	*r*
Pr_{avg}	2.33	2.04	1.75	0.964	-0.982
Tn_{95}	0.54	0.49	0.38	0.999	-1.000
R_{90}	1.08	0.84	0.59	0.969	-0.984
N_{95}	24.94	16.9	15.71	0.686	-0.828
F_{90}	1.9	1.79	1.66	0.980	-0.990

4.4 Objective Predictor Metric

An objective predictor metric for hydraulic engine mount cavitation was developed by combining the set or a particular subset of the four psychoacoustic metrics found to be significantly correlated to subjective ratings on an individual level. The psychoacoustic metrics were combined through multiple linear regression. Each metric was considered a potential predictor variable in a predictor metric model. All possible subsets of these predictor variables were used to model the subjective ratings, and the strength of each model was determined. The same measures of model strength that were previously used to analyze the single linear regression models were again used to analyze the multiple linear regression models. Additionally, two other strength measures were utilized. These were sum of residuals, which is a measure of model fit, and Mallow's C_p criterion, which measures model bias. For C_p and sum of residuals, smaller values indicate an unbiased and simpler model.

Table 4.4 The variables used in determining the best predictor model and their correlation

Predictor Variables	R^2=	*r*=	C_p=	Sum of residuals
Pr_{avg} , Tn_{95}, F_{90}	1.0000	1.0000	3.0000	0.00069
Tn_{95}, R_{90}, F_{90}	1.0000	1.0000	3.0000	0.00030
Pr_{avg} , Tn_{95}, R_{90}	1.0000	1.0000	3.0000	0.00449
Pr_{avg}, R_{90}, F_{90}	0.9999	1.0000	5.0001	0.00866
Tn_{95}, F_{90}	0.8262	0.9090	5.2103	0.33463
Tn_{95}, R_{90}	0.0116	0.1077	90.1433	0.85458
Tn_{95}, Pr_{avg}	0.1190	-0.3450	12.4016	0.82762
R_{90}, Pr_{avg}	0.9880	0.9940	5.0122	0.09634
F_{90}, R_{90}	0.9413	0.9702	5.0624	0.21341
F_{90}, Pr_{avg}	0.8876	0.9421	5.1266	0.29228

The strength measures for several of the examined multiple linear regression models can be seen in Table 4.7. The model which had the best fitting values is highlighted in grey as seen in Table 4.7. This model was chosen as the objective measure, for the predictor metric for hydraulic engine mount cavitation. The model is given by

$$A = -5.89 * Tn_{95} - 2.83 * R_{90} + 6.57 * F_{90} \qquad \text{equation 4.1}$$

When using three predictor variables it was found all were highly correlated to the subjective ratings. It was found that Pr_{avg}, Tn_{95}, F_{90} and Tn_{95}, R_{90}, F_{90} had almost matching strength measures though Tn_{95}, R_{90}, F_{90} had the lowest sum of residuals.

4.5 Summary

The method used in this research to develop the predictor metric was a method of using raw time domain recordings and calculating psychoacoustic metrics. This method has vulnerabilities due to it being susceptive to random noise inside the vehicle. A way of lessening this effect is to apply a bandpass filter for the frequency range found to represent the noise. By doing this all other noises not in that frequency range will be cut off. The frequency range was found during this research in chapter 4.2. Even though a predictor metric with high correlation to the subjective ratings was found, it does not mean that it will have the same high correlation for other mounts that were not part of the study. Further work needs to be done to fully evaluate the predictor metric (equation 4.1) developed during the research against other mounts and test conditons.

CHAPTER 5

CONCLUSION

5.1 Overview

An objective metric was developed to predict the annoyance of hydraulic engine mount cavitation that highly correlated with subjective ratings.

During this research, subjective ratings for each of the three mounts were acquired from an expert evaluator. A filter analysis was performed in order to find the frequency range that the noise was operating in. Multiple psychoacoustic metrics were applied in order to find the best correlating to the subjective ratings; with average, 5^{th} percentile, 10^{th} percentile, 50^{th} percentile, 90^{th} percentile, and 95^{th} percentile of each metric being evaluated. Through that process the best singular predictor variables that best correlated to the subjective ratings was found. Those singular predictor variables were then grouped into all possible combinations as seen in Table 4.7. Then through multiple regression analysis the best combination of predictor variables was found. That combination of predictor variables was used as the objective predictor metric for hydraulic engine mount cavitation. The psychoacoustic metrics found to be the best correlated were 95^{th} percentile tone to noise, 90^{th} percentile roughness, and 90^{th} percentile fluctuation strength.

5.2 Recommendations for Future Work

Further work needs to be done in order to test this metric against other engine mounts. Other possible refinements could include only testing the frequency range that the sound is in. By doing this it would remove the effects of random noise inside the cabin on the psychoacoustic metrics.

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Appendix A: Specifications for model 356A15 triaxial accelerometer

Performance		
Sensitivity (±10 %)	100 mV/g	10.2 mV/(m/s²)
Measurement Range	±50 g pk	±490 m/s² pk
Frequency Range (±5 %)	2 to 5000 Hz	2 to 5000 Hz
Frequency Range (±10 %)	1.4 to 6500 Hz	1.4 to 6500 Hz
Resonant Frequency	≥25 kHz	≥25 kHz
Broadband Resolution (1 to 10000 Hz)	0.0002 g rms	0.002 m/s² rms
Non-Linearity	≤1 %	≤1 %
Transverse Sensitivity	≤5 %	≤5 %
Environmental		
Overload Limit (Shock)	±7000 g pk	±68600 m/s² pk
Temperature Range	-65 to +250 °F	-54 to +121 °C
Base Strain Sensitivity	0.001 g/με	0.01 (m/s²)/με
Electrical		
Excitation Voltage	20 to 30 VDC	20 to 30 VDC
Constant Current Excitation	2 to 20 mA	2 to 20 mA
Output Impedance	≤200 Ohm	≤200 Ohm
Output Bias Voltage	8 to 12 VDC	8 to 12 VDC
Discharge Time Constant	0.2 to 0.8 sec	0.2 to 0.8 sec
Settling Time (within 10% of bias)	<5 sec	<5 sec
Spectral Noise (1 Hz)	80 µg/√Hz	785 (µm/sec2)/√Hz
Spectral Noise (10 Hz)	15 µg/√Hz	147 (µm/sec2)/√Hz
Spectral Noise (100 Hz)	5 µg/√Hz	49 (µm/sec2)/√Hz
Spectral Noise (1 kHz)	2 µg/√Hz	20 (µm/sec2)/√Hz
Spectral Noise (10 kHz)	1 µg/√Hz	9.8 (µm/sec2)/√Hz
Physical		
Sensing Element	Ceramic	Ceramic
Sensing Geometry	Shear	Shear
Housing Material	Titanium	Titanium
Sealing	Hermetic	Hermetic
Size - Height	0.55 in	14.0 mm
Size - Length	0.80 in	20.3 mm
Size - Width	0.55 in	14.0 mm
Weight	0.37 oz	10.5 gm
Electrical Connector	1/4-28 4-Pin	1/4-28 4-Pin
Electrical Connection Position	Side	Side
Mounting Thread	10-32 Female	10-32 Female
Mounting Torque	10 to 20 in-lb	113 to 225 N-cm

Appendix B: Specifications for model 4942 microphone and 2671 pre-amplifier

Capacitance	14 pF
Diameter	1/2 inch
Dyn. Range	14.6 - 146 dB
Freq. Range	6.3 - 16000 Hz
Inherent Noise	14.6 dB A
Lower Limiting Frequency - 3dB	4 Hz
Optimised	Diffuse Field
Polarization	Prepolarized
Polarisation Voltage	
Preamplifier Included	
Pressure Coefficient	-0.01 dB/kPa
Sensitivity	50 mV/Pa
Standards	
TEDS UTID	
Temperature Coefficient	-0.006 dB/ºC
Temperature Range	-40 - 150 ºC
Venting	Rear
Input Type	

Diameter	1/2 Inch
Optimised	CCLD
Connector at Preamplifier	BNC
Connector at Instrument/Cable	
Calibration Facility	
Polarization Voltage Support	
Supply Voltage	28 V
Max Output Voltage	7 V
Max Output Current	19 mA
Frequency Range	20-50000 Hz
Attenuation	<0.35 dB
Noise A-weighted, typical	4 µV
Noise 22 4 Hz to 300 kHz, typical	15 µV
Input Impedance	1.5||0.4 G Ω ||pF
TEDS UTID	1025 from serial number 2264319

Appendix C-1: LMS Test.Lab Channel definition fields

Identification field	Explanation
OnOff	A switch to make the channel active. If on, it will be used in the following acquisition.
ChannelId	A sequential number assigned by the software. Cannot be altered by the user.
UserChannelId	A lengthy text string that can be used to annotate a particular channel
PhysicalChannelId	An identification string assigned by the software according to the physical input module to which the channel is connected. E.g. Tacho1: first input on a PDT module. This cannot be altered by the user.
ChannelGroupId	The name of the measured data group to which the channel belongs. Must be selected from the groups that have been defined.
Reference	A switch that declares this channel as a reference channel for FRF calculation .
DynamicRange	Lists the dynamic range in dB of the input module
Range	Selected input range for the channel in electrical units.
Range EU	Selected input range for the channel in engineering units. This is derived from the Range divided by the Actual Sensitivity.

Identification field	Explanation
Point	A field in which you can describe the point on the structure under test where the transducer is located. This can be in a number of formats: free, geometry, etc. The standard geometry format is "comp:node", where "comp" is the name of the component (to which the node belongs) and "node" is the name of the node (often a number). Default value is PointX where X is a sequential number.
Direction	Measurement direction for the point. Can be selected from the options in the dropdown menu.

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Appendix C-2: LMS Test.Lab Channel definition fields

Identification field	Explanation
Range Format	Determines whether Range EU is listed in a Linear, dB or Log format.
InputMode	Sets the type of transducer input. Must be selected from the available fields which will depend on the input module. Types are Voltage, ICP or Charge. Also defines the AC/DC coupling. For a PQBA module, 1/1 bridge (AC), 1/2 bridge (AC) and 1/4 bridge (AC) mode are available. For a PQBA II or BDS4 module, additionally to the bridge modes, also balanced current and dynamic strain modes are possible. The dynamic strain mode is the same as input mode "Balanced A, 2 wire AC" with the difference that for the dynamic strain input mode, the Sensitivity will be automatically calculated with formula: sensitivity = R*I*k with R the gage resistance, I the supply voltage and k the strain gage factor. For a VB8 module, all above bridged modes, voltage AC, voltage DC, ICP, potentiometer, sensor with excitation, differential sensor with excitation, single ended and sensor with 15V excitation ** For a DB8 module, Voltage DC, potentiometer, sen sensor with excitation, differential sensor with excitation, single ended and sensor with 15V excitation are available. For a DB8-II module, Voltage DC, potentiometer, ICP, sensor with excitation, differential sensor with excitation, single ended, sensor with 15V excitation and sensor with 15V excitation, inverted, are available.
Coupling*	Defines the input coupling which must be selected from the options that are dependent on the frontend module.
DCOffset	Defines the DC Offset applied by the tacho module in order to achieve the trigger level defined in Tracking Setup.
LPFilterOn	If 'On' a low pass filter is used during acquisition. Use the LPCutoff field to specify the cutoff frequency. In signature workbooks the LPFilterCharacteristics and LPFilterOrder fields specify the filter

Appendix D-1: LMS Test.Lab Transducer fields

Identification field	Explanation
Transducer Manufacturer	The name of the company that manufactured the transducer.
Transducer Type	Defines whether the transducer is an accelerometer, a microphone, or some other type.
Serial number	Serial number of the transducer.
Transducer Description	User-defined description of the transducer.
Actual sensitivity	The sensitivity is the electrical output per measured unit (Electrical unit/EU). The actual value is the value as determined by a calibration procedure and is the value that will be used for the measurements.
Actual sensitivity unit	This is the unit used to describe the *actual* sensitivity value e.g. mV/g or mV/(m/s²).
Calibration factor	This is the output in engineering units per measured electrical unit (EU/Electrical). The value is coupled with the Actual Sensitivity value.
Calibration factor unit	This is the unit used to describe the Calibration factor e.g. g/mV or (m/s²)/mV.
Nominal sensitivity	The manufacturer supplies the nominal value for the transducer. This value is used to set initial ranges for the calibration procedure and as a check that the measured value is good.
Nominal sensitivity unit	This is the unit used to describe the nominal sensitivity value e.g. mV/g.
Offset	The value of the offset of the transducer (electrical output when load = 0) as determined by a calibration procedure.
Offset unit	The unit for the offset e.g. mV.
Offset zeroing	In this field you can define the offset zeroing strategy: ▪ **Never**: by default, the offset of this channel will not be changed during zeroing ▪ **Once**: the offset of this channel will be changed during zeroing in the Acquisition Setup sheet, but not in the Measure sheet. ▪ **Always:** the offset of this channel will be changed during zeroing in the Acquisition Setup sheet and in the Measure sheet

Appendix D-2: LMS Test.Lab Transducer fields

Identification field	**Explanation**
Due for calibration on	Date when the transducer should be calibrated again e.g. Wed Jan 02 2005 or 2005-01-08 01:00:00 or 01/20/05 (MM/DD/YY).
Calibration valid for	Number of days that the calibration value is valid for.
Electrical unit	The measured electrical unit.
Measured Quantity	Specifies the physical quantity measured by the transducer.(*)
Polarity	Can be either a positive (+) or negative (-) sign.

Appendix E: LMS Test.Lab Signal conditioning fields

Identification field	**Explanation**
Pre-weighting*	Pre-weighting applied by conditioning unit. Default weighting is Linear.
FrontEndWeighting**	Weighting applied by the frontend.
TimeIntegration	Integration of time data applied by the frontend. Available options are None, Single or Double integration. Not available in SignatureRealTime acquisition workbooks
TimeTransformation	Only available in the HighSpeedRecording workbook. When switched on, it allows to show acceleration data in velocity and/or displacement format in the HighSpeedMonitoring workbook.
Pre-gain1 Calibration, Pre-gain2 Calibration	Preamplifier gain set by conditioning unit that is used during calibration.
Gain format	Defines whether the pre-gain is expressed as a multiplication factor (linear) or in dB.

Appendix F-1: Mount B Overall Data

Run 1 (dB)	Run 2 (dB)	Difference from Runs	Run 1 (dB)	Run 2 (dB)	Difference from Runs
95.47	95.43	0.04	93.23	92.80	0.43
94.42	94.51	-0.09	92.13	92.26	-0.13
94.14	94.37	-0.23	92.00	92.06	-0.06
93.66	93.95	-0.29	91.72	92.34	-0.61
93.16	93.80	-0.64	92.66	93.81	-1.16
93.48	94.13	-0.65	94.11	94.80	-0.69
93.95	94.51	-0.57	94.54	94.72	-0.18
94.25	94.69	-0.45	94.08	94.15	-0.07
94.56	95.27	-0.71	93.65	93.95	-0.30
95.67	95.99	-0.32	93.70	93.68	0.01
95.83	95.51	0.31	93.36	92.82	0.54
94.71	94.53	0.18	92.74	92.93	-0.19
93.78	93.20	0.58	93.41	94.16	-0.75
92.57	91.55	1.02	94.07	94.58	-0.51
91.97	92.54	-0.58	93.99	94.79	-0.80
93.51	94.30	-0.79	94.59	95.60	-1.00
94.46	94.35	0.11	95.51	96.07	-0.56
93.89	93.61	0.28	95.85	96.15	-0.30
93.65	94.18	-0.53	96.73	97.55	-0.82
94.29	94.94	-0.64	98.55	98.76	-0.21
94.54	94.74	-0.20	98.78	98.05	0.74
93.88	93.38	0.49	97.16	96.92	0.25
92.73	92.41	0.32	97.51	98.51	-1.00
92.65	93.31	-0.66	100.52	100.34	0.17
93.89	94.69	-0.80	101.45	99.78	1.67
94.82	95.18	-0.36	99.39	97.14	2.24
94.38	94.36	0.02	96.72	96.73	-0.01
93.32	93.77	-0.44	97.24	97.38	-0.14
93.81	94.92	-1.10	97.05	96.39	0.66
95.42	95.70	-0.28	95.59	95.01	0.58
95.62	95.12	0.50	94.60	94.53	0.07
94.59	94.71	-0.12	94.62	94.62	0.00
94.59	95.05	-0.46	94.95	95.04	-0.09
95.16	95.64	-0.47	95.92	96.48	-0.56
95.49	96.09	-0.60	97.61	98.01	-0.40
95.38	95.98	-0.60	98.36	98.10	0.26
95.56	96.13	-0.57	97.58	96.97	0.61
95.95	95.77	0.18	96.24	96.12	0.13
95.42	94.74	0.68	95.53	95.87	-0.34
94.73	94.60	0.14	95.13	95.61	-0.48
94.44	94.86	-0.42	94.76	95.27	-0.51
94.44	95.66	-1.21	94.71	95.10	-0.39

Appendix F-2: Mount B Overall Data Continued

Run 1 (dB)	Run 2 (dB)	Difference from Runs	Run 1 (dB)	Run 2 (dB)	Difference from Runs
95.69	97.13	-1.44	95.02	95.03	-0.01
97.61	98.38	-0.77	95.16	94.96	0.20
98.81	98.80	0.01	95.10	95.17	-0.08
98.54	97.82	0.72	95.30	95.63	-0.33
96.56	95.36	1.20	95.70	95.75	-0.05
93.96	93.21	0.75	95.62	95.55	0.06
93.03	93.32	-0.29	95.72	95.96	-0.24
93.96	94.72	-0.76	96.00	96.20	-0.21
95.15	95.61	-0.45	95.87	96.23	-0.37
95.49	95.89	-0.40	96.42	97.30	-0.88
96.22	96.70	-0.48	97.81	98.49	-0.68
96.92	96.53	0.39	98.63	99.30	-0.67
95.83	95.11	0.72	99.51	99.91	-0.40
94.66	95.11	-0.44	99.58	99.04	0.55
94.83	95.17	-0.34	97.82	96.95	0.87
94.58	95.21	-0.63	96.38	96.43	-0.05
95.38	96.05	-0.67	96.52	96.49	0.03
95.88	95.75	0.13	96.63	96.32	0.31
95.32	95.14	0.17	96.54	96.23	0.31
95.00	94.94	0.06	96.21	96.12	0.09
94.63	94.31	0.32	96.28	96.52	-0.24
94.03	93.59	0.44	97.02	96.84	0.18
93.42	93.45	-0.03	96.79	96.01	0.78
93.46	93.88	-0.42	95.42	95.08	0.34
93.54	93.77	-0.23	95.15	95.64	-0.49
92.93	93.47	-0.54	95.74	96.34	-0.59
93.11	93.99	-0.87	96.59	97.46	-0.88
94.85	95.87	-1.02	98.75	99.09	-0.34
96.72	97.39	-0.67	100.13	99.20	0.92
97.46	97.89	-0.43	99.13	97.17	1.96
97.70	97.66	0.04	96.21	94.46	1.75
97.13	96.31	0.82	94.13	93.89	0.24
95.27	94.31	0.97	93.91	94.15	-0.25
			93.66	94.02	-0.36
			93.71	94.51	-0.80
			94.06	94.33	-0.27

Appendix G-1: Mount C Overall Data

Run 1 (dB)	Run 2 (dB)	Difference from Runs	Run 1 (dB)	Run 2 (dB)	Difference from Runs
91.60	91.69	-0.09	92.59	92.71	-0.12
91.25	91.36	-0.10	94.29	94.43	-0.14
91.77	91.98	-0.21	95.97	96.06	-0.09
93.46	93.67	-0.21	96.57	96.55	0.02
94.93	95.14	-0.21	95.88	95.75	0.12
95.89	96.07	-0.18	94.64	94.53	0.11
95.73	95.78	-0.04	93.73	93.72	0.01
94.45	94.38	0.07	93.16	93.23	-0.07
92.84	92.79	0.05	92.26	92.33	-0.07
91.40	91.39	0.01	91.78	91.89	-0.11
90.07	90.07	0.00	93.35	93.50	-0.14
89.53	89.60	-0.07	94.98	95.11	-0.13
91.18	91.29	-0.12	95.97	96.07	-0.10
93.13	93.26	-0.13	95.88	95.91	-0.02
94.79	94.97	-0.18	95.02	94.96	0.06
95.33	95.44	-0.12	93.95	93.87	0.08
94.56	94.57	0.00	92.49	92.47	0.03
93.60	93.56	0.04	91.21	91.29	-0.08
92.46	92.41	0.06	91.03	91.23	-0.21
90.60	90.62	-0.02	92.91	93.16	-0.24
88.90	89.02	-0.12	94.93	95.07	-0.14
89.12	89.32	-0.20	96.12	96.24	-0.12
91.70	91.91	-0.21	96.54	96.61	-0.06
94.05	94.26	-0.21	95.94	95.87	0.07
95.61	95.77	-0.16	94.73	94.58	0.15
95.73	95.75	-0.03	93.19	93.09	0.11
94.84	94.78	0.06	92.05	92.08	-0.03
94.03	94.01	0.02	91.77	91.81	-0.04
93.39	93.42	-0.03	91.44	91.48	-0.05
92.68	92.68	0.00	93.31	93.42	-0.11
91.27	91.18	0.10	95.76	95.87	-0.11
91.30	91.40	-0.10	97.27	97.35	-0.08
93.62	93.78	-0.16	97.63	97.57	0.06
95.62	95.76	-0.14	96.75	96.52	0.24
96.65	96.70	-0.05	94.80	94.50	0.30
96.22	96.13	0.09	92.52	92.37	0.15
94.73	94.59	0.14	91.65	91.78	-0.13
92.91	92.79	0.12	92.90	93.08	-0.18
91.49	91.50	0.00	94.88	94.98	-0.10
91.82	91.97	-0.15	96.13	96.12	0.01
92.08	92.19	-0.11	96.56	96.49	0.07

Appendix G-2: Mount C Overall Data Continued

Run 1 (dB)	Run 2 (dB)	Difference from Runs	Run 1 (dB)	Run 2 (dB)	Difference from Runs
96.74	96.65	0.09	94.97	95.17	-0.20
96.79	96.73	0.06	94.63	94.69	-0.06
96.82	96.83	-0.01	93.89	93.98	-0.09
96.92	96.92	0.00	94.02	94.14	-0.12
96.16	96.12	0.04	93.76	93.82	-0.06
95.14	95.17	-0.03	93.96	94.11	-0.14
95.13	95.13	0.00	95.07	95.19	-0.12
94.67	94.63	0.04	95.20	95.26	-0.06
94.60	94.61	0.00	94.21	94.25	-0.05
95.18	95.14	0.04	93.89	93.99	-0.09
95.63	95.49	0.14	94.24	94.37	-0.13
95.80	95.62	0.18	94.07	94.29	-0.22
95.65	95.51	0.14	94.87	95.15	-0.29
95.04	94.98	0.06	95.93	96.06	-0.13
95.04	95.11	-0.07	95.34	95.33	0.01
96.00	96.08	-0.07	94.37	94.44	-0.07
95.84	95.79	0.04	94.62	94.74	-0.12
94.53	94.45	0.08	94.54	94.64	-0.10
94.12	94.10	0.01	95.01	95.16	-0.15
94.16	94.07	0.09	96.01	96.10	-0.09
93.61	93.52	0.10	95.99	95.95	0.04
93.67	93.68	0.00	95.47	95.40	0.08
94.16	94.20	-0.04	95.46	95.46	0.00
94.59	94.66	-0.08	95.16	95.24	-0.08
95.27	95.36	-0.10	94.86	95.03	-0.18
95.57	95.62	-0.05	95.88	96.09	-0.20
95.00	95.05	-0.05	97.41	97.54	-0.12
95.10	95.31	-0.22	97.82	97.83	-0.02
96.57	96.71	-0.15	96.80	96.77	0.03
96.74	96.66	0.08	95.16	95.17	-0.01
94.87	94.70	0.17	93.75	93.83	-0.07
93.78	93.82	-0.04	93.87	93.99	-0.13
94.35	94.38	-0.02	94.69	94.79	-0.10
94.44	94.50	-0.06	94.60	94.68	-0.08
95.35	95.51	-0.17	94.66	94.77	-0.11
96.08	96.17	-0.08	95.28	95.43	-0.15
95.83	95.83	0.01	95.42	95.59	-0.17
95.70	95.65	0.05	95.33	95.52	-0.19
95.25	95.17	0.08	95.66	95.83	-0.17
94.06	94.08	-0.02	95.18	95.23	-0.05
94.09	94.33	-0.24			

Appendix H-1: Mount A Overall Data

Run 1 (dB)	Run 2 (dB)	Difference from Runs	Run 1 (dB)	Run 2 (dB)	Difference from Runs
96.19	96.17	0.03	85.24	86.24	-1.00
93.28	93.32	-0.04	85.44	85.70	-0.26
88.59	88.63	-0.04	86.65	86.23	0.42
85.76	86.20	-0.45	87.11	87.58	-0.47
86.27	85.93	0.34	86.40	88.65	-2.25
85.99	85.31	0.68	86.17	88.49	-2.32
85.47	85.02	0.45	85.78	86.66	-0.88
85.54	84.80	0.73	86.25	86.78	-0.53
87.49	87.03	0.46	95.31	96.07	-0.76
93.30	93.15	0.15	99.95	100.16	-0.22
97.22	96.89	0.34	100.43	100.42	0.01
97.83	97.32	0.50	99.30	99.42	-0.13
96.42	95.89	0.52	98.01	97.87	0.14
94.25	93.80	0.45	93.79	92.93	0.86
90.00	89.78	0.21	87.13	86.92	0.21
84.43	85.58	-1.16	86.86	86.96	-0.10
83.80	84.91	-1.11	87.02	86.54	0.48
84.62	84.82	-0.21	87.28	86.57	0.71
85.25	85.19	0.05	87.86	87.77	0.09
86.06	86.07	-0.01	88.61	89.53	-0.92
87.01	87.05	-0.04	95.34	96.59	-1.25
92.31	92.56	-0.25	100.05	100.50	-0.45
96.65	96.58	0.07	100.65	100.59	0.05
97.45	97.24	0.21	99.41	99.19	0.22
96.06	96.01	0.04	98.13	97.63	0.51
93.93	93.87	0.07	94.24	93.02	1.22
90.63	90.24	0.40	88.00	86.63	1.37
88.21	88.69	-0.48	87.68	86.44	1.24
87.60	88.96	-1.36	88.57	87.88	0.69
86.63	88.99	-2.35	88.56	87.82	0.74
85.18	88.54	-3.36	87.05	85.81	1.24
84.59	87.69	-3.09	86.51	86.42	0.08
86.16	87.73	-1.57	94.56	95.56	-1.00
92.67	93.37	-0.69	99.77	99.98	-0.21
97.25	97.37	-0.12	100.65	100.39	0.26
98.03	97.73	0.30	99.64	99.47	0.17
96.37	95.94	0.43	98.54	98.30	0.24
93.90	93.58	0.32	94.87	94.20	0.67
89.95	89.46	0.49	87.88	89.20	-1.32
85.97	86.20	-0.23	86.55	88.43	-1.88
85.29	86.43	-1.13	87.07	87.26	-0.19

Appendix H-2: Mount A Overall Data Continued

Run 1 (dB)	Run 2 (dB)	Difference from Runs	Run 1 (dB)	Run 2 (dB)	Difference from Runs
86.69	86.05	0.64	86.78	86.75	0.02
86.16	85.05	1.11	86.83	87.52	-0.69
86.97	85.96	1.01	95.95	96.75	-0.81
94.24	95.42	-1.17	102.04	102.28	-0.24
99.67	100.17	-0.50	103.35	103.30	0.04
100.74	100.76	-0.02	102.36	102.29	0.08
99.78	99.84	-0.07	101.30	101.17	0.13
98.56	98.57	-0.01	98.16	97.70	0.46
94.86	94.12	0.74	90.81	90.25	0.56
87.89	86.89	1.00	85.90	85.79	0.11
85.27	86.25	-0.98	86.30	85.78	0.52
84.95	86.54	-1.59	86.80	86.07	0.74
85.96	86.89	-0.93	86.65	86.50	0.14
86.38	87.68	-1.30	86.40	86.97	-0.57
85.97	89.17	-3.20	95.41	96.22	-0.81
93.73	95.45	-1.72	101.70	101.98	-0.28
99.45	99.73	-0.28	103.12	103.14	-0.02
100.56	100.23	0.33	102.11	102.23	-0.13
99.65	99.66	-0.01	100.97	101.16	-0.19
98.70	99.20	-0.50	98.05	97.81	0.24
95.44	95.84	-0.40	91.84	91.01	0.83
89.33	89.75	-0.42	88.24	87.40	0.84
87.30	88.46	-1.16	87.30	86.86	0.43
86.33	88.13	-1.80	86.67	87.23	-0.56
85.94	86.77	-0.82	87.13	88.08	-0.95
85.55	86.37	-0.82	88.15	89.07	-0.92
85.53	88.14	-2.62	94.86	96.15	-1.29
86.50	89.35	-2.84	101.23	101.87	-0.64
87.18	88.64	-1.45	102.87	103.11	-0.24
87.64	86.97	0.67	101.98	102.15	-0.16
87.85	88.68	-0.83	100.85	101.09	-0.24
95.80	97.57	-1.77	98.01	97.93	0.08
101.59	102.59	-0.99	91.49	90.69	0.80
102.80	103.35	-0.55	86.93	85.05	1.88
101.90	102.06	-0.16			
100.88	100.68	0.20			
97.54	97.05	0.49			
89.70	90.10	-0.40			
85.05	86.59	-1.55			
85.90	86.92	-1.01			
86.70	87.17	-0.47			