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An active actuator based on giant magnetostrictive composite pendulum for vibration isolation

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Abstract. This paper proposes an active actuator based on giant magnetostrictive composite pendulum for vibration isolation, laying the foundation for vertical micro-vibration isolation. The performance of a single-stage pendulum vibration isolation system can be improved by increasing the pendulum length, along with the influence of the environment on the system increases. In precise experiments, effective isolation of vertical micro-vibration improves the accuracy of the experiments. Interference caused by micro-vibration can be attenuated by designed magnetostrictive actuators. Then, a suspension actuator consists of a composite pendulum and a driving device is designed. The composite pendulum is composed of a quartz fiber coated with a giant magnetostrictive material (GMM). The GMM can achieve the desired small strain in a designed magnetic field. GMM is applied on a quartz fiber to form a composite pendulum. Therefore, low-frequency active vibration isolation of single pendulum is realized. Compared with the passive vertical vibration isolation system, the system gets better vibration isolation and anti-interference ability. Compared with the traditional active vertical vibration isolation system, it has the advantages of system simplification, high integration and high sensitivity.

1. Introduction

There is a large demand for precise instruments with high measurement sensitivity, repeatability and measurement uncertainty in ultra-precision measuring, such as scanning probe microscopy (SPM), atomic force microscopy (AFM), holographic interferometer and confocal microscope. However, even the small vibration of amplitude or frequency may interfere the measurement result. That means, as the increasing accuracy of the instruments, the vibration of the external has an increasing influence on the accuracy of the instrument. The vibration isolation technology has become a bottleneck that limits the improvement of instrument accuracy, especially in suppressing the vibration interference signal of ultra-low frequency. Several systems, such as gravitational wave detection, dark matter detection, strong magnetic fields, and pulsar formation studies, all require a low-vibration environment. Compared to the external vibration, the measured signal is particularly weak, making it important to isolate the external vibration, especially the impact of ground vibration. In the absence of an ultra-low frequency vibration isolation system, the desired signals received by the gravitational wave detector may be annihilated in

the noise. Ultra-low frequency (0.1 Hz or less) micro-vibration isolation technology has become a hotspot in the field.

Low-frequency vibration isolation system is mainly divided into two types, passive vibration isolation system [1,2] and active vibration isolation system [3-6]. The passive vibration isolation system based on single pendulum is a mature one [1,2,7-11]. Increasing the swing length can improve the vibration isolation performance. The suspension of single pendulum has a certain weight. Therefore, a string mode resonance will occur if it is subjected to lateral disturbance under a certain tension. String mode resonance limits the length of the pendulum. In order to make the pendulum swing at a low frequency and with better vibration isolation performance, Kim K S *et al* combined the single pendulum and the spring to form an inverted pendulum [12], which is symmetrically distributed on both sides of the square vibration isolation platform. The inverted pendulum has a simple structure and reliable operation. VIRGO, a large interferometer designed to detect gravitational waves, proposed a 9-stage composite pendulum vibration isolation system SA (Super-Attenuator) [13,14]. It combines multi-stage single pendulum series and active vibration isolation, leading the improvement of the low frequency vibration isolation performance. However, the method has three defects. Firstly, the actuator and sensor are fixed on the first and second stage pendulums, making it difficult to isolate the vibration on the test mass. Secondly, the structure of the system is complex because of the installation of multiple sensors and actuators, making it heavily depend on initial installation. Thirdly, fixing the sensor on the test mass introduces low-frequency noise, such as thermal noise. Therefore, an active actuator based on giant magnetostrictive composite pendulum is proposed for vibration isolation.

2. Design of the active actuator

The suspension actuator, which utilizes the hysteresis effect of the GMM, is composed of a drive system and a composite pendulum. The drive system generates the desired magnetic field for driving the composite pendulum, including the variable magnetic field and the bias magnetic field. The variable magnetic field is generated by energizing the drive coil, and the bias magnetic field is provided by the permanent magnet. The composite pendulum is formed by coating the surface of a quartz fiber with GMM.

2.1. Design of the overall structure

The suspended active actuator consists of a composite pendulum and a drive unit. The composite pendulum comprises a quartz fiber and a coating of GMM coated on the quartz fiber. The composite pendulum senses external vibration and transmits vibration signal to the actuator. The driving device consists of an upper guiding magnet, a permanent magnet, a driving coil, a skeleton and a lower guiding magnet. The skeleton is a structure with a through hole in the middle, and its cross section is "H" shaped. The upper guiding magnet is fixed on the top of the skeleton, the lower one is fixed at the bottom, and the coil is nested round of the skeleton. The driving current of the driving coil is adjusted according to the vibration signal obtained by the system, in order to provide a driving magnetic field for the composite pendulum. The permanent magnet is nested round the upper guiding magnet, the driving coil, the skeleton and the lower guiding magnet, for providing a bias magnetic field for the composite pendulum. The composite pendulum passes through the center of the driver. The test mass is suspended by the vibration isolating element through the quartz fiber below the outer support structure.

Based on the designed structure, the suspension active actuator, wherein the composite pendulum senses external vibration, transmits the vibration signal to the actuator. The actuator actively controls the driving current of the driving coil according to the collected vibration signal to change the driving magnetic field of the composite pendulum. The magnetic field, with the help of the giant magnetostrictive effect of the GMM, makes the composite pendulum to produce a strain opposite to the direction of the external vibration, thereby reducing the interference of external vibrations on the system. The schematic of the active actuator is shown in figure 1.

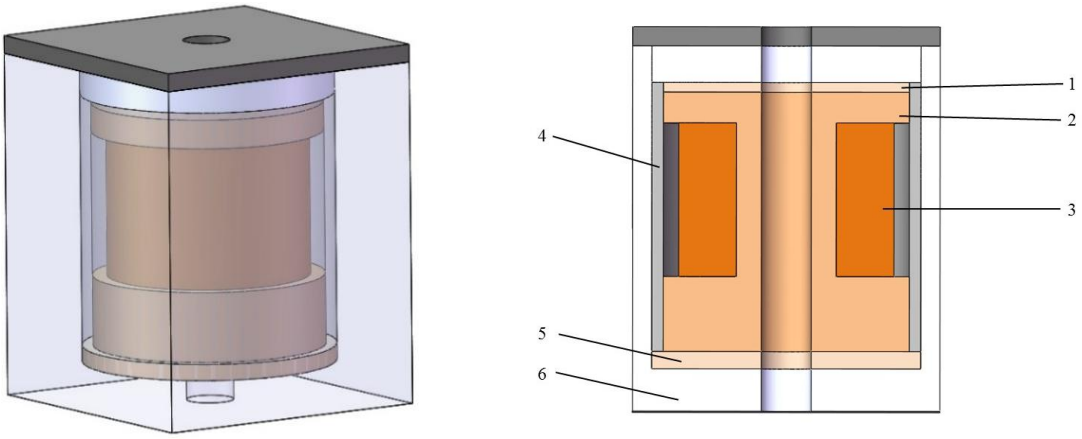

Figure 1. Schematic of the active actuator, in which, 1) and 5) are magnetizers, 2) is coil frame, 3) is coil, 4) is Permanent Magnet and 6) is shell.

2.2. Design of the composite pendulum

The composite pendulum is a quartz fiber coated with giant magnetostrictive powder on the surface. In this paper, the quartz fiber is single mode fiber. Firstly, the GMM and the glue are mixed at a mass ratio of 5:1 and stirred uniformly. Secondly, the fiber optic is completely immersed in the mixed solution, then slowly taken out after being sufficiently contacted. The process of taking out the fiber optic should be steady to ensure uniform adhesion of the mixed solution. Thirdly, the removed quartz fiber is placed on the mould to heat for drying, at 150°C for 3 minutes. After that, a composite pendulum is made. The schematic of the composite pendulum is shown in the figure 2. As shown, its size matches the size of the drive system to ensure that the amount of elongation is as large as possible.

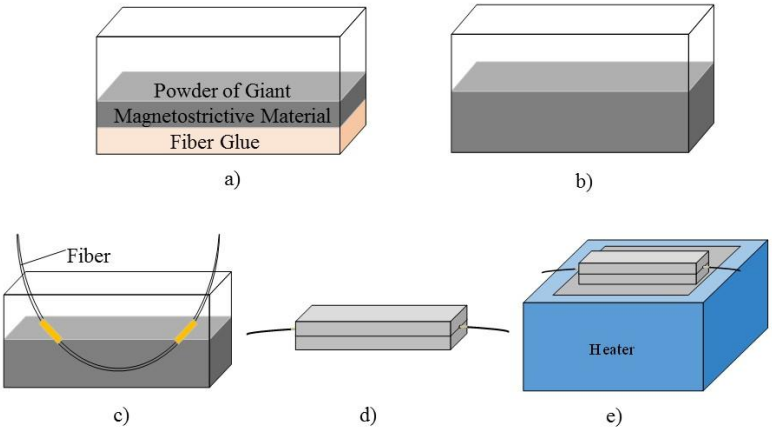

Figure 2. Schematic of the process of making a composite , in which, a) the ratio of weight between powder of GMM and fiber glue is 5:1; b) stir the powder of GMM and fiber glue uniformly; c) immerse the quartz fiber; d) take out the quartz fiber steady and place it in the mould; e) Thermoset the composite pendulum at 150°C.

In figure 3(a), the diameter of polyimide-layer, cladding, and core is 250 μm, 125 μm and 9 μm respectively. To improve the sensitivity of composite pendulum, polyimide-layer of area to be coated on the fiber is peeled off. So, the GMM is coated on the cladding of fiber optic directly and the schematic of composite pendulum is shown in figure 3(b). The coated length is 40 mm, the size of the drive system,

and the image of composite pendulum is shown in figure 3(c). The diameter of composite pendulum is 203.15 μm. The thickness of magnetostrictive film is about 39 μm.

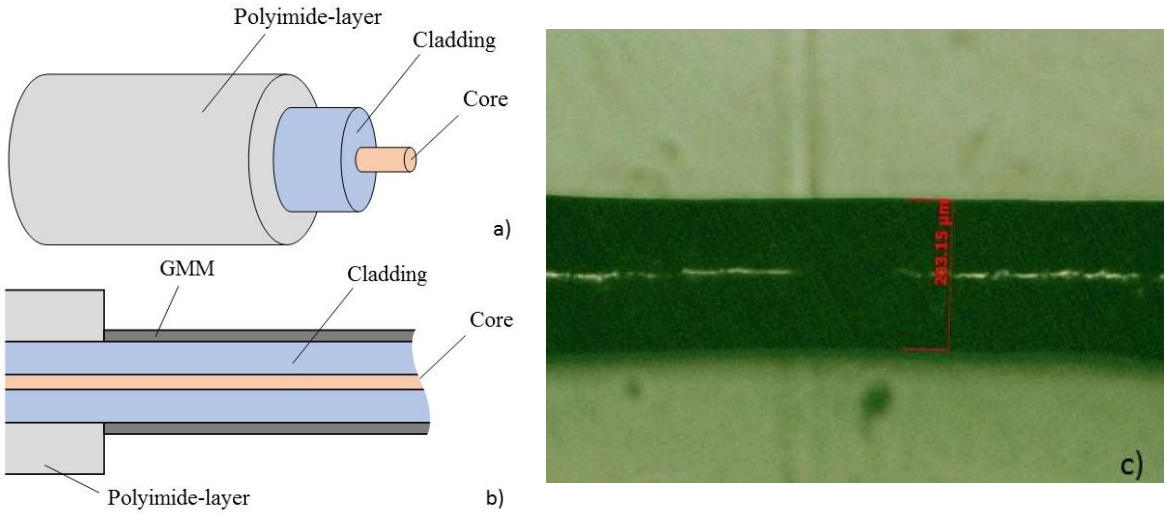

Figure 3. (a) is the schematic of fiber optic, (b) is the schematic of composite pendulum and (c) is the image of composite pendulum.

3. Experiments and results

The magnetic field is co-generated by the main coil in the giant magnetostrictive actuator (GMA), the Helmholtz compensation coil and the permanent magnet. The GMA is placed vertically. One end of the quartz fiber coated with the GMM is fixed on the bracket which is on the top of GMA. A certain weight is suspended at the other end. The composite pendulum is located on the central axis of the coil. The intensity of the central magnetic field is controlled by the magnitude of the input direct current. The coating layer of the GMM varies in a varying magnetic field, leading the change in the length of the cycloid. The schematic of the system is shown in figure 4.

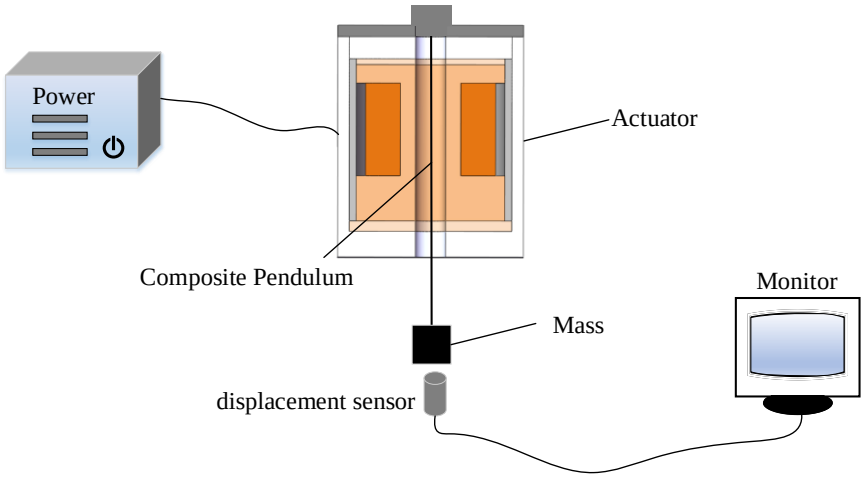

Figure 4. The schematic of the overall system.

The displacement sensor employed for the experiment is eddyNCDT 3010 displacement measuring system. The eddyNCDT 3010 operates without contact using eddy current technology. It can be used for making measurements on targets made of either ferromagnetic or non-ferromagnetic electrically

conductive materials without need to contact. 1) In order to ensure the measurement sensitivity of the sensor, if the thickness of the test mass is greater than 0.6 mm, the diameter of the measured surface should be greater than 1.5 times the diameter of the probe; 2) Irregular surface of the measured object will cause additional error to the actual measured value, especially for vibration measurement. The additional error signal is superimposed with the actual vibration signal, which is electrically difficult to separate. So, the measured surface should be smooth, there should be no defects such as nicks, holes, bosses, grooves, etc. 3) the characteristics of the sensor are related to the conductivity and permeability of the measured object. If the measured object is a magnetic conductive material, magnetic effect and eddy current effect exist simultaneously. The magnetic effect and eddy current effect on the contrary, it will cancel part of the eddy current effect, resulting in the low sensitivity of sensor. If the object is non-magnetic or weak magnetically conductive material (such as aluminum, material of the test mass), the eddy current effect is relatively strong due to weak magnetic effect. So, the sensor sensitivity is higher.

The relationship between the pendulum strain and the driving current was measured. The driving current increases at the step of 0.4 A. The result is shown in figure 5.

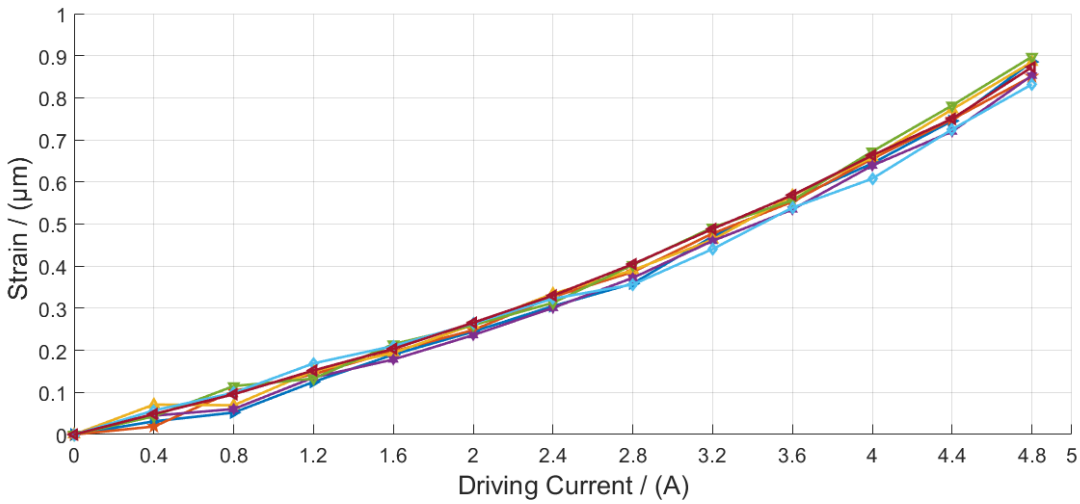

Figure 5. The measured data of the relationship between pendulum strain and driving current.

The strain of the composite pendulum in the driving magnetic field has a good linear relationship with the driving current. The repeatability of the pendulum strain calculated is ±2.38%.

4. Conclusions

In the composite pendulum, the GMM is coated on the surface of the quartz fiber. Therefore, the giant magnetostrictive effect of the GMM, the effect of the dimensional change under the action of the magnetic field, makes the composite pendulum a unity of the sensor and the compensation for vibration. When a vibration interference occurs, the current of the driving coil changes, leading the change of the magnetic field of the coating of the GMM. As a result, the coating of the GMM produces an external strain with the opposite vibration direction to compensate the external vibration, thereby reducing the interference of external vibration to the system and achieving the purpose of active vibration isolation.

The composite pendulum, which combines the perceptual vibration and the compensating vibration, only includes the quartz fiber and the giant magnetostrictive coating, thus realizing system simplification, self-sensing and active actuation.

The sensor and the actuator are not directly mounted on the test mass, making it possible to solve the problem of introducing low frequency noise in the conventional structure, in which the sensor and the actuator are mounted in the test mass. By reducing the noise source, the actuator gets the better vibration isolation of the low frequency vibration.

Acknowledgments
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