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Analysis of Parameters Assessment on Laminated Rubber-Metal Spring for Structural Vibration

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Abstract. This paper presents the analysis of parameter assessment on laminated rubber-metal spring (LR-MS) for vibrating structure. Three parameters were selected for the assessment which are mass, Young's modulus and radius. Natural rubber materials has been used to develop the LR-MS model. Three analyses were later conducted based on the selected parameters to the LR-MS performance which are natural frequency, location of the internal resonance frequency and transmissibility of internal resonance. Results of the analysis performed were plotted in frequency domain function graph. Transmissibility of laminated rubber-metal spring (LR-MS) is changed by changing the value of the parameter. This occurrence was referred to the theory from open literature then final conclusion has been make which are these parameters have a potential to give an effects and trends for LR-MS transmissibility.

Introduction

Rubber plantations in Malaysia have been started before the country achieved independence. Rubber seedlings were brought into the country by the British government to Kuala Kangsar Perak for the first planting. The area was chosen due to the condition of terrain which is suitable for rubber trees and within few years, the cultivation of rubber plantation has grown rapidly throughout the peninsular.

In practice, natural rubber (NR) is a versatile and excellent material because in 150 years, it was successfully used in many engineering applications [1-7]. It 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 the automotive industry, manufacturing, civil, railways, offshore, aerospace, defense and many more. It is also suitable for various applications according to user requirements. It becomes number one chosen material due to ability to withstand large deformations and store more elastic energy per unit volume compare other materials [1-7]. It also has inherent damping and spring like performance in term of vibration resonance. Besides, NR also has their unique response which is very little compressibility during the application of excitation force. By adding other materials inside the NR, it

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will be known as the composite material [4-7]. Two or more materials mixed together and finally the mechanical properties of this mixed material are anticipated better than the original one [8-9].

An internal combustion engine (ICE) or is a one of the essential parts in the vehicle powertrain system. Noise and vibration generated by ICE cannot be neglected and avoided because of its natural behaviour and fundamental source when the engine operates [10-11]. Engineers, scientists and researchers have been investigating this phenomenon and tried to eliminate for comfortable driving to driver and passengers, however their effort still failed. They presumed that if the behaviour cannot be eliminated, there must be having another method to reduce it and finally the engine mounting is applied. Overall, the design of engine mounting is suitable for certain frequency and it cannot operate. It happens when the engine running in high rotation per minute (RPM). According to open literature, the amplitude of vibration in the engine is directly proportional to the engine speed [10]. 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 the car body. Logically, the rest of 70 percent of the vibration amplitude can be considered, it is very large because by adding another vibration from other sources like a tire and road surface, the vibration amount will be increased and finally still annoying the driver and passengers [12].

In this paper, parametric study is a mainly topic needs to be discussed because based on previous research, many parameters are involved to make the results more trustworthy in the future.

Research Methodology : Parameters Selection

Parameter study is carried out for LR-MS in order to propose an ideal model for the future development. There are three important parameters being chosen which are mass, Young's modulus and radius and the description is below. The standard value for these three parameters that have been used in this study is a standard requirement for the Malaysia Rubber Board, which is 25 kg, 1.4 MPa and 0.05 m.

Mass is chosen as an important parameter because it can be used to influence the point of natural frequency, ω_n of the LR-MS. This can be proved by using the theory of natural frequency. Basically, the natural frequency can be written as

$$\omega_n = \sqrt{\frac{k}{m}} \quad (1)$$

where k is the stiffness of the system and m is mass.

Through the above Eq. (1), the natural frequency was influenced by two different parameters; one of them is directly to influence the stiffness k and indirectly for mass m . For mass, it affects the natural frequency in inversely proportional. This means that if the value of mass increases, the quantum of natural frequency will be reduced, and if the quantity of mass decreases, the natural frequency of the system will be the opposite. Thus, mass selection is important parameters for the above process. This is because, by increasing and decreasing the mass of the LR-MS, the first natural frequency of the system can be properly regulated, so it would make the process easier to control natural frequency of LR-MS to be the same as other system. This is to avoid the occurrences of resonance.

The second most important parameter in this study is the Young's modulus. In theory, Young's modulus has a very important bearing in the determination of the stiffness for certain materials. This can be simplified through the equation below.

$$k = \frac{EA}{L} \quad (2)$$

where E is the Young's modulus, A is the area and L is the length.

Through this equation, it can be noticed the value of stiffness is directly proportional to the Young's modulus, provided if the quantum of area and length of the material is in the same set of values. Stiffness is very important in principle for determining the resistance offered by an elastic body to deformation because when the stiffness value increases the elasticity of the material increased. Radius is one of three important parameters in this study because by using the value of the radius, the quantum of area of a material can be determined. In this study LR-MS is presented in a rod-shaped where the area can be determined by using the equation below.

$$A = \pi r^2 \quad (3)$$

where r is a radius.

In the above equation, the value of an area is directly proportional to the radius. It means, if the radius is increased the area also has grown, and if the value of radius decreases, the quantum of area is reduced. This relationship is applicable only to the material in the form of rods only because the above equation is applicable to rods only.

If the value of this area is taken from the Eq. (3), it means the area will influence the stiffness of the equation as stated in Eq. (2) and directly it proportional to the quantum of area. Realistically, the quantity of stiffness is directly proportional to the value of the radius. Therefore, if the radius of the LR-MS reduced, the stiffness of a material are also reduced, and if the value is added, then the stiffness will change to a greater rate.

Thus, the selection of these three parameters is very important to ensure the development of LR-MS more comfortable in the future. Besides, it also is able to regulate better in terms of usability and application so it is much easier.

Results and Discussion

Discussion of the results of parameter study is divided into three categories, namely the mass, Young's modulus and radius. Each parameter has a value of reference which are 25 kg, 1.4 MPa and 0.05 m. All the analysis starts from one until five DOF of LR-MS and all results were discussed as below.

3.1 Mass Results

In the study to find the effective mass of LR-MS system, a reference mass is allocated at 25 kg. This value of mass used as an original mass. Thus, some fraction of the mass is used to ensure the study is successful. There are three fractions chosen, which less than the reference mass are, and secondly the value is greater than reference mass fractions. The fraction less than the reference value of mass, are define in 10 kg, 15 kg and 20 kg, while the greater value fractions are define in 30 kg, 35 kg and 40 kg. By looking at the fractions, the difference for each value is only 5 kg. This differences in value is chosen as a control amount of mass. Three analyses have been conducted in this mass parameter study which are natural frequency, frequency and transmissibility at internal resonance to design a new system to meet the requirements of the isolator.

The value of natural frequency for LR-MS is increased when the quantum of mass is decreased due to the above analysis. By increasing the number of DOF in LR-MS, the result shows the location of the

natural frequency move to the left resulted to become small. This condition happens when LR-MS was carrying a lot of numbers of mass from a metal plate. A brief summary can be done in this analysis, where the natural frequency value is inversely proportional to the mass and increasing the number (of natural frequency?) by increasing the DOF.

In the internal resonance analysis, the frequency did not change during the increasing and decreasing of the value of mass. However, the quantum of frequency of the internal resonance began to change when more number of DOF added. Moreover, in the study of transmissibility, the value of internal resonance will be closer to unity after the value of mass become small, but it will be farther when the mass volume increase. By adding more mass on the LR-MS, the internal resonance value will be farther away from unity. In addition, the transmissibility will keep unity in place when performing the enhancement to the number of DOF. Therefore, the transmissibility is directly proportional to the quantum of mass and it is inversely proportional by increasing the number of DOF.

All of the results on the mass effect for one and four DOF of LR-MS are shown in Figure 1 and 2 and respectively. In addition, Table 1 summarized the effect of mass on the LR-MS with respect to the location for the first natural frequency, internal resonance in x-axis and internal resonance in y-axis.

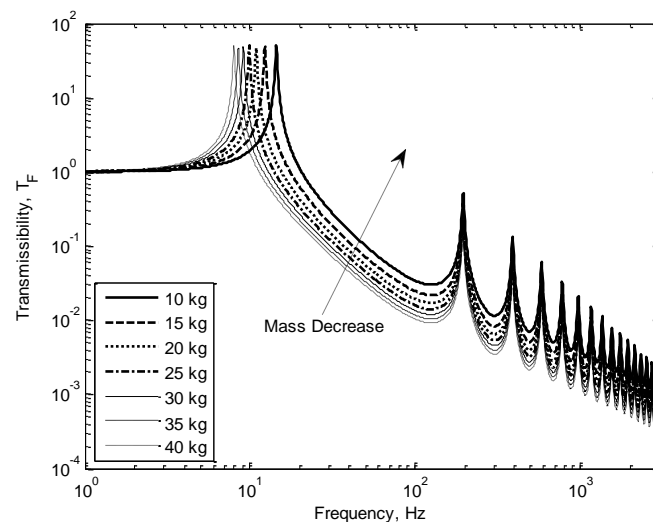


Figure 1. Mass effect on one degree-of-freedom of LR-MS

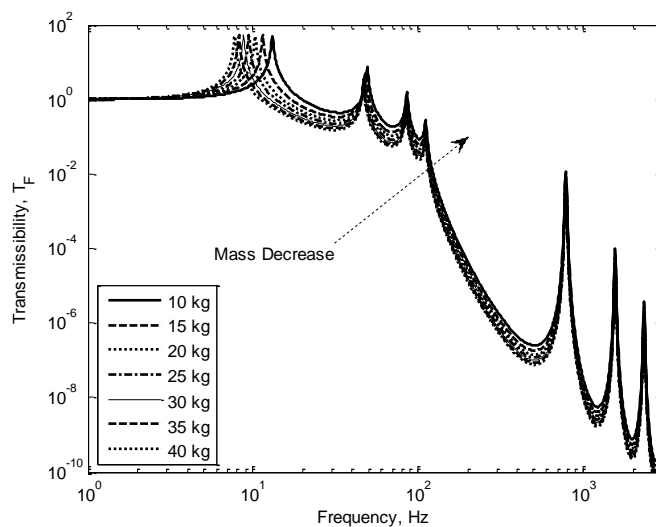


Figure 2. Mass effect on four degree-of-freedom of LR-MS

Table 1. Summary for mass effect on LR-MS

Location	Degree of Freedom, DOF	Mass (MPa)						
		10	15	20	25	30	35	40
First natural frequency, Hz	1	14.49	12.39	10.99	9.93	9.14	8.49	8.03
	2	14.10	12.05	10.79	9.84	9.06	8.49	7.96
	3	13.59	11.83	10.59	9.66	8.89	8.34	7.89
	4	13.22	11.51	10.30	9.48	8.81	8.26	7.81
	5	12.74	11.20	10.12	9.31	8.65	8.18	7.67
Internal resonance, Hz in x-axis	1	196.9	195.1	195.1	195.1	195.1	195.1	195.1
	2	393.2	396.8	393.2	393.2	396.8	396.8	396.8
	3	589.9	589.9	589.9	589.9	589.9	589.9	589.9
	4	785.0	785.0	785.0	785.0	785.0	785.0	785.0
	5	979.5	979.5	979.5	979.5	979.5	979.5	979.5
Internal resonance, T_r in y-axis	1	.5132	.3778	.3040	.2534	.2169	.1894	.1680
	2	.1364	.0959	.0774	.0636	.0525	.0456	.0403
	3	.0484	.0350	.0274	.0225	.0191	.0166	.0146
	4	.0120	.0087	.0068	.0056	.0048	.0041	.0036
	5	.0026	.0019	.0015	.0012	.0010	.0009	.0007

3.2 Young's Modulus Results

Preliminary work on LR-MS was undertaken by using the value of Young's modulus at 1.4 MPa. However, the research found the fact that Young's modulus contributes some influence in order to determine the natural frequency, frequency and transmissibility results in internal resonance region. A further research would examine a large, small and randomly selected Young's modulus with different values. Six values have been selected which are three of them larger than reference value and the rest smaller respectively. Differences in each fraction of the selected Young's modulus are at 0.2 MPa. The values that exceed the reference value are 1.6 MPa, 1.8 MPa and 2.0 MPa while a value less than the reference value are 0.8 MPa, 1.0 MPa and 1.2 MPa.

Through the analysis, it can be observed that the natural frequency decreases when the value of Young's modulus decreased. This is also can be seen that when the Young's modulus increases, the natural frequency increases too. This explains that the natural frequency for the LR-MS is directly proportional to the Young's modulus used. By referring back to Eq. (1) and Eq. (2), the result is valid and the reasons have been discussed previously. Meanwhile, when the amount of DOF increase, the quantum of natural frequency decreased. It happens because LR-MS carrying the most amount of mass because it adds more metal plate. It can be explained by using Eq. (1) where the value of natural frequency will decrease if the total mass is increased.

For internal resonance analysis, it can be concluded that the location of the frequency will be reduced if the value of Young's modulus decreases and the result will be opposite of the value of Young's modulus is increased. Besides Young's modulus affects the stiffness of this LR-MS, therefore, the stiffness will be directly proportional to the frequency of the internal resonance.

In transmissibility analysis, it can be noticed that the Young's modulus value did not affect the transmissibility. It happens when value of Young's modulus increases or decrease of the reference value, then the quantum of transmissibility produce similar results. This can be proved by the transmissibility theory as shown below.

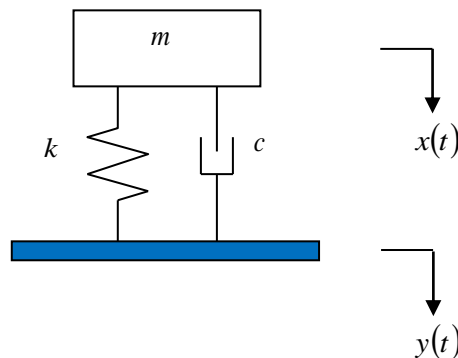


Figure 3. Mass-spring damper schematic diagram

By referring Figure 3, the equation of motion can be written as

$$\sum F = -k(x - y) - c(\dot{x} - \dot{y}) = m\ddot{x} \quad (4)$$

By rearrange the Eq. (4), new equation can be represented as

$$m\ddot{x} + c\dot{x} + kx = c\dot{y} - ky \quad (5)$$

From Figure 3, it is a single degree of freedom. It also can be called as base excitation phenomenon with the force came from m . Assuming that,

$$y(t) = Y \sin(\omega t) \quad (6)$$

Then, substitute Eq. (6) into Eq. (5), then the equation become

$$m\ddot{x} + c\dot{x} + kx = c\omega Y \cos(\omega t) + kY \sin(\omega t) \quad (7)$$

Just take an example as a simple absorber, the frequency, ω from Eq. (7) can be extended into

$$\omega = \frac{2\pi}{\tau} = \frac{2\pi V}{\eta} \quad (8)$$

where τ is shear force, V is volume and η is loss factor.

The steady-state solution is the superposition of the individual particular solutions and the system is linear. So, the new equation is

$$\ddot{x} + 2\xi\omega_n\dot{x} + \omega_n^2 x = 2\xi\omega_n\omega Y \cos(\omega t) + \omega_n^2 Y \sin(\omega t) \quad (9)$$

From the Eq. (9), solution for sine function can be written as

$$\ddot{x} + 2\xi\omega_n\dot{x} + \omega_n^2 x = f_{os} \sin \omega t \quad (10)$$

and

$$x_{ps} = A_s \cos \omega t + B_s \sin \omega t = X_s \sin(\omega t - \phi_s) \quad (11)$$

where

$$f_{os} = \omega_n^2 Y \quad (12)$$

$$A_s = \frac{-2\xi\omega_n \omega f_{os}}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n \omega)^2} \quad (13)$$

and

$$B_s = \frac{(\omega_n^2 - \omega^2) f_{os}}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n \omega)^2} \quad (14)$$

Variables A_s and B_s are determined by using rectangular form to make it easier to add the cost term. Then, for the particular solution for cosine function, the equation can be written as

$$\ddot{x} + 2\xi\omega_n \dot{x} + \omega_n^2 x = f_{oc} \cos \omega t \quad (15)$$

and

$$x_{pc} = A_c \cos \omega t + B_c \sin \omega t = X_c \cos(\omega t - \phi_s) \quad (16)$$

where

$$f_{oc} = 2\xi\omega_n \omega Y \quad (17)$$

$$A_c = \frac{(\omega_n^2 - \omega^2) f_{oc}}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n \omega)^2} \quad (18)$$

and

$$B_c = \frac{-2\xi\omega_n \omega f_{oc}}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n \omega)^2} \quad (19)$$

The magnitude equation can be obtained by adding the sine and cosine terms of the full particular solution. The magnitude equation can be represented as

$$X = \sqrt{\frac{f_{oc}^2 + f_{os}^2}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n \omega)^2}}$$

or

$$X = \omega_n \sqrt{\frac{(2\xi\omega_n)^2 + \omega_n^2}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n\omega)}} \quad (20)$$

By substituting Eq. (12) and Eq. (17) into Eq. (20), the new equation can be written as

$$X = Y \sqrt{\frac{1 + (2\xi r_s)^2}{(1 - r^2)^2 + (2\xi r_s)^2}} \quad (21)$$

where $r_s = \omega/\omega_n$

By simplifying Eq. (22), the transmissibility equation can be obtained as

$$\frac{X}{Y} = \sqrt{\frac{1 + (2\xi r_s)^2}{(1 - r^2)^2 + (2\xi r_s)^2}} \quad (22)$$

By using the equations stated above, it can be proved that the Young's modulus does not directly affect the transmissibility value. Thus, transmissibility could not be changed using this parameter. All of the results on Young's modulus effect for one and four DOF of LR-MS are shown in Figure 4 and 5, particularly. Moreover, Table 2 summarized the effect of Young's modulus on the LR-MS with respect to the location for the first natural frequency, internal resonance in x-axis and internal resonance in y-axis.

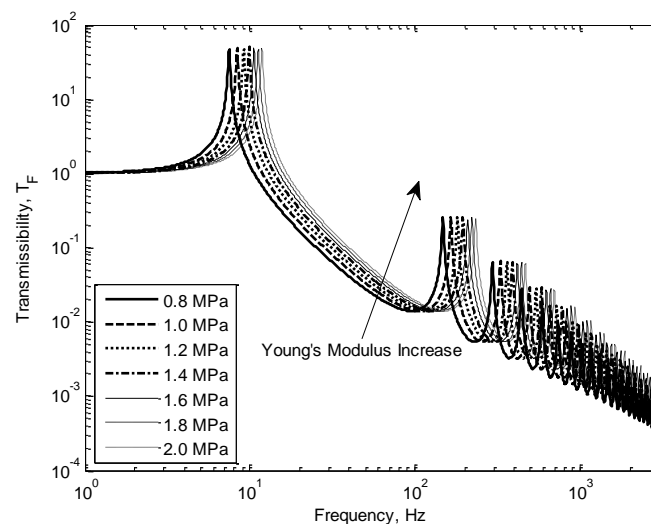


Figure 4. Young's modulus effect on one degree-of-freedom of LR-MS

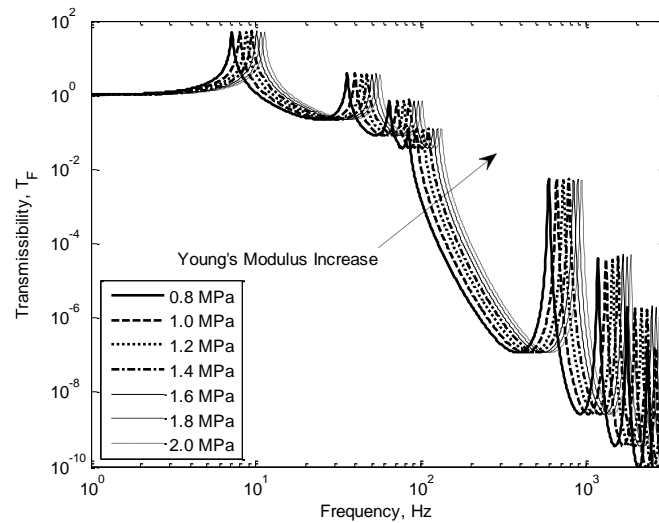


Figure 5. Young’s modulus effect on four degree-of-freedom of LR-MS

Table 2. Summary for Young’s modulus effect on LR-MS

Location	Degree of Freedom, DOF	Young’s Modulus (MPa)						
		0.8	1.0	1.2	1.4	1.6	1.8	2.0
First natural frequency, Hz	1	7.53	8.41	9.23	9.93	10.59	11.30	11.83
	2	7.39	8.26	9.06	9.84	10.50	11.09	11.72
	3	7.26	8.18	8.89	9.66	10.30	10.89	11.51
	4	7.19	8.03	8.81	9.48	10.12	10.79	11.30
	5	7.06	7.89	8.65	9.31	9.93	10.59	11.20
Internal resonance, Hz in x-axis	1	148.0	165.3	181.2	195.1	210.0	222.0	234.6
	2	300.9	333.1	361.9	393.2	419.4	447.4	468.5
	3	447.4	499.7	547.9	589.9	629.2	671.2	702.8
	4	595.4	665.0	729.2	785.0	837.4	893.2	944.0
	5	742.8	829.7	909.8	979.5	1045	1114	1167
Internal resonance, T_r in y-axis	1	.2581	.2594	.2579	.2534	.2338	.2576	.2420
	2	.0611	.0627	.0620	.0636	.0641	.0623	.0641
	3	.0212	.0218	.0212	.0229	.0220	.0211	.0215
	4	.0056	.0057	.0056	.0056	.0052	.0055	.0049
	5	.0012	.0012	.0012	.0012	.0011	.0012	.0009

3.2 Radius Results

This section will focus on the radius effect on LR-MS system. The main issue which will be addressed in this section is what will happen when the amount of radius is changed from one value to another. The previous sub section has reported on mass and Young’s modulus effects where it mentioned to use reference value to make it easy in doing the comparison. In this subsection the reference value that is used is 0.05 m. Then, six control values have been selected which are three of them lower than reference value and the rest is larger than the reference value. Only 0.01 m difference fraction for each

value has been selected. The control values are starting from 0.02 m, 0.03 m and 0.04 m for the lower reference value and 0.06 m, 0.07 m and 0.08 m for greater reference value.

The quantum of natural frequency will increase when the radius increased, and its value will reduce as soon as the radius decrease. Moreover, the increase can be seen in the radius of LR-MS, means it also will influence the value of cross-sectional area. This has been discussed in Eq. (3) where the value of cross-sectional area, it is directly proportional to the stiffness. If the cross-sectional increase in value, it also increases the stiffness. This also has been discussed in detail in the previous subsection through Eq. (2). In addition, the stiffness also directly proportional to the natural frequency, therefore, when the stiffness increase, it will normally natural frequency also increased. This is proved by the Eq. (1). Through this discussion, it has been proven that when the radius of the LR-MS is increasing, it will result in the increase of the frequency. By increasing the number of DOF, it will diminish the natural frequency because the weight is increased due to the metal plate.

In internal resonance analysis, it can be observed that the radius does not have any impact on the frequency of internal resonance therefore, it does not interfere with the location of the internal resonance. However, when the number of DOF is added, the frequency of internal resonance value will increase up two times. This phenomenon is difficult to understand and defined, because in theory, by increasing the number of DOF, it will add mass to the LR-MS and the natural frequency will decrease to a small value.

When the value of radius is decreased, the transmissibility for internal resonance will keep it unity value. Then, by increasing the quantum of radius, the transmissibility will be closer to unity. In summary, the radius is directly proportional to the transmissibility for the internal resonance. So when increasing the number of DOF, the transmissibility will avoid the unity. In conclusion, when the smaller radius is used, then the LR-MS will be further away from the unity and by increasing the number of DOF, then the LR-MS will be more ideal in terms of its transmissibility.

All of the results on the effect of radius for one and four DOF LR-MS are shown in Figure 6 and Figure 7. Additionally, Table 3 summarized the effect of radius on the LR-MS with respect to the location for the first natural frequency, internal resonance in x-axis and internal resonance in y-axis

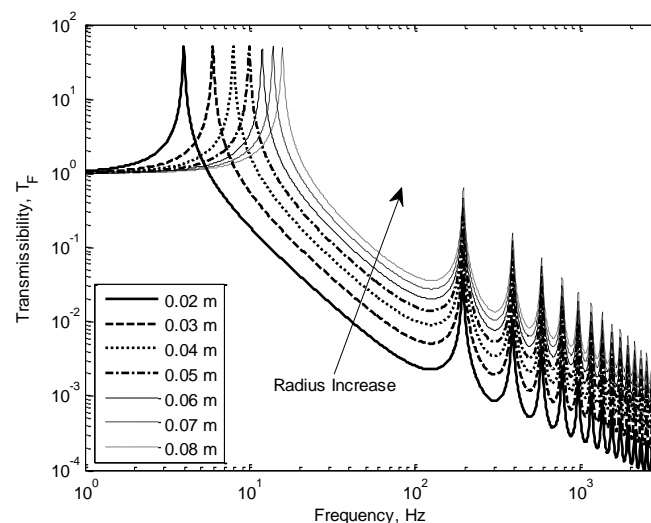


Figure 6. Radius effect on one degree-of-freedom of LR-MS

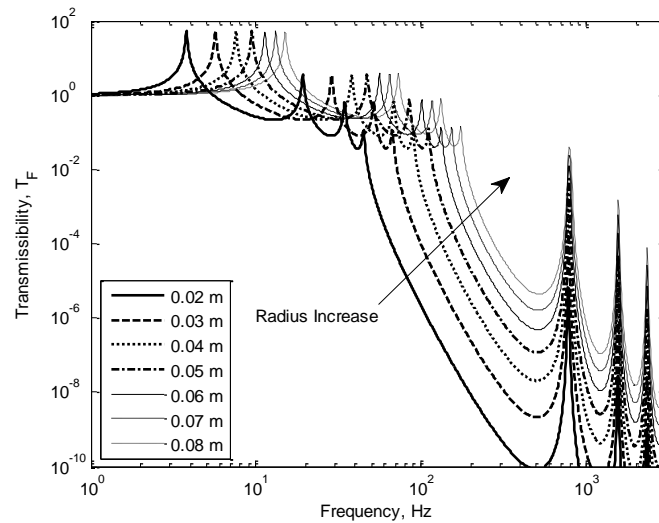


Figure 7. Radius effect on four degree-of-freedom of LR-MS

Table 3. Summary for radius effect on LR-MS

Location	Degree of Freedom, DOF	Radius (mm)						
		0.02	0.03	0.04	0.05	0.06	0.07	0.08
First natural frequency, Hz	1	3.99	5.98	7.96	9.93	11.94	13.84	15.75
	2	3.95	5.87	7.89	9.84	11.72	13.71	15.60
	3	3.89	5.82	7.74	9.66	11.51	13.46	15.32
	4	3.81	5.71	7.60	9.48	11.40	13.22	15.04
	5	3.74	5.61	7.46	9.31	11.20	12.98	14.76
Internal resonance, Hz in x-axis	1	195.1	195.1	195.1	195.1	195.1	196.9	196.9
	2	389.6	393.2	393.2	396.8	393.2	393.2	393.2
	3	584.5	589.9	589.9	589.9	589.9	595.4	595.4
	4	777.8	785.0	785.0	785.0	785.0	792.3	792.3
	5	979.5	979.5	979.5	979.5	979.5	979.5	979.5
Internal resonance, T_r in y-axis	1	.0418	.0937	.1652	.2534	.3532	.4592	.6284
	2	.0035	.0158	.0394	.0617	.0892	.1185	.1529
	3	.0002	.0018	.0087	.0225	.0414	.0635	.0914
	4	6×10^{-6}	.0002	.0015	.0056	.0131	.0240	.0383
	5	2×10^{-7}	1×10^{-5}	.0002	.0012	.0041	.0096	.0191

Conclusion

In conclusion, parameter assessment on laminated rubber-metal spring (LR-MS) for vibrating structure were performed for mass, Young’s modulus and radius on their effect to the natural frequency, location of the internal resonance frequency and transmissibility of internal resonance. Results obtained showed that for the effect of mass on the transmissibility, the value of internal resonance will be closer to unity after the value of mass become decreased and it will be further when the mass volume increased. Therefore, the transmissibility is directly proportional to the quantum of mass and it is inversely proportional by increasing the number of DOF. Furthermore, results also indicates that

Young's modulus parameter does not directly affect the transmissibility value. Finally, the effect of radius were also obtained which revealed that when the smaller radius is used, then the LR-MS will be further away from the unity and by increasing the number of DOF, then the LR-MS will be more ideal in terms of its transmissibility.

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