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Passive Isolation from Belleville Spring

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ABSTRACT

Vibration isolation is an interesting and important topic in handling all type of machinery and is essential for designing. Vibration isolation aims at isolating the mass (or base) from the excited base (or mass) by reducing the amplitude of vibration being transferred. The case under study is the type where mass is protected from the excited base. The existing rubber isolators in use are space consuming and might give troubles in places where space utilization is important aspect. To solve this, a mechanical isolator system with Belleville spring is considered and tested for design for systems ranging from Single Degree of Freedom (SDOF) system to Triple Degree of Freedom (TDOF) system. Before fixing any design parameters, parameters behaviour and its effect on transmissibility ratio (Td) is plotted using MatLab software and then the parameters are fixed in order to isolate the mass. After obtaining design parameters and calculating other needed parameters such as thickness, stress, stress ratio, and spring stiffness, it is observed that in all cases the stress ratio is less than unity which means that the design is safe and the isolation is also achieved after a certain excitation frequency value being not less than 450Hz.

Keywords:—*Vibration isolation, Belleville spring, Passive isolation*

I. INTRODUCTION

The main advantage in Belleville is that it occupies very less space and hence can be utilized in many applications where efficient space utilization is of paramount of importance. The main problem in the existing rubber isolator system is that it occupies huge space in the equipment and therefore Belleville spring is optimal replacement for rubber isolator system. In the following discussion, the procedure of solving and results are discussed in detail.

II. Literature Review

A detailed study of literature is necessary to understand the areas which are left unaddressed and make progress in a particular domain. The following literatures throw light on works pertaining to the basics of mechanical vibrations and all the necessary information on the state space equations and studies parameters that could be used for successful conduct of research. Engineer's edge website presents the sufficient information on the formulas required for calculating the necessary parameters of a Belleville spring. A detailed Figure of all the parameters have been mentioned and clearly understood. The formulas required to calculate the diameter ratio, calculation coefficient, Force at maximum spring deflection and limit deflection, Force exerted by the spring at working deflection, Maximum pressure stress on spring at working deflection, total number of spring set, stroke of deflection of a spring set, Force exerted by a spring set, Height of spring stack up and height of loaded spring stack up are listed clearly. This has been helpful in introducing the formulas in the MATLAB code. Mechanical vibrations by S.S Rao has been referred for the first five chapters which mostly deal about the basic introduction of various types of vibrations. The first chapter deals with free vibration of single degree of freedom. Detailed information on the response of damped system and base excitation and transmissibility ratio of single degree of freedom system has been taken from the second chapter. Torsional vibration in free undamped systems has been discussed in the same chapter. The various graphs provided on the parameters of the vibrations helped in understanding how the parameters affect the change in the behavior of vibrations with the change in frequency, for example the graph of frequency ratio Vs transmissibility ratio. Based on that the graphs have been used to understand the variations on how the spring constant changes with respect to the various parameters. Chapter four, deals with the vibration of system under various types of excitation conditions along with necessary explanation. Chapter five and six deals with double and multi degree of freedom with the respective subsections dealing with torsional vibrations and the transfer function used in MATLAB coding. F. Javier Cara gives an insight on the state space equation which is used in solving the MATLAB code for changing the time domain to frequency domain in triple degree of freedom for Belleville spring. A particular function called as bode function is used in the state space equation which is essential to convert the time domain to frequency domain without which the MATLAB code cannot be solved and the desired results cannot be expected.

III. Problem Definition

The existing rubber isolator in the system is comparatively ineffective and uses more space as well. The system needs a new type of mechanical isolator system which is relatively smaller in size and has better isolation if possible.

IV. Research Methodology

Before moving into the designing of mechanical springs, system natural frequencies of the four systems being used are to be considered so as to get system characteristics such as stiffness of the spring that is to be used for designing purposes. To determine the behaviour of these natural frequency systems, data of range of frequency for the system is to be considered along with the relation between transmissibility ratio (T_d), natural frequency of the system (ω_n), and excitation frequency of the system (ω).

This relation[2] is given as follows where X stands for displacement amplitude of mass being mounted and X stands for displacement amplitude of base being excited.

$$T_d = \frac{X}{Y} = \sqrt{\frac{1+(2\eta r^2)}{(1-r^2)+(2\eta r^2)}} \qquad (1)$$

Where, r is frequency ratio given by ω/ωn, η is damping ratio given by C/C_c, C is damping constant, and Cc is critical damping constant.

A simple MatLab code is to be developed so as to understand their relations. After analysing these relations, four natural frequencies for systems are decided. Another MatLab code is developed to understand and verify the characteristics and behaviour of these systems with their assigned natural frequencies.

Single Degree of Freedom (SDOF) system is a simple system with a base that is being excited and a mass (m) that is supported from base with help of a simple mechanical system of spring and damper. This type of system can be simply stated as grounded spring-mass-damper system.

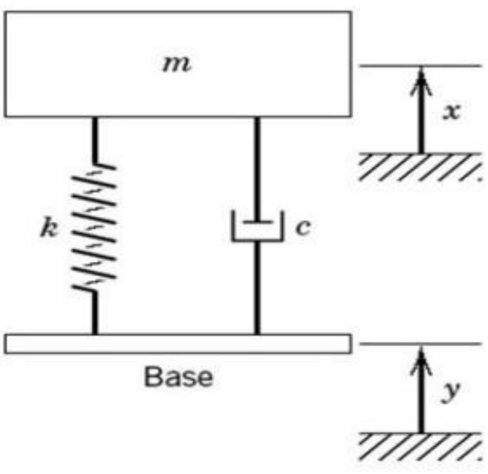

Figure 1: Simple illustration of Single Degree of Freedom system

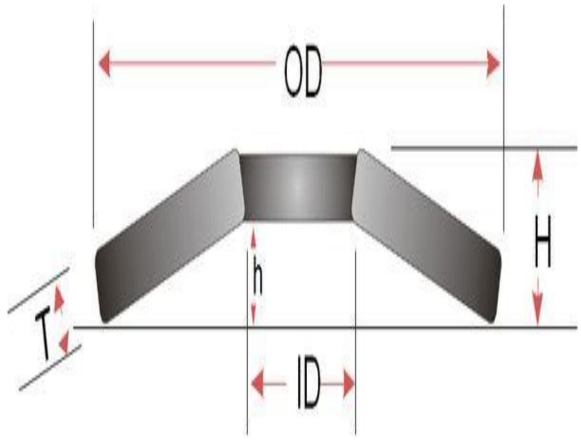

Figure 2: Nomenclature of a typical Belleville spring

In the above figure given, OD is the outer diameter of the spring (D), ID is the inner diameter of the spring (d), T is the thickness of Belleville (t), H is the total unloaded height of the spring, h is the height available for spring to compress. Before moving on, design equations 1 for Belleville which are to be considered are as follows.

$$k = \frac{4Et^3}{(1-\mu^2)\alpha D^2} \qquad (2)$$

$$\alpha = \frac{1}{\pi} * \frac{\left(\frac{\delta-1}{\delta}\right)^2}{\frac{\delta+1}{\delta-1} - \frac{2}{ln\delta}} \qquad (3)$$

$$\sigma = \frac{4Ets}{(1-\mu^2)\alpha D^2} * \left[\beta\left(\frac{h}{t} - \frac{s}{2t}\right) + \gamma\right] \qquad (4)$$

$$\beta = \frac{1}{\pi} * \frac{\delta}{ln\delta}\left(\frac{\delta-1}{ln\delta} - 1\right) \qquad (5)$$

$$\gamma = \frac{\delta-1}{\pi} * \frac{3}{ln\delta} \qquad (6)$$

Where, k is Spring stiffness (N/m), E is Spring modulus of elasticity (N/m2), t is Belleville thickness (m), μ is Poisson's ratio, D is Outer diameter of spring (m), α, β, γ are calculation coefficients, δ is Diameter ratio given by D/d, and d is Inner diameter of spring (m), σ is Stress in spring (N/m2), s is the working deflection of the spring (m), and h is the height available for spring to compress given by H-t (m).

Now that all required formulae are known, it is important to understand the effect of each of main design input on transmissibility ratio (Td). This can be done by developing MatLab codes while taking three different excitation frequencies as 100Hz, 300Hz, and 500Hz for better comprehension. Basic logic of the code is that other than the input dimension under study, all the other dimensions are fixed. As excitation frequency (ω) and other dimensions are considered, calculation of frequency ratio (r) is done by using above set of formulae. By using the obtained frequency ratio (r), transmissibility ratio (Td) is determined and a graph of varying dimension on x-axis and transmissibility ratio (Td) on y-axis is plotted.

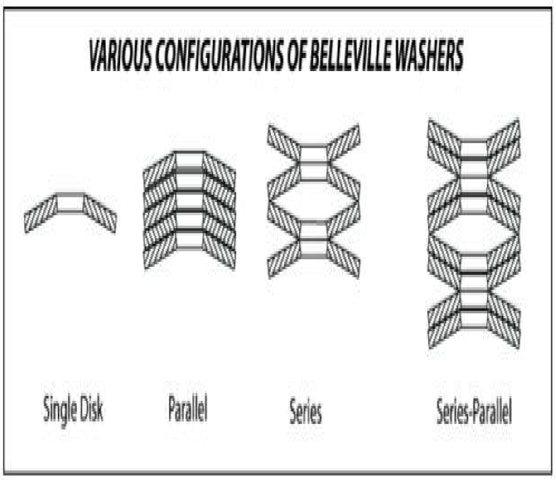

Figure 3: Different configurations of stacking for a typical Belleville spring

After analysing all the graphs, final main dimensions of spring are decided. Since there exists a possibility of stacking belleville spring as shown in the above Figure, different stacking are considered and the stacking of five unidirectional belleville springs in parallel is finalized according to requirement. Another MatLab code is developed so as to take finalized dimensions and natural frequency of the system as input and giving out total spring constant, individual spring constant, stress, stress ratio, and thickness as output. For better comprehension the study will be done for masses from one Kilogram to five Kilograms.

V. Results and Discussion

he MatLab code needed to understand the effect of relation between natural frequency and excitation frequency on transmissibility ratio (Td) and its output graph is shown below.

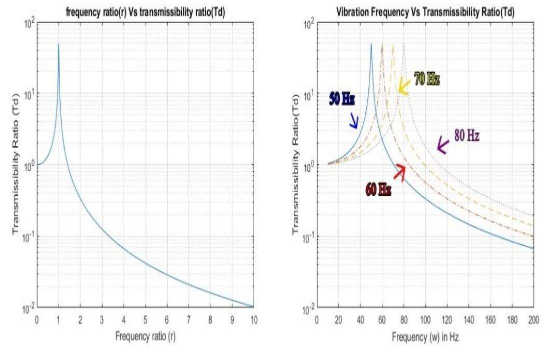

Figure 4: Graph (on left) for frequency ratio Vs transmissibility ratio for simple vibrating system and Figure. 8 Graph (on right) for behaviour of systems with their respective natural frequencies

Therefore, from the graph it can be inferred that the frequency ratio should be greater than or equal to √2 for isolation to occur. To study characteristics and behaviour of systems having natural frequencies of 50Hz, 60Hz, 70Hz, and 80Hz a MatLab code of Code 2 is used to obtain the following graph. From the graph, it is clear that for all frequencies 140Hz and above, isolation is achieved. It also confirms that if the excitation frequency is greater than or equal to √2, then isolation can be achieved. To finalize the design parameters, graphs obtained from MatLab codes are analyzed. It is to be noted that for a graph other than the varying dimension, all the other dimensions are set to be constant with finalized dimensions which are mentioned at end of this section. The graphs obtained from the MatLab codes are as follows.

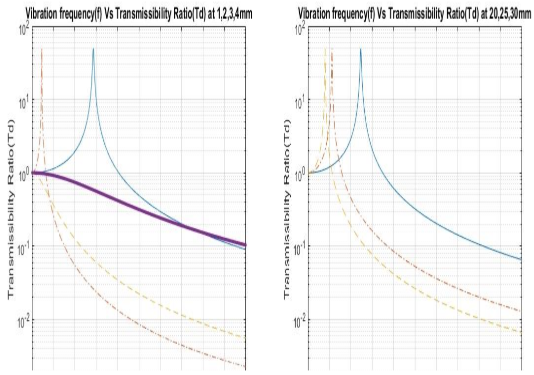

Figure 5: Vibration frequency Vs Transmissibility ratio for varying height on left and varying outer diameter on right

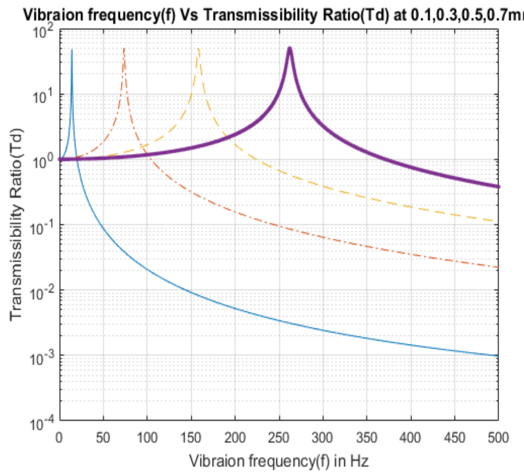

Figure 6: Graph of Belleville thickness Vs Transmissibility ratio for Belleville spring

From the above graphs it is clear that the design parameters of outer diameter of 25mm and more, Belleville height of 2mm to 4mm, and Belleville thickness of 0mm to 0.3mm can be considered for isolating the system. For other similar calculations, 0.2mm is fixed as Belleville thickness but for final calculations thickness will vary with each system. Belleville height 2mm, outer diameter 30mm, and inner diameter 18.5mm are finalized for design. Maximum deflection of 1mm is considered. Selecting material as ASTM A227 class II spring steel and giving its properties as input along with other finalized dimensions and system natural frequency in MatLab code the output we get is as follows.

The above tables give the outputs for each system of different natural frequencies and different masses. In all of tables, it is observed that nowhere stress ratio exceeds unity which means that the design of spring is safe and can be used without expecting any failures to occur.

VI. Conclusions

Therefore, from all the above results and their discussion, we can conclude that the Belleville spring can isolate the system effectively after 450Hz excitation frequency and above depending on mass of the system, damping ratio, and excitation frequency. It should also be noted that the spring when in parallel configuration achieves this result while series decreases the stiffness of spring and increases the maximum deflection of spring by using same number of springs. From this it is clear that for applications where high stiffness and less deflection is required parallel configuration can be used and for applications where low stiffness and high deflection are necessary series or mixed configuration can be used. From the final design considerations, it is also evident that the geometrical size of the spring is small. Since all the stress ratio values are well within one, this means that the design is safe and can be used in practical applications. Hence, the design is safe and it achieves passive vibration isolation.

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[3] http://nptel.ac.in/courses/112103111/

[4] http://oa.upm.es/15310/1/mechanical_system_modal_contribution.pdf

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