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Evaluation of the effectiveness of elastomeric mount using vibration power flow and transmissibility methods

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Abstract. This paper presents the results of an experimental work to determine the dynamic stiffness and loss factor of elastomeric mounts. It also presents the results of theoretical analysis to determine the transmissibility and vibration power flow of these mounts, which are associated with their contribution to structure-borne noise. Four types of elastomeric mounts were considered, where three of them were made from green natural rubber material (SMR CV60, Ekoprena and Pureprena) and one made from petroleum based synthetic rubber (EPDM). In order to determine the dynamic stiffness and loss factor of these elastomeric mounts, dynamic tests were conducted using MTS 830 Elastomer Test System. Dynamic stiffness and loss factor of these mounts were measured for a range of frequency between 5 Hz and 150 Hz, and with a dynamic amplitude of 0.2 mm (p-p). The transmissibility and vibration power flow were determined based on a simple 2-Degree-of-Freedom model representing a vibration isolation system with a flexible receiver. This model reprsents the three main parts of a vehicle, which are the powertrain and engine mounting, the flexible structure and the floor of the vehicle. The results revealed that synthetic rubber (EPDM) was only effective at high frequency region. Natural rubber (Ekoprena), on the other hand, was found to be effective at both low and high frequency regions due to its low transmissibility at resonant frequency and its ability to damp the resonance. The estimated structure-borne noise emission showed that Ekoprena has a lower contribution to structure-borne noise as compared to the other types of elastomeric mounts.

1. Introduction

One of the research and development efforts in automotive area is for controlling noise and vibration problems in order to achieve improvements in ride comfort. This can be done by improving the isolation system of its powertrain. Engine and mounting systems play critical roles in noise, vibration and harshness (NVH) of the vehicle. The main causes of vibration are the engine excitation force generated by gas pressure of fuel explosion in the cylinder, and the inertia force of the piston and connecting rod. The vibration is transferred through the mounting system to the seat track structure causing discomfort to passengers.

Various types of isolators have been proposed to attenuate the unwanted vibration of powertrain that is transferred to the body structure. Elastomers have been used as engine mounts to reduce vibration from the powertrain to the structure since 1930s. Compactness, cost-effectiveness and low maintenance are the main advantages of these elastomeric mounts.

Currently, most of the elastomeric mounts used for this application are made from petroleum-based synthetic rubber (SR). This is mainly due to their better resistance to heat, oxidation and oil as compared to natural rubber (NR). The use of petroleum-based raw material not only depletes the earth's non-renewable natural resources but also causes environmental hazards. Elastomeric mounts, which are disposed everyday, usually ends up in the landfill. Elastomers buried in landfill sites release high toxic chemicals into the groundwater, and carcinogens are also released to the environment. The increasing awareness of environmental sustainability in recent years has motivated researchers to explore the use of environmental-friendly non-petroleum-based raw materials in the development of eco-friendly elastomeric mounts.

NR is considered as an alternative to SR due to its advantages as a way to conserve land, that also acts as a sink for CO_2 generated by automobiles [1-6]. From the perspective of energy consumption in the preparation of these elastomers, NR also has an advantage over SR, as shown in table 1.

Table 1. Energy consumption for preparation of various elastomers [2]

Material	Approximately Energy Comsumption (GJ/t)
Natural Rubber (NR)	15-16
Polybutadiene Rubber (BR)	108
Polypropylene (PP)	110
Styrene-Butadiene-Rubber (SBR)	130-156
Ethylene-Propylen-Dien-Modify (EPDM)	142-179
Butyl Rubber (IIR)	174-209
Chloroprene (CR)	120-144

NR is categorized as 'green' material because its production uses natural material or renewable resources and it is produced with minimal waste. The use of these eco-friendly and low-energy products exerts less stress on the environment and improves carbon life cycle.

Ekoprena and Pureprena are advanced natural rubber products resulting from research and development activities conducted by Malaysian Rubber Board (MRB) in order to improve the properties of natural rubber depending on a conventional grade used such as Standard Malaysia Rubber (SMR). These advanced natural rubber products have been tested on curing characteristics and physical mechanical properties. The properties of Ekoprena and Pureprena were found to be quite similar to the properties of synthetic rubber. Ekoprena has properties such as oil resistant, low water absorption, high damping, high wet grip, low rolling resistance and gas permeability, while Pureprena has properties such as low creep, stress relaxation and low compression set, low water absorption, good dynamic properties, low protein and low ash. Unfortunately, there is no data or information available on the vibration control characteristics of these advanced natural rubber. Therefore the main aim of this work is to investigate the potential and suitability of these advanced natural rubber mounts as an alternative to the more widely used synthetic rubber mount in controlling vibration and noise. This paper presents the comparison between natural rubber and synthetic rubber mounts' effectiveness in controlling vibration and noise using transmissibility and vibration power flow methods. Vibration power flow is used as a tool, in addition to vibration transmissibility, in quantifying the effectiveness of the elastomeric mount, and to identify the elastomeric mount that contributes the most to structure-borne noise. The natural rubber considered in this work is a conventional grade, SMR CV60, and the advanced natural rubber are Ekoprena and Pureprena. The syntetic rubber used in this work is EPDM.

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2. Methodology

This section describes the experimental set-up and procedures for the dynamic test used to determine the dynamic stiffness and loss factor of the elastomeric mounts, as well as the analytical model to determine the characteristic of elastomeric mount associated with its contribution to structure-borne noise, namely the transmissibility and vibration power flow.

2.1. Dynamic Test

Dynamic test was conducted according to Japan Industry Standard (JIS) K6385-1977 [7] using the MTS 830 Elastomer Test System. The elastomeric mount was placed on a jig plate which was then fixed between two plates, figure 1. Preload considered in the dynamic test was 313.92 N. This preload which is about ¼ of the weight of the powertrain was also applied for the testing of the original elastomeric mounts. The frequency range was between 5 Hz and 150 Hz, and the dynamic amplitude applied in the radial direction was set to 0.2 mm (p-p). LVDT was used to measure the displacement and load cell was used to measure the force. Figure 2 shows the schematic drawing of the dynamic testing machine. The elastomeric mount was subjected to a single frequency sinusoidal signal at increment of 5 Hz. The time domain signals were analysed, and the dynamic stiffness and loss factor of these elastomeric mounts were derived from the measured force, displacement and the phase angle between the force and the displacement.

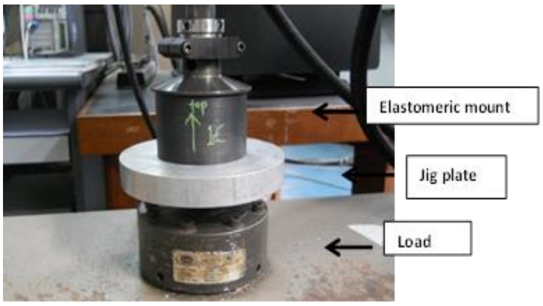


Figure 1. Elastomeric mount placed on a jig plate and fixed between two plates of the MTS 830 machine for static and dynamic tests.

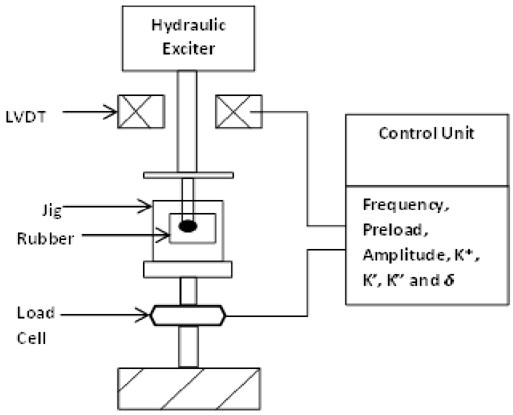


Figure 2. Schematic drawing of the dynamic testing machine.

2.2. Analytical Model to Evaluate the Effectiveness of Elastomeric Mount

In the analytical work, a simple 2 Degree-of-Freedom (DOF) vibration isolation system with a flexible receiver was modelled. The model is based on three main parts of a vehicle which are the powertrain and engine mounting, the flexible structure and the floor of the vehicle. The model is shown in Figure 3. M_1 represents the block mass, and K_1 represents the elastomeric mount's stiffness in complex form. M_2 represent the mass of the flexible structure, which consists of the mass of the beam and the mass of the plate that is attached to it. K_2 represents the beam stiffness. A harmonic force **F** of frequency ω acts upon M_1, in the line of motion (vertical direction).

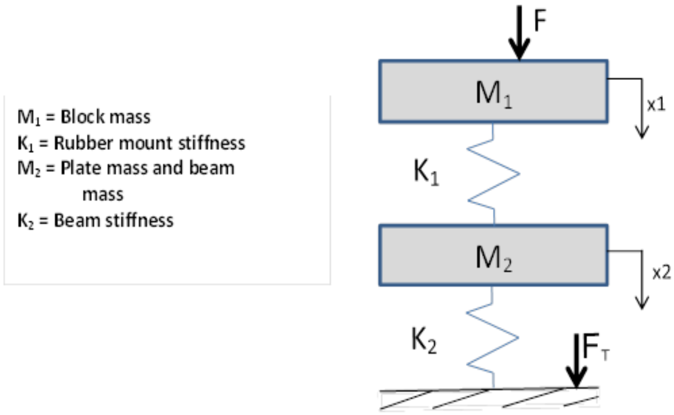


Figure 3. The 2- DOF model.

The transmissibility (*Tr*) for the elastomeric mounts was evaluated using measured values of dynamic stiffness and loss factor of elastomeric mount for a range of frequencies from 10 Hz to 150 Hz. The beam stiffness (K_2) has a constant value. The general equation of transmissibility (Equation 1) was derived from the 2-DOF model shown in figure 3. *Kd* is the dynamic stiffness of the elastomeric mount, δ is the loss factor of elastomeric mount, and *Kb* is the beam stiffness. *M* is the mass of the block and *Mb* is the mass of the beam and the plate.

$$Tr = \frac{F_T}{F} = \sqrt{\frac{(KdKb)^2 + (\delta KdKb)^2}{(KdKb - Mb\omega^2 Kd - M\omega^2 Kd - M\omega^2 Kb + M\omega^4 Mb)^2 + (\delta KdKb - \delta KdMb\omega^2)^2}} \quad (1)$$

The source acceleration (Equation 2) and receiver acceleration (Equation 3) were also derived from the 2-DOF model shown in Figure 3.

$$\tilde{a}_s = \omega^2 \left(\frac{F(Kd + Kb - Mb\omega^2 + j\delta Kd)}{KdKb - Mb\omega^2 Kd - M\omega^2 Kd - M\omega^2 Kb + M\omega^4 Mb + j\delta KdKb - j\delta KdMb\omega^2} \right) \quad (2)$$

$$\tilde{a}_r = \omega^2 \left(\frac{F(Kd + j\delta Kd)}{KdKb - Mb\omega^2 Kd - M\omega^2 Kd - M\omega^2 Kb + M\omega^4 Mb + j\delta KdKb - j\delta KdMb\omega^2} \right) \quad (3)$$

The vibration power flow through the elastomeric mount was evaluated using Equation 4 and Equation 5 [8-9], where M_{rs} is the apparent mass, which is obtained from the dynamic stiffness (K') and loss factor (η) of the elastomeric mount. The other components, a_s and a_r, represent the source and receiver acceleration, respectively. Both accelerations are in complex forms. The dynamic stiffness and loss factor from the measurement were required to determine vibration power flow through the elastomeric mount. The total vibration power flow was determined by the summation of the vibration power flow at each frequency from 30 Hz to 150 Hz. The values used to calculate transmissibility and vibration power flow are given in Table 2.

$$P = \frac{1}{2\omega} Im(\widetilde{M}_{rs}\tilde{a}_s\tilde{a}_r) \quad (4)$$

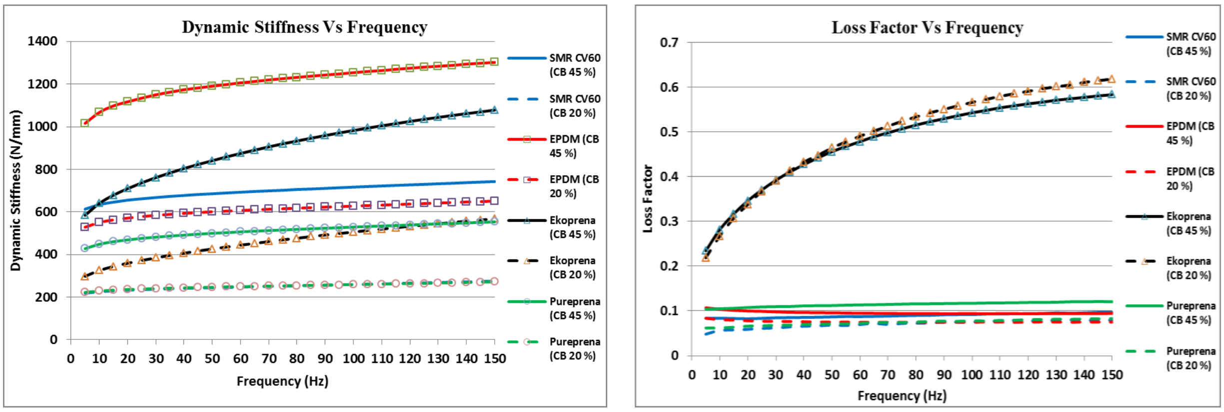
$$\widetilde{M}_{rs} = \frac{K\prime}{\omega^2} + j\delta\frac{K\prime}{\omega^2} \quad (5)$$

Table 2. Values used in the calculation of transmissibility and vibration power flow.

F (N)	M (Kg)	Mb (Kg)	Kb (N/m)
2.5 (average)	10 Kg	15.26 Kg	2189604 (constant)

3. Results and Discussion

Measurements of dynamic stiffness and loss factor were undertaken for eight different elastomeric mounts. These elastomeric mounts were SMR CV60 with carbon black (CB) content of 45% and 20%, EPDM with CB content of 45% and 20%, Ekoprena with CB content of 45% and 20% and Pureprena with CB content of 45% and 20%. Figures 4(a) and 4(b) show the dynamic stiffness and loss factor of these elastomeric mounts for a range of frequency between 5 Hz and 150 Hz, and for dynamic amplitude of 0.2 mm (p-p) and preload of 313.92 N.

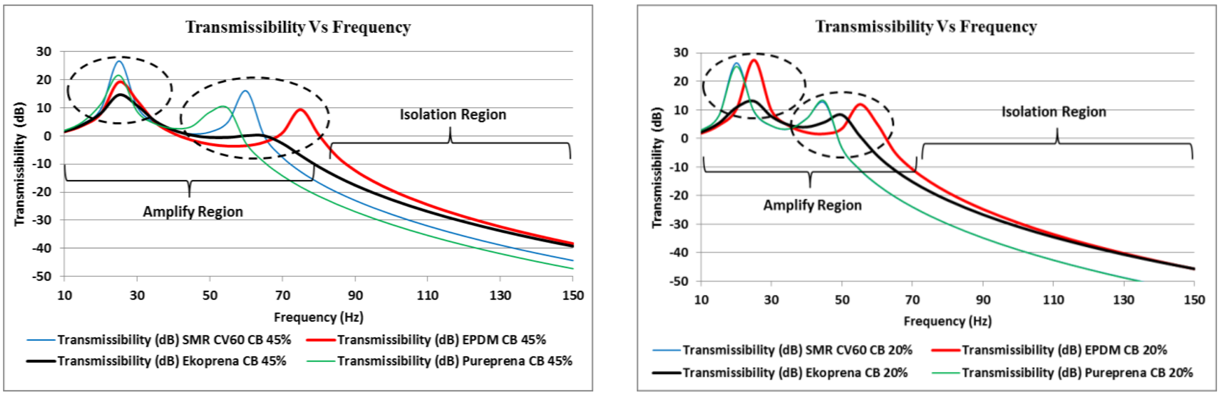


(a) (b)

Figure 4. (a) Dynamic stiffness of the elastomeric mount and (b) Loss factor of the elastomeric mount.

Figures 4 (a) shows that the dynamic stiffness increases with the increase in the frequency excitation from 5 Hz to 150 Hz for the natural rubber and synthetic rubber with 45% and 20% CB content. The dynamic stiffness also increases with the increase in CB content for both the natural rubber and synthetic rubber. Figure 4(a) shows that the synthetic rubber (EPDM) has the highest dynamic stiffness followed by natural rubber (SMR CV60, Ekoprena and Pureprena) for both cases of CB 45% and 20%. Ekoprena is however seen to have a relatively high dynamic stiffness although its hardness is close to SMR CV60 and Pureprena. Figure 4(b) shows that the loss factor increases with the increase in the frequency excitation from 5 Hz to 150 Hz for both natural rubber and synthetic rubber. The loss factor also increases with the increase in CB for both natural rubber and synthetic rubber. Figures 4(b) shows that Ekoprena has the highest loss factor followed by Pureprena, EPDM and SMR CV60, for both CB content of 45% and 20%.

Figure 5(a) represents transmissibility of elastomeric mounts with 45% carbon black (CB), while Figure 5(b) represents transmissibility of elastomeric mounts with 20% CB.



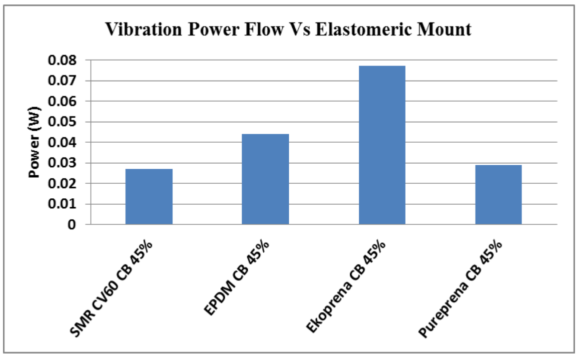
(a) (b)

Figure 5. (a) Transmissibility of elastomeric mounts with 45% CB and (b) Transmissibility of elastomeric mounts with 20% CB.

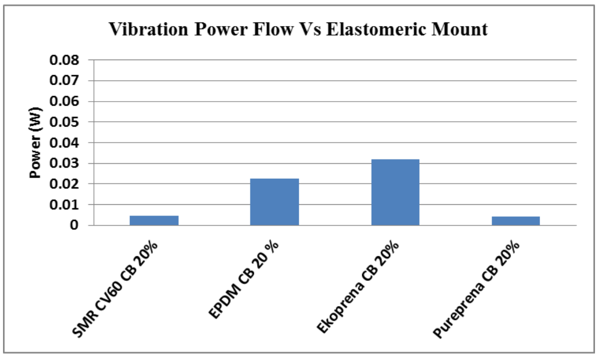
Two regions can be observed in Figures 5(a) and 5(b), namely the amplification and isolation regions. There are two resonance peaks (dot circle) in amplification region which are primary and secondary resonances. Based on the observation of the natural frequencies of the system in Figure 5(a), the natural frequency is about 25 Hz for primary resonance and 55 Hz to 75 Hz for secondary resonance. The natural frequencies of the system in figure 5(b) is about 23 Hz for primary resonance and 45 Hz to 55 Hz for secondary resonance. These natural frequencies are based on the dynamic stiffness of the elastomeric mounts. The dynamic stiffness of elastomeric mounts are in turn dependent on the CB content. The dynamic stiffness increases with the increase in CB content for both natural rubber (NR) and synthetic rubber (SR). The synthetic rubber (EPDM) has the highest dynamic stiffness followed by natural rubber (SMR CV60, Ekoprena and Pureprena) for both cases of CB content of 45% and 20%. The characteristics of high dynamic stiffness produced natural frequency (primary and secondary) at relatively higher frequencies for both cases of CB coontent of 45% and 20%. However natural rubbers (SMR CV60 and Pureprena) showed that the secondary resonance occurred at a lower frequency compared to EPDM and Ekoprena for both cases of CB contnet of 45% and 20%. It was also observed that natural rubber, SMR CV60 and Pureprena, are soft materials that produce low dynamic stiffness and low loss factor even for the same CB content as the EPDM and Ekoprena. Natural rubber, SMR CV60 and Pureprena, also showed low transmissibility at higher frequency as compared to EPDM and Ekoprena for both cases of CB content of 45% and 20%. Pureprena has low loss factor which makes it suitable to be used to reduce vibration at high frequency.

It is observed from Figures 5(a) and 5(b) that the elastomeric mounts based on synthetic rubber (EPDM) and natural rubber (SMR CV60 and Pureprena) produced higher transmissibility at resonant frequency (dot circles), about 25 Hz for primary resonance and 55 Hz to 75 Hz for secondary resonance for CB content of 45% and about 23 Hz for primary resonance and 45 Hz to 55 Hz for secondary resonance for CB content of 20%. Ekoprena, on the other hand, produced lower transmissibility at the same resonant frequencies for both cases of CB 45% and 20%. Ekoprena appeared to have a higher ability to reduce or damped resonance compared to the other elastomeric mounts. This is attributed to the higher loss factor of Ekoprena. By having a high loss factor, the magnitude of the transmissibility at the amplification region is reduced. On the other hand, the higher loss factor, also caused the value of the transmissibility to increase in the isolation region. The high loss factor is beneficial in the amplification region as it reduces the transmissibility at the resonance frequency. The results show that the natural rubber from Ekoprena and Pureprena are suitable to be used as an alternative to synthetic rubber (EPDM) for vibration isolation application. This is because Ekoprena has characteristic of high loss factor that makes it suitable to be used at low frequency to reduce vibration amplitude at resonance, while Pureprena has characteristic of low loss factor that makes it suitable for vibration reduction at high frequency.

The bar graphs shown in figures 6(a) and 6(b) are the total vibration power flow through each elastomeric mounts.



(a)



(b)

Figure 6. (a) Total vibration power flow through elastomeric mounts with 45% CB and (b) Total vibration power flow through elastomeric mounts with 20% CB.

Figure 6(a) shows the level of total vibration power flow through each elastomeric mount based on synthetic rubber (EPDM) and natural rubber (SMR CV60, Ekoprena and Pureprena) for the case of CB content of 45%. The results showed that Ekoprena was the highest contributor to the transmission of energy to the structure, followed by EPDM. SMR CV60 and Pureprena showed a relatively lower total vibration power flow. The higher total vibration power flow for Ekoprena is due to its high dynamic stiffness and loss factor as compared to the other natural rubbers (SMR CV60 and Pureprena) and synthetic rubber (EPDM). Referring to the vibration power flow formula, $P = \frac{1}{2\omega} Im\left(\widetilde{M}_{rs}\tilde{a}_s\tilde{a}_r\right)$, the apparent mass, $\widetilde{M}_{rs} = (\frac{K\prime}{\omega^2} + j\delta\frac{K\prime}{\omega^2})$ is a combination of dynamic stiffness and loss factor. Therefore, the characteristics of elastomeric mount that have high dynamic stiffness and high loss factor will produce high vibration power flow, while elastomeric mount that have low dynamic stiffness and low loss factor will produce low vibration power flow. If the CB content of Ekoprena is reduced from 45% to 20%, the total vibration power flow is reduced from 0.077W to 0.032W; approximately 58% reduction of the energy transmission to the structure is reduced as shown in figure 6(b). This is because the dynamic stiffness and loss factor of Ekoprena is reduced with the decrease in the CB content.

4. Conclusions

The results for the transmissibility and vibration power flow, presented in this work, indicate that vibration power flow can be used as a tool to augment vibration transmissibility in assessing the effectiveness of rubber isolators in controlling vibration and noise. Ekoprena and Pureprena were found to be suitable for this application, as an alternative to the more widely used synthetic rubber (EPDM). This is because Ekoprena has high loss factor, while Pureprena has low loss factor. Ekoprena is therefore suitable to be used at low frequency to reduce amplitude at resonance while Pureprena is suitable to be used to reduce vibration at high frequency.

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