VIBRATION ATTENUATION ON VACUUM CLEANER BY RUBBER MOUNT

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DECLARATION

I hereby declare that this thesis entitled **VIBRATION ATTENUATION ON VACUUM CLEANER BY RUBBER MOUNT** is original work accomplished by me under the guidance of Dr. Ooi Lu Ean. I confirm that the work submitted is my own research, except where otherwise stated. I confirm that appropriate credits that have been provided on supporting literatures and resources has been given within this thesis where reference has been made to the work of others.

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LIST OF SYMBOLS

dBA	A-weighted decibels
ω_n	Natural frequency
k	Stiffness
m	Mass
ζ	Damping ratio
f	Frequency
fr	Resonant frequency
$H(\omega)$	Transfer function
$F(\omega)$	Input force function
$X(\omega)$	Response function
$k(\omega)$	Frequency dependent stiffness
$n(\omega)$	Loss factor
Re	Real part
Im	Imaginary part

LIST OF ABBREVIATIONS

OSHA	Occupational Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
SPL	Sound pressure level
SDOF	Single degree of freedom
FRF	Frequency response function
ODS	Operating deflection Shape
DOF	Point and direction
ISO	International Organization for Standardization

ABSTRAK

Kebisingan yang dihasilkan oleh penyedut habuk biasanya terdiri daripada bunyi bising udara dan binaan struktur. Pengasingan getaran yang disebarkan oleh blower motor elektrik ke bahagian lain penyedut habuk juga dapat mengurangkan transmisi kebisingan. Untuk melemahkan tahap getaran penyedut habuk, sistem pelekap getah dilaksanakan dalam pemasangan perumahan motor. Oleh itu, analisis modal telah dijalankan untuk mendapatkan ciri-ciri struktur dari blower motor elektrik dan penyedut habuk. Selain itu, sifat dinamik seperti faktor kehilangan dan kekakuan yang bergantung kepada frekuensi adalah parameter yang penting untuk memilih pelekap getah yang paling sesuai. Oleh itu, ujian impak dijalankan untuk mendapatkan fungsi penerimaan jenis getah yang digunakan dalam sistem pelekap getah. Untuk mengurangkan pecutan tegak dan mendatar, sistem pelekap getah dicadangkan untuk pemasangan perumahan motor dengan menggunakan pelekap getah yang sesuai berdasarkan ciri-ciri dinamiknya. Terdapat tiga konfigurasi untuk mengkaji keberkesanan teknik pelekap getah dalam mengurangkan tahap getaran. Hasilnya, untuk konfigurasi A, pecutan mendatar menurun sebanyak 7.06% manakala pecutan menegak dikurangkan sebanyak 22.99%. Berikutan dengan konfigurasi B, pecutan mendatar dikurangkan sebanyak 28.66% manakala pecutan menegak menurun sebanyak 20.55%. Akhirnya, untuk konfigurasi C, pecutan mendatar dan tegak dikurangkan sebanyak 36.33% dan 14.33% masing-masing. Kesimpulannya, tahap getaran penyedut habuk dapat dikurangkan dengan berkesan dalam kedua-dua arah iaitu mendatar dan menegak. Oleh itu, sistem pelekap getah yang dicadangkan adalah salah satu kaedah yang sesuai untuk mengurangkan getaran yang disebarkan oleh blower motor elektrik.

ABSTRACT

Noise produced by a household vacuum cleaner is generally built of airborne and structure-borne noise. Isolation of vibration transmitted from the electric motor blower of a vacuum cleaner to the other part of vacuum cleaner also can reduce the transmission of noise. To attenuate the vibration magnitude of household vacuum cleaner, a rubber mounting system is implemented onto the motor housing assembly. Thus, modal analysis is carried out to identify the structural characteristic of electric motor blower and vacuum cleaner. Furthermore, dynamic properties such as loss factor and frequency dependent stiffness are the important parameters to select the most suitable rubber mount. Thus, impact testing is carried out to obtain the receptance function of each individual rubber mount. As the interest is to decrease vertical and horizontal acceleration, a rubber mounting system is proposed onto the motor housing assembly with a suitable rubber mount based on its dynamic characteristics. There are three configurations to study the effectiveness of rubber mounting technique in reducing vibration magnitude. In result, for configuration A, the horizontal acceleration is decreased by 7.06% while vertical acceleration is reduced by 22.99%. Following with configuration B, the horizontal acceleration is reduced by 28.66% while vertical acceleration is dropped by 20.55%. Last but not the least, for configuration C, horizontal and vertical acceleration are reduced by 36.33% and 14.33% respectively. In short, the vibration magnitude of vacuum cleaner is effectively reduced in both horizontal and vertical directions. Hence, the proposed rubber mounting is an appropriate method in reducing the vibration transmitted from the electric motor blower.

CHAPTER 1: Introduction

1.0 Overview

Noise and vibration control on household appliances is important as there is no hearing protection at home. Noise is unwanted sound produced when a vibrating object like motor in the household appliance causes air particles to vibrate. Hence, control of vibrating object or source can relatively reduce the noise level of a household appliance. In addition, exposure to noises above 85 dBA for a period of time will cause hearing damage to a person. According to Occupational Safety and Health Administration (OSHA), it permits exposures of 85 dBA for 16 hours per day. For every 5 dB increase in noise level, the allowable exposure time is reduced by half. On the other hand, based on National Institute for Occupational Safety and Health (NIOSH), the permissible exposure time before possible damage can occur is reduced into half for every 3 dBA increase over 85dBA. [1] Therefore, it is important to study on noise and vibration control on household appliances for noise control engineers.

Noise emitted by a vacuum cleaner consists of airborne and structure-borne noise. The airborne noise is mainly generated by the centrifugal blower while the structure-borne noise is mainly generated by the electric motor blower. The contribution of the structure-borne noise to the total sound pressure level (SPL) depends on the geometry of the electric motor blower and on its operating conditions. [4] As it is impossible to redesign the electric motor blower of vacuum cleaner to improve its operating point, structural modification would be made to reduce the vibration and noise caused by the electric motor blower of vacuum cleaner.

Based on the arrangement for mounting a motor blower assembly in a canister vacuum cleaner, a pair of resilient rubber rings is used. Each one is located on the front and rear of the assembly to isolate the motor from the vacuum cleaner housing. The desirability of isolating the motor blower assembly of a canister vacuum cleaner from the housing of the vacuum cleaner in order to reduce the transmission of noise. [5]

Therefore, this objective of this paper is to implement rubber mounting technique on the assembly of motor housing to further reduce the vibration magnitude. A proposed rubber mounting is carried out based on the dynamic characteristics of individual rubber mounts for attaining minimum vibration magnitude. The dynamic stiffness and loss factors of individual rubber mount provide a fundamental information of the heat loss also known as energy dissipation.

Overall, an impact technique for measuring the dynamic properties will be carried out to select the most suitable rubber to implement into the rubber mounting system. Hence, a rubber mounting system will be proposed to install within the housing assembly of the electric motor blower in the vacuum cleaner. The result of the existing and proposed design will be distinguished by comparing the vibration magnitude of electric motor blower. Therefore, there are three different configurations will be discussed in this paper to study the vertical and horizontal acceleration of electric motor blower.

1.1 Problem Statement

Due to high noise level produced by an operating household vacuum cleaner, the user will be suffering in hearing and headache if exposing to long period of time. Instead of redesign the electric motor blower of vacuum cleaner to improve its operating point, structural modification would be proposed to minimize the housing vibrations generated by the motor blower assembly and reduce the transmission of noise is in general known. Therefore, a rubber mounting system is proposed on the geometry of electric motor blower based on the dynamic behaviours of rubber mounts.

1.2 Objectives

1. To obtain experimental modal analysis of vacuum cleaner and electric motor by using impact testing.
2. To studying the dynamic characteristic of existing and proposed rubber mount for the motor housing assembly.
3. To propose a rubber mounting system on the motor housing assembly based on the dynamic characteristic of rubber mount.
4. To reduce the vibration magnitude of the electric motor blower transmitted to the vacuum cleaner.

1.3 Scope of Research

This study is first to understand the response of vacuum cleaner’s structure by carrying out modal analysis. Besides, an impact technique is done to study the dynamic stiffness and loss factors for the existing and proposed individual rubber mounts of motor housing. Then, magnitude of vibration of electric motor blower will be determined by the vertical and horizontal accelerations of electric motor blower which measured in three different configurations. Hence, a comparison between the existing and proposed design of motor housing assembly will be discussed.

CHAPTER 2: Literature Review

2.0 Overview

In this chapter, noise sources, noise and vibration reduction method, rubber mounting appropriate and summary are presented.

2.1 Noise Caused by Vacuum Cleaner

Based on the first part of the study by Čudina, M. and Prezelj, J. in 2007, it states noise produced by vacuum cleaner is mainly built from the mechanism principle of suction part in vacuum cleaner. The first source is due to the rotational blade of the electric motor blower and the second source is due to the unsteady flow of air producing huge turbulent flow inside the suction part. [2] Besides, in the second part of the study by Čudina, M. and Prezelj, J. in 2007, the design of vanned diffuser of electric motor blower is investigated. The result shows that pressure will be risen inside the electric motor blower when the electric motor is operating. Thus, this can generate noise from the vacuum cleaner. [3] Furthermore, according to the third part of the study by Čudina, M. and Prezelj, J. in 2007, the airborne noise is mainly generated by the centrifugal blower while the structure-borne noise is mainly generated by the electric motor blower. The contribution of the structure-borne noise to the total sound pressure level (SPL) depends on the geometry of the electric motor blower and on its operating conditions. [4] In 2000, Albas, E., Durakbasa, T., Eroglu, D. and Artesis, A.S. analyzes the failure of electric motor of vacuum cleaner during operating. It is found that faulty motors highly affect the performance and tend to generate additional unwanted noise. [5] According to the study by Benko, U., Petrovčič, J., Mussiza, B. and Juričić, D. in 2008, a quality check is demonstrated to detect the fault in isolation of electric motor with its housing. The outcome shows that there are high chances producing faulty motor due to manufacturing faults. [6]

2.2 Noise and Vibration Reduction Method

In 1989, Herron Jr, R.H. and Sumerau, W.R. have designed a vibration isolating system for the canister vacuum cleaner. The design focuses on the front and rear resilient rings to isolate the vibration of motor to the housing. Both rings also act as the support of motor inside the housing. [7] Referring to the study by Cinzia, B., Elisa, M. and Michele, U. in 2009, they have modified the pipe configuration by creating a new air path without angle and improved the air flow area by the creation of 32 holes in order to reduce noise emissions. [8] The study by Embleton, T.F.W. in 1963 states that the method of sloping the edge of the cutwater with respect to the impeller blades tips of the centrifugal blower can reduce the sound pressure level by 1dB or 2dB. [9] Furthermore, Jeon, W.H., Rew, H.S. and Kim, C.J. in 2004 reduce the noise source from the centrifugal blower by applying tapered impeller design. This method successfully reduces the overall sound pressure level by 4dBA. [10] On the other hand, in 2010, the study by Park, I.S., Sohn, C.H., Lee, S., Song, H. and Oh, J. discusses about improving the flow in suction nozzle as the resistance in flow path will affect the performance and generate unwanted noise. The result shows that the sound power level of noise is reduced up to 5dBA. [11]

2.3 Rubber Mounting Appropriate

Next, the paper from Timpner, F.F. in 1965 is applying an elastic mounting system on a powerplant to minimize the vibration transmitted to the vehicle. [12] The paper by Bretl, J. in 1993 demonstrates an optimized mounting system based on response sensitivities of each compartment of the vehicle to seek for the most effective way to reduce vibration. [13] Furthermore, in 2013, Alkhatib, F. explains the methods for engine mount modeling based on the six degrees of freedom and optimization method. [14] In 2005, the study by Lee, T.Y., Ooi, L.E. and Ripin, Z.M. designs a mounting system with consideration of dynamic stiffness and loss factor of the rubber mount. This mounting system is applied on a grass trimmer and the outcome shows 73% reduction in rolling vibration acceleration. [15] Therefore, Lin, T.R., Rarag, N.H. and Pan, J. demonstrate a simple experimental method which is impact testing to identify the frequency dependent stiffness of rubber mount and its damping features by applying the measured complex frequency response function from. [16] Meanwhile in 2014, Ooi, L.E. and Ripin, Z.M. have showed that either the impact or shaker technique is a suitable method to obtain the dynamic stiffness and loss factor of the resilient material. [17]

2.4 Summary

In short, the main noise source of vacuum cleaner is mainly produced by the motor blower. Also, there are many papers discussing about different methods to solve the noise generated by motor blower of vacuum cleaner. Yet, the rubber mounting technique on motor blower has not been studied previously. Therefore, it is great opportunity to further investigate the outcome in this study.

CHAPTER 3: Research Methodology

3.0 Overview

First, the response of vacuum cleaner's structure is studied by carrying out experimental modal analysis. Then, an impact technique is carried out to study the dynamic stiffness and loss factors for the existing and proposed individual rubber mounts of motor housing. Thus, magnitude of vibration of vacuum cleaner will be determined based on the vertical and horizontal accelerations of electric motor blower which measured in three different configurations. Hence, a proposed mounting system is implemented, and the effectiveness of vibration attenuation is studied.

3.1 Vibration Indicator for Vacuum Cleaner and Electric Motor Blower

Figure 3.1 shows the model of vacuum cleaner used for the study of vibration attenuation with its coordinate system. The model of vacuum cleaner used is Samsung SC5240 Canister Vacuum Cleaner with 1800W. Thus, the coordinate system of the vacuum cleaner must be well defined before all the measurement to be carried out. The center of mass of vacuum cleaner is assumed to be the center of mass of electric vacuum cleaner.

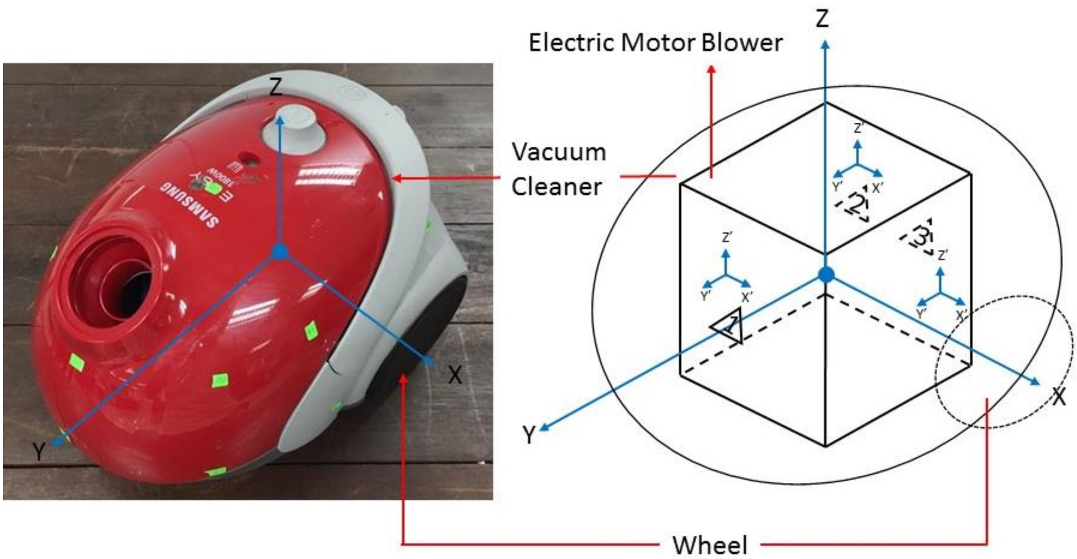


Figure 3.1: Coordinate System for Vacuum Cleaner.

Next, **Figure 3.2** shows the existing electric motor blower enclosed with housing in the vacuum cleaner with its coordinate system. The model of electric motor blower used is VCM-K70GV with 240V. There are three existing rubber resilient rings used to isolate the vibration transmitted to the housing assembly and to the other part of vacuum cleaner. Hence, the front rubber resilient ring is labelled as rubber "1" and the pair of rear rubber resilient rings are labelled as rubber “2” and rubber “3”. Also, the center of mass of electric motor blower is assumed to be located at the center of the global coordinate system.

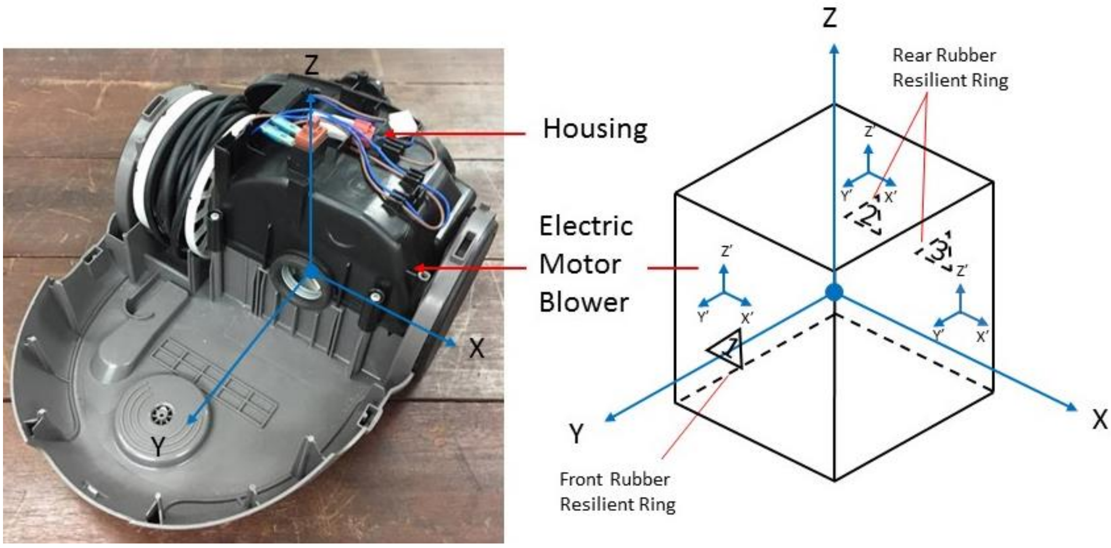


Figure 3.2: Coordinate System for Electric Motor Blower.

3.2 Modal Analysis

In this section, the structures of vacuum cleaner and its electrical motor blower are taken into concerned for experimental modal analysis. The purpose of modal analysis is to understand the vibration characteristic such as the resonant frequency and the mode shapes of the structures.

3.2.1 Experimental Modal Analysis for Motor Electric Blower

Figure 3.3 presents the set-up of experimental modal analysis for electric motor blower where the electric motor blower is suspended freely on a fixed rod. The global coordinate system of electric motor blower is also defined. The instrument used is data acquisition system, analyzer (LMS Spectral Testing), response accelerometer (Kistler, type: 3224A2) and impact hammer (Kistler, type: 9724A5000). The accelerometer response is located at point "F6" measuring the response according Y-axis of the coordinate system.

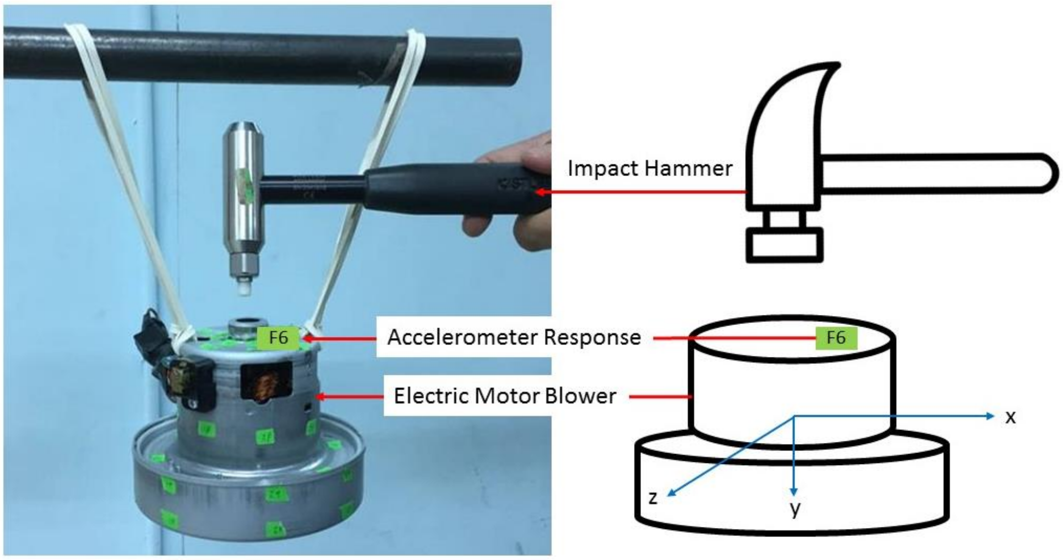


Figure 3.3: Measurement Set-up for Modal Analysis of Electric Motor Blower.

Then, **Figure 3.4** shows the geometric model of the electric motor blower which is constructed according to the actual structure. The geometric model is built through the definition of nodes, lines, and surfaces in an arrangement to represent the shape of the structure under the LMS Test Lab.

Thus, modal data acquisition is carried out by measuring the vibration response at all points on the structure. The label includes DOF information consisting of the point number and direction of the measurement sensor. Excited force direction is also known as the direction of impact hammer knocking on all point numbers labelled on the electric motor blower. Each point will be knocked for three times. The first input force is directed at +Y axis and second input force is directed at -X axis. Once both data are acquired, it will be fed into the modal analysis stage and each measurement signal will be associated to the point and direction on the structure mesh model.

Last but not least, the frequency response function will be generated and the modal parameters such as resonant frequencies, damping ratios and mode shapes can be obtained.

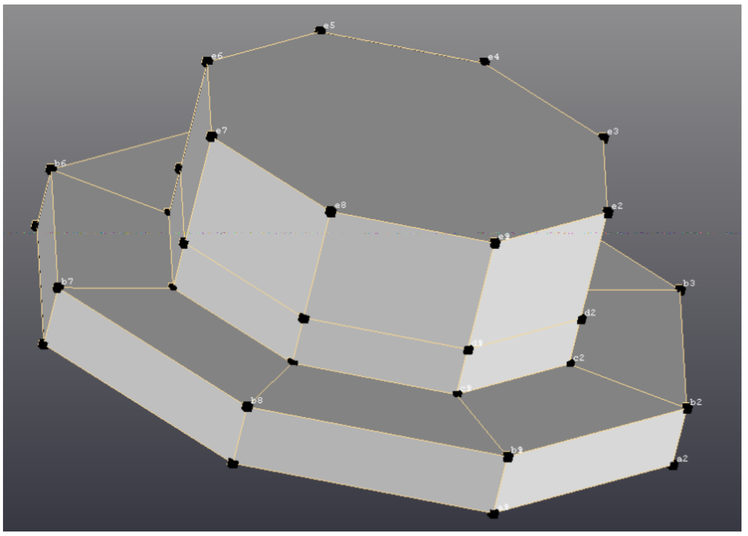


Figure 3.4: Geometric Model of Electric Motor Blower.

3.2.2 Experimental Modal Analysis for Vacuum Cleaner

Figure 3.5 shows the set-up of experimental modal analysis for vacuum cleaner where the vacuum cleaner is suspended freely on a fixed rod. Besides, the coordinate system of vacuum cleaner is defined. The instrument used is data acquisition system, analyzer (LMS Spectral Testing), response accelerometer (Kistler, type: 3224A2) and impact hammer (Kistler, type: 9724A5000). The accelerometer response is located at point "O" measuring the response according Z-axis of the coordinate system.

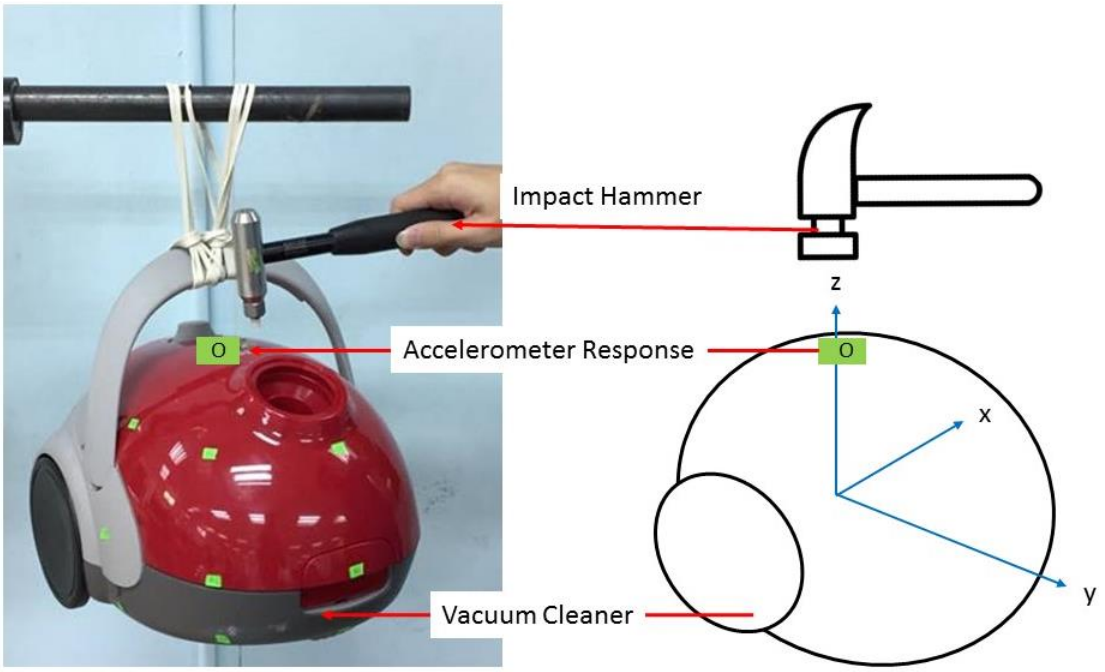


Figure 3.5: Measurement Set-up for Modal Analysis of Vacuum Cleaner.

Then, **Figure 3.6** presents the geometric model of the vacuum cleaner which is constructed based on the actual structure. The geometric model is built through definition of nodes, lines, and surfaces in an arrangement to represent the shape of the structure under the LMS Test Lab.

Furthermore, modal data acquisition is carried out by measuring the vibration response at all points on the structure. The label includes DOF information consisting of the point number and direction of the measurement sensor. Each point will be knocked for three times. However, the first input force is directed at -Z axis and second input force is directed at -X axis. Once both data are acquired, it will be fed into the modal analysis stage and each measurement signal will be associated to the point and direction on the structure mesh model.

In short, the frequency response function will be created and the modal parameters such as resonant frequencies, damping ratios and mode shapes can be found.

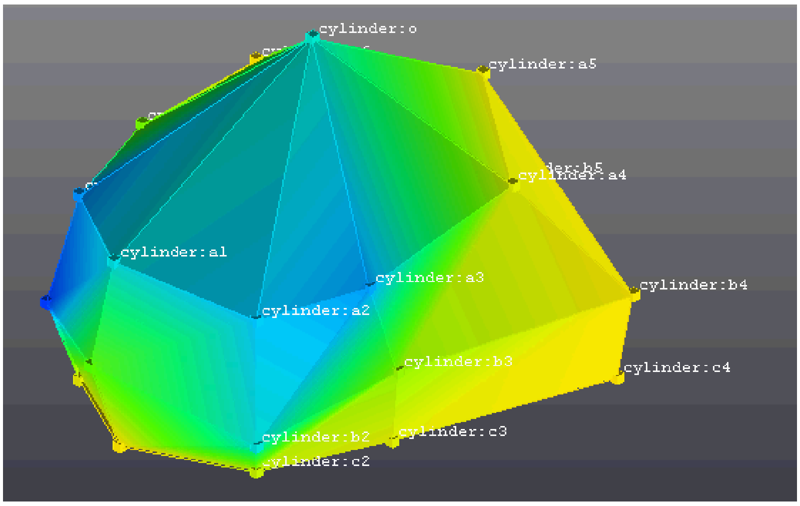


Figure 3.6: Geometric Model of Vacuum Cleaner.

3.3 Dynamic Properties of Rubber Mount

In this section, impact testing is demonstrated to obtain the dynamic properties such as receptance function, dynamic stiffness, frequency dependent stiffness and loss factor of the rubber mounts. Thus, a suitable rubber mount can be selected.

3.3.1 Measurement of Impact Technique for Rubber Mount

Figure 3.7 shows the set-up of impact technique for dynamic properties of rubber mounts. The instrument used is data acquisition system, analyzer (LMS Spectral Testing), response accelerometer (Kistler, type: 3224A2) which is located at point "A", impact hammer (Kistler, type: 9724A5000) and a preload mass. As the existing rubber mounts are used for mounting the electric motor blower in its housing, a 1.5kg of preload mass is chosen to apply the preload similar as the mass of the electric motor blower and the rubber mount is placed beneath the preload mass.

First, calibration of sensors is completed before measurement to eliminate any bias in the instrument. Then, the impact hammer is directed at -Y axis of the coordinate system. Once both data are acquired, it will be fed into data acquisition system. The result of dynamic properties for vacuum cleaner is analyzed and used for calculating the loss factor and frequency dependent stiffness.

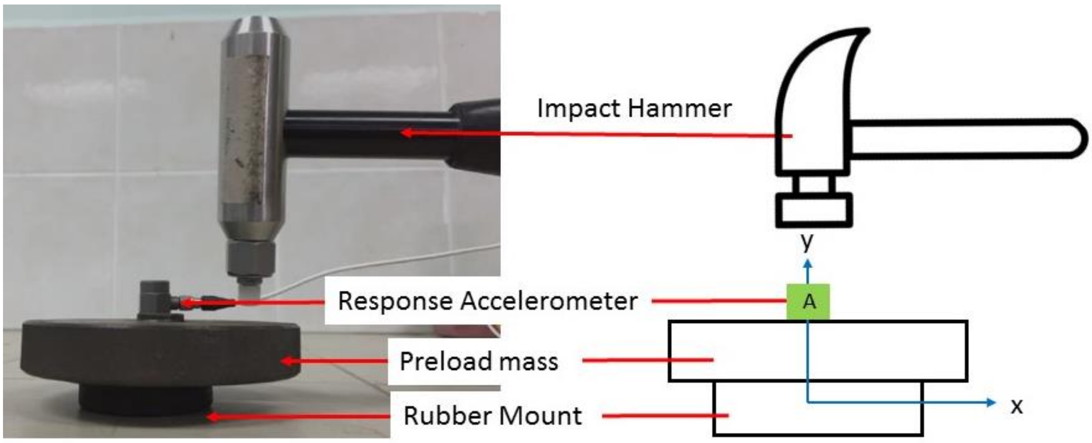


Figure 3.7: Measurement Set-up for Impact Testing.

The impact testing is repeated with three types of rubber mounts to obtain their individual dynamic properties. **Table 3.1** shows three types of rubber mounts which are the front resilient rubber ring, rear resilient rubber ring and the rubber damper ball. Front resilient rubber ring and rear resilient rubber ring are the existing rubber mount used for the motor housing assembly while rubber damper ball is the proposed rubber mount to implement into the proposed design. Therefore, a comparison between existing rubber mount and proposed rubber mount will be discussed to ensure that a suitable rubber mount is selected.

Table 3.1: Types of Rubber Mount.

Types of Rubber Mount	Description
 **Figure 3.8**: Front Rubber Resilient Ring.	**Figure 3.8** presents that the front rubber resilient ring (existing rubber mount) is well fitted into motor and its housing. The existing arrangement is to isolate the vibration of motor to the housing and whole body of vacuum cleaner.
 **Figure 3.9**: Rear Rubber Resilient Ring.	**Figure 3.9** presents the rear rubber resilient ring (existing rubber mount). There are two existing rear rubber resilient rings to mount motor with its housing. The design is to ensure vibration isolation can be achieved.
 **Figure 3.10**: Rubber Damper Ball.	**Figure 3.10** presents rubber damper ball (proposed rubber mount) which is used to be fitted into motor housing. This suggestion is to further isolate vibration of motor to the other part of vacuum cleaner.

3.3.2 Theoretical Background of Dynamic Stiffness and Loss Factor

By using impact technique, **Figure 3.11** shows that the experimental set-up can be represented as a single degree of freedom (SDOF) system.

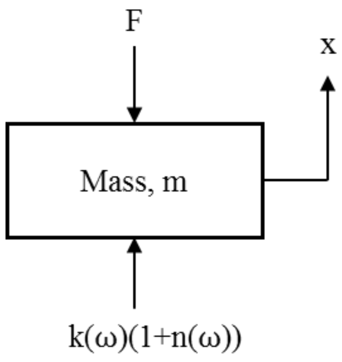


Figure 3.11:Concept of Dynamic Stiffness of Rubber Mount.

Then, the equation of motion for this rubber mass system can be presented in the equation below:

$$m\ddot{x}(t) + k(\omega)\big(1 + n(\omega)\big)x(t) = F(t) \quad \textbf{(3.1)}$$

where m is the mass of the system, $k(\omega)$ is the frequency dependent stiffness and $n(\omega)$ is the loss factor.

Besides, $H(\omega)$ is the complex receptance function which consists of real part, $Re\{H(\omega)\}$ and imaginary part, $Im\{H(\omega)\}$. Throughout the measurement, the dynamic stiffness can be derived as the reciprocal of the receptance function.

The phase angle, θ is the phase lag between the displacement response function and the input force function, and it can be calculated by using equation below:

$$\tan\theta = -\frac{Im\{H(\omega)\}}{Re\{H(\omega)\}} \quad \textbf{(3.2)}$$

To obtain the loss factor, $n(\omega)$ from the experimental data, it can be calculated by using the same equation as used by Ooi, L.E. and Ripin, Z.M [17] as shown below:

$$n(\omega) = \tan\theta(1 - \frac{\omega^2}{{\omega_n}^2}) \quad \textbf{(3.3)}$$

According to the study by Lin, T.R., Farag, N.H. and Pan, J. [8], the frequency dependent stiffness, $k(\omega)$ can be calculated by using the equation below:

$$k(\omega) = \frac{Re\{H(\omega)\}}{|H(\omega)|^2(1-r^2)} \quad \textbf{(3.4)}$$

where r is the frequency ratio, $r = \frac{\omega}{\omega_n}$, and ω_n is the natural frequency of the system.

Lastly, the calculated loss factor and frequency dependent stiffness will be compared to select the most suitable rubber mount for the proposed design.

3.4 Vibration Magnitude for Existing Design

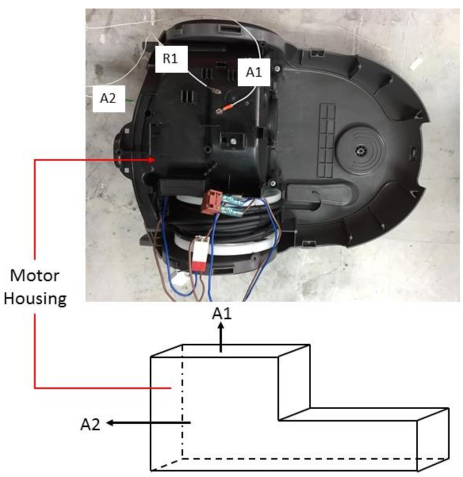
In this section, the vibration magnitude of electric motor blower is first identified from the data such as vertical acceleration and horizontal acceleration before any proposed design is proceeded.

3.4.1 Experimental Measurement for Vertical and Horizontal Acceleration

Table 3.2 shows that there are three configurations for experimental set up to study the vibration magnitude. Vertical and horizontal vibration acceleration of the electric motor blower housing and vacuum cleaner are the two main concerns that determine the effectiveness of mounting system in vibration attenuation of the electric motor blower. The instruments used for experimental measurements include the data acquisition system, analyzer (LMS Spectral Testing), one response accelerometer (Kistler, type: 3224A2) and two input accelerometers (Kistler, type: 3224A2). The response accelerometer is labelled as "R1" and both input accelerometers are labelled as "A1" and "A2".

The position of input acceleration for "A1" allows to study the acceleration in vertical direction with respect to the Z-axis of the coordinate system. Meanwhile, the position of input acceleration for "A2" allows to study the acceleration in horizontal direction with respect to the Y-axis of the coordinate system. The purpose of measuring these accelerations is to identify the vibration source and vibration magnitude corresponding to each direction of the existing design of vacuum cleaner.

Table 3.2: Experimental Set-up Configurations for Motor's Input Acceleration.

Experimental Set-up Configuration	Description
 **Figure 3.12**: Configuration A.	**Figure 3.12** presents configuration A where the input accelerometer A1 and A2 are placed on top of the motor housing and behind the motor housing respectively to measure the motor's input acceleration.