IDENTIFICATION OF NONLINEAR CHARACTERISTIC OF THE RUBBER MOUNT

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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 SYMBOLS

Symbols	Descriptions
$F(t)$	external applied force
m	rigid mass
$\ddot{x}$	acceleration from accelerometer
c	damping coefficient
$\dot{x}$	velocity
k	torsional stiffness
x	displacement
f	frequency

ABSTRAK

Paut getah adalah sejenis isolator getaran. Ia memberi suatu perantaraan di antara dua bahagian, redaman tenaga yang dihantar melalui paut getah. Aplikasi yang biasa adalah pepaut enjin di mana paut getah digunakan untuk mengurangkan getaran dihantar oleh enjin ke area penumpang. Kajian ini mengkaji ciri-ciri linear paut getah dengan menggunakan kaedah gelung histerisis. Ujian yang dilakukan dalam kajian ini adalah ujian penggoncang. Persediaan ujian terdiri daripada meter pecut, transducer daya, penggoncang, penguat kuasa, system perolehan data LMS dan tukul hentaman. Penggunaan LMS analyzer dan LMS test lab memastikan data yang diperolehi direkodkan dengan tepat mengikut ujian dan isyarat yang diterima. Ujian penggoncang telah dijalankan untuk menentukan ciri-ciri linear paut getah yang dioperasi pada pelbagai amplitude pengujaan dalam lingkungan 3.0N hingga 10.0N dan 0Hz hingga 300Hz untuk frekuensi pengujaan. Ia telah didapati bahawa kekukuhan paut getah berkurangan apabila amplitud pengujaan bertambah sebelum mencapai peralihan. Faktor kehilangan yang diperolehi daripada gelung histesisi bertambah apabila amplitude pengujaan bertambah sebelum mencapai peralihan. Paut getah menunjukkan ciri linear pada frekuensi 80Hz dengan amplitude yang berbeza pengujaan dalam lingkungan 3.0N hingga 10.0N.

ABSTRACT

Rubber mount is a type of vibration isolator. It provides an interface between two parts, damping the energy transmitted through the rubber mount. A common application is the engine mounting where the rubber mount is used to reduce vibration transmitted by the engine towards the passenger compartment. This paper investigates the nonlinear characteristic of the rubber mount using the hysteresis loop method. The test done in this paper is shaker test. The test setup consists of accelerometer, force transducer, shaker, power amplifier, LMS data acquisition system, impact hammer. The usage of LMS analyzer and LMS test lab ensured the data obtain is accurately recorded according to the test and the received signal. Shaker tests were performed to determine the nonlinear characteristics of the rubber mount which the range of operation is 3.0N to 10.0N for the amplitude of excitation and range of 0Hz to 300Hz for the excitation frequency. It was found out that the stiffness of the rubber mount decreases as the amplitude of excitation increases before achieving transition. The loss factor obtain from hysteresis loop increases as the amplitude of excitation increases before achieving transition. The rubber mount shows its nonlinear characteristic at the frequency of 80Hz with different amplitude of excitation ranging from 3.0N to 10.0N.

1.0 INTRODUCTION

Rubber is a unique material which its properties can deform linearly and non-linearly. The main properties of rubber that are damping coefficient and stiffness are highly referred to when choosing the right rubber for the right equipment. One of its application is rubber mount which is widely use in industries to reduce vibration of machines cause by rotational force, repetitive force etc. Rubber mounts may have as many as three important functions. First, they act as the attachment points for a part or a system to the chassis. Secondly, they function as isolation preventing noise and vibration from the engine or road conditions from being transferred to the driver and passengers. Rubber mounts can also be the adjustment point to keep the components properly aligned[1]. Most of these rubber components are subjected to static and dynamic loadings in service. To prevent failures during operation is one of the critical issues in rubber component design. Therefore, fatigue analysis and strength evaluation are very important in design procedure to assure the safety and reliability of mechanical rubber components [2].

The theory of nonlinear vibration isolation has witnessed significant developments due to pressing demands for the protection of structural installations, nuclear reactors, mechanical components, and sensitive instruments from earthquake ground motion, shocks, and impact loads. In view of these demands, engineers and physicists have developed different types of nonlinear vibration isolators [3]. It is found that, in general, rubber dynamic properties depend on static pre-load, vibration amplitude, temperature, and excitation frequency. Numerous work have been done in the last few decades to continually improve the understanding of the dynamic characteristics of rubber materials[4]. Different techniques have been developed to determine the dynamic characteristic of rubber. Servo-hydraulic systems are widely used to measure rubber static stiffness.

They are also used to measure the dynamic stiffness and damping of rubber at discrete frequencies[5].

Nonlinear properties of a rubber mount in which the output is not directly proportional to the input. Nonlinear problems are of interest because most systems are inherently nonlinear in nature. Nonlinear systems may appear chaotic, unpredictable, or counterintuitive, contrasting with the much simpler linear systems. Nonlinear characteristics is important as it describe the true nature of all the things in our surrounding instead of the linear characteristics that is usually shown for study purposed. Nonlinear characteristics is hard to describe as the properties of a thing changes per the external forces that is reacted upon the subject. Engineering knowledge of rubber material is still rather poor probably due to its complex nonlinear mechanical properties, the common use of rubber material has made it a subject drawing prior attention all over the world. It has been generally believed that dynamic stiffness and damping are dependent not only on additives in the material but also on temperature, geometry, frequency, and amplitude of motion [6].

A lot of experiment have been done to determine the characteristics of the rubber mount. A research journal which determine the dynamic stiffness and loss factor measurement of engine rubber mount using impact test show the usage of the impact technique to determine the characteristics of the rubber mount. In the research paper Ooi & Ripin (2011) stated that the impact technique is relatively simple experimental setup and can be used for measuring dynamic properties of engine mount in a real vehicle. The dynamic properties of engine rubber mounts which is represented by the dynamic driving point stiffness and dynamic transfer stiffness can be measured directly based on the location of the sensors. [7] The journal also used a different technique to determine the characteristic of the rubber mount which is using the shaker test. A verification of result obtain is done by comparing the result of impact test and result obtain from shaker test. From the data obtain, it showed that the data is almost the same where both method can be used to determine the characteristic of the rubber mount.

This study emphasizes on the non-linear properties of the rubber mount. As far as concern, the properties of rubber will change as an external disturbance such as heat, force etc. is acted upon it. The properties of rubber (damping coefficient, stiffness) change as the amplitude of excitation increases.

In 2000, Vahdati et al. [8] examined rubber mount using high frequency testing. Simulation results of the high frequency test machine showed that with the proper design of the test fixture, and appropriate selection of the reaction mass and reaction mass mounts, one can perform a high frequency dynamic stiffness test on rubber mounts at frequencies as high as 5000Hz.

In 2005, Lin et al. [4] examined the stiffness and damping of rubber mount using impact test technique and validate the result obtain with shaker test. The impact test technique provides a quick and easy way to evaluate the frequency dependent stiffness and damping characteristics of rubber isolators.

In 2013, Luo et al. [9] numerical investigation of nonlinear properties of rubber absorber is researched. The results indicate that characteristics of the nonlinear dynamic stiffness are closely associated with both displacement amplitude and frequency, although frequency dependency is not as great as amplitude dependency.

In 2009, Qian et al. [10] examined the fatigue life prediction of a rubber mount on test of material properties. The fatigue lives of the rubber mount at different loads were measured on a fatigue test rig to validate the accuracy of the fatigue life prediction method. The test results imply that the fatigue lives predicted agree well with the test results.

A lot technique available for the determination of rubber properties. An example is using the testing of Universal Testing Machine (UTM). In 2008, Woo et al. [11] done a study on material properties and fatigue prediction of natural rubber component.

Other test is dynamic testing under non-sinusoidal condition of rubber done in 1987 by J. A. Harris [12]. In this paper, nonlinearity in the dynamic behavior of rubber has been considered. A dynamic test system has been developed which incorporates the ability to perform a harmonic analysis. The result of this is that under a more complex system of vibrations, nonlinear rubbers will behave in a more linear fashion and will exhibit higher damping than indicated by their dynamic properties measured in conventional sinusoidal tests.

In 2007, Shaska et al. [13] research about the influence of excitation amplitude on the characteristics of nonlinear butyl rubber isolators. It is found that as the excitation amplitude of the nonlinear viscoelastic isolator increases, the response amplitude decreases and the transmissibility is improved over that of the linear isolator for excitation frequency that exceeds a particular value governed by the temperature and excitation amplitude.

Hysteresis is a time-based dependence of a system's output on present and past inputs. The dependence arises because the history affects the value of an internal state. To predict its future outputs, either its internal state or its history must be known.[14]. The simple explanation of hysteresis occurs in rubber is that the rubber is much harder to stretched rather than to be upstretched. The loading and unloading process take place where the loading force will be higher at a certain extension as the rubber has yet to undergo the specific length of extension whereas the unloading is a reduction of force applied where the force is being decrease at some point of extension thus the force required for the rubber to achieve an extension is lesser compare to the loading force.

The method used in this paper is hysteresis loop method. This method is used frequently to determine the properties of rubber. The test used in this research is shaker test with different frequency and amplitude of excitation. The aim for this project is to identify the nonlinear characteristics of rubber mount. The nonlinear region will be determined based stiffness result that will be obtained. This will show the nonlinear characteristics of the rubber mount.

2.0 THEORITICAL BACKGROUND

The measurement system has been modelled as a single degree of freedom (SDOF) system. By referring to [15], this system is a damped forced vibration system with an equation of motion:

$$F(t)=m\ddot{x}+c\dot{x}+kx \qquad (1)$$

Where ; $F(t)$ is the external applied force

; m is the rigid mass

; $\ddot{x}$ is the acceleration from accelerometer

; c is the damping coefficient

; $\dot{x}$ is the velocity

; k is torsional stiffness

; x is displacement

From the experiment, amplitude of acceleration can be obtained directly from the accelerometer. Then, the displacement is calculated using formula below:

$$x = \frac{\ddot{x}}{(2\pi f)^2} \qquad (2)$$

Where ; x is the displacement

; $\ddot{x}$ is the acceleration

; f is the frequency

The amplitude of excitation can be obtained directly from the force transducer. The stiffness is calculated using the formula below:

$$k = \frac{F}{x}$$

Where ; k is the stiffness

; F is the amplitude of excitation

; x is the displacement

3.0 METHODOLOGY

3.1 Sample Preparation and Testing Jig Fabrication

A mild steel material is selected for the testing jig to reduce the vibration during the experiment. The reason of choosing the mild steel as the material for the testing jig is because steel is commonly used in high loading due to its high strength. The testing jig is made as rigid as possible to avoid any unnecessary motion or movement during the test. The dimension for the testing jig is measured, taking into account all the equipment that will be used in the test. 3 rubber mounts with same height and width is selected to be analyzed. The bottom part of each rubber is tightened to an aluminium cube feet and the top part is tightened to a preload mass, 0.9kg.

The testing jig is fabricated using the material which had been selected, a little adjustment is made so the structure would fit perfectly for the test. The structured is made up of two square mild steel base plate, mild steel block for the stand and the support, and another mild steel plate attached to the top part of the stand which will the place to hang the shaker facing downward. Each of the part is cut according to their specific dimension and then is joint using welding process. The structure must be perfectly balance and up straight as unbalanced structure could cause improper vibration and affect the result of the test.

After the testing jig is fabricated, the testing jig is mounted on a testing table. Holes are drill on the based plate and the top plate to clamp the jig onto the testing table and for the mounting place of the shaker respectively. Nuts and bolts are used for clamping purpose between the jig and the testing table and for mounting of shaker to the jig. Both the jig and shaker are tightened to prevent unnecessary motion which would disturb the test and cause the result to deviate.

A stinger is used to connect the shaker and the rubber mount which is clamped together with the preload mass. One end of the stinger is connected to the shaker while another end is connected to a force transducer which is then mounted to the preload mass. The rubber mount is clamp to a round plate and the plate is then mounted to the testing table. All nuts are tightened to ensure no unwanted movement during the test.

3.2 Experimental Setup

A bump test is carried out before starting the real test to analyze the structural modal response of the system. The bump test is done using the impact hammer. The purpose of this test is to know the natural frequency of the system. It is important to know the natural frequency of the structure as if the system excited closed to the object’s natural frequency, the object will begin to resonate which dramatically increases the system vibration. In this test, the force is applied using impact hammer on the rubber mount at z-direction. The bump test for the rubber mount as shown in Figure 1.

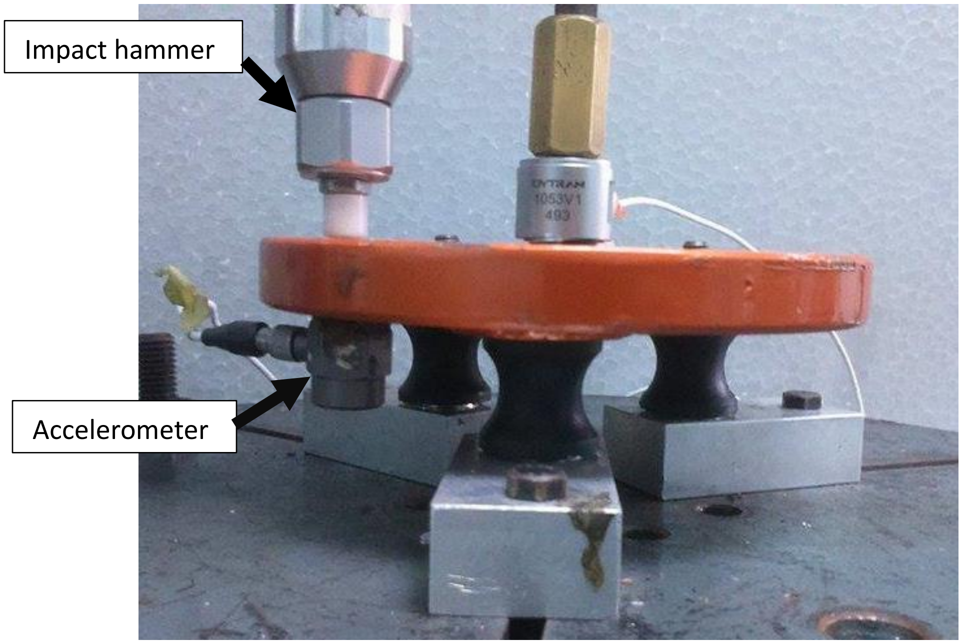

Figure 1: Bump test for the rubber mount

The natural frequency of the testing jig and testing table was also being measured. For the testing jig, the accelerometer is placed at the bottom of the steel bar. Force is applied in the z-direction, parallel to the accelerometer position. All the measured data was recorded. The bump test for the testing jig is shown in the Figure 2.

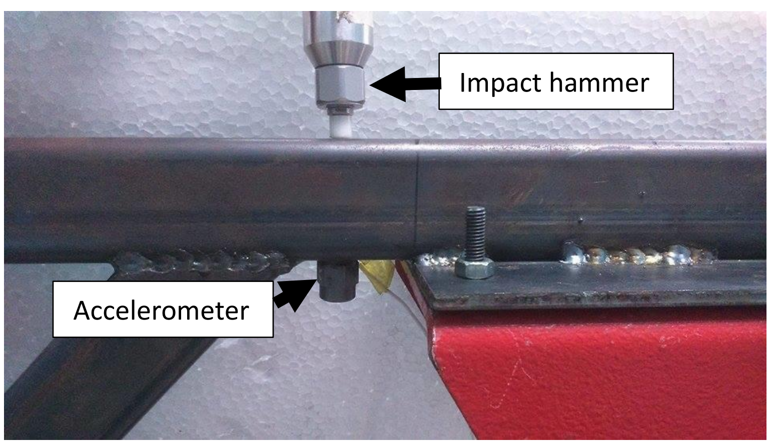

Figure 2: Bump test for the Testing jig

The layout for the shaker test experiment is as shown in Figure 3. The equipment used in the test consist of shaker, accelerometer (Kistler), force transducer (Dytran), data acquisition analyzer (LMS), structural dynamic amplifier, and laptop which is equipped with LMS test lab software. The force transducer is mounted between the stinger and the preload mass whereas the accelerometer is stick to the bottom side of the preload mass using wax aligned with the force transducer. Shaker is hang at the top of the rubber mount and is connected to the structure by the stinger. Force transducer will capture the excitation force by the shaker which will act as the reference whereas the accelerometer will be the response. The shaker, power amplifier, force transducer, accelerometer is connected to the LMS Scadas for analyzation purpose.

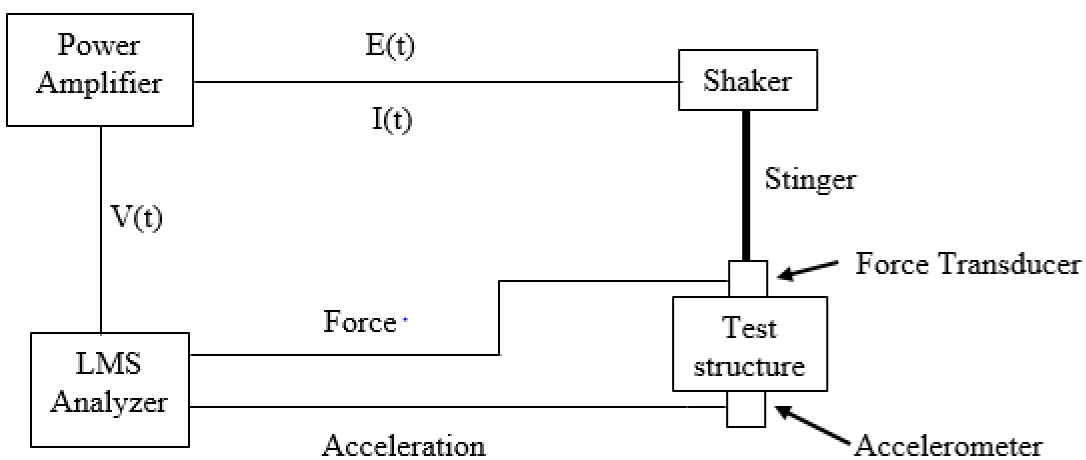

Figure 3: Layout for the shaker test

All the connection and position of the equipment is check as shown in Figure 4 before starting the experiment. On the LMS Analyzer, the force transducer is connected to the channel 1 as the reference point while accelerometer is connected to the channel 2 as the response point. Amplifier is connected to the channel out 1. The first test run is to check the coherence of the system. Sine Periodic chip function is selected. The excitation frequency is set at range of 0Hz to

300Hz. The structure is adjusted until the coherence value is approximately equal to 1 when the frequency is above 20Hz. This means all results above 20Hz are real value. Coherence is checked to know whether the peak is due to noise from the loose part or from structure properties. It is unity even in the presence of noise, since there is no information available to indicate that the output is not due to input.

Next, the sine swept function is selected. Two different tests are done: i) same amplitude of excitation different frequency; ii) same frequency different amplitude of excitation. The range of frequency varies from 50Hz to 300Hz with 50Hz interval and the interval will be lessened to get more accurate data. The range of amplitude of excitation varies from 3N to 10N with 1N interval. The rubber mount is shown in Figure 5.

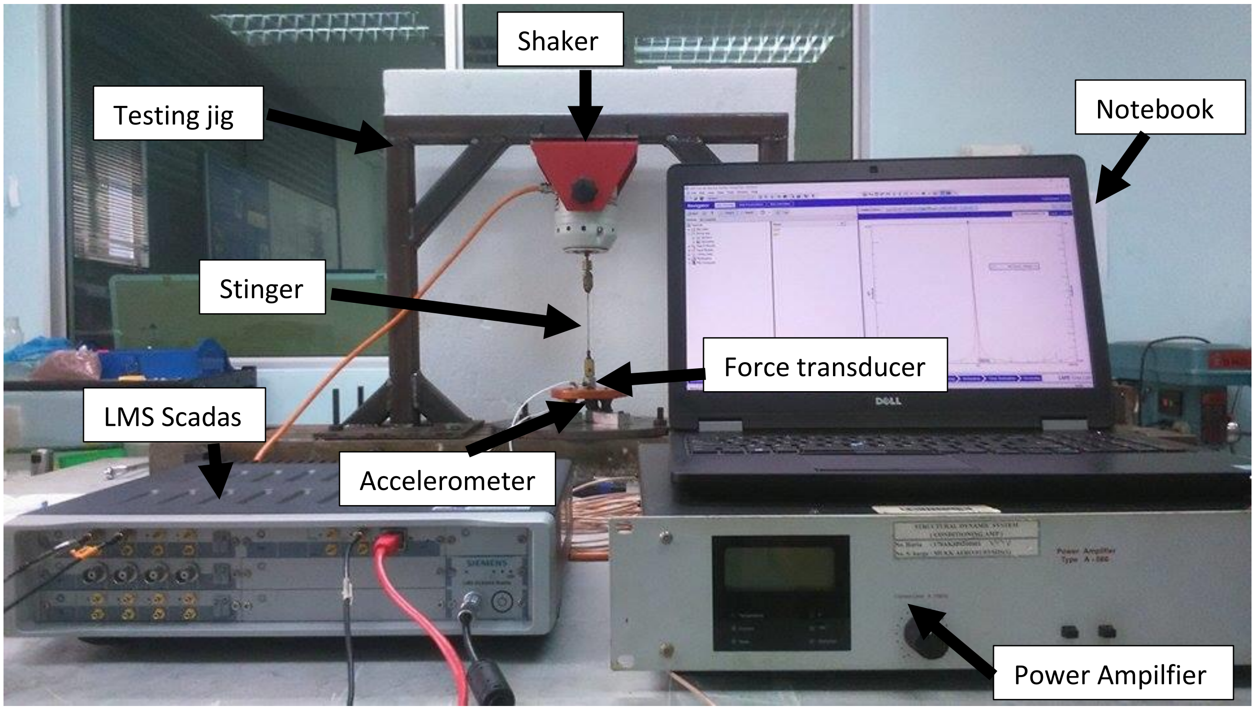

Figure 4: Experimental setup for shaker test

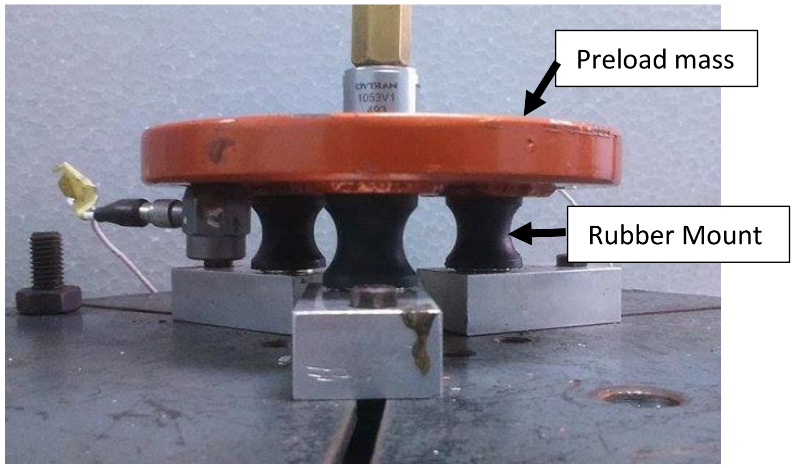

Figure 5: Experimental setup for rubber mount

4.0 RESULTS AND DISCUSSION

Bump test is done to determine the natural frequency of the system. It is tested in two different position which is the rubber mount and the testing jig. The bump test for the rubber mount is shown in Figure 6. Based on the graph, the maximum amplitude occurs at frequency 130Hz. The peak represents the natural frequency for the rubber mount.

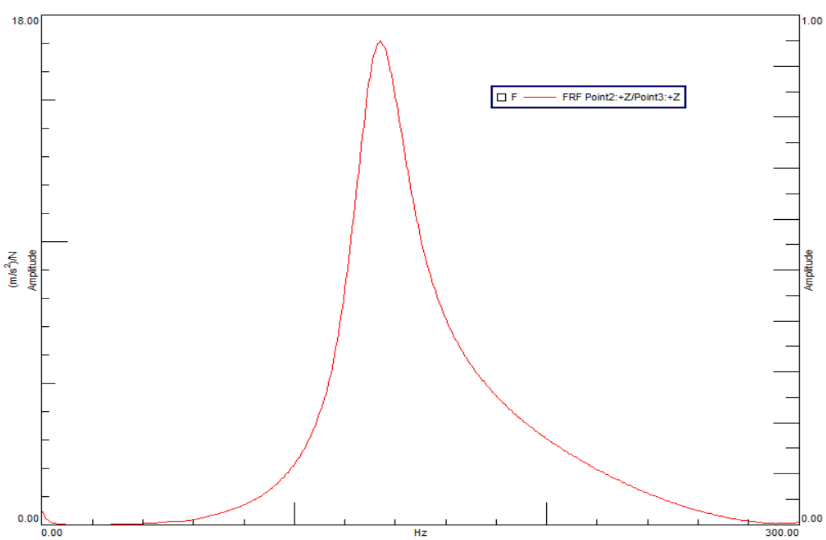

Figure 6: Frequency response function for bump test on rubber mount

Figure 7 shows the bump test result for the testing jig. The maximum amplitude is at frequency 305Hz. Since the frequency range is 0Hz to 300Hz, the result for the testing is too high and not in the frequency of interest. The existence of peak at 130Hz is due to the natural frequency of the rubber mount.

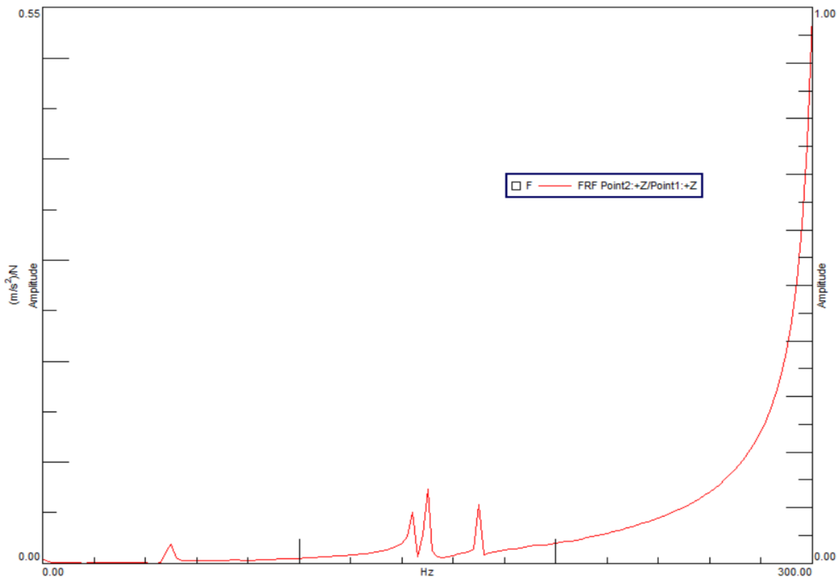

Figure 7: Frequency response function for bump test on testing jig

Figure 8 shows the result obtain from hysteresis loop method for same frequency but different amplitude of excitation. The experimental data of frequency 80Hz is the best results obtain as it clearly exhibits the hysteresis loop shape. The results show that when the amplitude of excitation is smaller, the hysteresis loop form a nice curve shape and sharp edge. As The amplitude of excitation increases, the hysteresis loop become less perfect of a loop which towards the shifting of the decrease and increase value or vice versa, the loop form a s-shape. The stiffness is calculated from this result where the gradient or slope of the graph is equivalent to the stiffness of the rubber mount. From the figure, it is noticeable that the slope of the hysteresis loop decreases as the amplitude of excitation increases. Hence the stiffness is decreasing as the amplitude of excitation increases. The hysteresis loop become larger as the amplitude of excitation increases which the loss factor is also increases where the loss factor increases as the results between the increase and decrease value deviate further from each other.

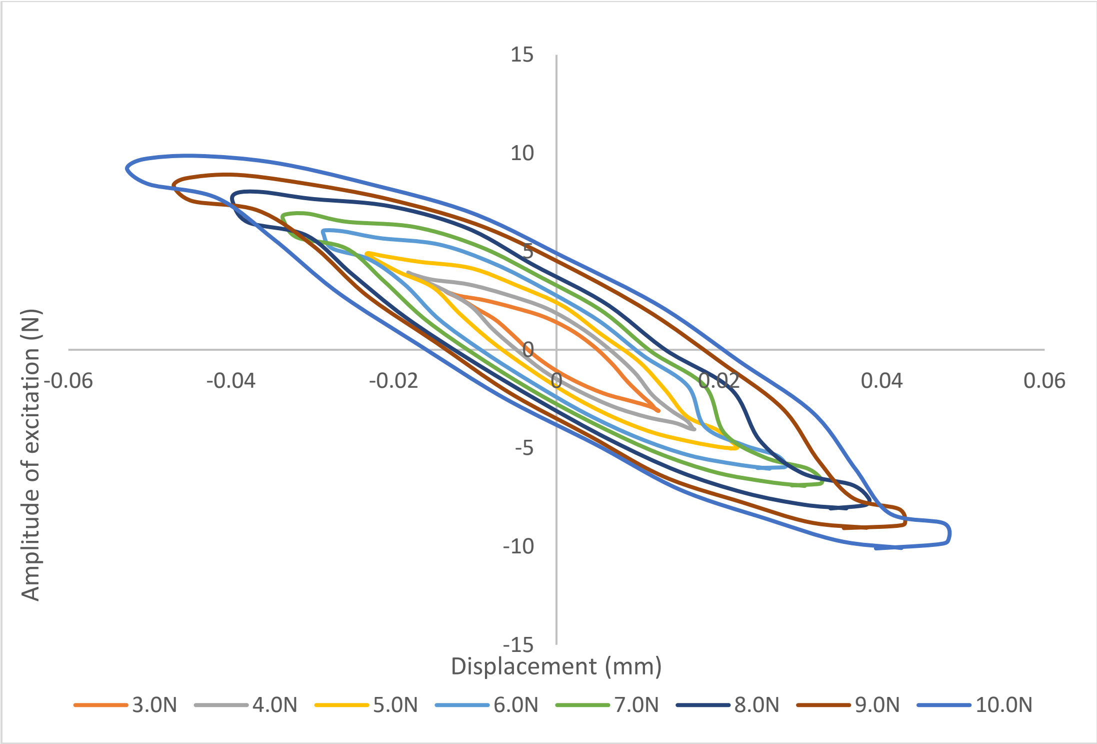

Figure 8: Hysteresis loop for frequency of 80Hz

The stiffness value is calculated from the data obtain. Figure 9 shows the stiffness value of the rubber mount at respective amplitude of excitation. From the graph, it is noticeable that the stiffness of the rubber mount is not linear to the amplitude od excitation as the usual properties of rubber would have shown. This is a point where the rubber shows its nonlinear characteristics when being address to 80Hz frequency. The stiffness decreases but start to show some decrease trend as the amplitude of excitation increase before achieving transition. This result is valid since from the graph of hysteresis loop, it shows a reduce trend of slope as the amplitude of excitation increases.

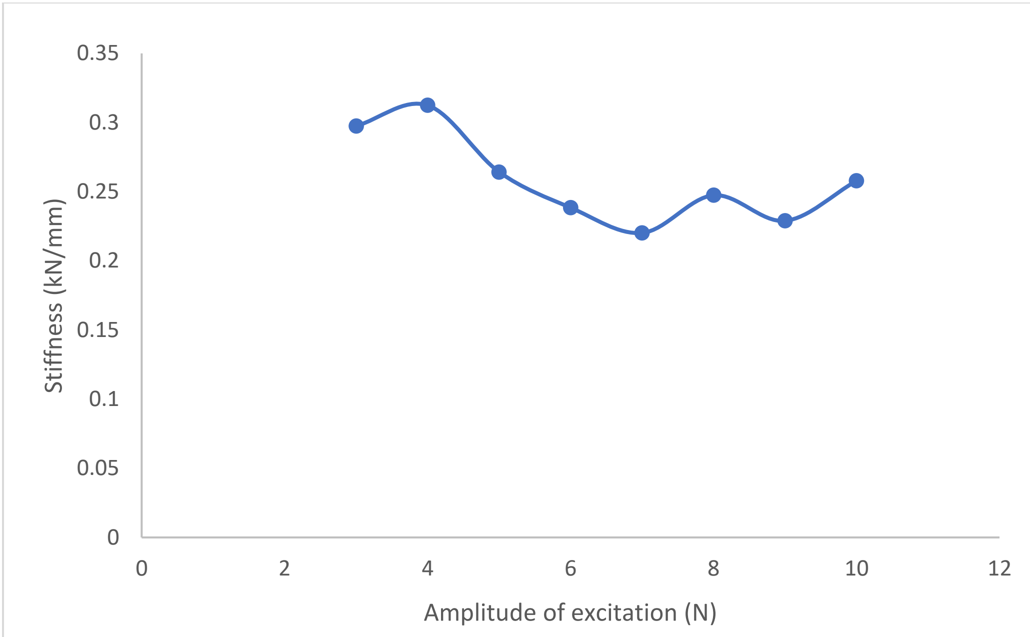

Figure 9: Stiffness at respective amplitude of excitation

By referring to equation (2) and (3), the loss factor of each hysteresis loop is calculated. Hysteresis loss occurs as a result from the B-H characteristic (Note: in this case study, B represent the amplitude of excitation and H represent the displacement) following a different path for decreasing and increasing value of H. Figure 10 shows the loss factor for respective hysteresis loop. From the graph, is at the highest loss factor is at amplitude of 5N. The loss factor shows an increasing trend at 4 -5N before achieving transition at 6-10N. Referring to previous figure on the hysteresis loop, this result is expected since the result from decreasing and increasing value deviates further from each other as the amplitude of excitation increases.

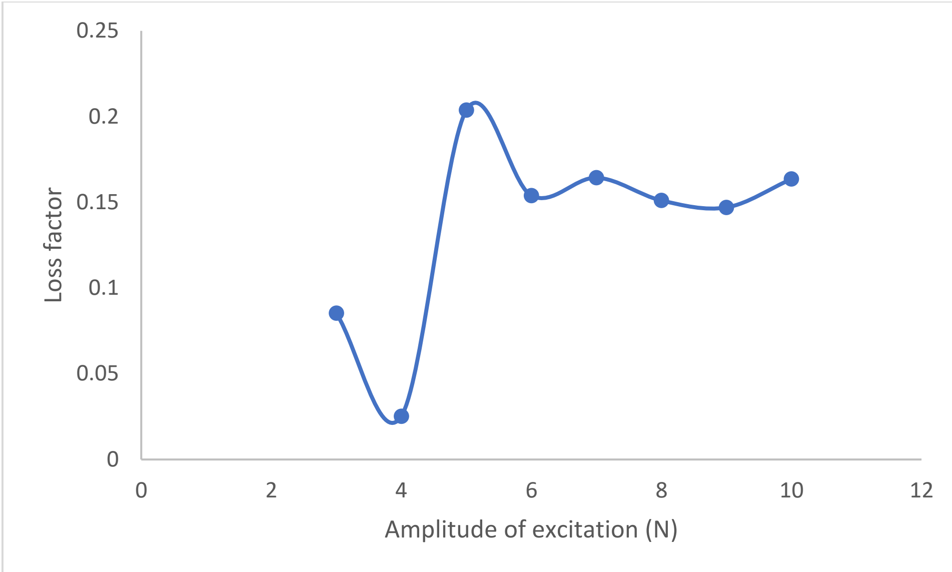

Figure 10: Loss factor for respective hysteresis loop

Figure 11 show the result obtain for hysteresis loop of 3.0N amplitude of excitation. The result doesn't show the hysteresis loop perfectly which due to the problem occurs during the test such as the wear properties of rubber as it become stiffer as the test continues. From the figure, the gap of the hysteresis loop become smaller as the frequency increases. The loss factor is decreasing as the frequency of excitation increase which the decreasing and increasing deviation is lesser as the frequency of excitation increases. From the figure, the stiffness of the rubber mount increases as the frequency of excitation increases, where the slope of the hysteresis loop become stiffer as the frequency of excitation increases. Due to the inconsistent shape of the hysteresis loop, is have made it impossible to calculate the stiffness of the rubber mount.

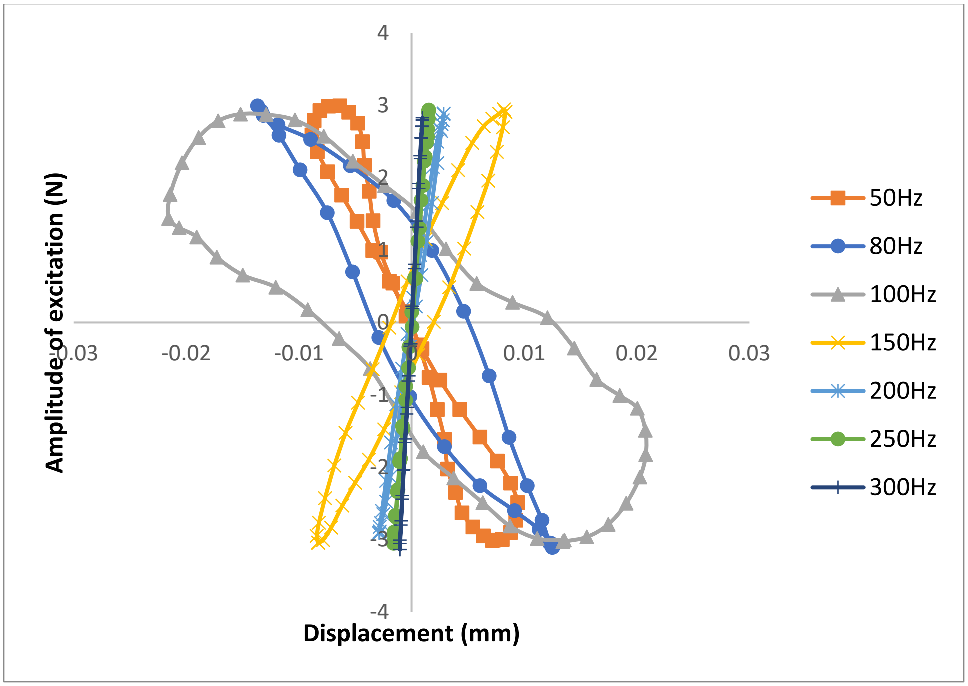

Figure 11: Hysteresis loop for 3.0N amplitude of excitation

5.0 CONCLUSIONS

This study shows the identification of nonlinear characteristic of the rubber mount using hysteresis loop method. A shaker test with the amplitude of excitation range from 3N to 10N and the excitation frequency range from 0Hz to 300Hz is performed on the rubber mount rubber mount. The force transducer measured the force exerted by the shaker to the rubber mount structure whereas the accelerometer measured the response amplitude of acceleration. The measured signal is analyzed and further calculate using given equation to obtain the stiffness and loss factor graph. Based on the results, the rubber mount's nonlinear characteristic occurs when it is excited at 80Hz with different amplitude of excitation which the stiffness trend shows a hike before achieving transition as the amplitude of excitation increases. The loss factor increases as the amplitude of excitation increases where the hysteresis loop shows a deviation in result between the increasing and decreasing value.

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