HORIZONTAL DISPLACEMENT OF LAMINATED RUBBER-METAL SPRING FOR ENGINE ISOLATOR

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ABSTRACT

This paper presents the study on horizontal displacement of laminated rubber-metal spring on engine isolator. Initially, lumped model is adopted in the analytical system of isolator for one degree of freedom system. Later, the power series technique is used to develop more complex analysis. In this model, natural rubber is used for isolator rod and the metal plate is reinforced inside the rod. This plate used to divide the natural rubber rod into more degree of freedom. Two types of results are recorded which are surface and standalone displacements. In these two displacements, the results show the displacement in axial axis is increased by increasing the number of metal plate. It happens because natural rubber properties have been influenced by metal plate and finally unique compressibility behavior occurred.

Keywords: LR-MS, displacement, natural rubber, metal plate and spring.

INTRODUCTION

In practice, natural rubber (NR) is a versatile and excellent material because in 150 years it was successfully used in many engineering applications [1]. The applications can be found in civil, railways, offshore, automotive, defence, aerospace and many more industries. It becomes number one chosen material due to the ability to withstand large deformations and store more elastic energy per unit volume compare other materials [1]. It also has inherent damping and spring-like performance in term of vibration resonant. Besides, NR also has their unique response which is very little compressibility during the application of excitation force.

Rubber bearings were developed for stress distribution and stress concentration of a laminated elastomeric bearing subjected to axial loads [2]. In this study, finite element (FE) approach is used to produce approximated solution. According to this study, the benefit of using NR is based on shape factor. It is because of the edge effect of the material is decreased when the shape factor is increased. The shape factor is one of the important parameters which can influence the flexibility of the material in order to block the unwanted energy transmitted into the system. In 2007, this research was complied with other researchers who studied the use of rubber bearings for new highway construction in Greece [3]. The rubber bearings are used as a supports for the highway bridges. In this study, two samples were used and located at the bridge column. Test result shows the stiffness and damping ratio have a good relationship with axial load as well as the frequency of the horizontal displacement. The total displacement of rubber bearings is proportional to the force apply.

In 2010, the study of laminated rubber bearing for earthquake phenomenon is found. This research is started by modelling of the hysteretic behaviour of rubber bearings under uni-directional horizontal displacement and constant horizontal compressive load [4]. Three types of bearing are used in these studies which are NR bearing, lead rubber bearing and high damping rubber bearing. Many experiments were conducted to analysis the bearings such as basic test, multi-step relaxation, cyclic test and simple relaxation. Finally, the researchers found that the NR bearing gives a better result compared to others in term of rate-dependent rheology.

Many researches of laminated rubber bearings were conducted and focused on horizontal displacement of the bearings. All of the researches in previous discussion are concentrated in civil engineering fields. However, there are some researches where the laminated rubber bearings are adopted and applied in automotive industries. In automotive industries, internal combustion engine (ICE) is a one essential parts inside the car. Noise and vibration generated by the engine cannot be neglected and it is annoying. These are because of the natural behaviour and fundamental source from engine motion [5,6]. Many efforts were performed to investigate this phenomenon which is trying to reduce the vibrations and finally the driver and passengers are in comfort. The researchers suggested that, by designing new engine mounting using NR, the unwanted noise and vibration are potentially cut off. However, this design only capable to use in certain range of frequency and not suitable for automotive engine.

In this paper, the horizontal displacement of laminated rubber-metal spring (LR-MS) is studied. The basic model is developed using lumped parameter and complex model is elaborated using power series technique. Initially, the NR is used as a basic isolator for automotive engine and metal plate is inserted one by one depends on how many degree of freedom (DOF) is needed. By inserting the metal plate, the lumped model becomes more complex and power series will help to minimize the complexity of the modelling in multi-body relationship. The horizontal displacement is important parameters because the results will show the compressibility amount that can be blocked by the LR-MS during excitation force application.

RESEARCH METHODOLOGY

This section describes the mathematical model development of laminated rubber-metal plate (LR-MS) using lumped parameter method. This study was conducted at Faculty of Mechanical Engineering (FKM), Universiti Teknikal Malaysia Melaka (UTeM). In this method, the physical system is initially started with mass-damper-spring model. According to method, the depth of understanding on physical model of the system is necessary before the derivation. In lumped system there are two parts needed to be considered which the first one is mass and the second are damper and stiffness. The schematic diagram for basic lumped model is shown in Figure-1.

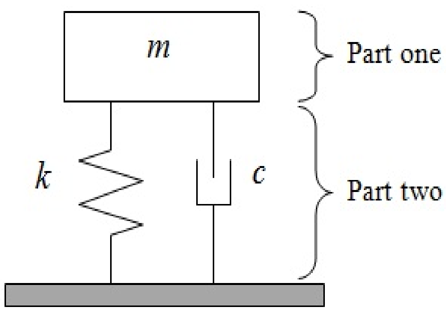

Figure-1. Schematic diagram of basic lumped model.

The equation of motion (EOM) for this lumped system can be derived into mathematical expression and shown in Eqn. (1).

$$m_1\ddot{y}_1 + c_1\dot{y}_1 + k_1 y_1 = 0 \quad (1)$$

In a matrix form, the EOM becomes

$$[m_1]\{\ddot{y}_1\} + [c_1]\{\dot{y}_1\} + [k]\{y_1\} = \{0\} \quad (2)$$

In this study, part one is represented the metal plate and part two is represented the natural rubber (NR), respectively. For metal plate, the important parameter is only the total of mass and for NR are stiffness and damping coefficient. The objective using the metal plate is to divide the NR rod will increase the degree of freedom (DOF) of the system itself. According to this statement, one DOF is not significant for adding the metal plate because the NR rod is already in one DOF. By adding metal plate, the LR-MS is created. The two DOF of the system is showed in Figure-2 where mass of metal plate and is rigid mass.

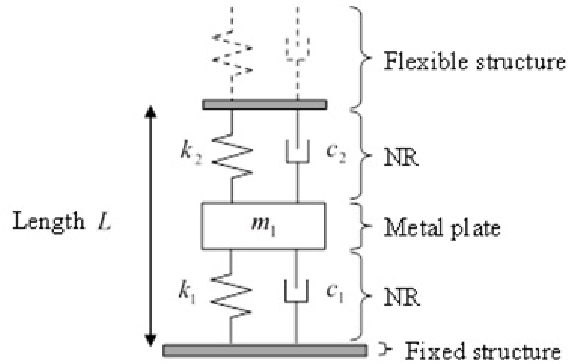

Figure-2. Two DOF of the system for LR-MS.

The flexible structure is designed to make the surface vibrates easily and representing the free boundary condition for LR-MS. The fixed structure representing the fixed boundary condition and there is no displacement happen. There are two types of force involved which are excitation force, and transmitted force. The excitation force is the vibration force from vibrating source and then transmitted to the LR-MS. Finally the transmitted vibration energy was occurred at fixed structure and called transmitted force. The EOM and matrix form for two DOF are shown in Eqns. (3) and (4)

$$m_1\ddot{y}_1 + c_1\dot{y}_1 + c_2\dot{y}_1 - c_2\dot{y}_2 + k_1 y_1 + k_2 y_1 - k_2 y_2 = 0 \quad (3)$$

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{y}_1 \\ \ddot{y}_2 \end{Bmatrix} + \begin{bmatrix} c_1+c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}\begin{Bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{Bmatrix} + \begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\begin{Bmatrix} y_1 \\ y_2 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \quad (4)$$

General lumped parameter method is shown in Figure-3. By using power series technique, the general equation of the system is developed. The formulation is started from the declaration of the highest DOF of the system. Let say the highest DOF of the system in N and this number will be represented the final DOF. The number of N can be from 0 to infinite number. Let take 6 is the highest DOF where this number considered the highest value of mass ***m*** and in mathematical expression in can be written as $\boldsymbol{m_6}$. Using the power series, the new mathematical expression can be represented as $\boldsymbol{m_{(N+1)-1}}$. The array for the power series can written as

$$N = 6 = m_{(N+1)-1} = m_6 \quad (5)$$

$$N = 6 = m_{(N+1)-2} = m_5 \quad (6)$$

$$N = 6 = m_{(N+1)-3} = m_4 \quad (7)$$

$$N = 6 = m_{(N+1)-4} = m_3 \quad (8)$$

$$N = 6 = m_{(N+1)-5} = m_2 \quad (9)$$

$$N = 6 = m_{(N+1)-6} = m_1 \quad (10)$$

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In schematic diagram of lumped parameter method in power series technique for LR-MS is shown in Figure-3.

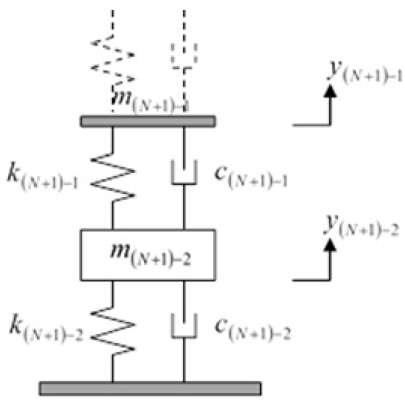

Figure-3. Lumped parameter in power series technique for LR-MS.

The mathematical expression for LR-MS using power series technique is shown in Eqn. (11).

$$\left(\begin{bmatrix} m_{(N+1)-6} & \cdots & \cdots & 0 \\ \vdots & m_{(N+1)-5} & \ddots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & m_{(N+1)-1} \end{bmatrix}\begin{Bmatrix} \ddot{y}_{(N+1)-6} \\ \vdots \\ \ddot{y}_{(N+1)-2} \\ \ddot{y}_{(N+1)-1} \end{Bmatrix}+\ldots \right.$$
$$\begin{bmatrix} c_{(N+1)-6}+c_{(N+1)-5} & -c_{(N+1)-5} & \cdots & 0 \\ -c_{(N+1)-5} & c_{(N+1)-5}+c_{(N+1)-4} & \ddots & \vdots \\ \vdots & \ddots & \ddots & -c_{(N+1)-1} \\ 0 & \cdots & -c_{(N+1)-1} & c_{(N+1)-1} \end{bmatrix}\begin{Bmatrix} \dot{y}_{(N+1)-6} \\ \vdots \\ \dot{y}_{(N+1)-6} \\ \dot{y}_{(N+1)-6} \end{Bmatrix}+\ldots$$
$$\left.\begin{bmatrix} k_{(N+1)-6}+k_{(N+1)-5} & -k_{(N+1)-5} & \cdots & 0 \\ -k_{(N+1)-5} & k_{(N+1)-5}+k_{(N+1)-4} & \ddots & \vdots \\ \vdots & \ddots & \ddots & -k_{(N+1)-1} \\ 0 & \cdots & -k_{(N+1)-1} & c_{(N+1)-1} \end{bmatrix}\begin{Bmatrix} y_{(N+1)-6} \\ \vdots \\ y_{(N+1)-2} \\ y_{(N+1)-1} \end{Bmatrix}\right) = \begin{Bmatrix} 0 \\ \vdots \\ 0 \\ 0 \end{Bmatrix} \tag{11}$$

NR material is used because of the flexibility property which offers a major advantage to the system. This property can act as a spring to block the vibration energy in certain amount before pass through the material. It is able to sustain large displacement. However, NR has disadvantages when the material is subjected to large static preload. This material is incompressible affected in solid block condition where a preload will cause the material to bulge outward [7-10]. In this phenomenon, bulge not only decreases the dynamic performance of the material but it is also reduces a life time of the material itself. The bulge effect can be solved by two methods. The first method is large dynamic preload is applied to replace the large static preload. The second method is the effect can be countered by increasing the stiffness of the LR-MS. In this way, implementation of metal plate by insertion in NR rod is one of the alternatives and the schematic diagram is shown in Figure-4. By increasing the stiffness in horizontal axis, it is believed that the bulging effect can be prevented and makes the rod more stable.

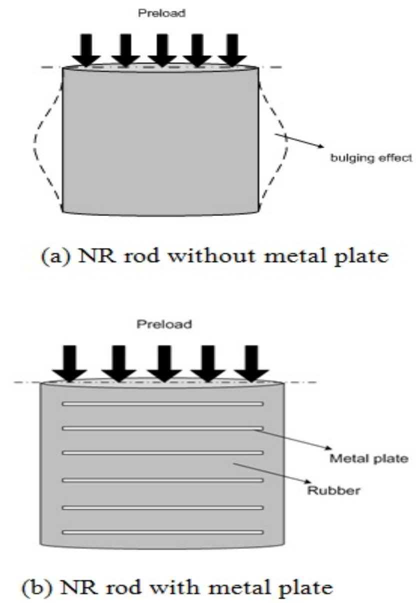

Figure-4. Bulging effect at NR rod.

RESULTS AND DISCUSSION

In this study, it was pointed out that the displacements of the LR-MS system are in multi DOF when the excitation force is applied at the top of the system in horizontal axis. The horizontal displacement results are recorded from one to six DOF. There are two types of displacement which are surface and standalone. Surface displacement happen only at the top of the LR-MS system but for standalone, the displacement recorded at each of the embedded metal plate and NR. The number of data is based on the number of DOF. Surface and overall displacement are shown in Figure-5, Figure-6 and Figure-7.

According to the results, the frequency range is from 0 to 50 Hz. There are many definitions regarding the low and high frequency. In this study, range 0 to 50 Hz is declared as a low frequency. This statement is supported by maximum amplitude occurred at low frequency. Low frequency is important issue and it needs to be discussed further because many vibration phenomena in industry happen in low frequency region.

In Figure-6, the maximum displacement is recorded as 1.95 x 10^{-3} mm at 4 Hz for six DOF and minimum displacement of 4.8 x 10^{-4} mm at 14.5 Hz for one DOF. These two results are supported previous statement which displacement or amplitude is inversely proportional to frequency range. At one DOF, the result shows low displacement because there is no metal plate embedded inside the NR. Theoretically, NR has very little compressibility if there are no any other materials influence their properties [11]. For six DOF results, maximum displacement is shown compared to others. Generally, metal plate can act as reinforcement at the

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middle of NR and finally influences the NR properties and significant compressibility happen inside the LR-MS. In term of displacement, by decreasing the DOF of NR, small displacement is recorded. Other than that, the graph has a peak and it bends where the curve is depended on the coefficient of the linear term which depends on the amplitude of the excitation force. The bend is proportional relation to the force applied.

Figure-7 shows the various results for standalone displacement from one to six DOF. The number of standalone displacement is depending on the number of DOF of LR-MS. According to these results, the standalone displacement is decreased by the increment of the number of metal plate. The number of metal plate influences the number of DOF and finally axial compression increased due to the compressibility behaviour of NR material. In contrast, by adding the metal plate in NR, the standalone displacement is slowly decreasing in axial direction.

CONCLUSIONS

LR-MS model is developed for automotive engine isolator. The lumped model and the power series technique are used to develop multi DOF of LR-MS. This system has been solved and blocked the vibration energy at high frequencies. However, the maximum displacement is recorded when number of the metal plate and DOF are increased simultaneously. This happen because of NR properties where it is influenced by metal plate and finally abnormal compressibility behaviour occurred.

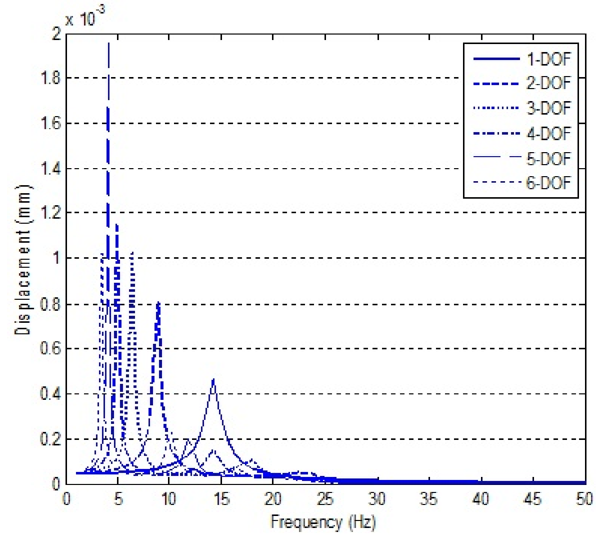
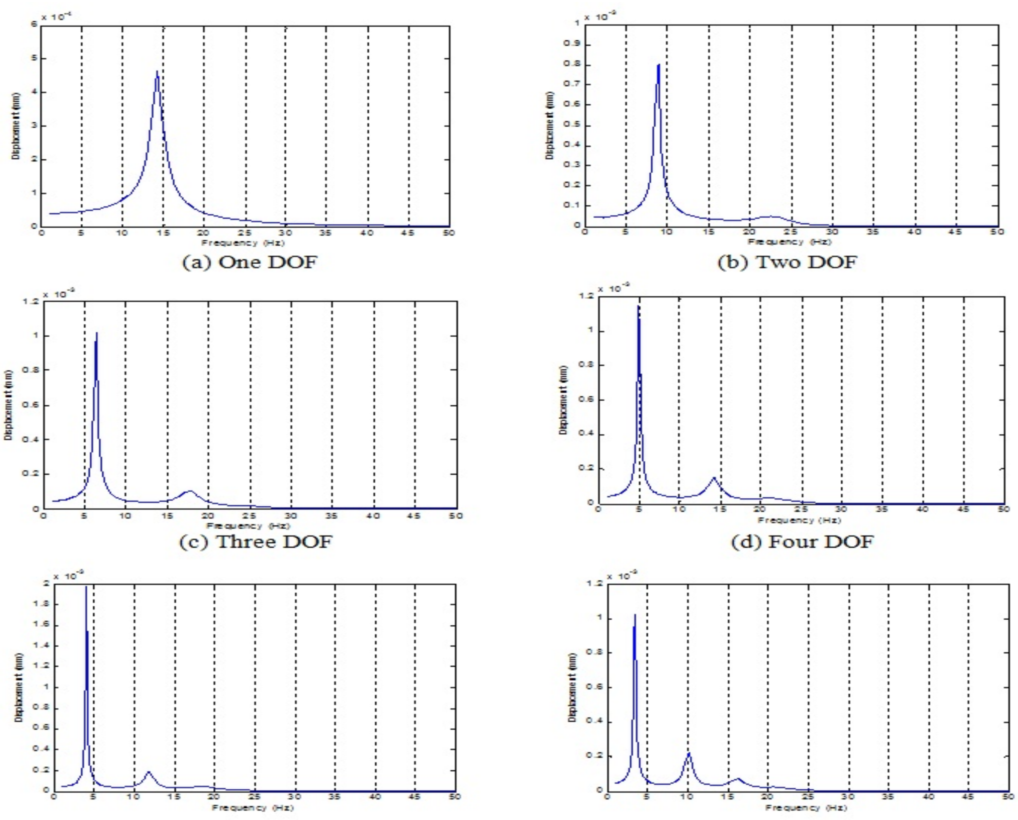


Figure-5. Comparison for surface displacement of LR-MS.



(a) One DOF (b) Two DOF

(c) Three DOF (d) Four DOF

e) Five DOF (f) Six DOF

Figure-6. Surface displacement for LR-MS.

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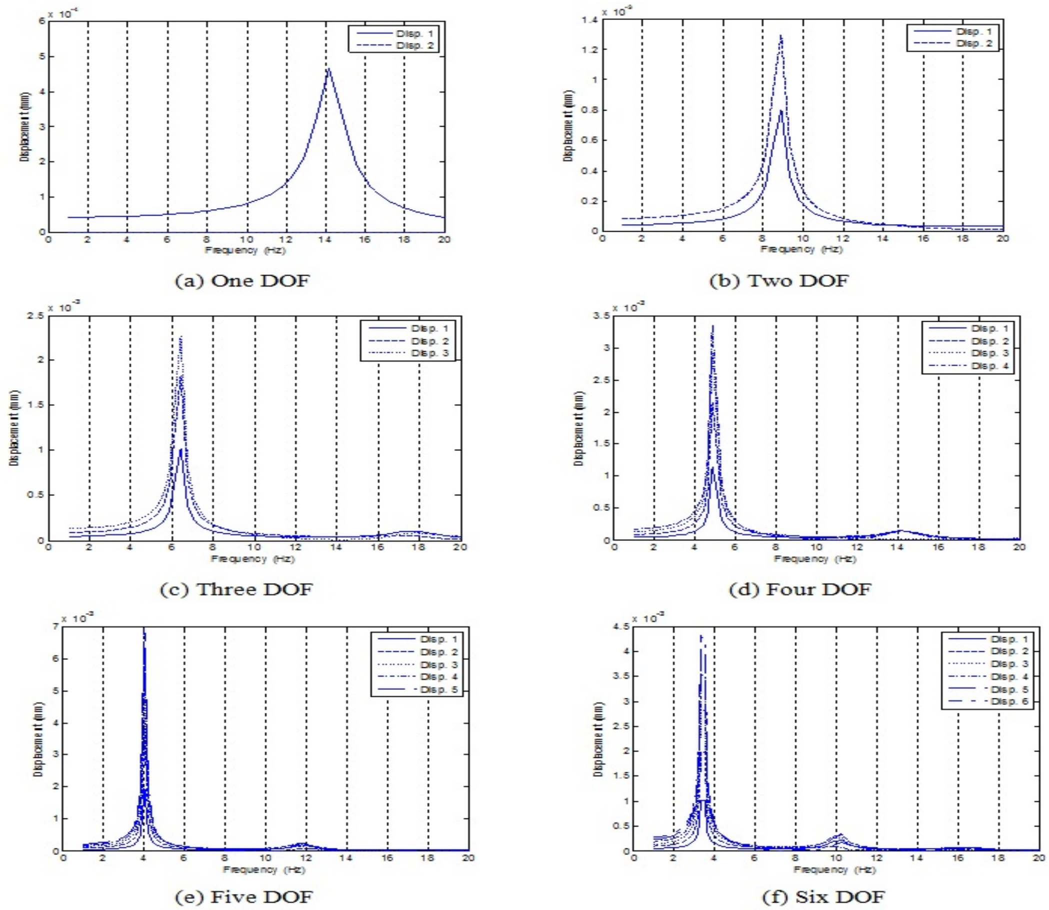

Figure 7. Standalone displacement on LR-MS for MDOF.

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