APPLICATION OF THE DYNAMIC VIBRATION ABSORBER TO REDUCE THE NOISE AND VIBRATION OF THE AUTOMOTIVE HVAC SYSTEM

By

MUHAMMAD SAFWAN ABDUL AZIZ

(MATRIC NUMBER : 103888)

Supervised by

DR. AHMAD ZHAFRAN AHMAD MAZLAN

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DECLARATION

This work has not been previously been accepted in substance for any degree and is not being concurrently submittes in candidature for any degree.

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This thesis is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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LIST OF ABBREVIATIONS

HVAC	Heating, Ventilation and Air Conditioning
SDM	Structural Dynamic Modification
MPV	Multi Purpose Vehicle
HIM	HVAC Integration Module
TXV	Thermal Expansion Valve
FRF	Frequency Response Function
FFT	Fast Fourier Transform
SPL	Sound Pressure Level
RPM	Revolutions Per Minute
AC	Air Conditioner

ABSTRAK

Projek ini bertujuan untuk mengkaji kesan Penyerap Getaran Dinamik (DVA) dalam mengurangkan bunyi dan getaran yang diklasifikasikan sebagai jenis ‘humming’ yang terhasil dari kereta Proton Exora. DVA tersebut telah direka dan diperhalusi berdasarkan frekuensi semulajadi struktur paip penghawa dingin dan dipasang pada peringkat sistem dan kenderaan Proton Exora. Ciri bunyi dan getaran jenis ‘humming’ yang terhasil dari sistem penghawa dingin tersebut akan direkodkan dan perbezaan antara sifat bunyi sebelum dan selepas penambahbaikan akan dibandingkan. Pemasangan DVA kedalam sistem HVAC Proton Exora terbukti dapat mengurangkan kadar getaran paip penghawa dingin sebangayk 80% dan mengurangkan kadar bunyi dan getaran seluruh sistem ‘HVAC’ tersebut sebanyak 1.5 dB. DVA yang digunakan mempunyai julat frekuensi yang berkesan diantara 100 – 500 Hz untuk peringkat kenderaaan dan 75 – 250 Hz untuk peringkat sistem.

ABSTRACT

The purpose of this project is to study the effect of Dynamic Vibration Absorber (DVA) to reduce the humming type noise and vibration of the Proton Exora. The DVA was designed and tuned according to the natural frequency of the AC Pipe structure and applied to the system and vehicle level of the Proton Exora HVAC sytem. The humming type noise and vibration characteristics of the HVAC components were recorded and compared before and after the implementation of DVA. The implementation of DVA was found to improve the vibration level of the AC Pipe by 80% and subsequently improving the noise and vibration level of the whole HVAC system by 1.5 dB. It has been observed that the DVA has an effective frequency range of 100 – 500 Hz for the vehicle level and 75-250 Hz for the system level.

CHAPTER 1

INTRODUCTION

1.1 Overview of the HVAC System and DVA

1.1.1 HVAC System

The HVAC system of a vehicle as shown in Figure 1.1 is generally a closed system which made up of 4 main components, namely the compressor, condenser, thermal expansion valve, and evaporator. Firstly, the compressor will compress the refrigerant (R134a type) and the gas will change phase into high temperature vapour. At the condenser, a fan will blow air, where heat from the system will be released to the outside environment. Inside the system, the gas will change phase to liquid phase, and travelled through the pipe to the thermal expansion valve. Here, the high pressure liquid will flow through small orifice and be converted into low pressure liquid, which is having cool temperature. Heat exchange will occur at the evaporator where the blower will blow hot air through it, where the air will come into the evaporator and go out as cold breeze as the heat is absorbed by the fluid into the system. The fluid will then circulate back into the compressor, and the cycle repeats.

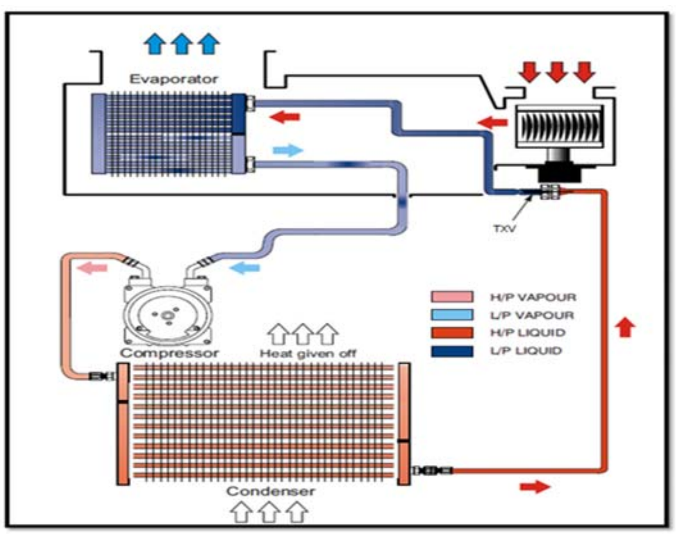


Figure 1.1 Automotive HVAC system

1.1.2 Dynamic Vibration Absorber (DVA)

DVA is one of the components that can be used in structural dynamic modification (SDM) method where a second spring mass system is added to a primary mass system and designed to absorb the input disturbance by shifting the motion of the original mass, into the newly added mass as shown in Figure 1.2. When a DVA is tuned to a specific target frequency, it will eliminate the amplitude of the target frequency, and in turn, will induce two new natural frequencies, each at higher and lower frequencies compared to the original natural frequency.

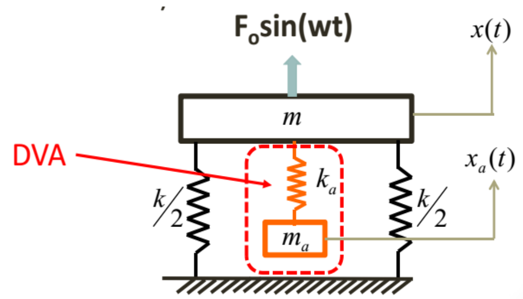


Figure 1.2 Schematic diagram for DVA (EMM342 Lecture note)

The DVA used in the project as shown in Figure 1.3 will be using a symmetrical design structure, with two known masses on both sides connected by a stainless-steel rod. The length between the two masses can be adjusted, according to the studied frequency. The stiffness of the spring can be visualized by the stiffness of the steel rod, where the deflection/bending of the steel rod will simulate the compression effect of a spring. As a result, this type of DVA will impose positive result on two axes, depending on the direction it is mounted.

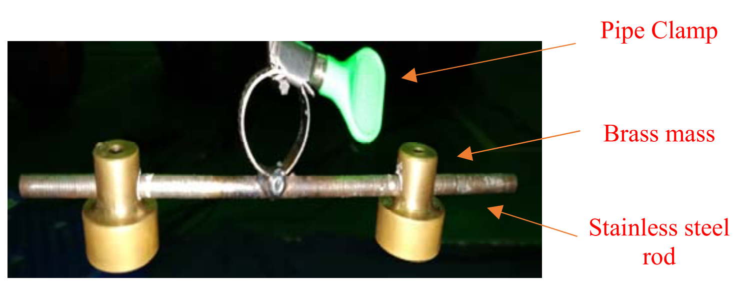


Figure 1.3 Example of DVA

Based on the stiffness of the stainless steel rod holding the two mass on both side, when vibration occurred at the middle of the DVA, the vibration will be shifted to the mass, in the form of deflection of the two ends. This in turn will make the vibration of the original structure to be shifted to the mass, leaving the original structure theoretically still.

1.2 Project Background

This project is a collaboration project between Universiti Sains Malaysia (USM) and Proton Holdings Berhad. Its conducted to reduce the noise produced by the HVAC system of PROTON Exora using SDM method, or specifically using DVA. The noise produced by the HVAC system was detected during the operation of PROTON Exora where significant noise level arises during driving, which affects driving comfort. From the components of the HVAC system, it is identified that the AC Pipe gives the most contribution to noise level of the system, which is identified as humming noise. This project was scheduled to start on May 2017 and expected to be completed on June 2019, where the whole project was divided into three phases. At the end of the project, it is hoped that improvement on the noise and vibration level of the HVAC system can be obtained.

1.3 Problem Statement

The noise and vibration of the HVAC system is a common problem for most of the automotive manufacturers. PROTON Exora as shown in Figure 1.4 is one of a Multi Purpose Vehicle (MPV) that induced a significant HVAC noise levels. A proper characterization of the vibration and noise level of the HVAC system has to be carry out to determine the root cause of the problem, and one of the noises can be humming noise

Figure 1.4 Proton EXORA

Therefore, in this study, the noise and vibration characteristics of the HVAC component (AC Pipe) at vehicle and system level are measured and analyzed. The noise and vibration then then validated using spectral analysis and subjective evaluation. Finally, the DVA is applied to reduce the noise and vibration level of the HVAC system.

1.4 Objectives

There are three objectives of the study which are:

- To conduct an Experimental Modal Analysis (EMA) for the HVAC system.
- To characterize the humming type of noise and vibration of the HVAC system (vehicle and system level).
- To compare the humming type noise and vibration level of the AC Pipe between vehicle and system before and after the application of DVA.

1.5 Scope of Work

In this study, noise characterization of the Proton Exora HVAC System will be conducted. It includes the noise produced from vehicle level, as well as the system level. Then EMA will be conducted on the components of the HVAC system, where the natural frequencies of the components can be determined and this will be useful in determining the best place to do improvements using SDM.

SDM method will then be applied by installing a DVA on the targeted structure. The data for the components are analyzed again using EMA. Apart from that, data for running system for both system and vehicle level will be recorded to decide whether the DVA results in improvement of the noise and vibration level of the system level, as well as for the vehicle level. The improvement between system level and vehicle level will also be compared whether if showing similar trend, or otherwise.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter will discuss briefly on the following topics:

- Noise and vibration of vehicle HVAC system
- Current available solution for the vibration and noise of HVAC system
- Structural Dynamic Modification (SDM) method

2.2 Noise and Vibration of Vehicle HVAC System

Heating, Ventilation and Air Conditioning (HVAC) system is one of the most important features inside a vehicle. It helps in providing a comfortable feeling for the driver and passengers. Nowadays, with advanced technologies of the vehicle in reducing thermal engine noise and silent electric vehicles, noise of HVAC system are becoming more prominent and major problem to be solved. Most of the noises originate from the electrical motor and aero-acoustic linked to the fan and interactions between HVAC components and airflow (Bennouna et al.,2018).

Current design of the HVAC system are producing too much noise, thus resulting in acoustic discomfort for the driver and passengers. Even though HVAC noise is not as loud as the overall noise produced by other components of the vehicle, it affects driver's subjective perception and may lead to feeling of nervousness or annoyance (Ji Hyun et al.,2012). These noises appear due to the design of the HVAC system itself, where it relies on the circulation of liquid refrigerant and water to perform their respective function of AC, thus producing noise. The system itself does not responsible for the total noise level experienced inside the cabin, but the individual generation at specific frequency of the different components (Toksoy et al., 1995).

The noise and vibration produced by the HVAC system have a huge impact in vehicle cabin acoustic performance. From the measurement as shown in Figure 2.1, the core factors influencing the type and noise level are HVAC system design, cabin volume, seat fabric and insulation of cabins including carpet (Mavuri et al.,2008). There is a study of a vehicle HVAC system as a component as well as a system including air ducts and vents. The study prove that the influence of geometrical properties of the interior, such as the interior length, inclination of the windscreen, shape of vehicle's rear end as well as seats provides less importance to the noise originating from the HVAC system (Holhs and Becker, 2018).

Figure 2.1 Aachen Head in passenger seat (Mavuri et al.,2008)

A study was conducted on a lab scale vehicle HVAC system to investigate the noise and vibration characteristic (Wang and Watkins, 2007), where microphone was used to record the sound, with a pre-amplifier and variable voltage DC power supply is used to supply power to the HVAC system, as shown in Figure 2.2. Based on this study, it showed that the fan induce a significant amount of noise from the overall noise level. Another finding shows that the cover of motor vent passage hole and the seal of weld gap does not change the total noise level, but only reduce the noise spectral peaks at the blade passing frequency which also affect the cavity resonance peaks at lower frequencies.

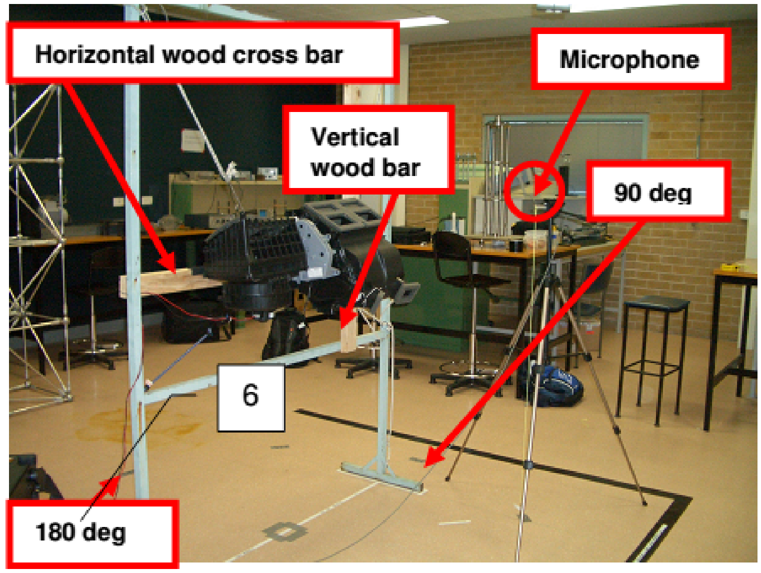


Figure 2.2 HVAC system laboratory test rig and setup(Wang and Watkins, 2007)

The noise originating from the HVAC system can be divided into four main types, which are humming, hissing, clicking and air rush noises (Hidayat, 2017) and these noises are due to the operation of the components of the system. For the hissing type of noise, it mainly originates from the thermal expansion valve and evaporator pipe inlet. Humming noise are coming from the AC pipe, compressor, and the power steering pump. Clicking noise solely coming from the engagement and disengagement of the magnetic clutch inside the compressor. And finally the air rush noise, coming from the flow of air inside the vents, and the blower.

2.3 Current Available Solution for the Vibration and Noise of HVAC System

One of the cost-effective way to improve interior cabin noise that originated from the HVAC system is using biodegradable natural materials such as juta felt and waste cotton (Sneha and Mohanty,2018). These materials are found to have higher sound absorption coefficient than other common sound absorbing materials as shown in Figure 2.3. In the study, the noise levels are reduced by 5dBA and loudness level by 7 sones.

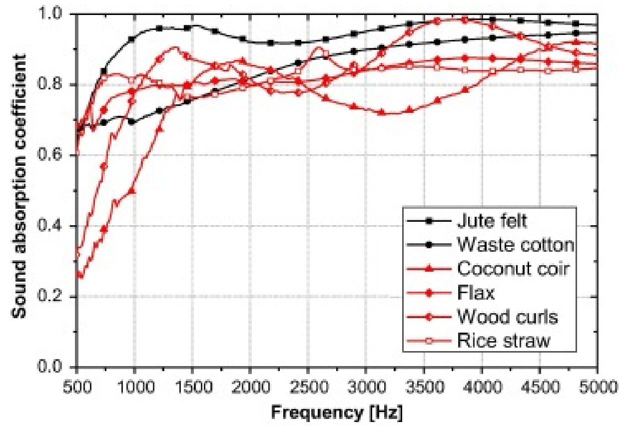


Figure 2.3 Comparisons of sound absorption value using various materials (Sneha and Mohanty,2018)

Air rush noise are also proven to be reduced using different variations of fan speed. Higher rotational speed of the fan will result in higher sound pressure level (SPL). The air rush noise may also be improved by changing the geometry of the HVAC system that was subjected to air flow (Wang and Watkins, 2007). The study shows that certain geometry such as removing of imperfection gap will reduce air flow turbulence.

2.4 Structural Dynamic Modification (SDM) Method

SDM method is one of the way that can be implemented to reduce the vibration level of a structure. The main objectives are to reduce vibration levels, shift resonance, improve dynamic stabilities, perform modal synthesis, and also to optimize the weights and cost (Nad, 2007). With the mentioned method of modification, the modal properties of selected modified structures are studied in dependency of spatial and physical properties, which confirms that using SDM method is very effective in changing the dynamic properties of a vibrating system.

In engineering field, SDM method has been implemented vastly across many structures. This was proven by applying SDM method to an active suspended handle to overcome the limitation of a piezo stack actuator. By increasing the stiffness of the lower beam of the handle that supports the actuator, it results in shifting of the modes of the structure beyond the operating frequency range (Mazlan, 2015). Another study by Walaack in 1989 shows that, by adding rib stiffener and mass modification on a structure does change the natural frequencies of the structure. In this study, the comparison also has been made by using the method of Finite Element Analysis (FEA) and EMA, where SDM by experiment has fast analysing speed as the advantage compared to using the FEA.

The SDM method has also been applied on the existing products. A study on drum brake squeal showed that the torsional mode of the deflection shape of the drum brake obtained using EMA was reduced by the application of a SDM method (Hamid ,2013). Another application was for an electric grass trimmer, where the DVA was tuned to around 220Hz, to match the operating frequency of the grass trimmer in attenuating the handle vibration (Hao et. Al., 2011). The results shows the average reduction of 82% and 67% in Z and X direction respectively as shown inFigure 2.4.

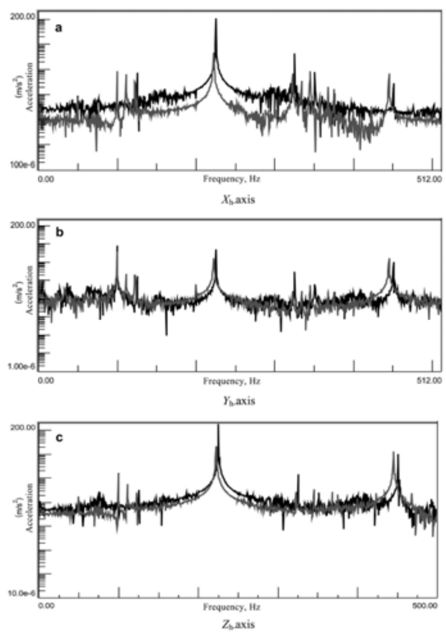


Figure 2.4 Acceleration spectra of electric grass trimmer with and without TVA (Hao et. Al., 2011)

SDM method has also been applied on a minivan's roof (Li et. al, 2012), where the addition of damping adhesives, changing local beads and utilization of DVA with 33Hz tuned setup resulting in reduction of SPL of the minivan by around 2 dBA as shown in Figure 2.5.

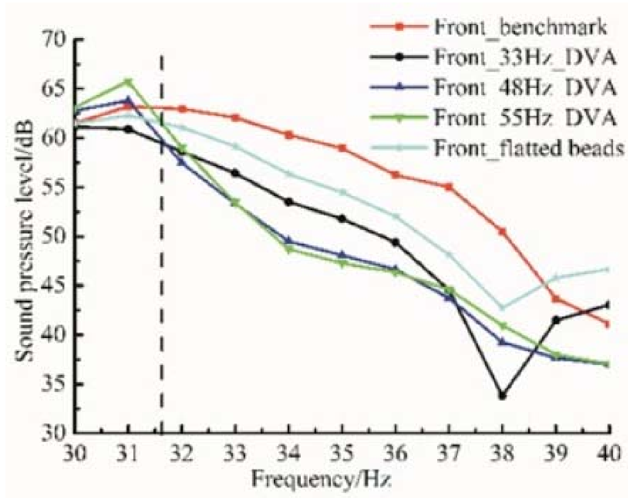


Figure 2.5 SPL of minivan model (Li et. al, 2012)

Another study on motorcycle handle, DVA application resulted in various attenuation levels ranging from 59-68% at different speed in the X and Z direction. The vibrations originating from the engine and road surface roughness when the motorcycle move at the speed of 30-50 km/h (Saifuddin, 2012). Another study is on the orbital sander (Ripin, 2011), where DVA was applied to the orbital sander main structure together with addition of mass resulting in shifting of the resonant frequency, and thus reducing the vibration produced by the object.

2.5 Summary

From the literatures, three main summary can be made as follows:

- HVAC system can produce noise, eventhough its very small in amplitude, but can result in discomfort, nervousness and annoyance.
- Solution on improving the noise and vibration level of HVAC system mainly focuses on changing the materials and geometry of the HVAC system
- DVA is a very effective method in reducing the vibration of the original structure by shifting the vibrations to different frequencies.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter will discuss briefly on the following topics:

- Setting of HVAC system in system and vehicle levels
- EMA of HVAC components at vehicle and system levels
- Noise and vibration characterization of vehicle and system levels
- Design of DVA and implementation

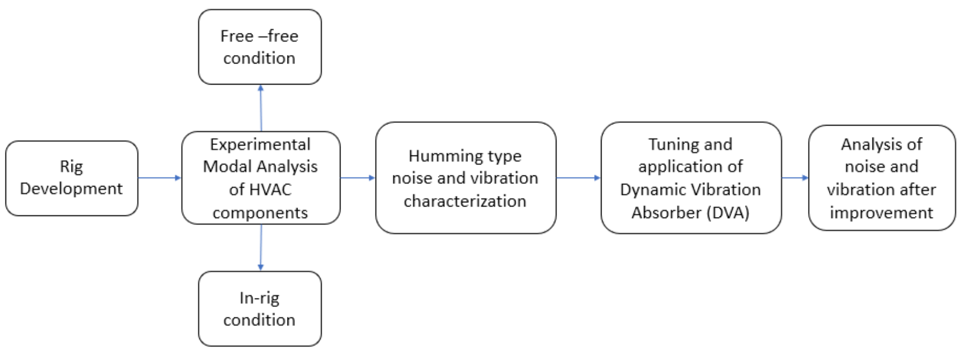


Figure 3.1 Flowchart of the project

3.2 Setup of the Proton Exora HVAC System

In this study, two main software will will be used, which is LMS TestLab and LMS TestXpress together with instrumentation such as data logger SCADAS Mobile, accelerometer, microphone, calibrator and impact hammer which will be connected as shown in Figure 3.3Figure 3.4 for the vehicle and system level, respectively..

LMS TestLab will be used to conduct the EMA, where it will be connected to an impact hammer and accelerometer to record the natural frequencies of the structure.

LMS TestXpress will be used to record the vibration and noise data (spectral testing), where it will be connected to a microphones and accelerometers.

DVA will be applied to the system, and again, the noise and vibration level will be measured. The data will then be analyzed and compared.

The study will involve two levels, which is vehicle and system level. In vehicle level, the measurement will be conducted on the HVAC system of a working Proton Exora, whereas is system level, the measurement will be conducted on a rig scale of Proton Exora HVAC system. Figure 3.2 shows the test methodology of the study.

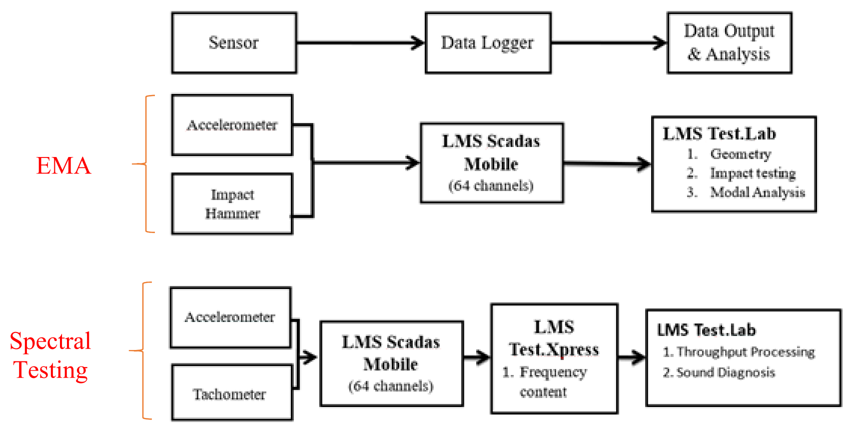


Figure 3.2 Test methodology

3.2.1 Vehicle Level Setup

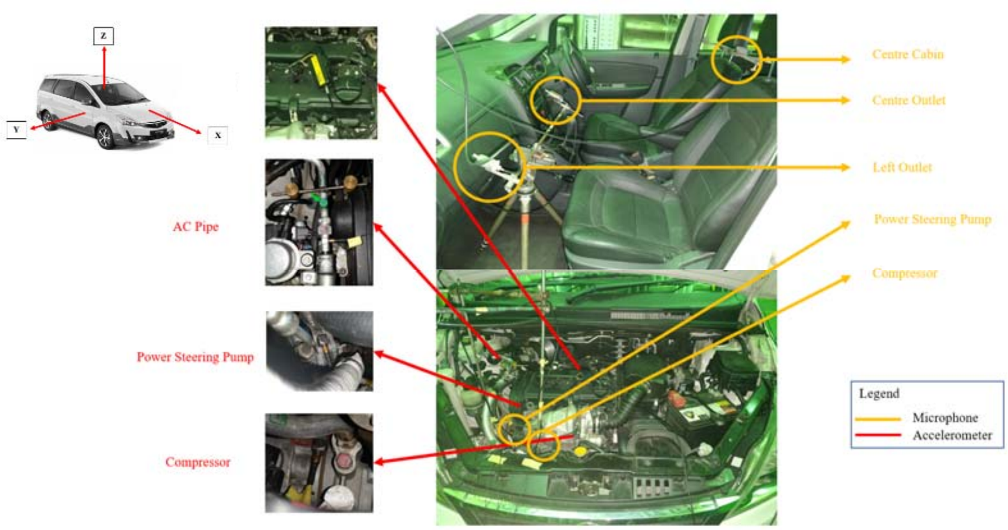


Figure 3.3 Equipment setup for vehicle level

Firstly, all of the equipments are prepared and connected as shown in Figure 3.3. for the vehicle level, the measurement was conducted inside a semi-acoustic chamber in the Noise Lab located at Proton.

Three types of sensors are used, which is the tachometer, accelerometer, and microphone. Tachometer will be used to collect data on the speed of the engine, the accelerometer will be used to collect vibration level of the AC Pipe, power steering pump, and compressor. The microphone will be used to collect sound data from power steering pump, compressor, centre cabin, centre cutlet and left outlet. The arrangement of the accelerometers are alligned according to the direction of the vehicle, where the front side of the car was set as X-direction, left side of the car was set as Y-direction and top of the car was set as Z-direction.

3.2.2 System Level Setup

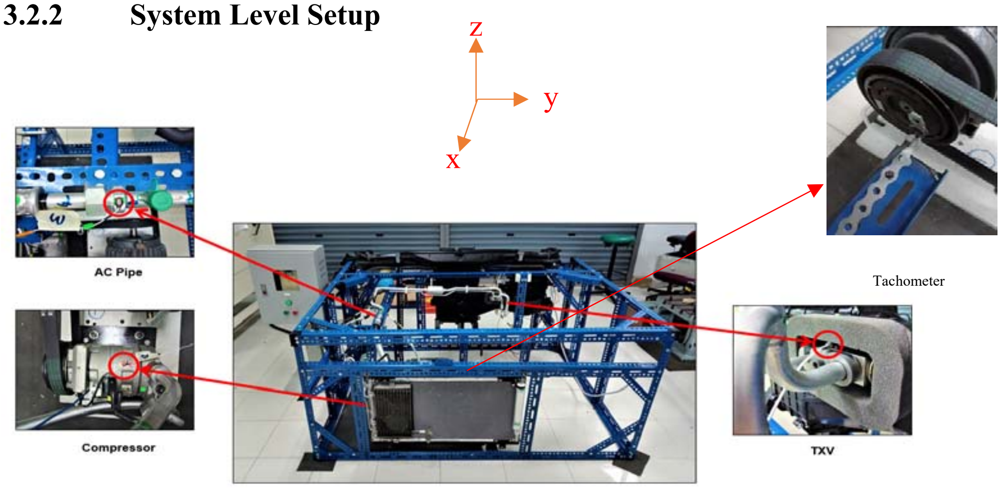


Figure 3.4 Equipment setup for system level

Firstly, a rig of Proton Exora HVAC system was built as shown by Figure 3.4, comprising each of the components from the original vehicle system, with the original scale and arrangement according to the vehicle setup. This is to ensure that the error due to difference in component arrangement is minimized.

In system level, only two types of sensor were used to obtain the data required to analyze the vibration data, which is the tachometer and accelerometer. This is due to the limitation of equipments and facilities required to obtain the result. Noise measurement has to be conducted in a noise isolated chamber, because even the slightiest external noise can interfere with the data obtained.

Accelerometers are attached to three components, which is compressor, thermal expansion valve (TXV) and the AC Pipe. In this project, the orientation of the accelerometers was alligned according to the vehicle setup, where the front side of the rig was set as X direction, right side of the rig was set as Y direction, and top of the rig was set as Z direction. Tachometer was attached at the motor to visualize the rotational speed as to mimic to the engine running.

3.3 Experimental Modal Analysis (EMA) of the HVAC System

The targeted noise and vibration for this study was humming noise, which was identified from three components, compressor, power steering pump, and AC pipe. It was identified that the AC pipe was best suited for the application of the DVA, due to its easy to reach location and small structure, compared to the compressor and power steering pump, which are located further inside the engine bay and requires a lot more work and cost for improvement.

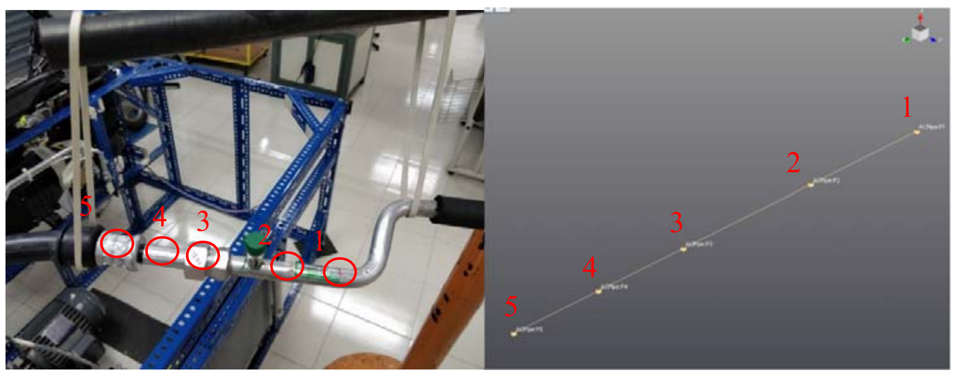
A tri-axis accelerometer was connected to a 16-Channel LMS Scadas Mobile, where it logs the data from the sensor, and convert it to digital form. It is then connected to a laptop with LMS TestLab or LMS TestXpress software. These two softwares are no-compromise sound and vibration analyzer with high speed system for the analysis of frequency content.

Then, the structure of AC Pipe was selected to be studied, and 5 points of interest at the AC pipe was chosen as shown in Figure 3.5. The length of the structures was measured and the data was recorded using LMS TestLab Geometry.

Impact testing was conducted to obtain the natural frequencies of the AC Pipe. Roving hammer method are used, where the accelerometer are attached at point 4 of AC pipe and using impact hammer to hit at all 5 points, in Y and Z directions. X direction will not be done due to structural constraints. The data are then analyzed using LMS TestLab Modal Analysis.

3.3.1 Free-Free Condition

The components involved in this part is the Compressor, AC Pipe and TXV. The components will be hung onto a fixed support using a rubber, where the vibration from the support or the structure does not get transmitted to each other.



(a) (b)

Figure 3.5 (a) AC Pipe on free-free condition during measurement and (b) Geometry in LMS software

For the AC Pipe and Compressor, the same geometry will be used for the in-rig measurement, due to the easy to reach structure. However for the TXV, the geometry used are different. Obtaining the free-free condition data will helps in determining whether there are any resonance due to the structure itself. If the case is resonance due to the structure, then the vibration can be reduced by other means as well such as increasing the stiffness.

3.3.2 In-rig Condition

In this section, EMA was conducted with the components attached inside the rig together with the complete HVAC system.

However, the geometry of the TXV used is only in 2 dimensional due to the constraint of the components. The structure was inserted deep into the instrument panel, thus it is impossible to conduct EMA using three-dimensional structure.

3.4 Noise and Vibration Characterization of the HVAC system (Humming)

3.4.1 Vehicle Level

The measurement was conducted in a semi acoustic chamber in Noise Lab at Proton. This will isolate any unwanted sound and noise due to external source.

The equipments was setup as shown previously in Figure 3.3. Three tri-axis accelerometers were attached to the AC Pipe, compressor and power steering pump while five microphones were attached as the engine bay and inside the cabin.

Two different conditions of data were taken, which is idle condition and RPM tracking with engine is on. For idle condition, the vibration and noise data will be recorded for 30 seconds when the engine is idling at around 850 rpm, starting after the engine speed was stabilized. While for RPM tracking, the noise and vibration data will be collected at RPM range of 950-1500 rpm, which was obtained by manually pressing the accelerator pedal inside the vehicle.

All of the data recorded was analysed using LMS TestLab Signature Throughput Processing and LMS TestLab Sound Diagnosis.

3.4.2 System Level

The measurement of the running rig was conducted in the Vibration Lab, USM. Due to the limited facilities and equipments, noise data was not taken, as the data obtained would be unreliable.

A tri-axis accelerometer was attached to the AC Pipe, while Uni-axial accelerometer was attached to the Compressor and TXV.

Similar to the vehicle level, the data was recorded in two conditions, which is idle condition and RPM tracking. In idle condition, the speed of motor was adjusted to 850 rpm to mimic the running of the engine. For RPM tracking, the speed of the motor was increased manually as linear as possible using the knob of the motor speed controller unit as shown in Figure 3.6.

Figure 3.6 Motor speed controller unit

3.5 Design of the DVA for the HVAC System (Humming)

The SDM method used in this project is by using DVA. The DVA was built using a stainless steel rod, and two brass masses on both side of the rod. The structure was attached to the AC Pipe using a pipe clamp which was welded to the stainless steel rod, as shown in Figure 3.7.

Figure 3.7 DVA used in the project

The structure of the DVA works with the same principle as the schematic diagram as shown in Figure 1.2 previously. The stiffness of the rod will act as the spring for the masses. By adjusting the length between the masses, the DVA can be tuned according to the targeted frequency of the target structure.

3.5.1 Theoretical Modelling of the DVA for the HVAC System

The theoretical modelling of the DVA relative to the targeted frequency and known masses can be obtained from the derivation of the formula for deflection,

$$x = \frac{FL^3}{3EI} \tag{3.1}$$

And substituting Hook's Law

$$F = kx \tag{3.2}$$

We get,

$$L^3 = \frac{3EI}{k} \tag{3.3}$$

Since

$$\omega^2 = \frac{k}{m} \quad \text{and} \quad \omega = 2\pi f$$

The length between the mass and the center of DVA can be shown as:

$$L^3 = \frac{3EI}{(2\pi f)^2 m} \tag{3.4}$$

Where,

L = Length to the masses (m)

E = Young's modulus of elasticity (Nm^{-2})

I = Bending moment of inertia (m^4)

f = Frequency (Hz)

m = Mass of weight (kg)

3.5.2 Implementation of the DVA to the HVAC System

With the values obtained from the calculation in Equation (3.4), the DVA was applied to the Point 2 of AC Pipe structure as shown in Figure 3.8. This point was chosen because it gave the best space for easy attachment of the DVA. However, due to the uncertainties variations in the material and structure, the DVA has to be further tuned manually.

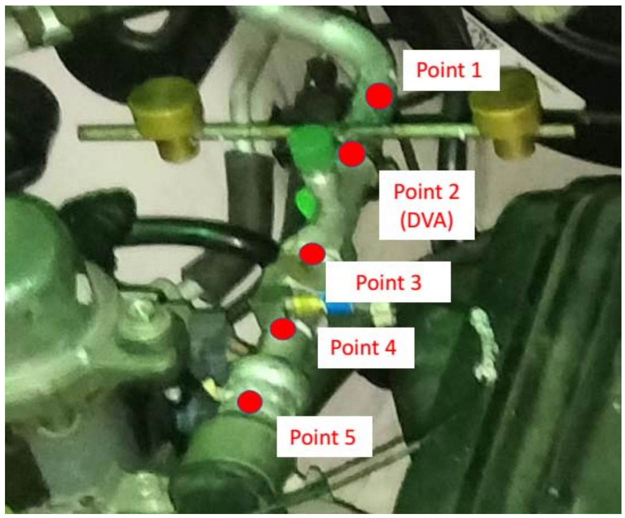


Figure 3.8 DVA attachment Point (Point 2)

The DVA was attached to a clamp, and accelerometer was mounted to the mass. Using LMS TestLab software, scoping was done for the structure where the input force was applied to the attachment point using impact hammer, and the natural frequency of the DVA was recorded. The length of the DVA was further adjusted so that the natural frequency of the DVA can follow the natural frequency of the AC Pipe as in-rig condition.

It is to be noted that the distance of the masses of the DVA might not be the same with the calculated value using the theoretical method. This is largely due to the variance in real life situation and the material of the structures. So the value obtained from the calculation will be used as a reference to start the tuning process.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

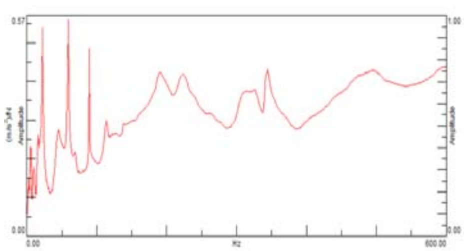
This chapter will discuss briefly on the following topics:

- Results of the modal analysis at vehicle and system levels
- Results of humming type noise and vibration at vehicle and system levels
- Results of humming type noise and vibration after the implementation of DVA

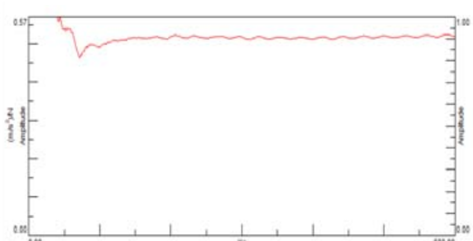
4.2 EMA Results of the HVAC System Components (Humming)

4.2.1 Free-Free Condition

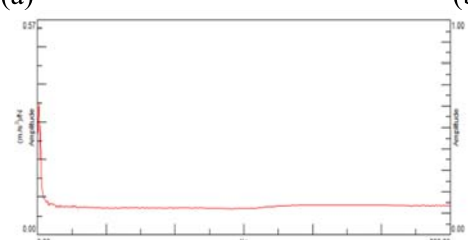
Figure 4.1 (a-c) shows the FRF of the AC pipe, TXV and compressor in free-free condition, respectively. The FRF for free-free condition across all components are showing almost flat trend, with only peaks with very small amplitude. However, AC Pipe are showing multiple natural frequencies of 23 Hz, 58 Hz, 97 Hz and198 Hz across the humming noise region. This showed that this component contribute in the humming noise produced for the HVAC system.



(a)



(b)

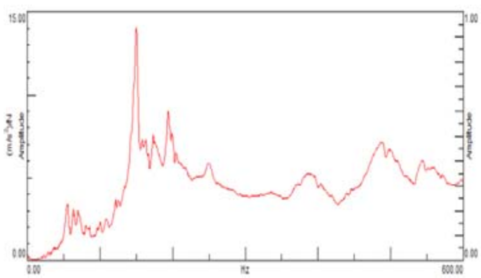


(c)

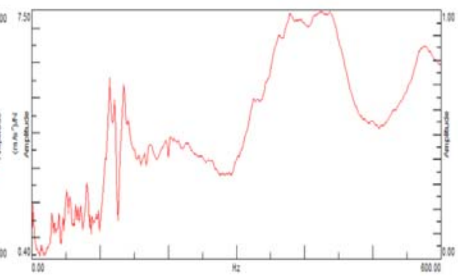
Figure 4.1 FRF of (a)AC Pipe (b)TXV and (c)Compressor in free-free condition

4.2.2 In rig Condition

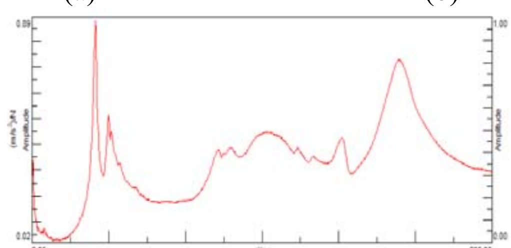
Figure 4.2 (a-c) shows the FRF of the AC pipe, TXV and compressor in-rig condition, respectively. When attached to the system, the components are showing peaks at around 100-150Hz for AC Pipe and TXV, and around 50-120Hz for the compressor. Furthermore, the TXV are showing higher amplitude of peaks at 400Hz area. Comparing with the free-free condition, we can conclude that the attachment to the main rig structure influences the natural frequencies of the components. This may create resonance with all of other components in the HVAC system.



(a)



(b)



(c)

Figure 4.2 FRF of (a)AC Pipe (b)TXV and (c)Compressor in-rig condition

4.3 Noise and Vibration Characteristics of the HVAC System

Table 4.1 Results summary for Vehicle level

Noise	Test Method	Engine	Air Condition	Blower Speed	Sensor Setup Location	Noise Frequency	Component with highest contribution
Humming	Idle (850 rpm)	On	On	1	**Accelerometer** • AC Pipe • Power Steering Pump • Compressor **Microphone** • Centre cabin • Power Steering Pump • Compressor	100 – 350 Hz	• AC Pipe • Power Steering Pump
	RPM Tracking (950 – 1500 rpm)					50 – 300 Hz	• AC Pipe • Power Steering Pump

Table 4.2 Results summary for System level

Noise	Test Method	Engine	Air Condition	Blower Speed	Sensor Setup Location	Noise Frequency	Component with highest contribution
Humming	Idle (850 rpm)	On	On	1	**Accelerometer** • AC Pipe • TXV • Compressor	100 -450 Hz	• AC Pipe
	RPM Tracking (950 – 1500 rpm)					100 – 450 Hz	• AC Pipe

4.3.1 Vehicle Level (Idle Condition)

Figure 4.3 - Figure 4.5 shows the frequency response (FFT) of the AC pipe, power steering pump and compressor in vehicle level during the idle condition, respectively. From the figures, the FFT of all three components studied are showing an increment of amplitude for the humming frequency range after switching on the AC system.

For the AC Pipe, it showed amplitude increment around 150 Hz range in the Z direction. For Y and Z direction, the frequency across 200 – 500 Hz are more affected by the AC unitThe Power Steering Pump showed biggest increase of amplitude at around 250 Hz in Y direction. Fot the compressor, there are new peaks occurred at just abone 300 Hz. The lower frequency peaks formation is mainly due to the functioning of the compressor itself.

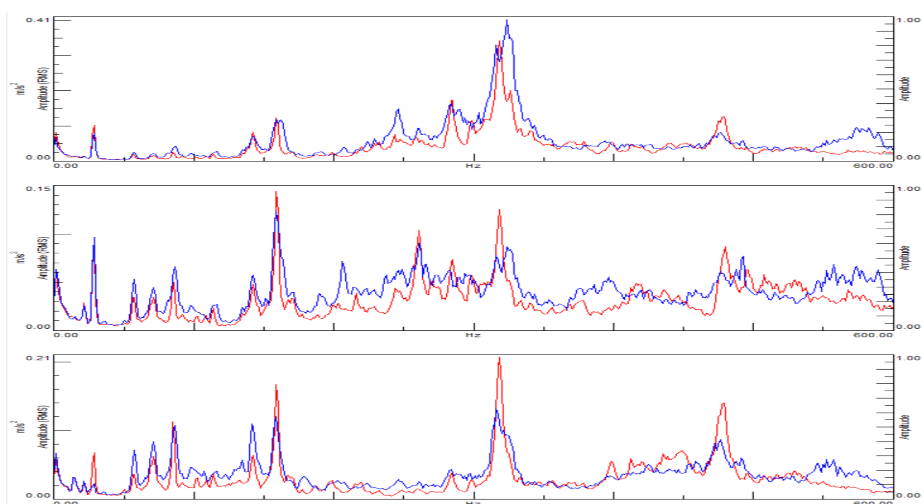


Figure 4.3 FFT of AC pipe on X-direction (Top), Y-direction (Middle) and Z-direction (Bottom) with AC off (Red) and AC on(Blue)

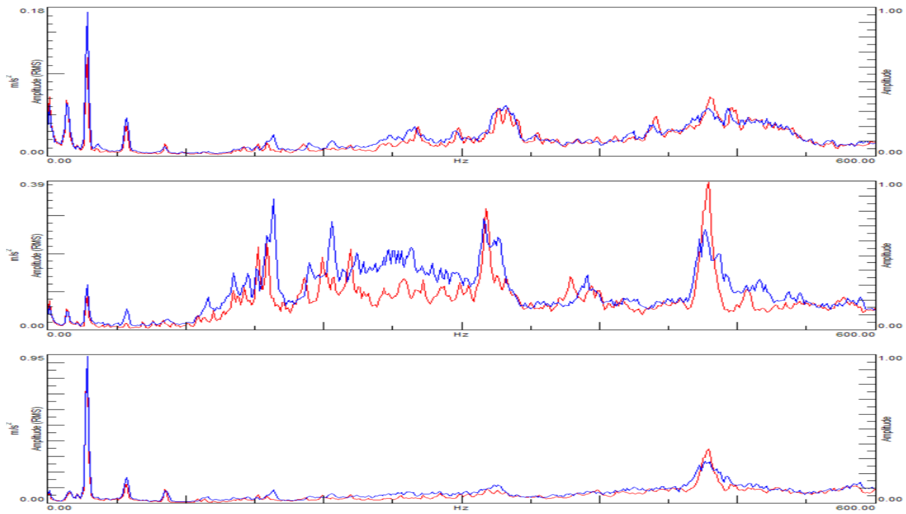


Figure 4.4 FFT of power steering pump on X-direction (Top), Y-direction (Middle) and Z-direction (Bottom) with AC off (Red) and AC on(Blue)

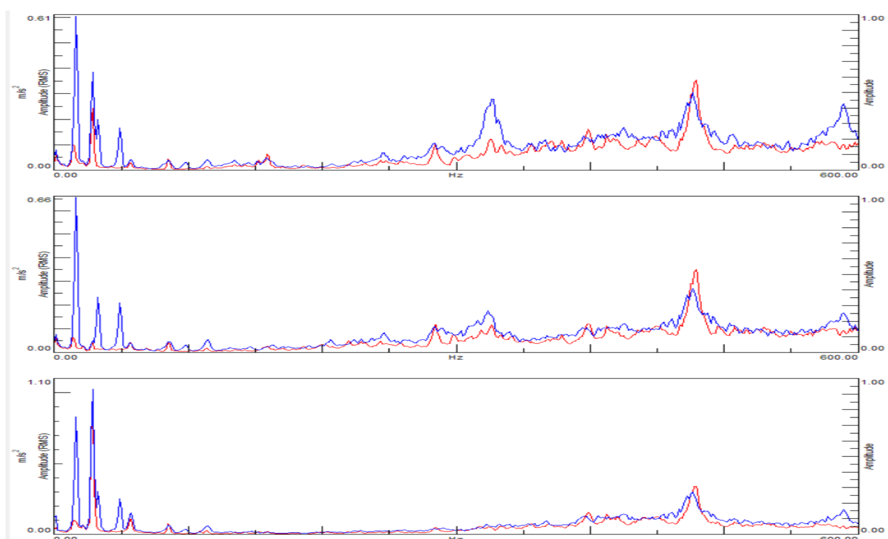


Figure 4.5 FFT of compressor on X-direction (Top), Y-direction (Middle) and Z-direction (Bottom) with AC off (Red) and AC on(Blue)