CHARACTERIZATION OF THE NOISE AND VIBRATION PATTERNS OF THE VEHICLE HVAC SYSTEM UNDER VARIOUS OPERATING CONDITION

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DECLARATION

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

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LIST OF ABBREVIATIONS

PROTON - Perusahaan Otomobil Nasional

HVAC – Heating, Ventilation and Air Conditioning

SDM – Structural Dynamic Modification

MPV – Multi Purpose Vehicle

DVA – Dynamic Vibration Absorber

HIM – HVAC Integration Module

TXV – Thermal Expansion Valve

FRF – Frequency Response Function

SPL – Sound Pressure Level

FFT – Fast Fourier Transform

CAD – Computer Aided Design

CAE – Computer Aided Engineering

AC – Air Conditioner

IP – Instrument Panel

ABSTRAK

Kebisingan dan getaran mempunyai impak penting terhadap persepsi pelanggan tentang kualiti kenderaan dan tahap bising dalaman kabin adalah antara aspek penting. Salah satu tahap hingar tertinggi dalam kabin kini timbul daripada sistem pemanasan, pengudaraan dan bersyarat udara (HVAC). Bunyi HVAC adalah masalah umum bagi kebanyakan pengeluar automotif. Dalam kajian ini, masalah bunyi HVAC disiasat untuk kenderaan Proton Exora. Proton Exora adalah kenderaan jenis pelbagai guna (MPV) yang menghasilkan tahap bunyi HVAC yang agak ketara berbanding dengan kenderaan Proton yang lain. Sehubungan itu, kajian ini bertujuan untuk menyiasat sumber bunyi HVAC untuk kedua-dua kenderaan dan sistem dengan pencirian bunyi dan getaran yang betul dari sistem HVAC kenderaan di bawah pelbagai sistem operasi. Pertamanya, kajian ini dijalankan untuk tahap kenderaan di mana bunyi dan getaran sistem HVAC diukur dan dianalisis terus daripada kereta sebenar. Manakala, untuk tahap sistem, rig ujian dibangunkan khusus untuk memasang sistem HVAC lengkap sama seperti di tahap kenderaan. Semua unit dan komponen pemasangan seperti pemampat, kondensor, injap pengembangan haba (TXV), penyejat, blower, paip penghawa dingin, dan hos yang berkaitan dibekalkan kepada USM oleh PROTON. Motor elektrik digunakan untuk menggerakkan takal pemampat untuk menjalankan sistem HVAC keseluruhan.

Untuk pengukuran hingar dan getaran, penderia mikrofon dan pecutan digunakan dengan mencari semua komponen yang berkaitan untuk dianalisis. Ujian dijalankan di bawah dua corak kereta dalam keadaan melahu dan dengan kelajuan tinggi atau pengesanan rpm di mana tachometer digunakan untuk mengukur kelajuan enjin. Dari data yang dikumpulkan, analisis dibuat termasuk analisis spektrum dan analisis pesanan. Kemudian, pengesahan dibuat oleh pengesanan bunyi dari getaran menggunakan diagnosis bunyi dari perisian LMS Test.Lab. Di samping itu, dengan bantuan kamera bunyi, sumber bunyi pada komponen dan bahagian yang berkaitan boleh didapati. Selepas menentukan sumber dan jenis bunyi bising seperti bunyi mendesir, berdengun, mengklik dan hembusan udara dari sistem HVAC, justifikasi yang betul dibuat mengenai penjanaan bunyi bising daripada komponen berkaitan dan bagaimana ia beroperasi. Penyumbang utama dari setiap jenis bunyi HVAC dikenal pasti untuk penyelesaian reka bentuk dan tindakan pencegahan yang akan dicadangkan pada masa akan datang. Ini akan diambil sebagai inisiatif untuk memperbaiki garis panduan reka bentuk semasa untuk sistem HVAC dengan tahap bunyi yang rendah untuk keselesaan penumpang.

ABSTRACT

Noise and vibration have imperative impact on customer perception of vehicle quality and cabin interior noise levels are some vital measures. One of the highest in-cabin noise levels now arises from heating, ventilating and air conditional (HVAC) systems. The HVAC noise is a common problem for most of the automotive manufacturers. In this study, the HVAC noise problem is investigated for Proton Exora vehicle. Proton Exora is a multi-purpose type vehicle (MPV) which induced a considerable HVAC noise level compared to the other Proton vehicles. Regarding to this issue, this study aims to investigate the source of the HVAC noise for both vehicle and system level by a proper characterization of the noise and vibration patterns of the vehicle HVAC system under various operating system. First, the study is carried out for vehicle level where the noise and vibration of HVAC system are measured and analysed directly on real car. Whereas for system level, a test rig is developed specifically to assemble a complete HVAC system exactly as in vehicle level. All the assembly unit and components such as compressor, condenser, thermal expansion valve (TXV), evaporator, blower, air conditioner pipe, and related hose is supplied to USM by PROTON. An electric motor being used to drive the compressor pulley to run the whole HVAC system.

For measurement of noise and vibration, microphone and accelerometer sensors is used by locating all of them at related components to be analysed. Test conducted under two patterns of car in idle and by elevated speed or rpm tracking where tachometer is used to measure the engine speed. From data collected, analysis is made includes the spectrum analysis and order analysis. Later, verification is made by noise detection from real time vibration and noise data using sound diagnosis from LMS Test.Lab software. In addition, with the aid from sound camera, source of noise at related components and parts can be located. After determining the source and type of noise such as hissing, humming, clicking, and rush noise from the HVAC system, a proper justification is made regarding the generation of noise from related components involved and how they operate. Main contributors from each type of HVAC noise is identified for design solution and countermeasure to be proposed in future. This would be taken as refinement initiative to improve current design guideline for HVAC system in order to come out with HVAC system exhibits low noise level for a better passenger in cabin comfort and experience.

CHAPTER 1 – INTRODUCTION

1.1 Project Overview

This project is a part for the first phase of two-year project collaboration between Perusahaan Otomobil Nasional (PROTON) and Universiti Sains Malaysia (USM). The title of the project is **Noise Reduction of the Proton Exora Air Conditional System using Structural Dynamic Modification (SDM) Method** which started on May 2017 and targeted to complete on April 2019. Upon completion of this project, it hopes that it would be able in providing a design guideline for the HVAC system regarding the improvement and countermeasure for any noise and vibration problems for Proton vehicles.

For the first phase, this project focusing on **Characterization of the Noise and Vibration Patterns of the Vehicle HVAC System under Various Operating Conditions.** Measurement of noise and vibration of Proton Exora HVAC system will be carried out on both vehicle and system level, where the first part focusing on the measurement of noise and vibration of HVAC system of Proton Exora on vehicle level while the second part on the system level. In this phase, the first part of data collection on vehicle level has been successfully completed within 12 weeks starting from 19 Jun 2017 to 8 September 2017 conducted at Proton Noise Lab. Two students were assigned by USM to do the industrial training at PROTON. The team of PROTON and USM have collected all the measurement data for both noise and vibration of Proton Exora HVAC system in vehicle level. Based on the result, it enables the team to determine the relationship between vibration and noise characteristics of the HVAC components at specific frequency range.

For the final year project, it will be specifically focusing on the second part of noise and vibration measurement of Proton Exora HVAC system covering only on the system level with the same objective as in the first part of vehicle level to characterize the type of noise produced by the HVAC system under the influence of vibration of constituent components. Based on the planning and theory, a test rig will be developed to set up the Proton Exora HVAC system by taking concern all the important guidelines and principles so that it may be operated slightly the same as in vehicle level. When the test rig is all set and the HVAC system could be functioned perfectly, data measurement under various operating conditions will be carried out followed by the post processing analysis of the data in aiming to come out with results justification. Both data obtained from measurement of noise and vibration on both vehicle and system level will be compared to see whether it is going with same trend or not before making the conclusion on this study.

The second phase which is the main goal for this project which the **Application of the Structural Dynamic Modification (SDM) Method to Reduce the Noise and Vibration of Vehicle HVAC System**. SDM is defined as a technique to predict the effect of physical structure alteration on the structural response. This technique is applied because of unsatisfactory dynamic characteristics of the structure, such as natural frequencies, undesirable vibration response, structural strength and dynamic instability of the structure. The parameters of modification for the SDM included the mass, stiffness, damping and the application of dynamic vibration absorber (DVA) In this phase, simulation works is carried out to study the effect of SDM to the overall vehicle HVAC system performances through a series of result verification which will be planned on the next part of the study.

1.2 Background Study

Driver and passenger comfort is a key factor for most customers in purchasing a vehicle. The comfort of the occupants extends also to the noise that they are subjected to, including HVAC noise. Responsible for the heating, cooling, circulating, purifying and dehumidifying the air in the cabin, the HVAC unit has a large impact on the well-being of the occupants of the vehicle, since it can be a significant sound source in the cabin. Among most of automotive manufacturers, the noise of the heating, ventilating and air conditional (HVAC) system is a common problem for them.

There are several types of noise produced by HVAC system that would be oppressing the customer’s ears such as hissing, humming, air rush and compressor engagement noise. These noises can contribute to the significant issue for driving comfort. The automotive air conditional system has several assembly parts such as compressor, condenser, radiator fan, drier, thermal expansion valve (TXV), blower and evaporator as shown in **Figure 1.1**. These parts can contribute to the noise problem for the vehicle.

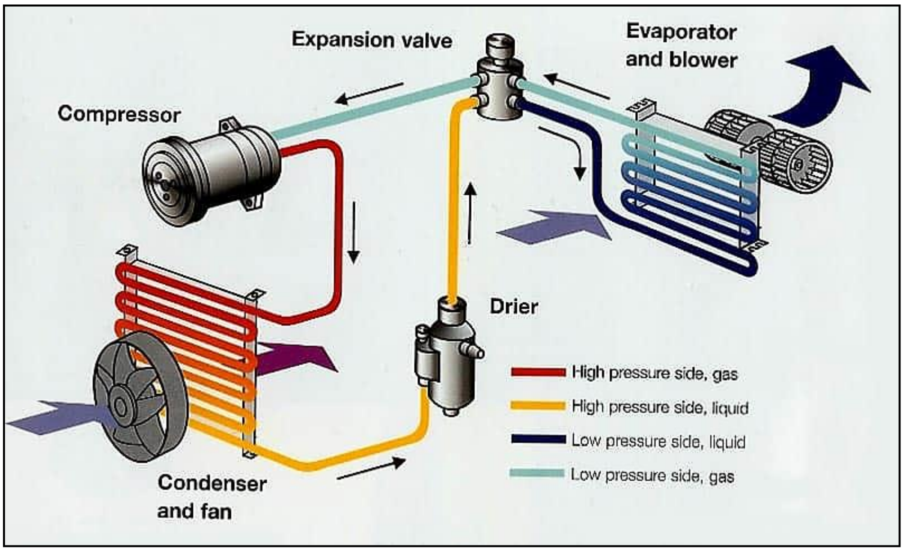


Figure 1.1: Vehicle air conditional system [15]

Proton Exora as shown in **Figure 1.2** is a multi-purpose type vehicle (MPV). It is designed for a family-type user vehicle and equipped with a good handling and control system with a reasonable price. That makes the Proton Exora a most affordable MPV car compared to the other MPV car manufacturers. However, due to the high level of noise from the Proton Exora HVAC system, the vehicle will later become a second option for the customers. Therefore, it is important to determine the source of the HVAC noise from the Proton Exora air conditional parts in order to reduce the noise effects to the vehicle and subsequently improve the vehicle comfortability while driving. In addition, as initiative to extend the marketability of the proton Exora, a proper guideline is hoped may be obtained through this study and become a valuable tool for industry to use.

Figure 1.2: Proton Exora [14]

This study focused to investigate the source of the HVAC noise for both air conditional system and vehicle levels. The noise and vibration of the air conditional system are measured for all the assembly parts in vehicle such as compressor, condenser, radiator fan, drier, thermal expansion valve (TXV), blower and evaporator. The type of measurement includes the spectrum analysis, modal analysis and sound camera of the HVAC system.

1.3 Problem Statement

The noise of the HVAC system is a common problem for most of the automotive manufacturers. Proton Exora is one of the Proton vehicles that induced a significant HVAC noise level. The proper characterization of the vibration and noise of the HVAC system should be carried out to determine the root cause of this problem. Therefore, in this study, the vibration and noise characteristics of the Proton Exora HVAC system is measured and analysed in term of modal analysis, spectral analysis, sound diagnosis and sound camera method.

1.4 Objectives

The main objectives of this study are:

- To construct a lab-scale test rig of Proton Exora HVAC system.
- To measure and identify types of HVAC system noise and vibration of Proton Exora for both vehicle and system level.
- To analyse and compare all types of HVAC system noise and vibration of Proton Exora for both vehicle and system level.

1.5 Scope of Work

In this study, the characterization of the noise and vibration patterns of the vehicle HVAC system under various operating conditions will be carried out based on the procedure which involves a series of data measurement, analysis and verification for all vibration and acoustic noise that being quantified from the HVAC system. As stated before, this characterization phase for noise in HVAC system comprises of two parts involving both vehicle and system levels. A complete setup of HVAC system will be developed on a test rig and then the test will be carried out exactly same as in vehicle level.

For data measurement, all vibration and acoustic noise of constituent components of HVAC system will be measured at various conditions by placing sensors which connected to the integrated device for data acquisition. From all these data, the analysis will be conducted to identify all types of noises existing in the HVAC system. In this analysis, the noise that being identified by subjective hearing will be traced out at its specific frequency range by observing how significant of both noise and vibration amplitude values on the collected data. As all the frequency range of each type of noise has been obtained, proceed with the validation of the frequency range at the specific components of HVAC system is done by pointing with sound camera subjected to the frequency range obtained. Then, the saturation of the noise level will be monitored to verify the assumption of noise frequency range that made before.

CHAPTER 2 – LITERATURE REVIEW

2.1 Overview

This chapter will discuss briefly on the following topics:

- Automotive HVAC system
- Noise and vibration sources of HVAC system
- Experiment setup of automotive HVAC System

2.2 Automotive HVAC System

Current design of the HVAC systems relies on the circulation of liquid refrigerant and air to perform their respective functions of cooling and heating. The design then exploits forced convection and conduction in the heating or cooling of ambient temperature air. This air is then expelled via ducting into the cabin of the vehicle to achieve the required temperature. The system is split into two sections, one dealing with the liquids as the working fluid and the other one with air. Both the liquid and air sides of the system can produce noise from various components. For example, the main components such as compressor can produce significant source of noise. Most of the liquid side of the system is located within the engine bay of the vehicle with only two liquid-to-air heat exchangers positioned in the air handling unit. On the contrary, the air handling unit exists within the Instrument Panel (IP) of the vehicle that is located inside the cabin [1],[11].

Noise and vibration have the important influence on a customer's perception of vehicle quality where the cabin interior noise level is the main criterion. The interior sound levels of automobiles have significantly reduced over the years, with the reductions in power train, tyre and external wind noise. One of the highest in-cabin noise level that arises is from HVAC systems. Since it is located just behind the vehicle instrument panel(IP) of the cabin. Thus, quieter climate control systems are desired by car manufacturers. Research and development have been conducted to investigate the HVAC noise generation and transmission mechanism [1]. For example, the study on noise refinement solutions for vehicle HVAC systems by Wang and Watkins from RMIT University, Australia [3]. Even though there are some studies in the HVAC systems, there are still insufficient data produced from the HVAC system due to the less concern of the passenger comfort inside the cabin by some automotive manufacturers and designers [4],[9]. Hence, to uphold the comfortability of driver and passenger at the best level, the noise from the HVAC system should be taken into consideration by providing the guideline on its characteristics and a proper endeavours of countermeasure solution.

2.3 Noise and vibration sources of HVAC system

In the reference investigation, the liquid side of the system is neglected [3]. Testing is only conducted on the air handling unit in a laboratory test rig as shown in Figure 2.1(a) and 2.1(b). Therefore, a major objective of this investigation to determine through the testing and the mechanism that responsible for generating the predominant noise within the system with the development strategies for the noise reduction [3]. The sources of air conditioning system noise are thought to be the air conditioner and the air conditioning ducts. But it is difficult to separately measure and evaluate those with actual cars [6].

In the automotive HVAC system, although the air handling hardware is not responsible for the total noise level inside the cabin, its individual frequency generation may be dominant within the confined cabin environment [12]. This is due to the driver and occupant's sensitivity towards the noise is high due to their proximity to the HVAC unit.

Suspected major contributors of the noise within the system are the centrifugal fan (both blower and motor) and aerodynamic flow through the ducting and vent geometry as what being done in a study of automotive HVAC blower wheel for flow, noise and structural integrity [4],[7],[10]. There is a study that focusing on the reduction of the noise output associated with the circulation of air in the current production of HVAC units [13]. The study shows that the highest noise magnitude is generated when the unit is set to the full face and full cold settings. Structural vibration of the system did not contribute to the major frequency spectrum components of the cabin noise and the HVAC noise is the air borne predominant .

2.4 Experiment setup of automotive HVAC system

There is a study on development of HVAC system in lab-scale size to investigate the vibration and noise of the HVAC system [1]. **Figures 2.1(a)** and **2.1(b)** show the HVAC system layout with the respective parts of the system.

1 - Air Inlet – recirculate setting

2 - De-mist and Front Vent – ducting connection port

3 - Centrifugal Fan Housing

4 - HVAC Integration Module (HIM) – dynamic vent controller

5 - Rear Vent – ducting connection port

6 - Main Heat Exchanger Housing

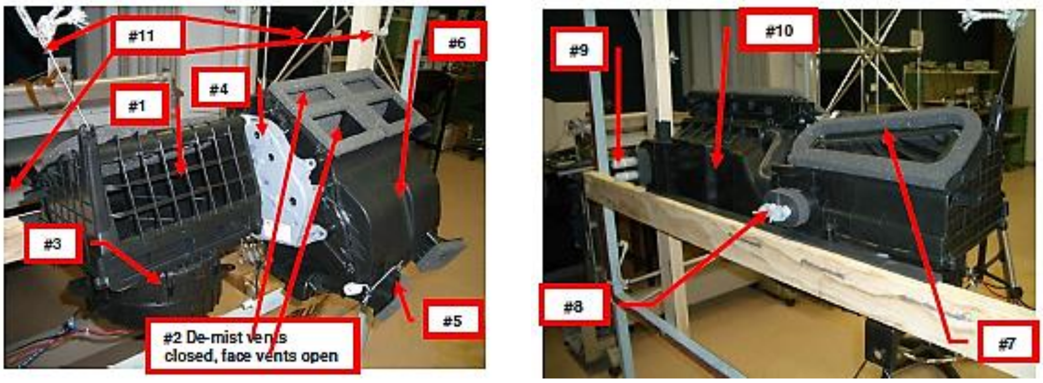
7 - Air Inlet – fresh air / re-circulate

8 - Refrigerant Lines – cooling

9 - Water Lines – heating

10 - Main Ducting – from fan to heat exchangers

11 – Bungee cords



(a) (b)

Figure 2.1: HVAC system layout **(a)** front view **(b)** and back view.

From the study, a microphone and its pre-amplifier are used to measure the sound pressure level. Variable voltage DC power supplier is used to power up the HVAC system. Two digital multi meter are used to measure the voltage and current supplied to the HVAC system and a stroboscope is utilized to measure the fan speed.

A microphone was mounted 1.35 meter above the floor and 1 meter away from the surface of the HVAC system by a tripod as shown in **Figure 2.2**. The microphone measurement points are selected at a 1-meter radius away from the HVAC system (free-field) to eliminate errors associated with the near-field or reverberant-field measurements [1],[9],[8]. Eight positional points are selected at 45 degree increments from a 0-degree datum directly in front of the system as shown in **Figure 2.3**. B&K Pulse intelligent data acquisition and analysis system is used to record sound pressure spectrum and levels. Speed of the centrifugal fan is measured with the aid of a stroboscope. The fan wheel is marked with a black arrow for reference. The strobe flash frequency is read until the marking on the wheel looked stationary. It was noted that non-consistent HVAC features of various vehicles tested had little effect on the test matrix [1].

The settings of the HVAC system dictate the path of the air flow through the unit and givens an impact on direction of propagating soundwaves. The unit is tested for acoustic emission under the worst-case scenario which the settings of Full Face – Full Cold – Re-circulate[1], [3]. All the valves and vents on the system are controlled by the HVAC Integration Module (HIM). To achieve the required setting, the connecting rods from the HIM that physically operated the vents are removed. The vents are then fixed back in place to simulate the correct settings.

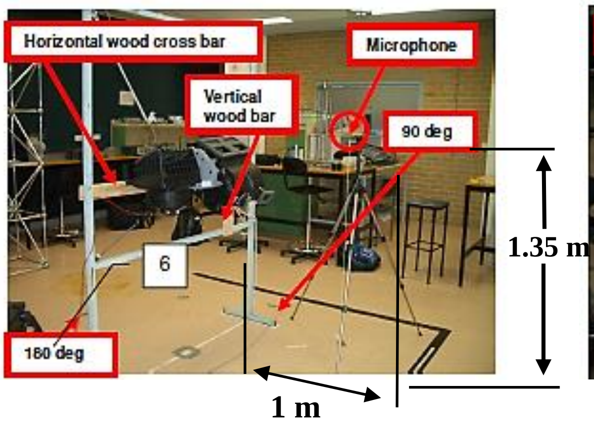


Figure 2.2: The HVAC system laboratory setup.

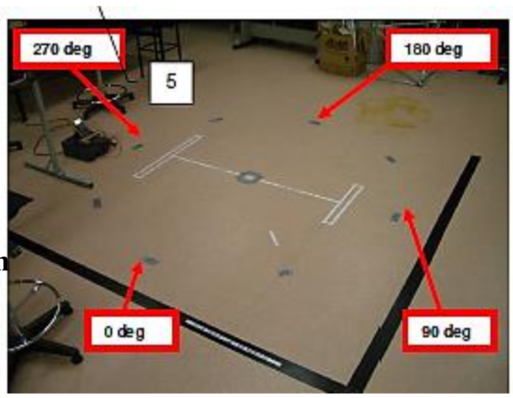


Figure 2.3: Microphone measurement points marked on the floor.

Four bungie cords are used to suspend the HVAC unit within the test rig frame at each corner of the test unit as shown in **Figure 2.1(a)**. Precisely, within the test rig frame, a horizontal wood cross bar is used to provide the vertical positioning of the HVAC unit as in **Figure 2.2**. A vertical wood support bar is installed to provide the horizontal positioning of the HVAC unit [1].

Based on results of this study, it was proven that by increasing the fan will increase the total noise level and the magnitude of the predominant noise spectral peaks. Another finding from this study is regarding the cover of motor vent passage hole and the seal of weld gap which do not change the total noise level, but do reduce the noise spectral peaks at the blade passing frequencies which also affected the cavity resonance peaks at the low frequencies[1],[11]. Application of the acoustic felt is most effective at the inlet area and least effective at the face of air registers. The most noise reduction is achieved at the points closest to the felt application area. Application of the felt material in the HVAC system is able to reduce at least 2 dB(A) of the total noise level and the noise spectral peaks in the frequency range above 200 Hz.

2.5 Summary

- HVAC system is split into two sections, one dealing with liquids as the working fluid and the other one with air. Both the liquid and air sides of the system produce noise from various components**.**
- Suspected major contributors of the noise within the system are the centrifugal fan (both blower and motor) and aerodynamic flow through the ducting and vent geometry.
- By increasing the fan speed will increase the total noise level and the magnitudes of the predominant noise spectral peaks.

CHAPTER 3 – METHODOLOGY

3.1 Overview

This chapter will discuss briefly on the following topics:

- Noise and vibration characterization on vehicle level
- Noise and vibration characterization on system level

3.2 Noise and vibration characterization of HVAC system on vehicle level

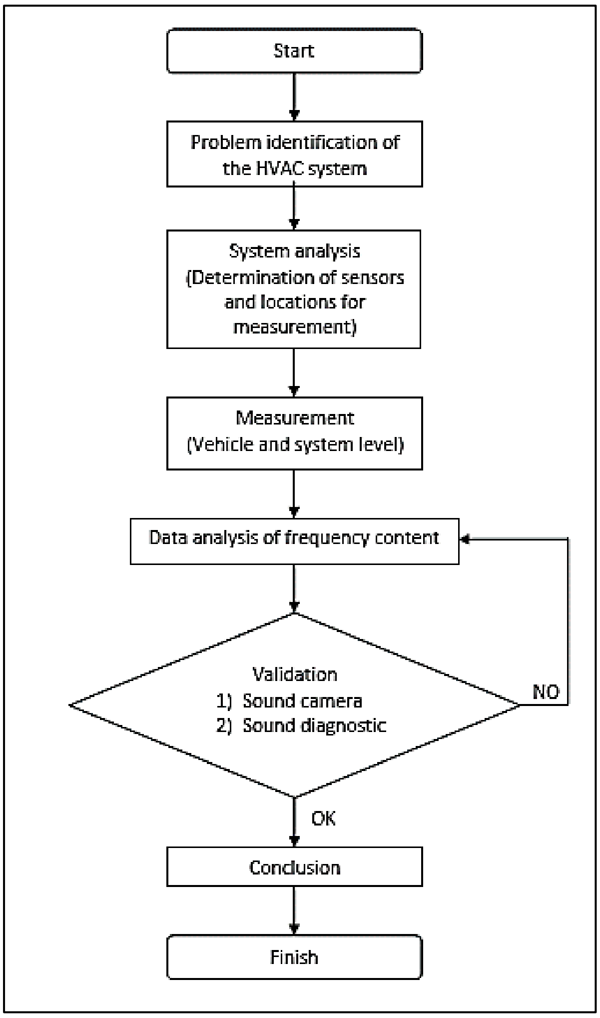


Figure 3.1: Flow chart for HVAC system characterisation.

The flow chart regarding overall project methodology is illustrated in **Figure 3.1**. From the figure, the study is set to start by identifying the main problems related on the noise and vibration occurrence in the HVAC system. After all types of noise produced by the HVAC system is clearly recognized, the objectives for this project is listed down as the guideline of what is the goals of project to be achieved. As overall knowledge involving HVAC system in terms of component function, design and installation has been successfully understanding the test is started to collect all the important data for the HVAC noises. Various parameters are taken into consideration for the test to get various noises patterns. Based on the data obtained, further analysis is made in detail involving the vibration and noise response. Proposed assumption and idea to relate those data with each component involved in the HVAC system is later to be initiated.

In this project, accelerometer and microphone are the main sensors need to collect and record the vibration and noise data. All the data collected are analysed based on the real-time response and frequency spectral data using LMS Test.Xpress software. Next, the frequency range at which each type of HVAC noise may occur is determined by identify the peak amplitude of response exploiting. However, frequency range obtained for each HVAC system noise is basically just preliminary postulation at this level and need to be confirmed and verified by multiple series of investigation.

One of the analysis used is Sound Diagnosis which performed using LMS Test.Lab Acoustic software. By importing the measurement data into LMS Data Streaming Format (LDSF) file, an audio track could be created by user from the data collected. Noise detection is performed by applying frequency filters on the audio track that make it easier to track the frequency content of the HVAC noises. Therefore, by tracking out HVAC noise that having an identical character similar as the subjective hearing could be comparatively recognized before specified the frequency range filtered from the overall sound recorded.

Another analysis conducted to verify the data obtained is through sound mapping using the sound camera. In this method, pre-setting of frequency range is set as input based on the previous finding in spectral analysis and sound diagnosis. Then, the sound camera is pointed to the specific area. Components or parts associated with the sound wave frequency that has been set will appear with colour mapping from the monitor display of sound camera. The colour map represents the sound pressure level (SPL) of noise been created.

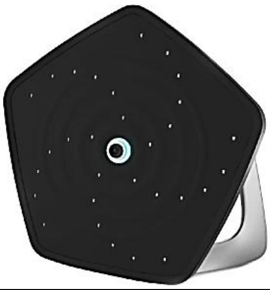
Another test that been carried out as a part of vibration and noise characterization is the impact testing, as a support data to be referred during noise and vibration spectral analysis. This analysis mainly to study the natural frequency of the component involved in each components or structures of HVAC system. Natural frequency is the frequency which a structure could oscillate if it is disturbed from the rest position and then allowed to vibrate freely. In this test, accelerometer is attached to the component to measure the output vibration and compared with the reference input from impact hammer force. Modal analysis is then performed from the data obtained in impact testing. The pattern appears as a Frequency Response Function (FRF) graph shows the natural frequency of the component and the mode shapes of the test structure can be animated with the respect to the natural frequency. However, for the vehicle level test there is some challenges in conducting this impact testing on each component of HVAC system due to limitation of space.

3.2.1 Equipments and sensors

Table 3.1 shows all the equipments and sensors used for the noise and vibration measurement of HVAC system on vehicle level. The general equipments and sensors connection is shown in flow chart of **Figure 3.2**.

Table 3.1: Equipments and sensors used for the characterization of noise and vibration at vehicle level.

No	Items	Quantity	Detail Images
1	LMS Scadas Mobile (64 channels)	1 set	
2	Tri-axial Accelerometer	5 units	
3	Microphone	3 units	

4	Sound Camera	1 set	
5	Impact Hammer	1 set	
6	Tachometer	1set	
7	Portable Accelerometer Calibrator	1 unit	
8	Portable Microphone Calibrator	1 unit	

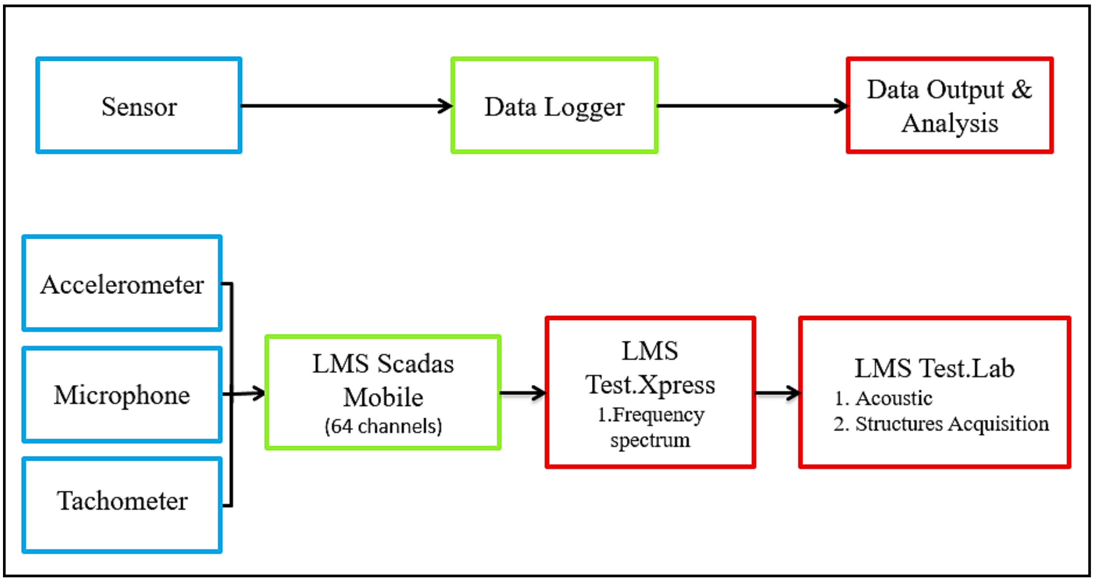


Figure 3.2: General connection for equipment and sensor.

Based on chart in **Figure 3.2**, three sensors are used for the noise and vibration measurement of HVAC system. Triaxial accelerometer is attached on component to record the vibration in three directions of *x*, *y* and *z* axis. For the noise or sound produced, it was set to be recorded using the microphone with an offset location of 10 cm distance from the component. To record the engine rotational speed, a tachometer is used to and the analysis can be made based on engine rpm reading. These three types of sensors are connected on data logger equipped for this test which is LMS Scadas Mobile. In this project, the 64 channels LMS Scadas Mobile is used to accommodate high channel count involving large units of sensors in the measurement. For the data output and analysis, two types of software are used which is LMS Test.Xpress and LMS Test.Lab. LMS Test.Xpres is used for the sound and vibration analysis with the high-speed system for the analysis of frequency content while the LMS Test.Lab Acoustic is used to conduct the sound diagnosis with a powerful set of highly integrated tools. Finally, the LMS Test.Lab Structures Acquisition is used to perform the modal analysis from the impact testing on the HVAC system component.

3.2.2 Experimental setup

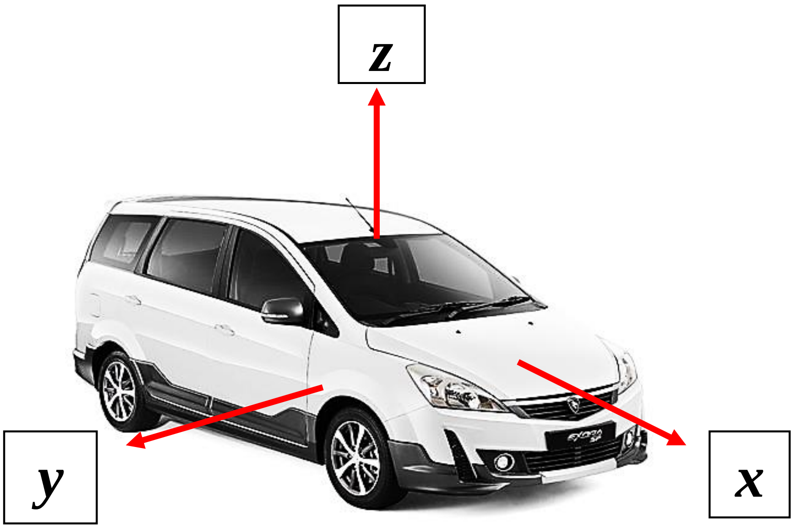
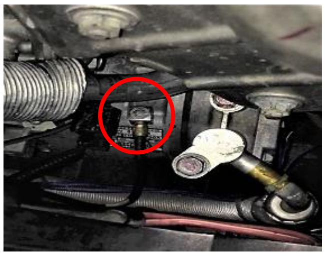
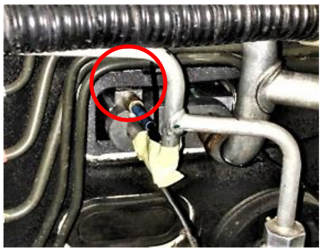
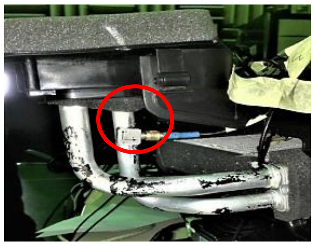
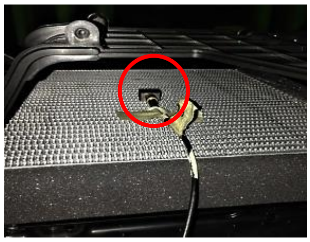


Figure 3.3: The three axes direction of the vehicle.

Figure 3.3 shows the axis direction for accelerometer on the vehicle level. All components of the vehicle for each test method is following this direction. The sensor locations for both accelerometer and microphone at the related HVAC components is shown as in **Table 3.2.**

Table 3.2: Sensor locations on HVAC components in the vehicle level.

No	Type of sensors	Type of measurements	Sensor locations	
1	Accelerometer	Vibration	On top of compressor body	
2	Accelerometer	Vibration	On the top of condenser part	

3	Accelerometer	Vibration	At TXV body	
4	Accelerometer	Vibration	Evaporator pipe inlet	
5	Accelerometer	Vibration	Evaporator core body	
6	Accelerometer	Vibration	On top of power steering body	
7	Accelerometer	Vibration	On top of AC pipe	
8	Microphone	Noise	10 cm from AC centre outlet	

9	Microphone	Noise	Driver left ear	
10	Microphone	Noise	10 cm from the compressor body	
11	Microphone	Noise	10 cm from the power steering body	
12	Microphone	Noise	10 cm from the AC left side outlet	

From **Table 3.2**, the accelerometer is mounted at seven main components of HVAC system. Vibration response is measured in three cartesian direction *x*, *y* and *z* axis. To measure the noise level, five microphones is located at various positions. It detects the sound pressure and transforms to the electric signal which can be interpreted by the measuring instrument. Three of them are positioned inside the vehicle cabin to express the real hearing experience as passenger while another two on specific components to get a detailed study on noise contribution. Two types of tests are carried out which at idle state and elevated engine speed. The test is conducted in an anechoic room as it is a suitable environment to perform noise measurement whereby the room is considered acoustically dead since there is a little or no sound reflections

3.3 Noise and vibration characterization of HVAC system on system level

To perform a satisfactory analysis for the noise and vibration response of the HVAC system, it would be a good practice to implement the test only for the HVAC system level by means it is isolated from any other system as in real vehicle level. A complete assemble of the HVAC system is developed on the rig structure fabricated. Real operation of the HVAC system must be set accordingly as in a vehicle to provide a similar system condition and the reliability of the test results. An electric motor is used to provide the drive action to compressor as an engine in a real vehicle. A suitable motor performance should be selected to provide enough power to run the whole HVAC system on the rig.

3.3.1 Design and the implementation of the HVAC rig system

Initial draft of the test rig is first developed in a CAD software. A complete assembly of HVAC system is included together on the rig structure to make it easier in identifying an optimal dimension of the rig for the fabrication process. **Figure 3.4** shows the complete design of the HVAC system in a rig structure. A motor is set to be placed together with the compressor on similar base as they share the belting drive. The base material should be a solid rigid structure as motor and compressor will be directly attached on it. The design produced will be the reference blueprint for next fabrication and components assembly process. Figure 3.5 shows the actual implementation of the HVAC rig system.

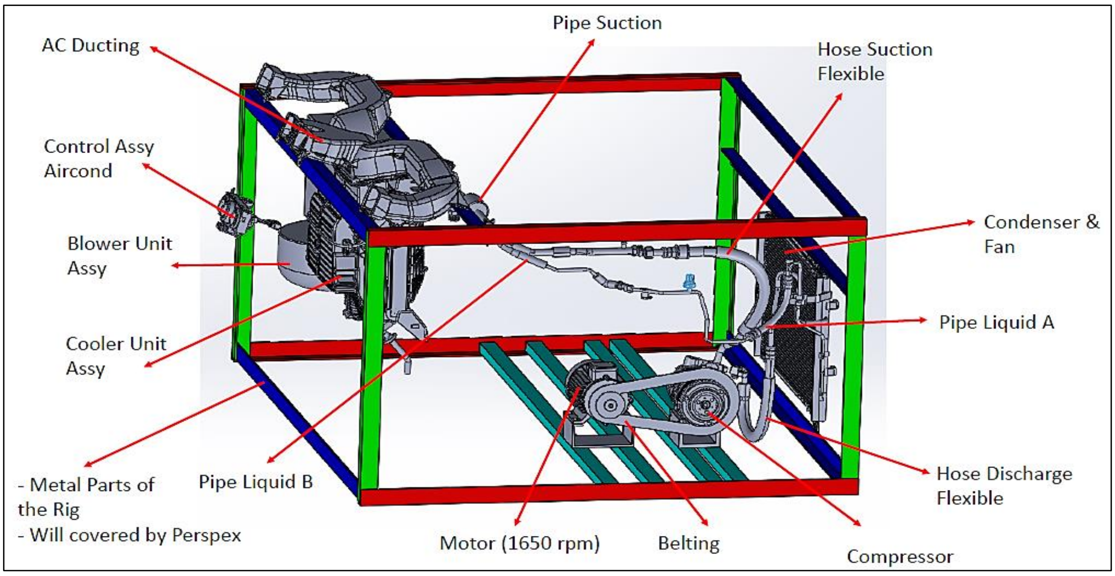


Figure 3.4: Design of HVAC system in CAD software

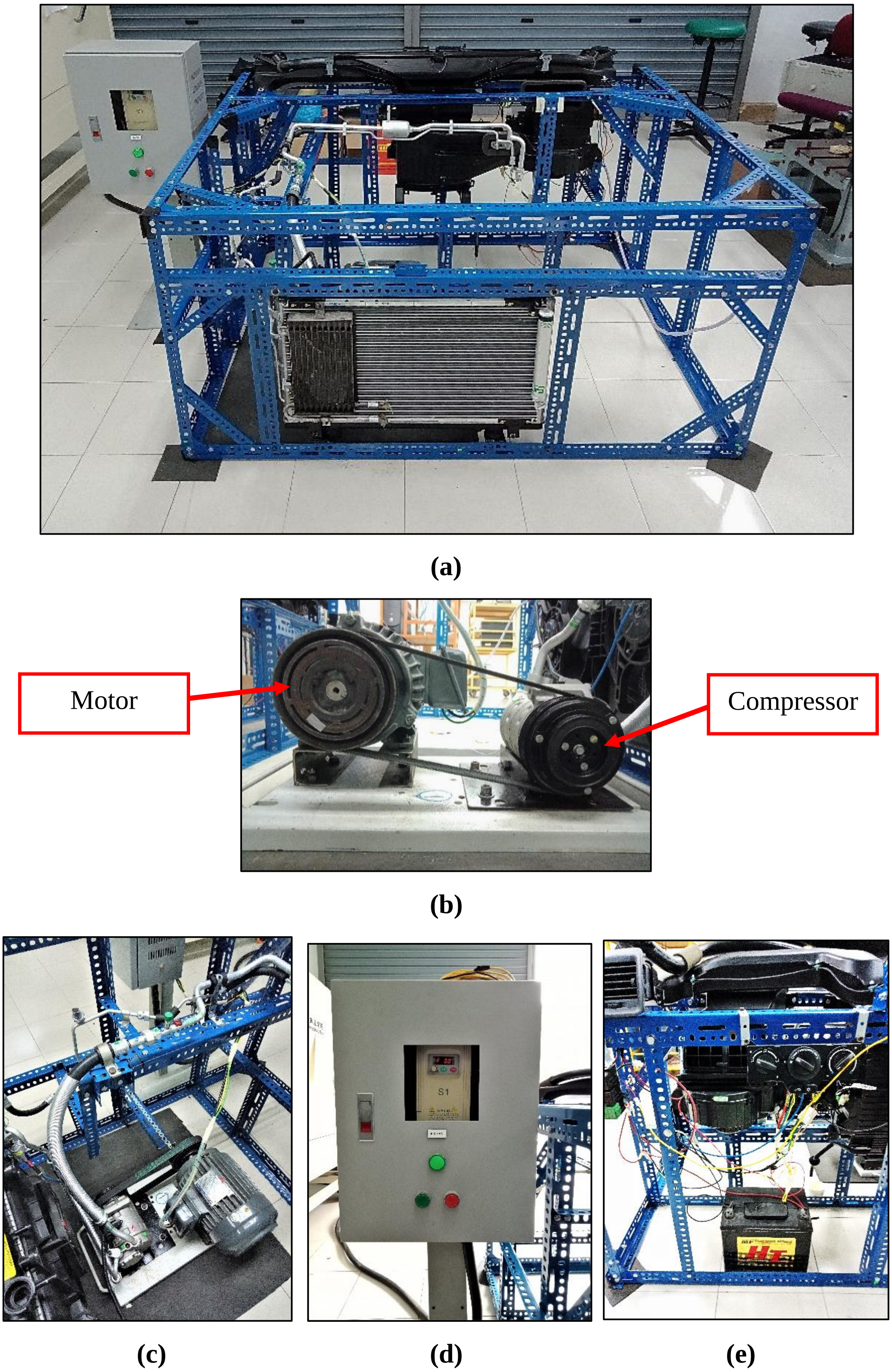
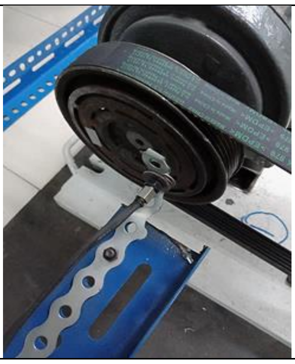


Figure 3.5: Actual implementation of HVAC system on test rig**. (a)** complete rig setup and assembly. **(b)** Motor as replacement to the engine driving the compressor to operate the system. **(c)** Mechanical components assembled and mounted as in real car. **(d)** Motor speed controller unit and emergency switch. **(e)** Electrical wiring of the HVAC system.

3.3.2 Noise and vibration spectral measurement

Table 3.3 shows all the equipment and sensors that used in carried out the noise and vibration spectral measurement of the HVAC system on system level. In **Table 3.4,** the accelerometer location is shown at the components involved for the noise and vibration measurement.

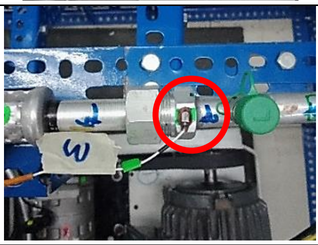
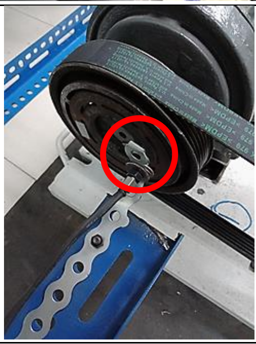
Table 3.3: Equipments and sensors used for noise and vibration measurement of the HVAC system.

No	Item	Quantity	Detail Image
1	LMS Scadas Mobile (64 channels)	1 set	
2	Uniaxial Accelerometer	5 units	
3	Portable Microphone Calibrator	1 unit	
4	Tachometer	1unit	

5	Battery	1 unit	
6	Battery charger	1 unit	

As for the system level measurement, the sensors and equipments used are have much difference as what have been used in vehicle level. Besides, the type of tests remains the same comprising of idle and rpm tracking. Only that, the maximum rotational speed of the drive could be reached up until 1800rpm as per motor specification. Due to the limitation arise for the test environment, the noise measurement by microphone is unable to carry out because there is no large anechoic room available to provide a sufficient place for the whole test rig. Hence, only vibration measurement will be collected and the noise of each components are extracted using the Sound Diagnosis method in LMS Test.Lab Acoustic as presumed previously in **Figure 3.2**. The lack of appropriate anechoic room will only affect the characterization of the air rush noise since it will fully be done using microphone sensor only. For other type of noises, the analysis can still be done for HVAC components using the data from accelerometer. Even though sensors and equipments setup has been reduced, the acoustic response still can be simulated based on data from vibration measured by accelerometer for the results confirmation and verification. So, there is no any issues on the characterization of HVAC system of the noise and vibration at various operating condition as in the actual vehicle level.

Table 3.4: Sensors location on HVAC components in system level measurement.

No	Type of sensors	Type of measurements	Sensor locations	
1	Accelerometer	Vibration	On top of motor body	
2	Accelerometer	Vibration	On the top of compressor body	
3	Accelerometer	Vibration	At AC Pipe	
4	Accelerometer	Vibration	At TXV body	
5	Accelerometer	Vibration	Evaporator Pipe inlet	
6	Tachometer	Rotational speed	Pulley of Motor	

CHAPTER 4 – RESULTS AND DISCUSSION

4.1 Overview

This chapter will discuss briefly on the following topics:

- Results of HVAC system measurement and analysis at vehicle level
- Results of HVAC system measurement and analysis at system level

4.2 Results of HVAC system measurement and analysis at vehicle level

Table 4.1: Summary on HVAC noise identification results in vehicle level

No	Noise	Test method	Engine	Air condition	Blower speed	Sensor setup location	Noise Frequency (Hz)	Component with highest contribution
1	Hissing	Idle (850 rpm)	On	On	1	**Microphone** • Centre Outlet • Left side outlet • Cabin **Accelerometer** • Compressor • Condenser • TXV • Evaporator pipe inlet • Evaporator core	4500-5500	• Evaporator pipe inlet
		Rpm tracking (850-3000 rpm)	On	On	1			
2	Humming	Idle (850 rpm)	On	On	1	**Microphone** • Compressor • Power steering pump • Cabin **Accelerometer** • Compressor • Power steering pump • AC pipe • Evaporator pipe inlet • Evaporator core	300-350	• Power steering pump • Compressor • AC pipe
		Rpm tracking (850 - 1400 rpm)	On	Off	-		400-500	
			On	On	1		150-250	
3	Clicking (Compressor Clutch Engagement)	Idle (850 rpm)	On	On	1	**Microphone** • Centre Outlet • Left side outlet • Compressor **Accelerometer** • Compressor • Condenser • TXV • Evaporator pipe inlet • Evaporator core	150-300	• Compressor
4	Air rush	With Vents	Off	Off	1	**Microphone** • Centre Outlet • Left side outlet • Compressor **Accelerometer** • Compressor • Condenser • TXV • Evaporator pipe inlet • Evaporator core	1400-1700	• HVAC Blower
		Without Vents	Off	Off	1			