APPLICATION OF THE STRUCTURAL DYNAMIC MODIFICATION (SDM) METHOD TO REDUCE NOISE AND VIBRATION OF VEHICLE HVAC SYSTEM

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DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

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(Signature of Student)

Date:

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In the name of Allah, the most beneficent, the most merciful

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LIST OF ABBREVIATION

WORDS	DESCRIPTION
HVAC	Heating, ventilating and air conditioning
SDM	Structural Dynamic Modification
DVA	Dynamic Vibration Absorber
TXV	Thermal Expansion Valve

MENGGUNAKAN MODIFIKASI DINAMIK STRUKTUR (SDM) UNTUK MENGURANGKAN BUNYI DAN GEGARAN DALAM SISTEM HVAC KERETA

ABSTRAK

Sistem pemanasan, pengalihudaraan dan penghawa dingin (HVAC) merupakan antara sumber utama bunyi dalam kenderaan yang boleh menyumbangkan kesan negatif pada bunyi persekitaran. Operasi sistem itu sendiri menghasilkan gegaran yang tidak boleh dielakkan dan menyebabkan bunyi yang tidak diingini terhasil. Bunyi yang terhasil akan menjadi lebih kuat apabila gegaran sesuatu komponen dipindahkan ke komponen lain kemudian bertembung dengan frekuensi natural komponen tersebut. Frekuensi natural sesuatu komponen bergantung kepada berat dan kekenyalannya. Pengubahsuaian terhadap salah satu faktor tersebut mampu mengubah frekuensi natural sesuatu komponen. Kajian ini memfokuskan untuk mengurangkan spesifik bunyi yang terhasil dari sistem HVAC dengan menggunakan metod modifikasi dinamik struktur terhadap komponen yang terlibat. Sistem HVAC peringkat makmal dihasilkan untuk mewakili sistem sebenar di dalam kereta. Ukuran terhadap bunyi dan getaran diperingkat kenderaan dan peringkat sistem dijalankan dan hasil ukuran dibandingkan. Penyerap getaran dinamik (PGD) digunakan sebagai alat untuk mengurangkan getaran komponen yang spesifik dalam HVAC peringkat sistem. Keputusan menunjukkan bahawa, frekuensi semula jadi komponen telah dialihkan yang menghasilkan julat frekuensi yang berkesan pada skala 100-500 Hz. Kesan DVA juga diperhatikan untuk sistem pengendalian HVAC yang mana pengecilan getaran yang signifikan telah dicapai untuk rangkaian kekerapan operasi 100-300 Hz.

APPLICATION OF THE STRUCTURAL DYNAMIC MODIFICATION (SDM) METHOD TO REDUCE NOISES AND VIBRATION OF VEHICLE HVAC SYSTEM

ABSTRACT

Heating, ventilating and air-conditioning (HVAC) system represents a major source in vehicle noise and vibration that contribute a negative effect on the acoustical environment. The operating system itself have produce a significant vibration which subsequently produced an unwanted noise. Noise is amplified when the vibration of components transferred to other components and excites its natural frequency. Natural frequency of a components is depending on its mass and stiffness and can be modified by these two parameters. This study is focusing on the specific HVAC noise and vibration reduction by implementing structural dynamic modification (SDM) method to one of the component involved. The lab-scale of HVAC system is set up to represent the actual HVAC system at the vehicle level. Noise and vibration of HVAC system in vehicle and system levels are measured and compared. From this data, the Dynamic Vibration Absorber (DVA) is designed and applied for a specific component of the HVAC system. The results show that, the natural frequencies of component have been shifted which resulting a wide effective frequency range of 100-500 Hz. The effect of DVA also been observed for the operating HVAC system whereby a significant vibration attenuation has been achieved for operating frequency range of 100-300 Hz.

Chapter 1

INTRODUCTION

1.1 General Overview on Vibration and Structural Dynamic Modification (SDM)

Vibration can be defined as a periodic motion of a particles from rest position to another position. Basically, noise and vibration are highly related where the noise can be produced from the vibration. Vibration in machines or mechanical structure are typically undesirable since it will produce stresses, energy losses and increasing in load. If vibration of the structure occurred for sufficient of time, structural wear could occur which lead a reduction of accuracy and in some cases, it might lead to failure. The main factor of controlling the vibration is the mass, damping and stiffness of the structure.

Structural dynamic modification (SDM) is one of the method that can be used to improve the vibration of a structure or components. SDM can be defined as a method by which dynamic behavior of a structure is improved by predicting the modified behavior such as lumped masses, rigid links, dampers or by adjusting the configuration parameters of the structure itself. This method basically is done using software and simulation, which is more accurate and less effort on fabrication. The modification done to the structure is made to satisfy criteria of static design such as reduction of stress concentration. The focus is based on the modal properties of the structure which is natural frequencies and mode shapes. These criteria are determined by its mass, stiffness and damping distributions.

These properties are also called spatial properties of the structure and often quantified by mathematical model of the structure. This model representing the physical properties of the structures including geometrical parameters and material properties which include stiffness, mass and damping properties. By finite element(FE) modeling, it is possible to predict the modification in terms of mass, stiffness and damping properties changes. These three factors are main consumers to vibration. However, to simulate the real structure, geometrical parameters such as thickness, length and diameter is more important and must be considered. Usually, this information can be collected by measurement or 3D-drawing of the structure. The changes of material properties like damping coefficient, density and young modulus of the structure also need to be alert.

Structural modification is needed when there is undesirable dynamic characteristics of the structure. This happened when the structure encounters imbalance among itself due to static or dynamic loading. Generally, dynamic loading will contribute greater response to the structure than static loading, which also lead to higher stress concentration during dynamic response. The structure that not prepared for the additional dynamic stress could lead to undesirable vibration. The design of the structure itself may lead an unnecessary vibration due to less concern about balancing of the mass between the structure. The material chosen also to need to be concern in the physical properties.

When working under dynamic environment, other factors need to be alert is vibration resonance. Resonance occurred when vibration of a component is transfer to other components due to equal in excitation frequency. SDM method can be used to shift the resonance factor, hence reducing the vibration for whole structure. The shifting could be done either by adjusting the mass, damping or stiffness of the components structure or by adding a dynamic vibration absorber(DVA). However, the limitation of this method is the modification that been strategies may not be able to apply to the real structure. The physical constraint, such as the total mass change by this modification is not applicable to real structure. There is a limitation of modification that practical or feasible to implement in real life structure. The changes of modal properties of modified structures are studied in dependency on changes of spatial and physical properties

1.2 Project Background

This final year project is a second phase part 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 Method"** which started on May 2017 and will complete on April 2019. The first phase of this project is already completed during internship period from June until September 2017.The first phase is more focusing on measurement and collecting data on vehicle level. This project has several targets. Firstly, to improvised design guideline with the additional of SDM method and secondly SDM method will be one of the design solution and countermeasure for any noise and vibration problems for the Proton vehicles.

The noise of the heating and ventilating air conditional (HVAC) system is a common problem for most of the automotive manufacturers. 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 HVAC system has several assembly parts such as compressor, condenser, fan, drier, thermal expansion valve (TXV), blower and more as shown by **Figure 1.1**. These parts can contribute to the noise problem for the vehicle. Therefore, it is important to determine the source of the HVAC noise from the vehicle HVAC parts to improve the vehicle comfort ability while driving.

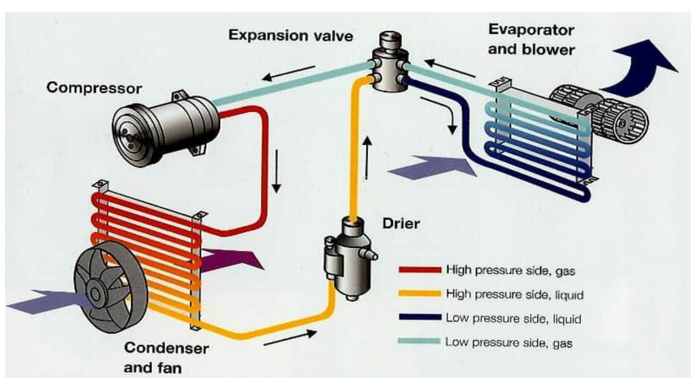


Figure 1.1: Vehicle air conditional system (Proton)

This second phase study will be applying the SDM method using the data collected from test conducted. The rig of the complete Proton Exora HVAC components will be fabricated. The purpose of the rig is to compare the vibration level of all HVAC components between vehicle and components level. The SDM method will be applied to one type of the noise only, which is hissing noise. The aim of SDM is to reduce the vibration and noise on components involve, hence reducing the hissing noise produce.

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. A proper characterization of the vibration and noise of the HVAC system must be carried out to determine the root cause of this problem. SDM is one of the passive vibration and noise control method that can be used to reduce the noise and vibration of the HVAC system. Therefore, in this study, SDM method is applied to reduce the vibration and noise of the Proton Exora HVAC system.

1.4 Objective

The objectives of this project are listed as below:

1) To develop the lab-scale (System level) setup of Proton Exora HVAC system
2) To measure and identify the hissing type noise characteristics of the Proton Exora HVAC system (Vehicle and system levels)
3) To apply SDM method to reduce the vibration and noise of the Proton Exora HVAC system (System level)

1.5 Scope of Work

This project is divided into two parts. The first part is to fabricate the rig of Proton Exora HVAC components to become a complete HVAC system. The purpose of the rig fabrication is to measure and compare vibration and noise of the system between vehicle and components levels. The second part is to apply the SDM method to the HVAC system to reduce the vibration and noise of HVAC system. The SDM is firstly study using LMS software and then tested to the actual HVAC system.

CHAPTER 2

Literature Review

2.1 Overview

This chapter will discuss on following topics:

- Type of noise from the HVAC system
- Current available solution to reduce noise from HVAC system
- Structural Dynamic Modification (SDM) method
- Dynamic Vibration Absorber (DVA)

2.2 Type of Noise from the HVAC System

The study of noise and vibration have an important influence on the customer's perception and cabin interior noise level is an important factor to describe the quality comfort of the vehicle. One of the highest interior sound produce is from the HVAC system(Mavuri *et al.*, 2008). The most contribute noise from the system is an air rush noise. A benchmarking study was performed to investigate and compare the noise produce inside the cabin. The study includes number of passenger inside the cars. A binaural head system was used in front passenger seat to measure noise levels. The test was conducted on relatively new production vehicle at idle condition, which is in stationary condition with engine off to eliminate engine and external noise source. It was discovered that the design of HVAC system itself has contribute in producing this noise. Based on the study, it is found that size or price of the vehicle may not correlate to noise produce inside the cabin due to complexity of the HVAC system itself.

HVAC system is important to be installed inside a building to give a comfort feeling in a building environment. Hence, HVAC system is designed to provide human acoustic comfort besides thermal and air quality requirements (Bujoreanu and Benchea, 2016). Acoustic measurement is conducted inside anechoic room with three types of commercial air handler (AHU) with different ducting cross section and inlet-outlet configuration. The parameters in measurement is vary in fan speed and duct air flow is slowly adjusted from fully open to fully closed, ranging between 0-500 Pa. Thirdoctave band analysis of random noise of AHU from HVAC system is analyzed using standard procedure ISO 3744:2011 as shown in **Figure 2.1**. The ambient and power supply sound pressure level is recorded for data noise analyzing reference. The noise source generated from the HVAC system is multiple source, not only a single source from the air circulating duct located insides the room. The results indicate that the fan power and air flow pressure are contribute to the acoustic performance of the HVAC system.

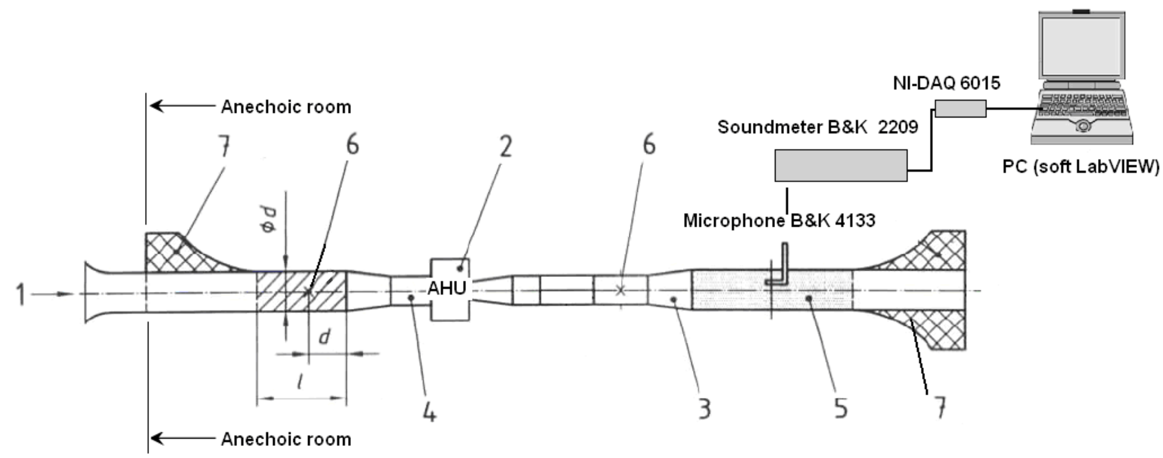


Figure 2.1: Test arrangement for in-duct noise measurement according to ISO 5136:2010

2.3 Current Available Solution to Reduce Noise from HVAC System

The most significant interior noise of vehicle is contributed from the HVAC system as air handling unit of HVAC system is located behind vehicle instrument panel by (Wang and Watkins, 2007). Modification has been made on internal structural geometry of the system to insight the effect for structural feature to the overall Sound Pressure Level (SPL) and frequency spectrum components. The test rig of the system is developed, and several locations are selected to undergo acoustic felts test. The study found that the fundamental and second order of blade passing frequency (BPF) are identified and related to fan speed. When the fan speed increase, the BPF increase and lead to increases in total noise level. To encounter this, the motor vent passage hole is covered, and weld gap is sealed. However, the result shows that the total noise level do not decrease, but noise spectral peaks at the blade passing frequencies is reduced.

There is a study that state that HVAC noise is not as loud as the overall noise level However, it affects driver subjective perception and may lead to feelings of nervousness or annoyance (Yoon *et al.*, 2012). Therefore, it is important to reduce noise from this system. HVAC noise samples are taken from various vehicle and evaluation is obtained. The main objective of this study is to apply SDM to determine characteristic trigger of the noise. Multiple regression model is generated, and the regression analysis produced diagnostic statistics and regression estimation. Based on the three objective numerical inputs, which is loudness, sharpness and roughness, the neural network (NN) models were created. The purpose of this model is to estimate human perceptions. Then, the models are compared with sound quality output indices and hearing test results. From the study, the result demonstrated that NN is highly correlated with sound quality indices, which led to determination of suggested method for sound quality prediction.

HVAC system is one of the air conditioning system commonly use inside buildings facilities. This system is a main noise contribution as noise emitted when the system is running. There are high frequency and low frequency noises, and high frequency noise able to be reduce using passive devices. However noise components at low frequencies below 400-500 Hz is hardly to reduce (Cocchi *et al.* , 2000). Active noise control (ANC) is very efficient at low frequency and ideal to be implemented to achieve acoustic comfort over the whole audible spectrum. Two microphones which is one for sampling and one for error signal and a wide-band loudspeaker is used to test the performance of ANC toward noise reduction. The system connected to a room and the noise source as shown in **Figure 2.2.** The results show that the method has small influence on the air flow inside the ducting system. The active control that been applied to the HVAC system has affected the noise contribute from the system where the overall attenuation was better than 6dB. Future improvement is suggested using compact anechoic termination in concomitance with the HVAC system with a standard configuration and the optimization of such noise control system.

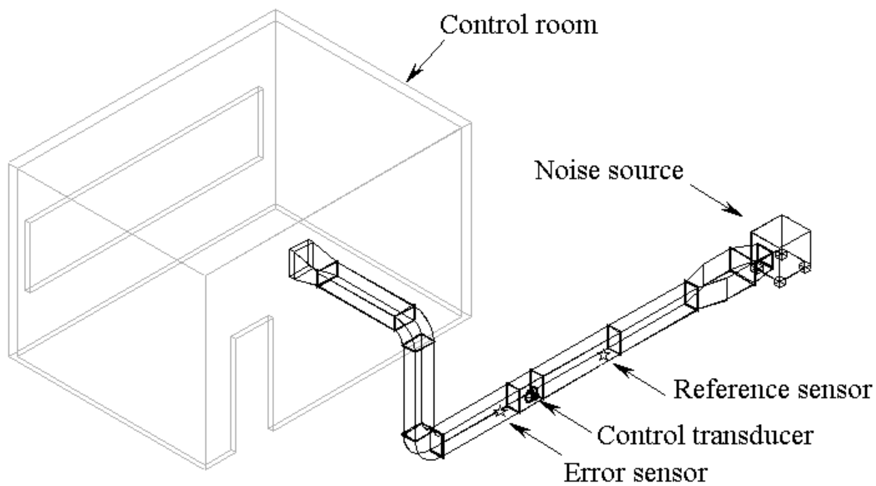


Figure 2.2: Control room configuration

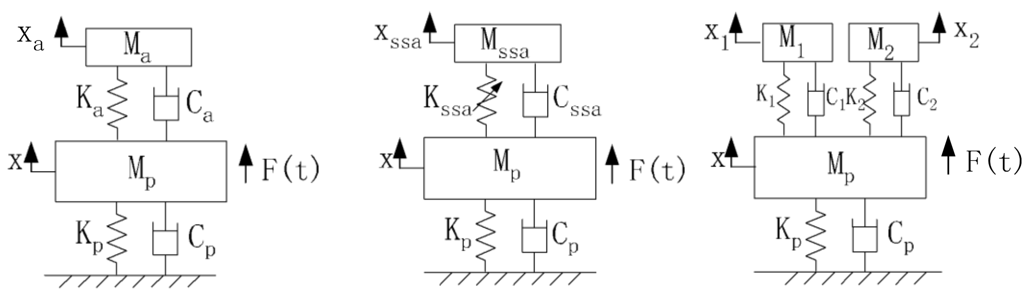
2.4 Structural Dynamic Modification (SDM) Method

The literature shows that the purpose of applying SDM is to save design time and modification that could be done on the models of structures, dynamic test or updated models (Kundra, 2000). The study presents the SDM method using mathematical model that focusing on mass, stiffness and damping matrices of the structure. The mathematical model is extracted in form of frequency response function (FRF) which could be obtain by analyzing data from the test conducted on the structure. FRF data basically generated by computer simulation via modelling and the study shows the same example methods of modification such as mass, beams and tune absorber.

Another study shows the comparison and advantages of SDM method using Finite Element Analysis (FEA) and prototype fabrication with a testing (Wallack *et al*., 1989). In the study, SDM is used to explore a larger number of design modifications without having to fabricate and retest each other, or without having to build and analyze a varies type of finite element models. The study shows the validity and accuracy of the SDM approach by modeling rib stiffeners and comparing SDM-generated results with those of FEA and modal test results. The parameter used such as adding stiffness to the structure using rib stiffeners. The test is firstly done on the original structure to verify the data. After modification on the structure, the test is conducted against and the results are compared.

The same procedure is done using FEA method. After that, both results from real structure and FEA are compared. The result shows that FEA method give more accurate data to SDM application.

In SDM method, DVA and State-Switched absorber(SSA) are common methods that can be applied either to structure or components itself. The comparison of performance between DVA and SSA are studied for a single-degree-of-freedom (SDOF) system under dual harmonic excitation(Sun *et al*, 2008). The study is focusing in comparing the performance of single DVA, single SSA and dual DVA in the scope of vibration control. Each of the absorber is mounted on the identical system and the displacement of the system is measured. **Figure 2.3** shows how the method is applied to the system.



(a) Single DVA (b) SSA (c) Dual DVAs

Figure 2.3: Single DVA, SSA and dual DVAs mounted on identical primary systems.

Based on the study, the performance of dual DVA and single SSA is almost equal and both are better that single DVA performance. The advantage of dual DVA over the single SSA is a lower ratio of tuning frequencies, more rapid optimization process and lower requirement for the anti-fatigue property of the material.

There is a study that shows the application of SDM method to an active suspended handle to overcome the displacement limitation of a piezo stack actuator by increasing the stiffness of the lower beam of the handle that supports the piezo stack actuator(Mazlan and Ripin, 2016). This study which used SDM method can improve the performance of an active suspended handle and compared with the data collected from the experiment. This study focusing on the stiffness of the handle by referring to the force and the displacement of the handle with concerning the operating frequency. SDM method is used to alter the stiffness of the handle and compare with the previous result. The study shows that the increased stiffness shifted the modes of the structure beyond the operating frequency range. It is found that the modified handle has a better performance compare to original handle. This shows that the SDM method is effective in solving this issue.

2.5 Dynamic Vibration Absorber (DVA)

Dynamic vibration absorber, or also known as vibration neutralizer, is a tuned spring-mass system which reduces or eliminates the vibration of harmonically excited system. This absorber is widely used in machinery and structure vibration passive control with the design based on the fixed point (Zhang *et al*, 2015). The theory is based on the approximation since the damper of the primary system is neglected. The fixed point is not coincided with the resonance point of the natural frequency of the primary system. A two degree of freedom dynamic model with a primary system is fabricated and set to be damper for the system. The natural frequency of primary system need to be identified before the damper is fabricated. Frequency ratio between the primary system natural frequency and absorber are calculated numerically. The analytical equation which related to the frequency ratio is derived to verify the reliability of the parameters.

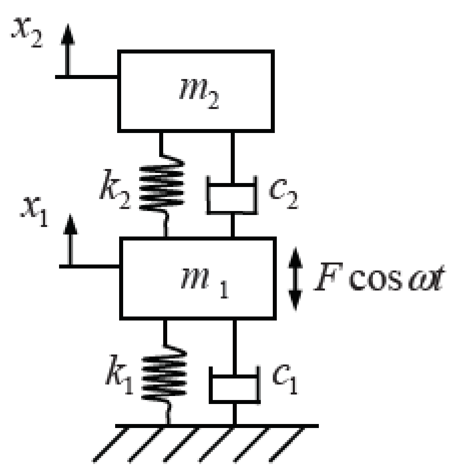


Figure 2.4: Model of DVA with primary system

However, there is an error for some parameters calculated by fixed point theory because the practical damper of primary system is neglected. Average value is being used to calculate the ratio of the absorber. On this derivation, optimal frequency ratio and damping ratio of absorber including the consideration of non-existing damper on primary system can be calculated and can be used as reference for designing the dynamic absorber. Theoretical formula that described the relations of optimal frequency ratio, damping ratio and maximum amplitude can be derived to check the parameters reliability.

The main factor of implementing dynamic vibration absorber on primary structure is the design of the absorber itself. Two numerical approaches can be applied for an optimum design of the absorber. The first approach is using Chebyshev's equioscillation theorem while second approach is minimizes compound subject to a set of the constraint (Liu and Coppola, 2010). Both of the methods are applied on classical system and compared with the analytical solution. The theorem is applied to determine optimum damped DVA for damped primary system. Optimum design problems for special damped DVA are investigated. The approximate optimum tuning parameter is derived, and the model is attached to the primary system. These two numerical methods are used to solve the design problem. There is discrepancy between numerical and analytical solutions where Chebyshev's method need to be modified with addition of selection criterion. The optimum tuning parameters decreased with the increased of damping ratio or mass ratio. The limitation of Chebyshev's theorem can be overcome by modification on the equation.

2.6 Summary

- HVAC system contribute a significant noise and create discomfort for human acoustic either in vehicle or building. The noise source is from the components itself and the air ducting that channel the air inside the cooling area.
- The solution for noise reduction of HVAC system is mainly focusing of the modification on components that contribute high sound pressure level.
- Structural dynamic modification is one of the effective method that can be applied to the system for noise reduction strategy since it is time and cost saving because modification could be done on the models of the structure.
- Dynamic vibration absorber is a tool that operative in reducing or eliminating the vibration of the system. The design of the absorber is the main factor for vibration reduction strategy.

CHAPTER 3

Methodology

3.1 Overview

This chapter will discuss briefly on following topics:

- Noise and Vibration Characterization (Hissing) in Vehicle Level
- Noise and Vibration Characterization (Hissing) in System Level
- Modal Analysis on Hissing Related Components
- Structural Dynamic Modification (SDM) Strategy of HVAC system

3.2 Noise and Vibration Characterization (Hissing) in Vehicle Level

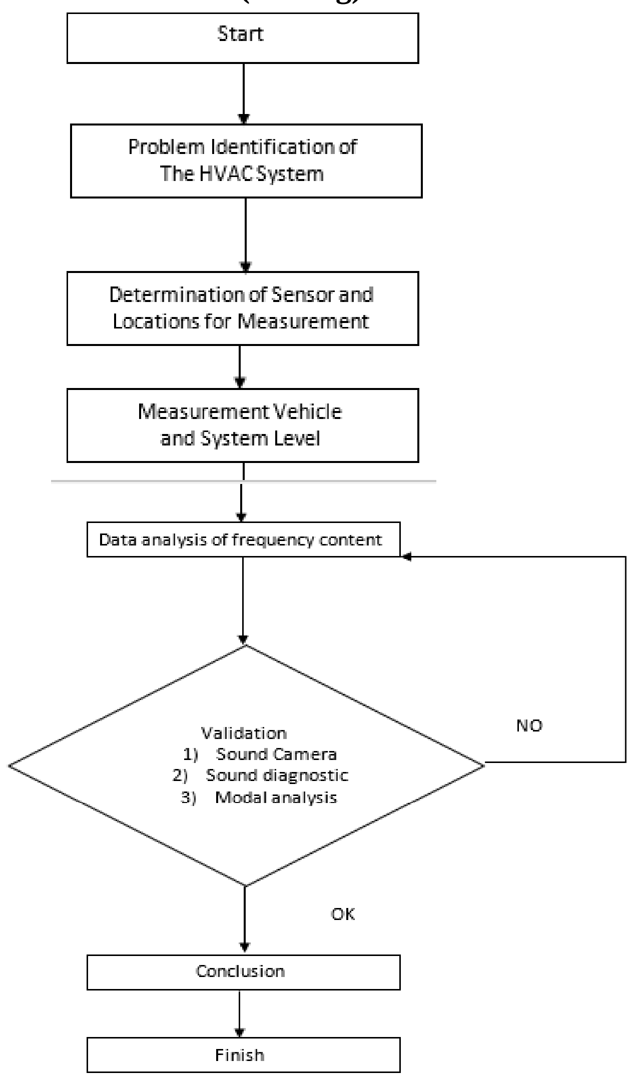


Figure 3.1: Flow chart for noise and vibration (Hissing) HVAC system characterization

The flow chart of the project methodology is shown in **Figure 3.1**. From the figure, the study is started by identifying the main problem which related on the hissing noise of the HVAC system. All of component on the HVAC system is studied to understand each component function including the design and method of installation. Then, the test procedure and equipment required is listed for measurement of test preparation. To obtain accurate noise data, the test is conducted inside the anechoic room. Anechoic rom is sound insulation room to avoid ambient noise during test. The engine noise firstly to be determined as reference in the data. A complete Proton Exora car is used in the test. There are two test patterns have been decided for hissing noise measurement. The first measurement pattern is in idle condition, where the car engine and HVAC system in under static condition. The second pattern is rpm tracking, where the rpm is being increased manually. Certain rpm range has been decided to investigate the hissing noise level. The measurement test for both patterns are run in sequent and all the important measurement data required regarding the HVAC hissing noise issue which exist on the Proton Exora model is collected. Based on the data obtained, further analysis is made in detail and how to relate it with each component involved in the HVAC system.

In the vehicle level measurement, accelerometer and microphone are main sensors to collect and record vibration and noise data. Accelerometer is a vibration sensor, and, in this measurement, 3-axis accelerometer is used. Microphone is a sound level sensor and located at specific position for noise analysis. Both sensors are connected to the data logger LMS Scadas mobile. For rpm tracking measurement, tachometer is used as rpm sensor for engine rpm data collection. All the data is analyze using frequency spectrum in LMS Test.Xpress. Vibration and noise frequency spectrum are compared to determine hissing frequency range. The frequency range is selected based on highest peak on the frequency spectrum graph. Then, the frequency range is verified using LMS Test.Lab to identify type of noise produce for specific frequency range that has been selected. The noise analysis from the software is compared with subjective hearing.

The last analysis is the modal analysis using an impact hammer as another alternative to verify the data. This analysis mainly to study the natural frequency of the component involved in each of HVAC system noise. Natural frequency is the frequency which a structure would oscillate if it were disturbed from its rest position and then allowed to vibrate freely. In this test, accelerometer is attached to the component to measure the impact value and compared with the reference input from impact hammer. The pattern appears on the FRF graph shows the natural frequency of the components. However, for the vehicle level test there is some challenges in conducting this modal analysis on each of the components of the HVAC system due to limitation of space to reach certain component.

3.2.1 Equipment and Sensor

Equipment and sensor used in this measurement is shown in **Table A1** in **Appendix A** with the location of sensor on the test subject. The general equipment and sensor connection is shown in the chart form in **Figure 3.2**.

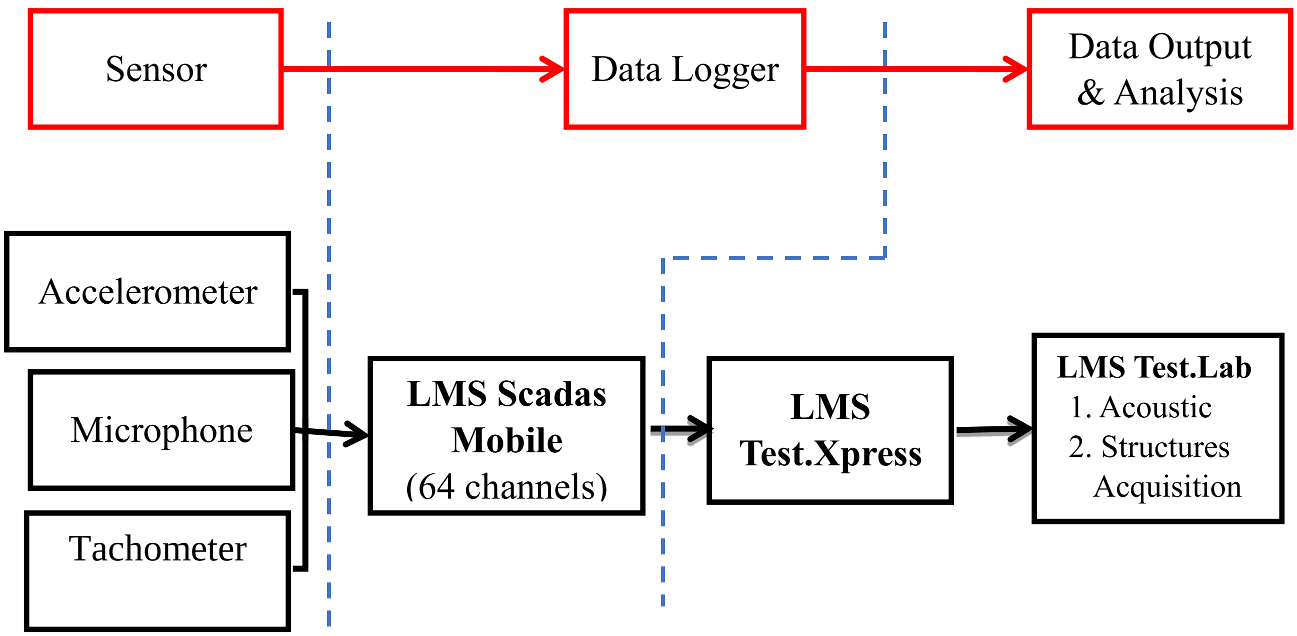


Figure 3.2: General connection for equipment and sensor

Based on **Figure 3.2**, three sensors are connected to LMS Scadas mobile as data logger. The accelerometer and microphone are calibrated using the portable calibrator to ensure the data collected from each sensor is valid. Triaxial accelerometer is attached on selected component as shown in **Table A2** to record the vibration in three directions of X, Y and Z-axis. The axis is set as car axis for all components as shown in **Figure 3.3**. For the noise measurement, the sound is recorded using microphone with offset location of 10 cm distance from the component. To consider on the engine speed, tachometer is used to monitor the engine speed and analysis can be made upon engine rpm basis. These three sensors are connected on data logger which is the LMS Scadas Mobile. In this project, the 64 channels LMS Scadas Mobile is used to accommodate high channel count involving large units of sensor in the measurement testing. Then, the data output is analyze using two types of software which is LMS Test.Xpress and LMS Test.Lab. LMS Test.Xpres is a no-compromise sound and vibration analyzer with the high-speed system for the analysis of frequency content. LMS Test. Lab Acoustic is a sound diagnosis software with a powerful set of highly integrated tools. Then, LMS Test.Lab Structures Acuisition is used to perform modal analysis by impact hammer testing on the HVAC system components involved.

3.2.2 Experimental Setup (Hissing)

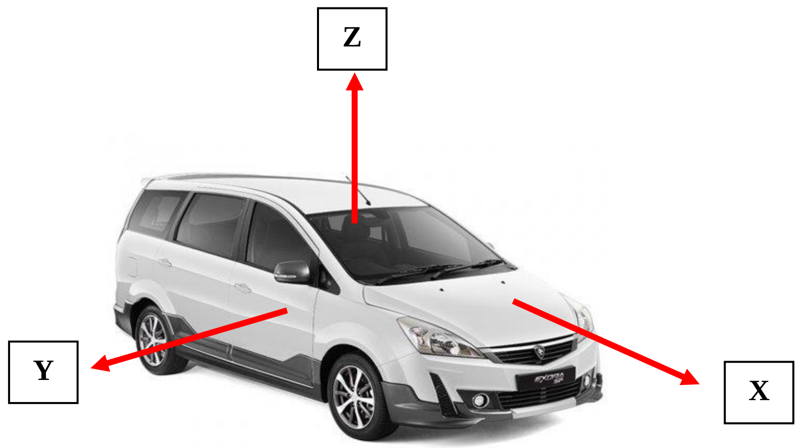


Figure 3.3: The 3-axes direction for car

Figure 3.3 shows the general direction for accelerometer. All components in the vehicle for all test method are following this direction. The sensor location that being attached for accelerometer and microphone at the HVAC system is as shown in **Table A2** in **Appendix A.**

3.3 Noise and Vibration Characterization (Hissing) in System Level

Noise and vibration of hissing noise is investigated in system level. The HVAC system of Proton Exora car is assemble on rig structure to represent the real system operation. The rig is fabricated, and the HVAC component is assembled exactly as real system in the car. The motor is replacing the engine function to operate the whole system. The motor selected must able to run the system as in the car operation.

3.3.1 Design and Implementation of the HVAC System

Using a Solidwork software, HVAC system is design with complete assembly for whole system including motor position. The design is focusing on mechanical part of the system. **Figure 3.4** shows the completed design of HVAC system in a rig structure. Motor position is aligned parallel with compressor and connected with the belting system. The base for motor allocation on the rig structure must be thick and strong metal due to high vibration produce when motor is running. The design is use in reference for fabrication of the rig.

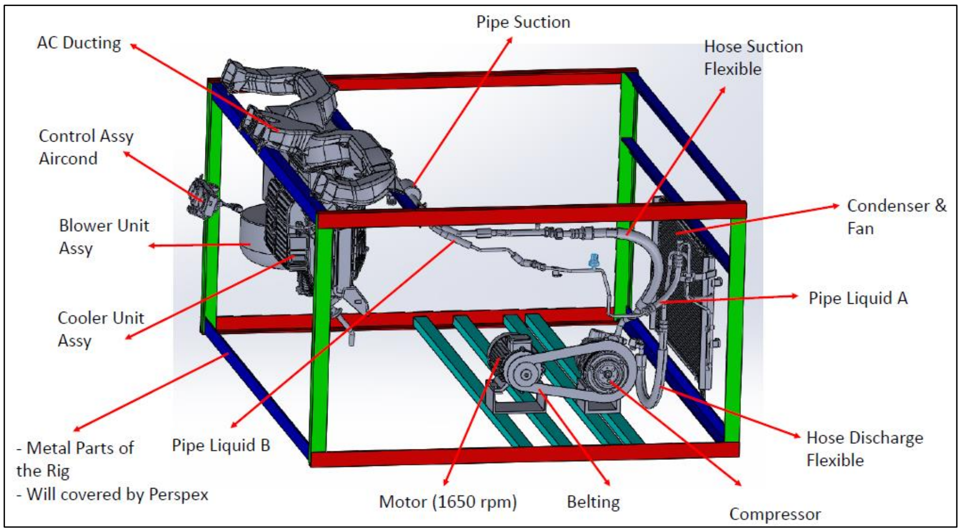


Figure 3.4: Design of HVAC system in CAD software

The fabrication of the rig is based on the complete design that has been done. The HVAC component is assembled and mounted in position as same as in vehicle assembly. The main critical component is an alignment between motor and compressor. The belting that connecting compressor and motor pulley must tense enough to run the system with loading gas. The motor is mounted on heavy base, as shown in **Figure 3.5** to avoid vibration of motor transfer directly towards other component in the system. The motor is connected to controller to control the motor speed. The controller used is a 3-phase power supply controller with displaying the speed in frequency unit. The complete assemble of all HVAC component is display in **Figure 3.6.**

Figure 3.5: The base use for motor mounting and connection between motor and compressor with belting system

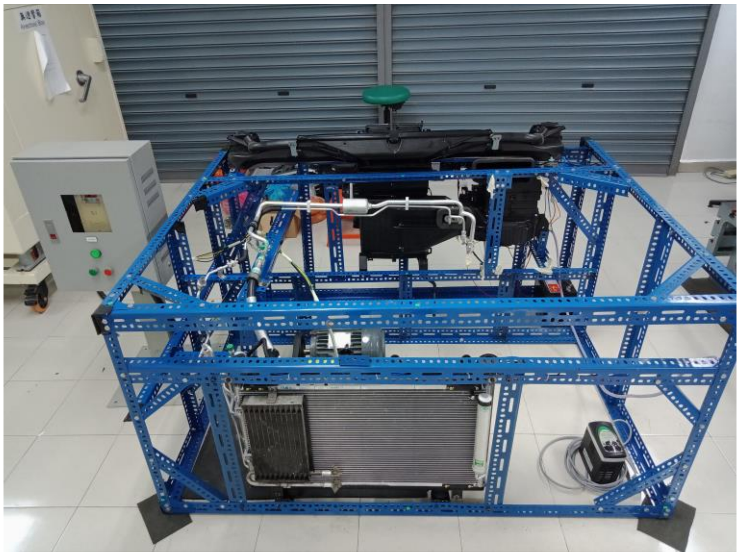


Figure 3.6: Actual implementation of HVAC system

The HVAC system is operated with two main power supply, which is direct power supply to the motor and a battery for the HVAC system functioning. **Figure 3.7** shows the electrical planning for whole system include safety emergency button. The system has activation button to control the engagement of compressor, with also connected with the battery power supply. The control panel also has a blower speed controller to control the blower speed that will flow the air throughout the air ducting. The control panel shown in **Figure 3.8** is exactly functioning as in the vehicle HVAC system. The system has sensor located inside the evaporator core to automatically cut-off the compressor engagement when the system achieved certain low temperature. This sensor acts as safety precaution, because if the system is running for a long time, a very low temperature will occur inside the system that may damage the operation and components.

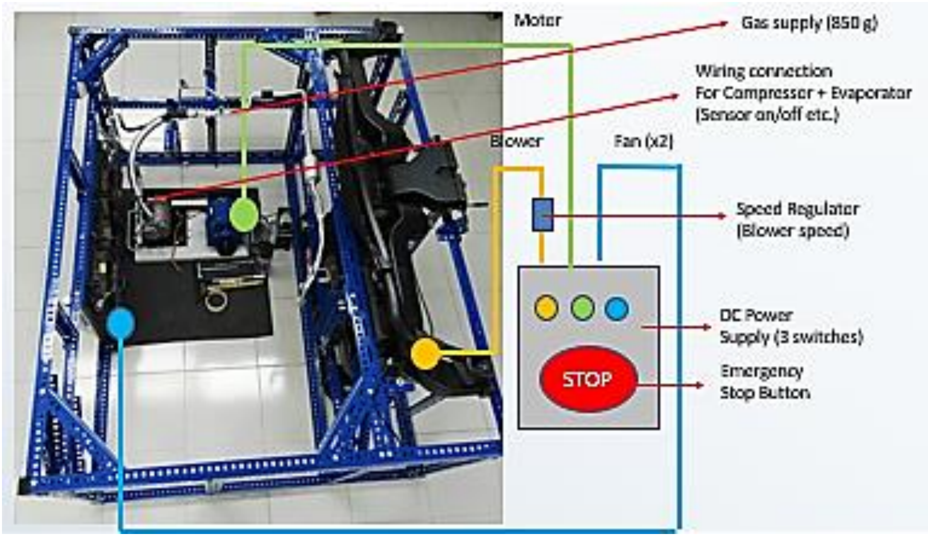


Figure 3.7: Electrical connection on the system

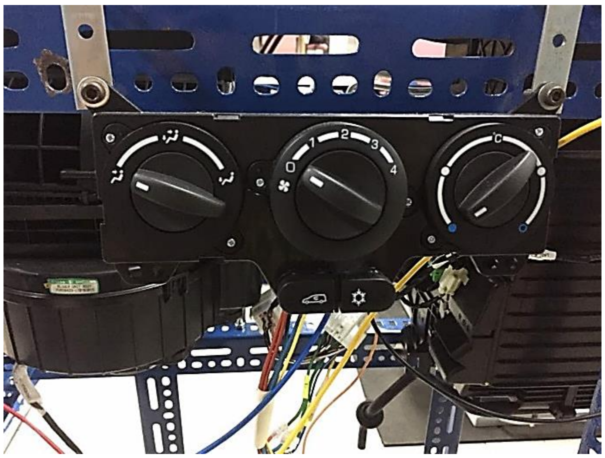


Figure 3.8: The control panel that control the compressor engagement and blower speed

3.3.2 Modal Analysis of Hissing Related Components

Modal analysis is carried out to obtain the natural frequencies of components. There are two patterns of test, free free condition and in-complete system structure. Free free condition is where the component is hanging individually using rubber band as shown in **Table A4** in **Appendix A**. Equipment and sensor use for the test is shown in **Table A5** in **Appendix A**. Accelerometer is attach on the component and impact hammer is used to apply external force on the component. The geometry for each component in LMS Test.Lab is also shown in **Appendix A**. Natural frequencies and mode shapes for each component for both test patterns are determine using the LMS software.

Impact testing is also done on same components with complete assembly of the whole system without a loading gas. **Table A6** in **Appendix A** shows the test setup and the geometry in the LMS Test.Lab software. The same equipment and sensor shown in **Appendix A** is used in the testing and the test procedure is repeating same as the free free condition impact testing. Natural frequencies for each component related is compared with natural frequencies of free free condition for references.

3.3.3 Vibration Characterization (Hissing) in System Level

When the HVAC system in-rig structure can fully operate with a loading gas, the vibration measurement on components involve for hissing noise is done to study the vibration behavior of the system in rig structure. Accelerometer used in this measurement is uniaxial, which can extract vibration data in one direction only. Microphone is not applicable in this measurement since the measurement is conducted in an open space area, that the ambient noise will influence the data. The location of accelerometer in each component is shown in **Table A3** in **Appendix A**. There are two test patterns conducted for system level vibration measurement. The first pattern is idle where the motor is running with speed of (850rpm), similar to the vehicle level measurement. The speed of motor is controlled by a speed regulator power supply as shown in **Figure 3.9**. The second test pattern is rpm tracking from 850 rpm to 1800 rpm. Due to limitation of motor specification and speed maximum at 1800 rpm, the measurement up to 300 0rpm as in vehicle level cannot be done. The overall overview of accelerometer location for both test patterns are displayed in **Figure 3.10**.

Figure 3.9: The 3-phase speed regulator power supply that connecting motor which control motor speed

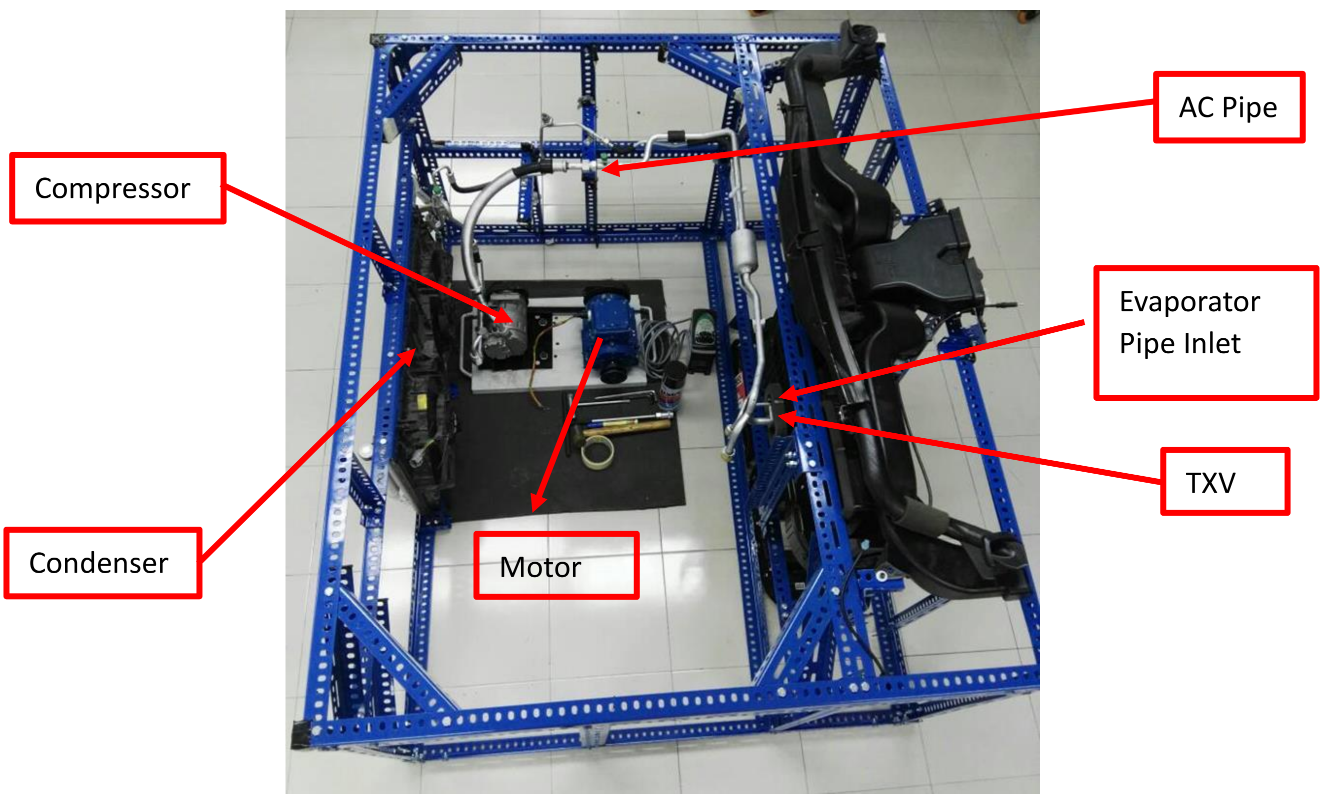


Figure 3.10: Accelerometer location overview for idle and rpm tracking measurement in system level

3.4 Structural Dynamic Modification (SDM) Strategy on the HVAC System for Hissing Noise

The strategy of dynamic modification method is firstly done by selecting component to be modified. Then, the natural frequency of the component selected on the system need to be determine. The highest peak of natural frequency of the component is determine by impact testing. The selected natural frequency is used as reference in SDM application. SDM is applied on a point of selected component to modified component natural frequency.

3.4.1 Modelling of Structural Dynamic Modification (SDM

For the hissing noise, aircond pipe as shown is **Figure 3.11** is selected as component to be modified. Accelerometer is placed on the component and impact hammer shown in **Appendix A** is used to obtain the natural frequency of the pipe. The geometry of the pipe is shown in **Figure 3.12**. Natural frequency on the rig structure is compared with the natural frequency on free free condition for reference.

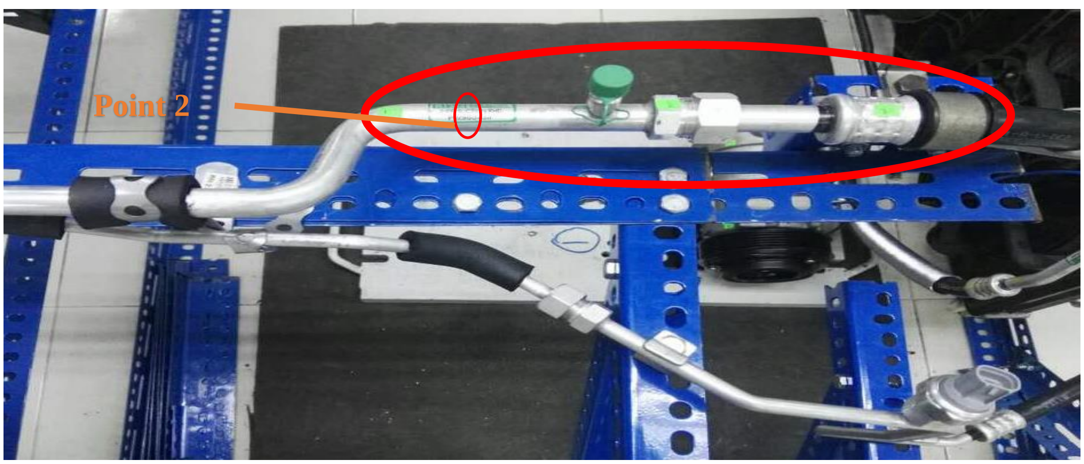


Figure 3.11: Aircond pipe selected on the HVAC system

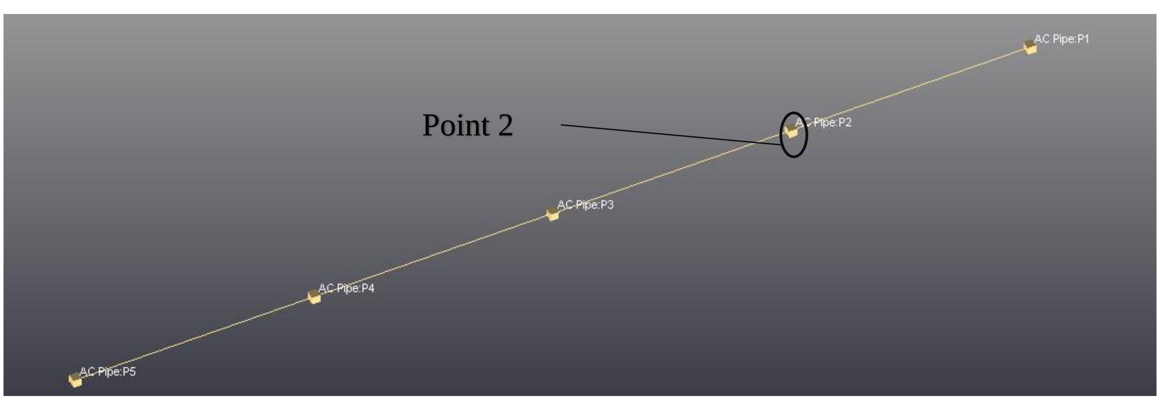


Figure 3.12: Aircond pipe geometry for impact testing on rig structure

From the geometry in **Figure 3.12,** point 2 is selected as a point for SDM attachment as shown in **Figure 3.13.** Dynamic vibration absorber option is used from the software that need to be implement on the point 2 of the aircond pipe. The mass prediction of the absorber is included in the modification. **Figure 3.14** shows the mass (0.132 kg) and targeted frequency been selected (148 Hz), and the prediction stiffness and damping value will automatically have generated for the modification.

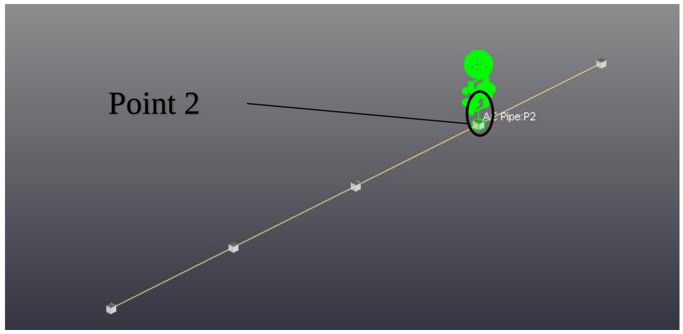


Figure 3.13: DVA attach on point 2 of aircond pipe

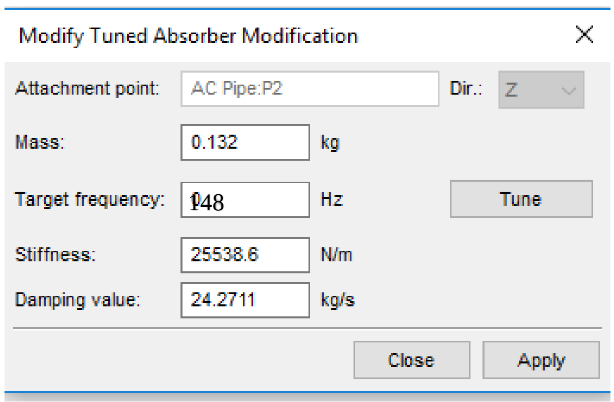


Figure 3.14: Specification of the DVA

The tuning of the DVA is dependence on theoretical calculation to have first assumption of distance between the two weighs from the center rod as shown in **Figure 3.15**. This distance becomes the first reference before the DVA is tuned into targeted frequency. The calculation is shown as below:

$$\text{Force, } F=k\partial \tag{3.1}$$

$$\text{The deflection of cantilever beam, } \partial = FL^3/3EI \tag{3.2}$$

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

$$\text{Natural frequency, } w^2=k/m_a$$

$$k=(2\pi f)^2\times m_a \tag{3.4}$$

Substitute 4 into3

$$L^3=\sqrt[3]{\frac{3EI}{(2\pi f)^2\times ma}} \tag{3.5}$$

Second moment of inertia of rod is given by:

$$I = 1/4\pi r^4 \tag{3.6}$$

Considering Eq. (3.1) - (3.5), the **estimated length** for the given secondary mass values can be calculated.

Where, ma is the each of the secondary mass (kg)

r is the radius of the cantilever beam (m)

L is the length of the cantilever beam (m)

f is the excitation frequency (Hz)

E is the Young modulus of elasticity of the cantilever beam (N/m2)

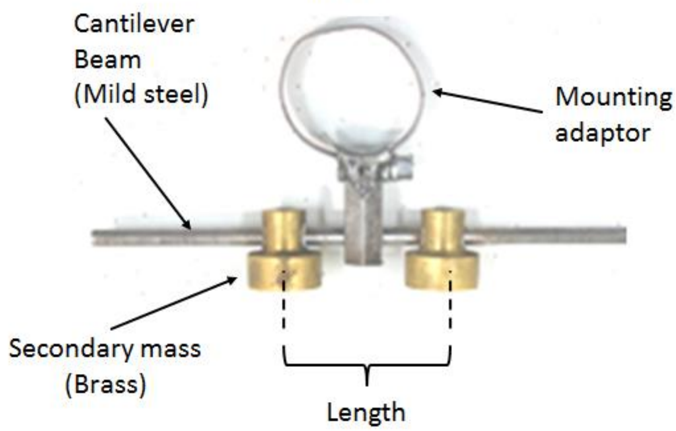


Figure 3.15: The arrangement of weighs on DVA

3.4.2 Implementation of Structural Dynamic Modification on the HVAC Rig

DVA is chosen to be implemented on the aircond pipe for structural dynamic modification. DVA is a mass spring damper system with two weights attach on a single rod as shown in **Figure 3.16**. The weight distance from each weight center is adjust until its natural frequency approaching targeted frequency (148 Hz) on the selected component. This process is known as DVA tuning frequency. LMS Test.Xpress is used in the tuning process. The tuning of DVA is done with the DVA attach on aircond pipe, and an accelerometer is placed on the DVA structure. An external force is applied on the DVA structure and the frequency is recorded.

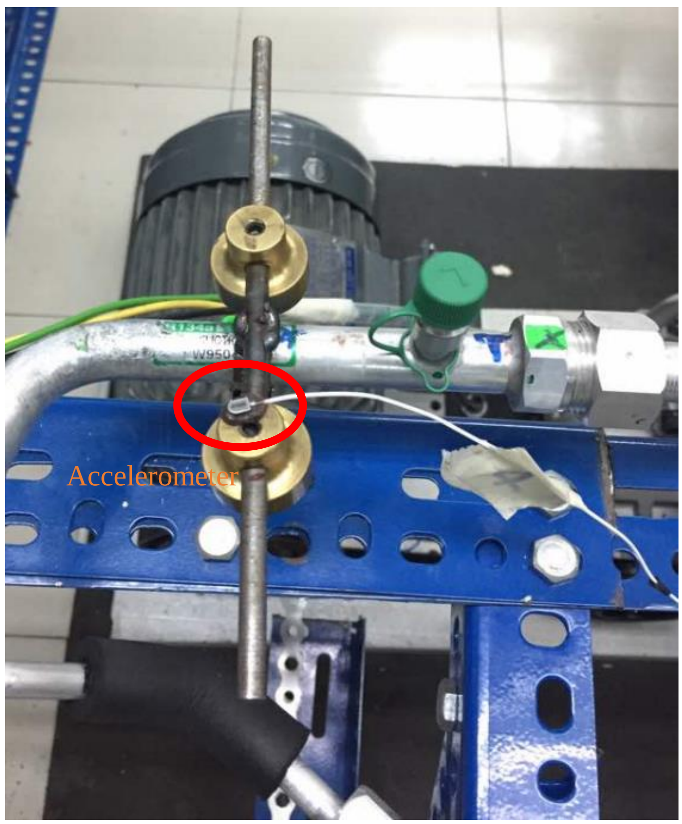


Figure 3.16: DVA on aircond pipe and accelerometer attach on DVA