Dynamic Measurement of Engine Mount Properties Using Hysteresis Loop Method

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Abstract: Engine mounting system is usually used for isolating the engine vibration caused by the disturbance force of engine. Rubber is common materials found in most of the engine mounting system as its high damping properties. Loss factor of the rubber represent the energy loss of the system while it is reducing the vibration. In this paper, the hysteresis loop method is used to evaluate the dynamic properties of the engine mount. The dynamic measurement of engine rubber mount properties is experimentally investigated by using shaker. The response displacement and the excitation force is captured by using the accelerometer and force transducer. The tests are performed under different frequency and different excited force amplitude. The hysteresis loops are obtained for each for each of the test and the loss factor and the stiffness are calculated based on each of the hysteresis loop. The comparison of the different loss factor and stiffness are compared to identify the viscoelastic properties of the rubber mount. The results are then compared with the sine swept method to validate the dynamic properties of engine mount at different frequency.

Keywords: Hysteresis, Stiffness, Loss Factor.

1 INTRODUCTION

Rubber is an unique material that its viscoelastic behavior could deform linearly and non-linearly under different excitation frequency and amplitude. One of the applications is rubber mount which is widely used 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. Third, it function as isolation preventing vibration from the engine or road conditions from being transferred to the driver and passengers[1].

Viscoelasticity is a property of materials that exhibit both viscous and elastic characteristics when undergoing deformation[2]. The behavior of viscoelastic material can be affected by different frequency and amplitude. The frequency dependent of material properties is often foreseen, e.g., the increase in Young's modulus for an increasing frequency due to viscous effects within the material. As discussed by Knothe et al. [3] in their review on modeling of railway tracks, the most widely encountered model when considering rubber materials or components, taking a frequency dependent of dynamic characteristic into account, is the Kelvin-Voigt model where an elastic frequency independent stiffness is coupled in parallel with a viscous dashpot.

An alternative to way obtain good description of viscoelastic materials’ frequency dependent while reducing the required number of parameters is by using constitutive relations including time derivatives of non-integer order, known as fractional derivatives. Shimizu et al. [4] give thorough reviews on the use of fractional derivatives in dynamic modeling of viscoelastic materials. Shimizu et al. suggested that viscoelastic materials can be described accurately by the fractional calculus model with a few experimental parameters, and that the fractional calculus approach can lead to well-posed problems even when incorporated into the finite element formulation. However, the author does not focus on conducting the experiment in their paper.

Frequency dependent properties of engine mount can be exhibits in linear and non-linear behavior. Lin et al. [5] was conducted the experiment to study the frequency dependent of stiffness and damping values. They found that the single degree of freedom of the spring-mass model using constant stiffness and
damping values can only predict the response of the system accurately at resonance but not at non-resonance frequencies. However, their experiment focused on low excitation frequency since the authors only wanted to study the dynamic characterization of engine mount in linear region only.

Another experiment was conducted by Sjoberg et al.[6] to determine the frequency dependent stiffness in non-linear regions. The outcome from their studied exhibited that increase of frequency will increase the stiffness of the rubber. The non-linear behavior only displayed at higher excitation frequency. At lower excitation frequency, the linear behavior is performed. Nevertheless, this paper only focused on simulation method and validated its result with experimental method.

Dynamic properties of engine mount also can be determined by studies the amplitude at different excitation. At current time, the amplitude dependent of dynamic characteristic is often studies in term of linear behavior only. Kari et al. [7] and Hofer et al. [8] found that the higher the amplitude, the lower the stiffness of the rubber. However, their paper only proved the simulation method that can be used to determine the dynamic characteristic of rubber. Although Berker et al. [9] are analyzed the steady state rolling rubber wheel in term of linear and non-linear behavior of amplitude dependent of dynamic characteristic, but still not focused to study the non-linear region of amplitude at different excitation.

Frequency and amplitude dependent for viscoelasticity properties of rubber was studied and conducted in several methods. One of the ways to study the dynamic characterization of engine mount is using sine sweep method. Ripin et al.[10] was conducted the experiment by using sine swept method to determine the dynamic characterization of engine mount. The electromagnetic shaker is used as an excitation source to excite the engine mount system to obtain the frequency response function and dynamic stiffness of rubber mounts.

Lin et al. [5] was studied the stiffness and damping of engine mount using impact test technique and validated the result that obtained from sine swept method. Impact technique provides a quick and easy way to evaluate the frequency dependent stiffness and damping characteristics of engine mount. The result in their studies indicated that engine mount damping coefficient is a linear function of frequencies in low frequency range.

Another method to determine the dynamic properties of engine mount is using simulation method. Luo et al. [11] was developed the numerical method to study dynamic characterization of rubber mount . The results indicated that characteristics of the non-linear dynamic stiffness are associated with both amplitude and frequency. However, the results from simulation shows that only amplitude dependency validated with the experimental result.

Hysteresis loop method also can be used to determine the stiffness and loss factor of engine mount. It could be used to identify the frequency dependent and amplitude dependent properties. A plot of amplitude of instantaneous force versus instantaneous displacement in a material of all value of time is referring as hysteresis loop. The linear dependent for dynamic characterization of rubber mount will visualize the hysteresis loop in elliptical shape. For non-linear dependent, the shape of elliptical of hysteresis loop will be change to s-shape. [12].

The aim for this paper is to study the dynamic characterization of rubber mount in in different excitation of frequency and amplitude. The change behavior of rubber mount at different excitation of frequency and amplitude from linear to non-linear will be identified in this paper. The hysteresis loop method is used in this experiment to determine the dynamic stiffness and loss factor of rubber mount.

2 THEORETICAL BACKGROUND

The measurement system has been modelled as a single degree of freedom (SDOF) system. This system is a damped forced vibration system with an equation of motion:

\[ F(t) = mx + cx' + kx \]  \hspace{1cm} (1)

where \( F(\omega) \) is the external applied force, \( m \) is the rigid mass, \( x'(\omega) \) is the acceleration from accelerometer, \( c \) is damping coefficient, \( x(\omega) \) is a velocity, \( k \) is stiffness and \( x(\omega) \) is a displacement.

The equation of motion of rubber mass system with frequency dependent stiffness \((k(\omega))\) and loss factor \((\eta(\omega))\) can be written as:

\[ mx'' + k(\omega)(1+j\eta(\omega))x = F \]  \hspace{1cm} (2)

from the equation (2), the sloop of the loop represent as the stiffness of the engine mount. From equation (2), the loss factor, \( \eta \) can be written as:

\[ \eta = \frac{D}{2\pi W_o} \]  \hspace{1cm} (3)
Where $D$ is energy dissipated and $W_e$ is energy of the system. $W_e$ can be written as:

$$W_e = \frac{1}{2} k \dot{X}^2$$

(4)

The $k$ in equation (4) equal to maximum force, $F_e$ divide by maximum displacement $X_e$. So the $W_e$ can be written as:

$$W_e = \frac{1}{2} F_e X_e$$

(5)

Combine equation (3) and equation (4):

$$\eta = \frac{D}{\pi F_e X_e}$$

(6)

3 EXPERIMENT SETUP

From Figure 1, three solid engine mounts with diameter of 15 mm and 20 mm length are used as the test object for this experimental investigation. The preload mass of 0.9 kg is used to measure the preloading effect of the rubber properties.

![Figure 2. Experiment setup for sine swept method.](image)

The experimental setup which is used for both frequency and amplitude experiment are shown in Figure 2. This setup consists of three engine mount, an accelerometer, a force transducer, power amplifier and the electromagnetic shaker as the excitation force. The force transducer is connected to the shaker via the stringer. The force transducer is used to measure the input force from the shaker and analyzed it using LMS spectral testing. The accelerometer measured the acceleration of response of engine mounts and analyzed in LMS spectra testing.

The results measured by hysteresis loop method are then validated by using sine swept method. The sine swept method used the electromagnetic shaker as an excitation source to excite the engine mount system. The frequency response function and dynamic stiffness of engine mount is obtained and the frequency dependent stiffness and loss factor are calculated. The same setup as Figure 2 is used to conduct the sine swept experiment to validate the result using hysteresis loop method.

![Figure 4. Experiment setup for engine mount](image)

4 RESULT AND DISCUSSION

The frequency response function, FRF of the system is analyzed and recorded. The FRF was used to determine the natural frequency of the system. Stiffness and loss factor of the rubber was calculated from hysteresis loop using equation from section 2.

The natural frequency of the rubber mount is indicated by the pick value of the frequency response function as shown in Figure 3. Based on the graph, natural frequency of rubber mount is 113.5 Hz.

![Figure 3. Frequency response function of the rubber mount](image)

Figure 4 shows the hysteresis loops that measured at the excitation frequency of 80Hz but different excitation force amplitude. The excitation force applied are from 3N to 10N.
From Figure 4, the shape of the hysteresis loop change when the excitation force increased. The slope of the loop also changing when the excitation force increases. It can be seen from the elliptical shape of hysteresis loop become s-shape when the applied force are 5N and above. The engine mount start to behave non-linearity when the applied force is 5N and above. This s-shape of the hysteresis loop is indicated as non-linearity as mentioned by Aiken et al. from their analytical studied of hysteresis model [13].

![Figure 4: Hysteresis loop measured under different force amplitude.](image)

The slope of the loop represent the stiffness of the engine mount. The equation (2) from is used to calculate the slope and stiffness of engine mount. The results are shown in Figure 5 as stiffness at different excitation force amplitude. From the graph, it shown that stiffness decreases when the excitation force increases. This finding is similar to the result reported by in Berg and Mats [14]. However, they control the excitation displacement amplitude instead of force amplitude.

![Figure 5: Stiffness under different excitation force amplitude.](image)

The loss factor of engine mount is calculated by using equation(5). The area of the loop per area of the system represents as the loss factor as stated by Nashif et al. [12] in their studied. From figure 6, the loss factor increases when the excitation force is below than 4N. When the excitation force more than 5N, the loss factor decreases. It is because when the excitation force more than 5N, the behavior of the loop is changing from linear non-linear behavior.

![Figure 6: Loss factor under different excitation force amplitude.](image)

For second measurement, the engine mount are then excited at different excitation frequency but constant at 3N excitation force. The results are shown in Figure 7.

![Figure 7: Hysteresis loop measured under different excitation frequency.](image)

Figure 7 shows that the hysteresis loop of different frequency at 3N excitation force. Since this paper is to evaluate the performance of the engine mount under different excitation force level and frequency, the 3N is focused in the experiment to understand the trend of the graph at different frequency.

From Figure 7, the direction of the slope is anti-clockwise. For excitation from 50 Hz and 100 Hz, the figure shows that the slope angle of the loop is negative. Meanwhile, the slope angles of the loops change to positive when the frequency excited from 150 Hz and above. This is due to the natural frequency of the engine mount. Savi et al. [15]
indicates same observation as the results above. It is because, when excitation frequency increases, the slope angle changes from negatives to positives when frequency passes through the natural frequency.

Figure 8: Stiffness obtained under different excitation frequency.

Figure 8 shows stiffness obtained under different excitation frequency at 3N excitation force. From Figure 8, when the frequency excited from 50Hz to 100 Hz, the value of stiffness is decrease from 95.72kN/mm to 78.48kN/mm and reach the minimum value at 70.33kN/mm. Then, stiffness starts to increase when the frequency excited above the natural frequency. The negative slope from 50Hz to 113.5Hz is caused by the phase transformation passing through natural frequency, which has also had been observed by Vance et al. in their studied[16].

Figure 9: Loss factor obtained under different excitation frequency.

Figure 9 shows the loss factor obtained under different excitation frequency and constant excitation force amplitude at 3N. When the excitation frequency is below then natural frequency, the loss factor is increases. Meanwhile, the loss factor decreases when the excitation frequency is more than the natural frequency. It is because the natural frequency of the engine mount is affecting the loss factor of the engine mount.

5 VALIDATION

The stiffness that calculated from hysteresis loop method is compared with the stiffness measured direct from sine swept method. The percentage different is calculated and shows in table 1.

Table 1: Percentage different of stiffness from hysteresis loop method with sine swept method

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>k value of hysteresis loop method (kN/mm)</th>
<th>k values of sine swept method (kN/mm)</th>
<th>Percentage difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>95.71</td>
<td>94.31</td>
<td>1.4</td>
</tr>
<tr>
<td>100</td>
<td>78.48</td>
<td>76.40</td>
<td>2.7</td>
</tr>
<tr>
<td>150</td>
<td>102.82</td>
<td>104.26</td>
<td>1.3</td>
</tr>
<tr>
<td>200</td>
<td>171.12</td>
<td>172.12</td>
<td>0.5</td>
</tr>
</tbody>
</table>

From Table 1, the percentage difference values are below than 3%. Since the percentage differences are small, the result measured from hysteresis loop method is validated.

6 CONCLUSION

Measurement shows that the dynamic stiffness of one of the most common, commercially available rubber mount is strongly dependent on both excitation amplitude and frequency. For different excitation of amplitude, the shape of hysteresis loop is changing from smooth elliptical to s-shape elliptical when the force excited from 3N to 10N. The stiffness of engine mount for different excitation amplitude is decreasing since the slope of the loop is decreasing. The loss factor under excitation from 3N to 4N is increasing since the shape of the loop is elliptical shape (linear behavior), meanwhile the loss factor under excitation force from 5N to 10N is decrease since the shape of the loop is changing to elliptical s-shape (non-linear behavior). For experiment of rubber mount at different excitation frequency, the natural frequency affects the slope of the hysteresis loops. Below the natural frequency, the slope is negative and changing the slope direction anti-clockwise. Since the slope is decrease, the stiffness also decreases. Moreover, the lost factor is increasing since the area of the loop is increasing when the excitation frequency near the natural frequency. When the excitation frequency is higher than the natural frequency, the stiffness increases because the slope of the loops is increased. At higher than natural frequency, the lost factor is decreased since the area of the loop is decreased. The percentage differences of stiffness value from hysteresis loop method and sine swept method is
below than 3% and it shows that the result from hysteresis loop method is validated.

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REFERENCE


