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Static and dynamic analysis of a high static and low dynamic stiffness vibration isolator utilising the solid and liquid mixture

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A B S T R A C T

A new type of Solid And Liquid Mixture (SALiM) vibration isolator with the high static and low dynamic stiffness (HSDLS) is proposed for vibration isolation of heavy machines with low excitation frequency. The static analysis is first presented to obtain the stiffness property of the isolator, and it is found that the isolator exhibits approximately piecewise bilinear stiffness, as a result of which, when subjected to vibration, the isolator operates in the soft stiffness segment, and meanwhile, the stiff segment of bilinear stiffness can ensure the isolator's loading capacity. Following the static analysis, the design criterions are developed to satisfy the expectant requirements including natural frequency and static deflection. Then, the force transmissibility of the proposed isolator is compared with the common SALiM isolator, and the comparison result indicates that the SALiM isolator with HSDLS isolator exhibits more outstanding performance, that is, lower resonance frequency and wider effective isolation frequency range. Hence, it is proven that the presented isolator is capable of isolating low frequency (<10 Hz) or ultra-low frequency (<1 Hz) vibration at a relatively smaller static deflection.

1. Introduction

The demand for low frequency vibration isolation devices keeps growing in many industrial fields such as the offshore platform [1], optical instruments for gravitational wave detections [2] and support systems for the entire aircraft ground vibration tests. To achieve an effective isolation for heavy machines with low frequency vibrations, the soft spring stiffness is required for a linear isolator, but soft stiffness will cause an undesirable large static deflection. And this drawback could be overcome by adding a negative stiffness spring element to a positive stiffness spring element. This type of isolator possesses the high static and low dynamic stiffness (HSLDS) so that it can support heavy machines with a small static deflection and also have soft dynamic stiffness. So far, a number of HSDLS isolator configurations have been proposed, and they could be categorised into two groups according to the mechanism to create negative stiffness. The first group is to use structural nonlinearities. Carrela [3] and Kovacic [4] gave a quasi-zero-stiffness (QZS) vibration isolator, which comprises a vertical spring and two oblique springs. And three different configurations regarding the characteristics of the oblique springs were studied. Yang considered a nonlinear vibration isolation system incorporating a negative mechanism consisting of two rigid bars, connected at one end while the other two ends are subjected to compression forces [5]. The similar configurations are found in Refs. [6–8]. The second group introduces the negative stiffness with magnets, which provides the negative restoring force and cancels out part of the positive spring's linear restoring force [9–12]. Zhou realised a HSLDS isolator which connects a mechanical spring, in parallel to a magnetic spring that is constructed by a pair of electromagnets [9]. In Ref. [10], Carrela presented a type of isolator that comprises two vertical mechanical springs, between which an isolated mass is mounted. At the outer edge of each spring, there is a permanent magnet, and the combination of magnets acts as a negative stiffness counteracting the positive stiffness provided by the mechanical springs. Other mechanisms to produce HSDLS characteristic also exist, which can be found in [13,14].

On the other hand, recently the Solid And Liquid Mixture (SALiM) vibration isolator was suggested also for vibration isolation of heavy machines with low frequency [15–17], and some progresses have been made in modelling, nonlinear dynamics analysis and vibration isolation performance. In Ref. [15], authors designed a vibration isolator which comprises a U-shaped multilayer-alloy-bellows type container filled with SALiM. Those elements could be pneumatic with air or pressurised gas depending on the requirements. The quasi-static test in [15] proves that the SALiM isolator of that type has the piecewise linear-nonlinear stiffness and the simulation analysis shows that it has ability to

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isolate the frequency less than 10 Hz. Therefore, it is potentially suitable for the applications where the lower frequency vibration isolation is necessary, such as marine ships, buildings [18,19] and rail transport [20,21].

In order to further improve the SALiM isolator's loading capacity and effectiveness of low frequency, the above-mentioned SALiM isolator's distinguished feature of piecewise linear-nonlinear stiffness inspires us to redesign the isolator's configuration, which can help realising the isolator's high static and low dynamics stiffness. Hence, the novel type of SALiM isolator with the high static and low dynamics stiffness is proposed in this paper. And differently from the before-mentioned isolator, the redesigned structure makes the proposed device operate in the soft piece of piecewise smooth stiffness (i.e. operating stiffness) when it is subjected to vibration, and meanwhile, the stiffer segment (i.e. loading stiffness) can ensure the isolator's loading capacity. Therefore, the presented isolator not only has low dynamic stiffness, but also possesses the capability of supporting heavy machines at a small static deflection. Moreover, compared with the existing high static and low dynamics isolator using negative stiffness elements, the proposed isolator in this paper differs in three aspects. First, due to advantages of SALiM, although there is no visible negative stiffness element, it can possess the superiorities of negative stiffness spring. Second, most of HSLDS isolators possess smooth nonlinear stiffness [9–14], but the underlined isolator exhibits approximately piecewise linear stiffness characteristic, which brings simplicity for design of vibration isolation. Third, the isolator's stiffness characteristic can be tuned conveniently by altering the quantity of elastic solid elements.

The motivation of this paper is to establish a mechanics model of SALiM isolator with HSLDS, to develop its design criterion and to estimate the dynamic properties of isolator system, such as vibration isolation performances and nonlinear dynamics behaviours. The structure of this paper is as follows. First of all, the HSLDS isolator is described. Then in the static analysis, the stiffness characteristic is studied by theoretical analysis and a quasi-static test. Subsequently, in dynamic analysis, the design criterion of the isolator is developed, and the force transmissibility is evaluated. Finally, the effects of stiffness's nonlinearity on the system's dynamics behaviours are explored.

2. Description of the SALiM isolator with HSDLS

Fig. 1 shows a schematic diagram of the proposed SALiM vibration isolator with HSDLS. Two supporting rods (4) clamped on the base plate (5) are used to support the multilayer bellows container (3). And four suspension rods (2) of container (3) connect to the loading plate (1). When the isolated machine is in vibration, the excitation force is transmitted to the bottom of container firstly through suspension rods, then to its top end via the bellows container and internal SALiM, and lastly to the base plate through supporting rods. As described above, SALiM filled in the container consists of elastic solid elements and hydraulic liquid. Note that the elements could be filled with air or pressurised gas depending on the property requirement. It is reasonable to assume that the compressibility of the hydraulic liquid can be neglected compared with the compressible elastic elements. And the radial deformation of bellows structure can be neglected due to its very high radial stiffness.

Assuming that the isolator works in the normal atmosphere environment, the air pressure is denoted as P_a, and the liquid pressure is P_o. There is a pressure difference $(P_a - P_o)$ acting on the bottom of container (see Fig. 2), which produces a part of the restoring force $(P_a - P_o)S_e$, where S_e is the effective area of the container. The liquid pressure P_o in the container decreases as the isolator is compressed at a quasi-static speed. Therefore, the pressure difference $(P_a - P_o)$ will become larger and larger until that the liquid pressure P_o decreases to zero.

Note that the initial internal air pressure of solid elements is equal to standard atmosphere pressure P_a. The volume of solid element expands due to the pressure difference between internal air and liquid pressure. Eventually, there comes to a point where the elastic restoring force of solid elements is balanced by its internal pressure when the liquid pressure P_o becomes zero. It is clear that the stiffness (i.e. loading stiffness) of the isolator in this stage is contributed by both of bellows container and solid elements. However, after passing the discontinuity point, the solid elements stay in the equilibrium state and do not provide restoring force any further, and thus the isolator's operating stiffness exactly equals the container's stiffness. In consequence, the type of SALiM isolator exhibits piecewise nonlinear (or linear approximately) stiffness the with high static and low dynamic characteristic. Differently from the common SALiM isolator, the proposed device operates in the soft stiffness (i.e. operating stiffness) segment when it is subjected to vibration, as shown in Fig. 3. Meanwhile, the stiff stiffness segment (i.e. loading stiffness) can ensure the isolator's loading capacity.

In practice, there exist various types of solid elements. Fig. 4 gives two different types. One is the hollow rubber sphere element and the other is the metal U-shaped bellows element. Compared

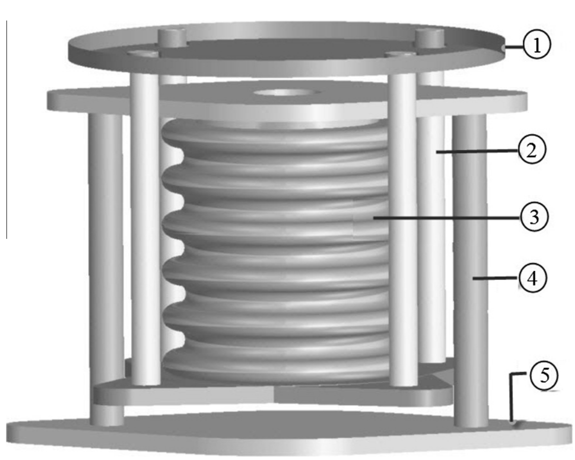

Fig. 1. Schematic picture of the HSLDS isolator, ① loading plate, ② suspension rods, ③ bellows container, ④ supporting rods, ⑤ base plate.

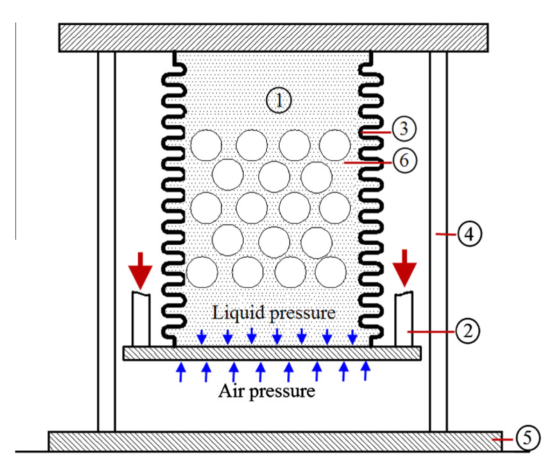

Fig. 2. Diagram of the force regime of the HSLDS isolator, ① working liquid, ② suspension rods, ③ bellows container, ④ supporting rods, ⑤ base plate, ⑥ elastic solid element (see Fig. 3(a)).