A review and study of effectiveness of negative stiffness mechanisms in vibration isolation methods

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Abstract: This review paper acquaints the study of effectiveness of various negative stiffness mechanisms in the process of isolation of vibration energy. There are many vibration isolation techniques available for control over the vibrational energy. The negative stiffness mechanism is the emerging technology in the field of vibration isolation. Hence, it is necessary to study the different ways to achieve the negative stiffness phenomenon using different mechanical principles. Different kinds of mechanisms with fundamental principles like mechanism using pneumatic system, magnetic phenomenon and mechanical linkages are studied and analyzed in this review paper. Further the results referring the references are discussed and concluded.

***Keywords* - Vibration isolation; Negative stiffness mechanism; Negative stiffness behaviour;**

1. Introduction

Vibration isolation of a system is a process of eliminating or reducing the effects of vibrational energy acted upon the system. The vibrational energy can be generated by internal functioning or by external stimulus to the system. The study of vibration isolation becomes important for effective functioning of the equipment or systems. There are different kinds of vibration isolation devices, which differs as active type isolators and passive type isolators. Active type isolators require external power to the system for working process of the system and passive type vibration isolator does not require any external power supply, which works on its own functioning. It is important to study the passive type vibration isolators because they are simple and easy in operation as well as cost effective. There are different for approaches to the passive type vibration isolators like traditional isolators such as springs, damping materials, rubbers, dampers, etc. However, there disadvantage is there specificity and linearity towards the application. Hence, it becomes necessary to study different nonlinear as well as wide ranged field of application. Negative stiffness mechanisms are one of the most effective methods of vibration isolation. As they can be both passive as well as active type isolator, it becomes necessary to study the effectiveness of passive kind with respect to the active type isolator.

2. Negative stiffness behaviour

The fundamental frequency of the system needs to be minimized to isolate the vibrational energy in lower frequency range. It is possible by reducing the equivalent dynamic stiffness of the system, as the frequency remains directly proportional to the stiffness of the system. As in a transmissibility curve, the vibration isolation region starts as the ratio of frequencies goes beyond value of $\sqrt{2}$. Hence, to reduce the dynamic stiffness of the system, it is desired to generate a mechanism, which resists the effect of positive stiffness of the system. The negative stiffness mechanism is a mechanism, which can be an assemblage of springs and mechanical components that generates the equivalent effect of negative stiffness of the system. In simple words, negative stiffness means the inverse proportionality between force of application and displacement of the mass or the desired location. The negatives stiffness is the equivalent behavior of the system, which can be studied and observed by the example of a buckled beam. As shown in the following figure, the force is applied to the buckled beam at the center. The beam is resisting the force as it starts applying on it until midline shown reference to the original straight beam. If, further the force is applied, then the buckled beam will tend to move forward without resisting the applied force. This behavior of the beam tending to assist the force rather than resisting it is the negative stiffness behaviour [5].

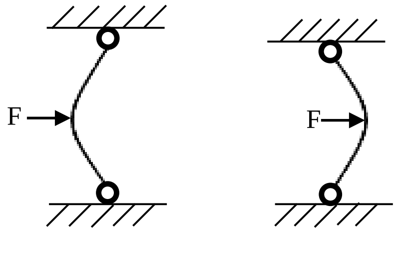

Figure 1. Negative stiffness behavior of a buckled beam.

3. Literature survey

In this paper, the literature survey is carried out for evaluation of effectiveness of different kinds of negative stiffness mechanism over each other as well as with active type vibration absorbers.

Thanh Danh Le et al. [1] proposed and experimented a vibration isolation system with negative stiffness mechanism in 'infra-frequency' vibration conditions, which ranges from 0.5-5 Hz as shown in fig.2. In this paper, the nonlinear stiffness characteristics of the system is assessed. The relationship between configurative parameters of the system and the equivalent dynamic stiffness of the system is demonstrated. An experimental apparatus has been developed to examine the characteristics of the vibration transmissibility of the system according to various values of the configurative parameters. This paper also provides information related the dynamic response of the system with and without negative stiffness structure. Finally, the results shows the vibration isolation in infra-frequency range.

C.M.Lee et al. [2] states that by minimizing fundamental natural frequencies of a vibratory system using a negative stiffness spring in the system is the only method to acquire infra-frequency vibration isolation. In this paper, a negative stiffness mechanism with the help of the load bearing spring is developed and tested as shown in fig.3. The paper presents an approach based on the consistent theory of thin shells, for designing compact springs in terms of their compatibility where fundamental frequencies are kept minimal. In the approach, a generic model of the proposed system with negative stiffness mechanism is applied to the designing of a driver seat for comfort purpose.

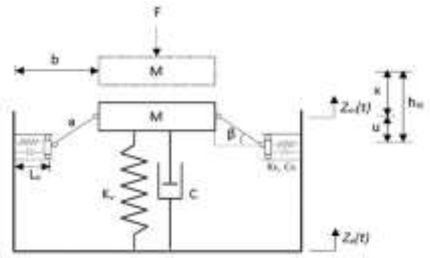

Figure 2. Horizontal spring arrangement negative stiffness mechanism.

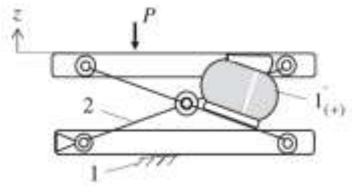

Figure 3. Negative stiffness mechanism using load-bearing spring.

E. Palomarea et al. [3] has developed a negative stiffness mechanism based on a combination of two double–acting pneumatic linear actuators. These comprises with single degree of freedom system, which consist of a mass and a pneumatic actuator spring. Later in experiment, Pneumatic spring is replaced with a hydraulic actuator for desired input parameter. The pneumatic actuators are placed horizontally with hinged ends at both sides as shown in fig.4. When the rear part in actuator is pressurized, the vertical force applied by the pneumatic actuators will work opposed to the pneumatic spring reducing the fundamental frequency of overall system. Experimental tests and simulations showed improvements regarding sprung mass isolation in decreasing the natural frequency and improved the vibration isolation range.

Wenjiang Wu et al. [4] proposed a negative stiffness mechanism system using magnetic spring for elimination of vibrational energies as shown in fig.5. This isolation system consist of a positive stiffness spring and the negative stiffness element, which are in parallel configuration holds the attribute of high static and low equivalent dynamic stiffness. This magnetic sprig based negative stiffness system consists of three cuboidal magnets, which are arranged in repulsive interaction with each other. An analytical expression of the stiffness is analyzed, and it is shown that the magnetic sprig based negative stiffness system is approximately linear for small oscillations. The experiment has demonstrates that the magnetic sprig based negative stiffness system can lower the fundamental frequency of the overall system.

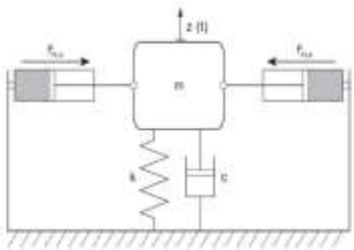

Figure 4. Pneumatic actuator based NSS.

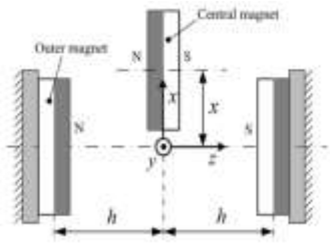

Figure 5. NSS using magnetic elements.

Lia Kashdan et al. [5] developed metamaterials that can achieve higher damping than currently available materials via negative stiffness behaviour. The paper also states constrained compliant mechanism that can show negative stiffness behaviour and opposes the extremal vibrational stimulus as an absorption capacity. Buckling model for negative stiffness concept as shown in fig.1 is studied with different states in process to analyze negative stiffness behaviour. Force versus transverse displacement at various instants is analyzed and concluded behaviour of the system.

Y.C. Wang et al. [6] has observed the behaviour of the buckled plastic ruler to demonstrate negative stiffness phenomenon as shown in fig.6. It is same as the buckled beam studied above in [5] with example of plastic ruler. The stability analysis of negative stiffness element is examined. A spring model with arrangement of both positive and negative stiffness behaviour is analyzed and studied as shown in fig.6.

Mengnan sun et al. [7] has proposed a vibration isolation system as shown in fig.7 for various applications like vehicles on-orbit spacecraft and high precision instruments. In the model, the scissor like structure with spring elements in mechanical combination is used to isolate the vibrations to the base. It has a disadvantage of intrinsic nonlinearity, therefore they have utilized this negative stiffness structure thereto excavate its disadvantage.

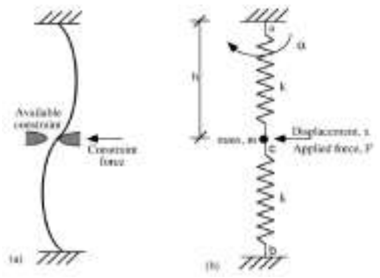

Figure 6. Plastic ruler negative stiffness behaviour.

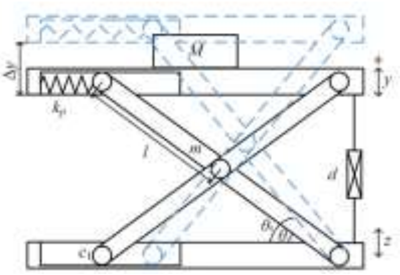

Figure 7. Scissor like structure based NSS.

4. Results and discussion

The results evaluated in this paper are based on the literature outputs, which is further presented in the form percentage as a response of mass displacement or application amplitude with respect to the excitation signals. Achievement of literatures are further discussed in tabular form as follows:

Horizontal springs negative stiffness mechanism is an assemblage of mechanical elements like springs and links, which is subjected and tested for various types of excitation signals like sinusoidal wave and random signal [1]. The tested model's response is much effective for sinusoidal wave excitation as the vibration absorbance level is 97.64% and for random signal, it is about 88.88%.

Pneumatic cylinders are used as the source to generate the negative stiffness. The system is subjected to the multi-frequency vibrations ranging from 0.3-4 Hz is responded in medium manner as the percentage for mass displacement with respect to the excitation signal is approx. 62% which is a good number but not much effective.

The MS-NS (Magnetic spring - negative stiffness) system is an active type vibration isolator as the electromagnetic component needs an external power supply. Since, the repulsive power of electromagnet is exceptional in its functionality. Hence, the results obtained from this literature is upto the expectation as the percentage output for vibration isolation is ranging from 98.57% to 99.6%.

A scissor like structure [11] is shown in fig.7 with combination of mechanical springs for generation of negative stiffness effect of overall system. The analysis is done between the equivalent dynamic stiffness of the overall system with the fundamental parameters of the system. The system is then subjected to the vibrations in vertical plane only to analyze the better response of the system. The system is very effective in reducing the vibrational energies impacting vertically and committed to lower the fundamental frequency of the system.

5. Conclusion

Negative stiffness mechanisms are one of the best method for isolating the external vibrational energies. The analysis done in this paper is effectiveness of the negative stiffness systems with each other and other methods. The active type negative stiffness based mechanisms are most effective vibration isolator as they results in better response for desired location or unsprung mass. There are two types of active type isolator and two passive types of vibration isolator are studied in this paper. In results and discussion, it is observed that the passive type vibration isolators using negative stiffness mechanisms are less effective than the active type, but the results are much closer to the effectiveness of active type vibration isolators as well as the results are closure to the desired output. The horizontal soring based negative stiffness mechanism has 97.64% vibration absorbance level and the active type, which is magnetic principle based negative stiffness mechanism has an output of approx. 99%, so it can be observed that the effectiveness passive type vibration isolator with NSS is appropriate and beneficial.

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