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Topology Optimization and Flexible Building Block Design and Analysis of Compliant Mechanism for Vibration Isolation

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Abstract— Compliant mechanisms are designed for different type of applications because of the stability, zero backlash,ease of manufacturing and robustness endowed by their unitized construction. This paper presents an application of compliant mechanism for vibration isolation system with rigid foundation. Vibration isolators are specified for those rotating machines that could impart enough forces. Structural optimization approach is focused on the determination of the topology, shape and size of the mechanism. The building blocks are used to optimize a structure for force transmission. Flexible building blocks method for the optimal design of compliant mechanisms. A library of compliant elements is proposed in FlexIn. These blocks are in limited number, the basis is composed of 36 elements. The approach used to establish the actuator model of the block and its validation by commercial finite element software. The force transmitted to the rigid foundation through the isolator is reduced to avoid transmission of vibration to other machines. The design drawing model is compared with the existing isolator model, displacement transmissibility or amplitude for varying disturbance frequency and the force transmitted for corresponding disturbance frequency. Isolation efficiency of design drawing model is proven to be high when compared with the existing model.

Index Terms— Compliant mechanisms, flexible Building blocks, vibration isolators, FlexIn, topology optimization, Passive Isolation, Active Isolation.

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1 INTRODUCTION

A mechanism is a mechanical device used to transfer or transform motion, force, or energy. A complaint mechanism also transfers or transform motion, force, or energy. Unlike rigid link mechanisms, the compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than the movable joints. An example of compliant crimping mechanism is shown in figure 1.

Compliant mechanism is a breed of elastic mechanism that gains its mobility from relative flexibility of its members and compliant mechanisms is the potential for a dramatic reduction in the total number of parts required to accomplish a specified task. It also to provide efficient and low cost passive vibration isolation. Due to their monolithic (joint less) construction, compliant transmissions offer many inherent benefits including low cost, zero backlash, ease of manufacture, and scalability.

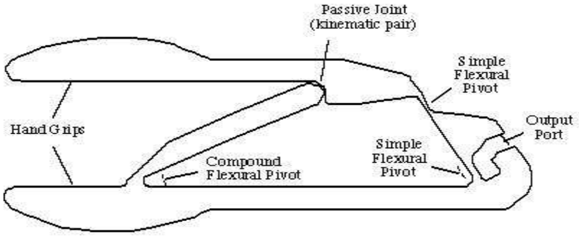

Fig 1: Complaint crimping mechanism

Compliant mechanisms also have a smaller number of movable joints, such as pin (turning) and sliding joints. This results in reduced wear and need for lubrication. It is possible to realize a significant reduction in weight by using a compliant mechanism over their rigid-body counterparts. This may be a significant factor in aerospace and other applications.

1.1 Types of Vibration Isolation Systems

Vibration isolation systems can be categorized in various ways. One is to categorize them according to control schemes: passive, active, and semi active systems. Simple diagrams illustrating basic elements in these three types of vibration isolation systems are shown in Figure 2. The actual implementation may be different from and is usually more complicated than what are shown in the figure 2.

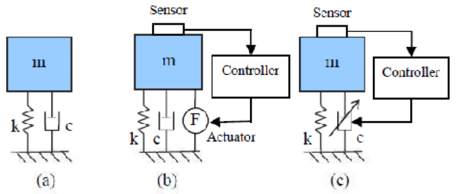

Fig 2: simple models showing basic elements in different types of vibration isolation systems: (a) passive, (b) active, and (c) semi active system

1.1.1 Active vibration isolation

An active vibration isolation system, on the other hand, uses external energy to directly cancel energy in the system by using actuators, sensors, and controllers. Actuators must be able to provide desired forces or displacements to the system, sensors are used to detect the motions of the system (acceleration, velocity, or relative displacement), and controllers are used to

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calculate the required external forces or displacements and send signals to control the actuators.. The transmissibility plot of a typical active system is shown as a dashed line in Figure 3.

1.1.2 Semi-active vibration isolation

A semi active system combines features of a passive system and an active system. Similar to an active system, it uses actuators to apply forces or displacements. However forces or displacements cannot be applied arbitrarily, but they are functions of the motions of the system. In other words, actuators in a semi active system are treated as passive elements whose properties such as a damping ratio and stiffness can be varied so that the control can be implemented without adding external energy into the system, except a small amount of energy required to change the properties of the actuators.

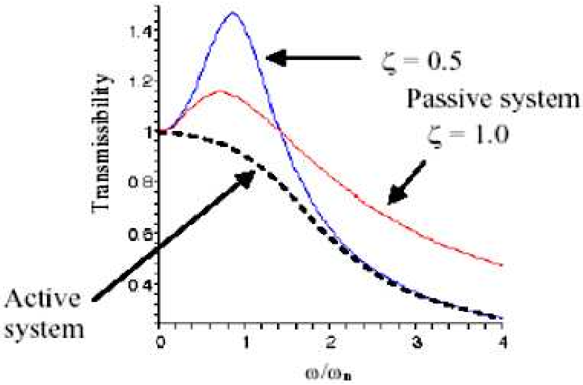

Fig.3: A Vibration transmissibility of passive system (solid lines) and an active system (dashed line)

Sensors are used, as in active systems, to detect the motions of the system and controllers determine the desired properties of the actuators.

1.1.3 Passive vibration isolation

Typically, in a passive vibration isolation system, an elastic element and a damping element are employed to limit the amplitude of vibrations and dissipate energy away from the system. A passive system has predetermined properties, which cannot be adjusted while the system is in operation. The vibration transmissibility depends on disturbance frequency. A transmissibility plot of a typical passive system is shown as solid lines in Figure 3, for different values of damping ratio. A passive system is only effective for disturbances with frequencies much higher than its natural frequency. However, in practice a disturbance may have a frequency varying with time or may consist of a spectrum of frequencies. In the former case, the effectiveness of the vibration isolation system is degraded when the disturbance frequency moves toward the natural frequency of the system. In the latter case, the system reduces the vibration of high frequency spectrum but amplifies the vibration of spectrum near the natural frequency. Adjusting the system damping parameters involves a tradeoff between isolation at different frequencies and the resulting overall performance may not be satisfactory.

1.2 Compliant Mechanisms and Vibration Isolation Systems

We propose compliant mechanisms as a means to provide efficient and low cost vibration isolation. Due to their monolithic (joint less) construction, compliant transmissions offer many inherent benefits including low cost, zero backlash, ease of manufacture, and scalability. Although leaf springs and cantilever beams employed in previous research are in effect of "Compliant mechanisms", the motion amplification mechanism proposed in this paper offers a more effective solution. The scope of this study is limited to low frequency isolation because the use of compliant mechanisms in active vibration isolation systems has the greatest advantage in the low frequency range. Since many passive systems are effective and sufficient for high frequency isolation, the need of active systems for high frequency isolation is less than that for low frequency isolation. We also focus on understanding the effects of the compliant design parameters and attempt to solve problems systematically. The preliminary results of FEA from ANSYS demonstrate that a compliant mechanism can be effectively used to reduce the amount of force transmitted to the surface. Figure 4 illustrates how a compliant mechanism can be integrated into a vibration isolation system.

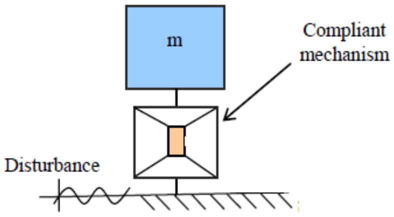

Fig 4: Models illustrating the concept of using a compliant Mechanism in vibration isolation

1.3 Design of Compliant Mechanism Using Topology Optimization

By using the topology optimization the compliant mechanism is designed. The topology optimization predicts the optimal distribution of the material in the design domain. It is very promising for systematic design of compliant mechanism because topological design is automated by the given prescribed boundary conditions. Its success relies very much on the problem formulation. The topological design of compliant mechanism is solved as a problem of material distribution using the optimality criteria method.

1.4 FlexIn: A compliant mechanisms stochastic design methodology

Compliant Building Blocks

The optimal design of compliant mechanisms made of an assembly of basic building blocks chosen in a given library. A library of passive compliant elements is proposed in FlexIn. These blocks are in limited number: the basis is composed of 36 elements (see Figure 5).

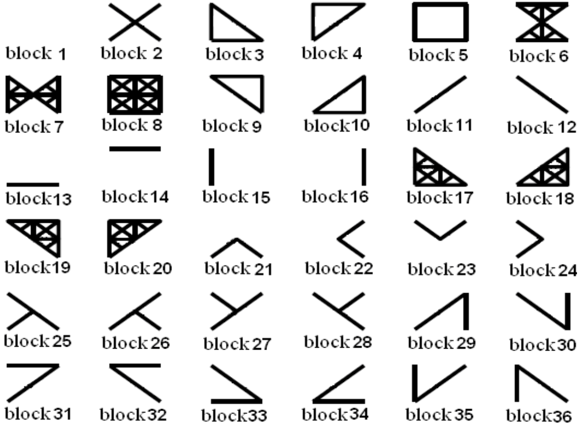

Fig 5: Library of compliant building blocks for planar compliant mechanisms synthesis using FlexIn

2 PROPOSED APPROACH

Vibration Control involves the correct use of a resilient mounting or material in order to provide a degree of isolation between a machine and its supporting structure. A condition should be achieved where the amount of vibration transmitted from, or to, the machine is at an acceptable level. In this preliminary study, existing coil spring isolator which is used to reduce the force transmitted from or to the machine. A compliant mechanism is designed to reduce the force transmitted to the foundation by reducing the displacement transmissibility (Figure 6) of various frequency ratios.

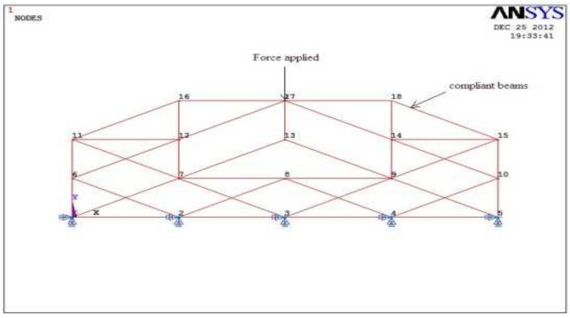

Fig 6: A Finite element model of compliant mechanism

TABLE 1.
PROPERTIES OF THE MODEL USED IN FEA.

Element type	2D elastic beam 2D mass
Number of elements	37 elastic beam elements 1 mass element attached at 17th node
Young's modulus	200x109pa
Poisson's ratio	0.3
Density	7860 kg/m3
Cross section	305mm width x 4mm thickness
Overall dimension	500 mm x 165 mm

The compliant mechanism is assumed to be made of structural steel. The gravity and structural damping are ignored for these preliminary analyses. The motion of output is contributed by displacement controlled input.

3 HARMONIC ANALYSIS

3.1 Linear Harmonic Response

The harmonic response analysis solves the time-dependent equations of motion for linear structures undergoing steady-state vibration. The entire structure has constant or frequency-dependent stiffness, damping, and mass effects. All loads and displacements vary sinusoidally at the same known frequency. Element loads are assumed to be real (in-phase) only.

3.2 Harmonic response of Coil spring isolator

Initially the displacement amplitude (Figure 6) is calculated for various frequency ratios from 1.5 – 5 for damping ratio ζ = 0.3 of coil spring isolator. The force transmitted (Figure 8) for the corresponding amplitude and frequency ratios are also calculated.

3.2.1 Displacement amplitude

Displacement amplitude is calculated using the static displacement frequency ratio and damping ratio.

$$\frac{X}{\delta_{st}} = \frac{1}{\sqrt{(1-r^2)^2+(2\zeta r)^2}}$$

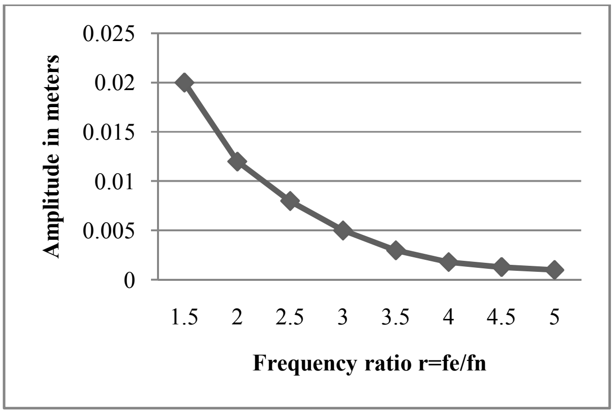

Fig. 7 Amplitude for different frequency ratio with constant damping ratio ζ=0.3

3.2.2 Force transmitted

Force transmitted for the corresponding displacement amplitude is calculated using known material constant and damping coefficient, it is taken as ζ = 0.3 for maximum value and natural frequency of the coil spring isolator.

$$F_T = X\sqrt{(k^2 + c^2\omega^2)}$$

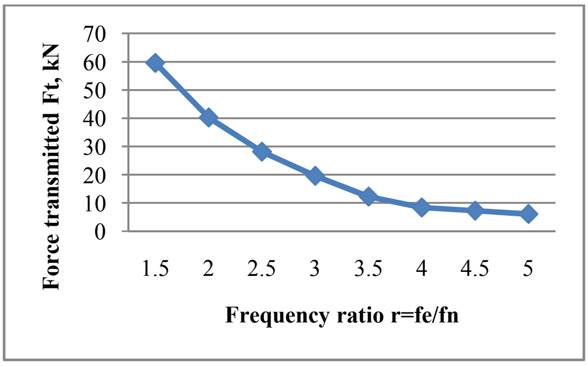

Fig 8: Force transmitted for corresponding frequency ratio, r

3.3 Harmonic response of compliant isolator

The displacement amplitude (Figure 9) is calculated for various frequency ratios from 1.5 – 5 with damping ratio ζ =0.3 for compliant mechanism using ANSYS. The force transmitted (figure 10) for the corresponding amplitude and frequency ratios are also calculated.

3.3.1 Displacement amplitude

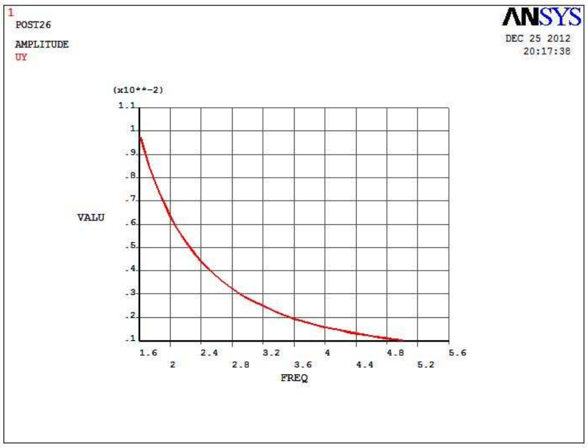

Fig 9: Displacement amplitude for corresponding frequency ratio ranges from r, (1.5-5) for compliant mechanism.

3.3.2 Force transmitted

The force transmitted (Figure 10) for the corresponding amplitude and frequency ratios are also calculated by using the equations.

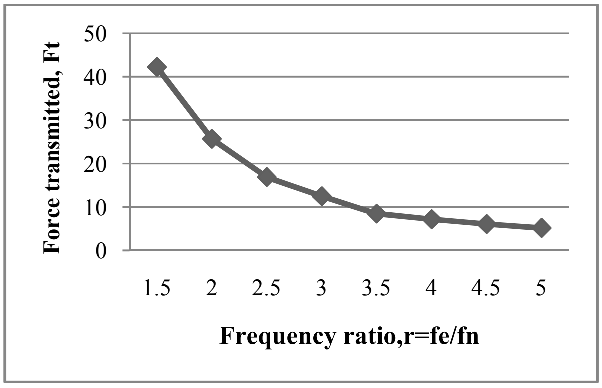

Fig 10: Force transmitted for varying frequency ratio

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4 RESULT AND DISCUSSION

4.1 Transmissibility Ratio

The force transmitted by using compliant mechanism is compared with the existing isolator with constant damping ratio ζ = 0.3 (Figure 11).

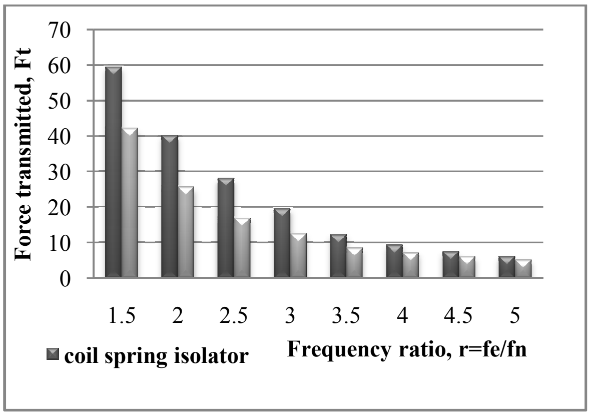

Fig 11: Force transmission of existing isolator with the compliant mechanism

Transmissibility Ratio Tr = (Force transmitted in kN / Disturbing force in kN)

4.2 Isolation Efficiency

Isolation Efficiency η in percent transmission is related to Transmissibility as

η = 100 (1-Tr) %

Isolation efficiency of the existing isolator and designed compliant mechanism is compared (Figure 12).

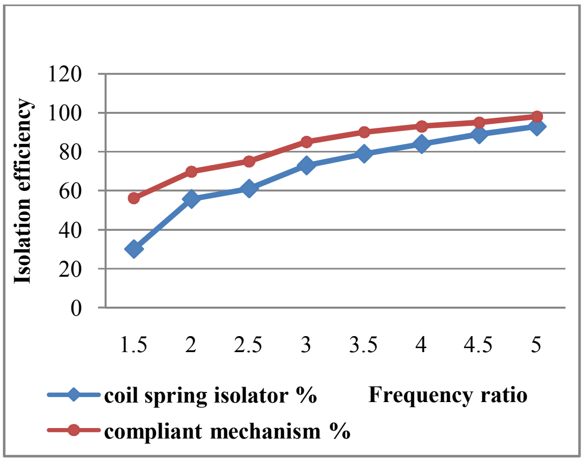

Fig 12: Isolation efficiency vs frequency ratio

TABLE 2
ISOLATION EFFICIENCY OF COIL SPRING ISOLATOR AND COMPLIANT MECHANISM

Frequency ratio	Coil spring isolator %	Compliant mechanism %
1.5	30	56.2
2	55.7	69.7
2.5	61.1	75
3	73	85
3.5	79	90
4	84	93
4.5	89	95
5	93	98

5 CONCLUSION

Compliant mechanisms which are proposed to provide cost effective and high performance passive vibration isolation systems. Their function is to transmit the force for various displacement amplitude of corresponding frequency ratios. The preliminary results from FEA using ANSYS show that a compliant mechanism can provide effective vibration isolation from a sinusoidal disturbance with known frequency ratios. In this paper, we demonstrated, through harmonic analyses, that the disturbance of 0.01m amplitude, isolation efficiency of 56% at 1.5 Hz (for coil spring isolator isolation efficiency for corresponding amplitude and frequency ratio is 30%) and by 98% at 5Hz for the amplitude of 0.001m (for coil spring isolator isolation efficiency for corresponding amplitude and frequency ratio is 93%) by using compliant mechanism.

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