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Predicted Transmissibility of an Experimental Approach for a Laminated Rubber-Metal Spring

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ABSTRACT

This paper presents a study of predicted transmissibility of an experimental approach for a laminated rubber-metal spring. Lumped parameter system approach is used to derive the mathematical model and test rig is designed to validate the analytical results. It is found that increasing the number of metal plates inside natural rubber rod, more internal resonances appear which degrades the isolation performance. However, the system shows better transmissibility at high frequency where the slope rolls off steeper that from the rubber system without the embedded metal plates.

Keywords: natural rubber, lumped system, transmissibility, axial force, vibration energy.

INTRODUCTION

Natural rubber (NR) is a type of sustainable material and very popular in Malaysia and around the world due to its many applications. The applications can be found in automotive industry, manufacturing, aerospace, defense and many more. This material is suitable for various applications according to user requirements. By adding other materials inside the NR, it will be known as the composite material. Two or more materials mixed together and finally the mechanical properties of this mixed material is anticipated better than the original one [1,2].

In automotive industry, internal combustion engine (ICE) is a one of the essential parts in vehiclepowertrain system. Noise and vibration generated by ICE cannot be neglected and avoided because of its natural behavior and fundamental source when the engine operates [3,4]. Engineers, scientists and researchers have been investigated this phenomenon and tried to eliminate to for comfortable driving to driver and passengers, however their effort still failed. They presumed that if the behavior cannot be eliminated, there must be have another method to reduce it and finally engine mounting is applied. Overall, the design of engine mounting is suitable for certain frequency and it cannot operate. It happen when the engine running in high rotation per minute (RPM). According to open literature, amplitude of vibration in engine is directly proportional with engine speed [4]. From previous study, conventional engine mounting can only absorb up to 30 percent of the vibration amplitude generated by the engine and the rest will transfer to car body. Logically, the rest 70 percent of the vibration amplitude can be considered it very large because by adding another vibration from other sources like tire and road surface, the vibration amount will be increased and

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finally still annoying driver and passengers [2].

In this study, NR is used for new isolator for automotive engine. The different between engine mounting and isolator is, engine mounting can only absorb the vibration energy but isolator has a potential to block vibration energy to the car body. Furthermore, metal plate is inserted through NR rod by using vulcanization method. The main function of this metal plate is to divide the NR into several sections but still in same rod. In addition, the number of sections also known as a degree of freedom (DOF) which means by inserting one metal plate into NR rod, it will make the rod to becomes 2 DOF. By adding more metal plate, the NR rod is expected to give more stiffness and finally has an ability to block more vibration energy generated by the engine. The mathematical modeling of NR rod will be derived using wave propagation method and the results will be validated by experiment. According to this paper, it will be presented the way how to produce the new testing rig for NR rod with certain boundary conditions and certain agreements.

2. *Research Methodology:*

The study of laminated rubber-metal spring (LR-MS) (before called NR rod) is developed at Faculty of Mechanical Engineering (FKM), Universiti Teknikal Malaysia Melaka (UTeM) cooperate with Lembaga Getah Malaysia (LGM), Sungai Buloh, Malaysia. This study is conducted from scratch where it is started with development of mathematical modeling of LR-MS using wave propagation method, development finite element (FE) model using numerical software and final stage is development of test rig for validate the results from modeling and FE model.

In operation of ICE, there are two forces involved which called excitation force, F_e and transmitted force, F_t. When transmitted force hit the car body, the vibration energy is transferred simultaneously and finally the car body including driver and passengers will feel discomfort by the unwanted vibration amplitude. To solve this problem, engine mounting was implemented to reduce the vibration amplitude. This conventional mounting can be classified as a one DOF [5]. Therefore, it can be operated only in certain frequencies. To upgrade the system to operate well and smoothly with large range of frequencies, LR-MS isolator is introduced where the DOF of isolator also can be increased rapidly using metal plate.

The flexibility of NR offers major advantages where it can act as spring to block the vibration energy. From previous research, NR is able to sustain large deflections [6]. The problem occurs when the material is subjected to large static preload. NR is affected incompressible in solid block condition where a preload will cause the material to bulge outward [6,7]. Theoretically this bulge not only decreases the dynamic performance of the material but also reduces its life time. Figure 1 illustrates the bulging effect where the axial force is applied into NR rod. However, this problem can be countered by increasing the stiffness of the isolator. The way to increase the stiffness is by reinforcing the metal plate into NR rod. Figure 2 illustrates the LR-MS by implementing the axial force at the top. Finally, by increasing the stiffness in NR rod, the bulging effects are reduced and the block will be more stable.

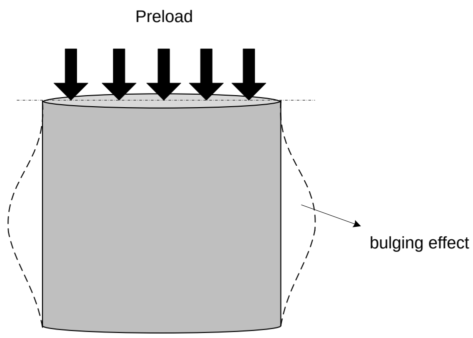


Fig. 1: Bulging effect at NR rod.

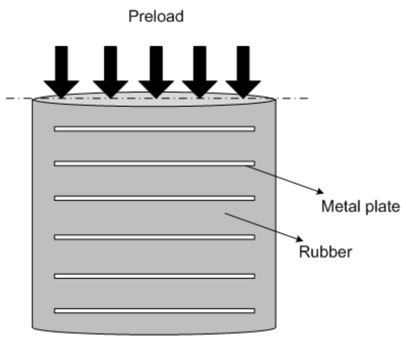


Fig. 2: Bulging effect at LR-MS.

In the analytical approach to identify LR-MS isolator, it is shown that LR-MS isolator has the ability to block the vibration energy from the engine. At the first stage of the mathematical modeling of LR-MS, lumped model is used to represent the model by consisting mass m, damper c and stiffness k components. The lumped mass also has an individual mass which is known as M . Before adding the metal plate, the NR mathematical model is consisting of a mass constant value of stiffness k and damping c. Then, the metal plate is applied which represent as a rigid solid mass m without any stiffness and damping influence the mass [6]. The schematic diagram by adding one metal plate and creating two DOF in LR-MS is shown in Figure 3.

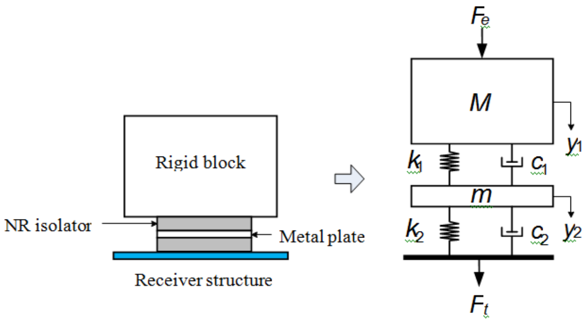


Fig. 3: Lumped model for LR-MS.

Two equations of motion are derived forthis lumped model and shown in Eq. (1) and Eq. (2).

$$M\ddot{y}_1 + c_1(\dot{y}_1 - \dot{y}_2) + k_1(y_1 - y_2) = F \tag{1}$$

$$m\ddot{y}_2 + c_1(\dot{y}_2 - \dot{y}_1) + c_2\dot{y}_2 + k_1(y_2 - y_1) + k_2 y_2 = 0 \tag{2}$$

Based on LR-MS, metal plate is added into the system. So, by adding three metal plates inside NR rod, the DOF is increased to three, the new matrix is given in Eq. (4).

$$\mathbf{M} = \begin{bmatrix} M & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 \end{bmatrix} \mathbf{C} = \begin{bmatrix} c_1 & -c_1 & 0 \\ -c_1 & c_1 + c_2 & -c_2 \\ 0 & -c_2 & c_2 + c_3 \end{bmatrix} \mathbf{K} = \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 + k_3 \end{bmatrix} \tag{4}$$

For validation of the results in analytical analysis, the development of experimental test rig is required. All the procedure for this experiment is following the condition that stated inside the BS EN ISO 10846-2:2008 Part 2: Direct method for determination of the dynamic stiffness of resilient supports for translator motion [8]. The schematic diagram of testing rig for NR rod and LR-MS is shown in Figure 4.

The main purpose using flexible foundation is to give free boundary condition to the system. It is very important to make sure the surface at $y = 0$ has a free motion when the dynamic force is applied by shaker. The auxiliary spring is used to bring vertical movement to flexible foundation. The rigid foundation is representing the fixed boundary condition of the NR rod and LR-MS. There is no motion involved and no displacement at $y = L$. Two force sensors are used to record the amount of excitation force F_e and transmitted force F_t at top and bottom of NR rod and LR-MS. The force data will be used to plot transmissibility graph and finally to validate the analytical and FE results.

The test rig can be used for two types of experiments which are normal translations and transverse translations. According to normal translations, the NR rod and LR-MS are exposed to translator vibration in the normal load direction and transverse vibrations perpendicular to the normal load direction. Roller bearings are used for suppressing unwanted input vibrations and for suppressing unwanted transverse forces on the flexible and rigid [8].

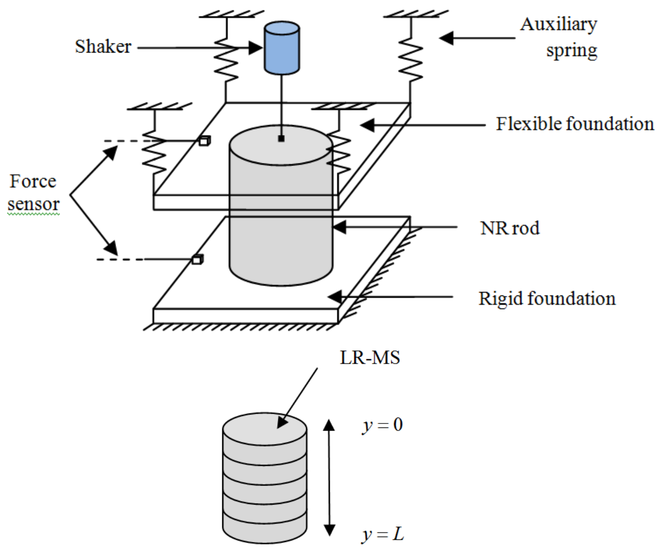


Fig. 4: Schematic diagram for NR rod and LR-MS testing rig.

There is one hypothesis on the experimental approach which is Mullins effect [9]. Mullins effect is a phenomenon and has potential to influence characteristics of the NR due to the compression load. By applying excitation force at the top of NR rod and LR-MS, the total length L of the isolator will be decreased. The reduction of the NR rod and LR-MS length has been implicitly with the reduction due to the total number of applying metal plate. Take a NR rod and LR-MS with cross sectional area A, so the stiffness will be become

$$k = \frac{EA}{L} \tag{5}$$

where E is the Young's Modulus .

The number of the metal plate is inversely proportional to the length of the NR rod and LR-MS. The relationship is written in Eq. (6).

$$N \propto \frac{1}{L} \propto k \tag{6}$$

Result and Discussions

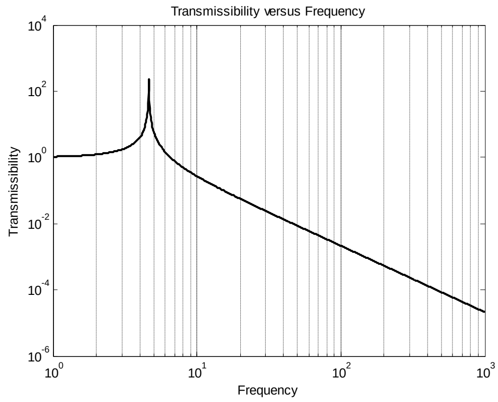
All the results in this study are illustrated in transmissibility plot. According to this plot, there are two main factors can effects the results which are non-dimensional frequency and damping value of the NR rod and LR-MS isolator. Theoretically, natural frequency of both isolators can be calculated using mathematical expression where the formulation is written in Eq. (7).

$$\omega_n = \sqrt{\frac{g}{\delta_s}} \tag{7}$$

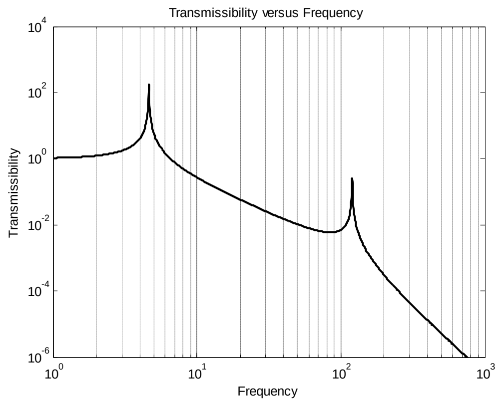
where g is the gravity acceleration and δ_s is the static displacement of the linear isolator.

The results for transmissibility of lumped system for analytical analysis are shown in Figure 5. Based on this figure, 1 DOF is better than others by comparison in term of transmissibility. But for higher DOF such as 2 and above, stability is improved and buckling due to static loading is prevented. In this analysis, the range of frequency is 1000 Hz.

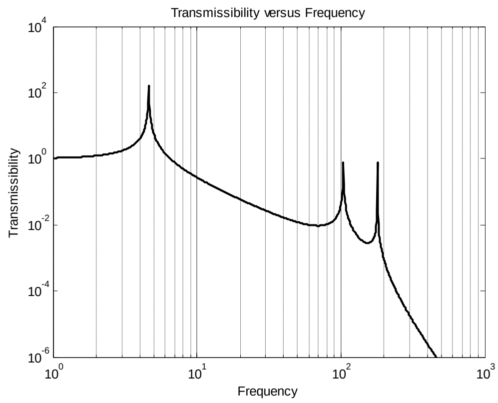
For experimental testing, the result is still in progress because test rig is still in development process. However, based on the previous section, the boundary condition, and many elements were taken for the mathematical modeling of LR-MS. However, the result will be same in term of pattern and the tolerance between analytical and experimental will be correlated less than 10 percent. Most important thing has been issued at previous section is the Mullins effect. The hypothesis result for experimental testing shown in Figure 6. The Mullins effect will give an effect in term of transmissibility. The effect can be seen to amplify the transmissibility at higher frequency. The graph shows fluctuations and slowly the fluctuations disappear by increasing the frequency. However, this is just hypothesis results based on the theoretical performance and it will be validated in future study.



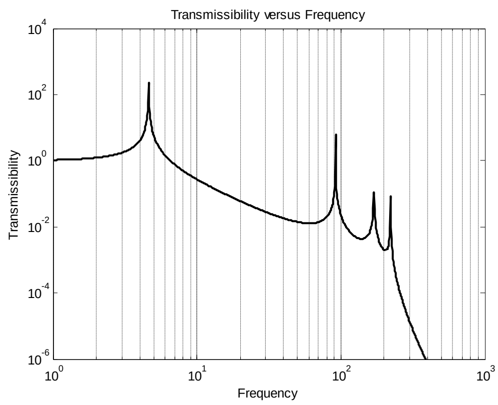
(a) One DOF



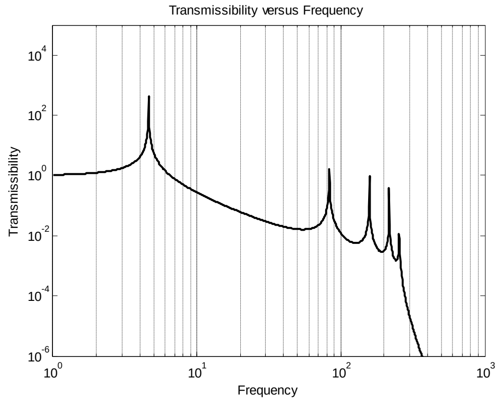
(b) Two DOF



(c) Three DOF



(d) Four DOF



(e) Five DOF

Fig. 5: Results of analytical analysis for LR-MS.

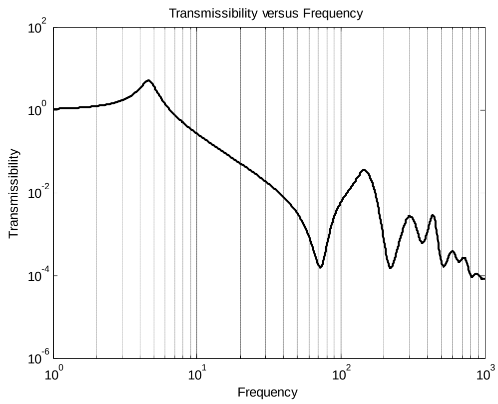


Fig. 6: Hypothesis of experimental testing result for LR-MS.

4. *Conclusion:*

LR-MS study in axial force is a new research and many previous researches are only focused on shear force reaction. The feasibility of this study is performed through modeling, simulation and experiment. The testing rig will be developed and the schematic diagram is shown in previous section. These methods are important to validate the results from analytical and FE study. Analytical results have been discussed at previous section and the hypothesis results will be worked out from experimental testing. This study can be a baseline reference for future approach.

Acknowledgement

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