Active and semi active vibration isolation systems based on magnetorheological materials

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Abstract

The paper presents active vibration isolation systems based on "smart" materials. Very promising "smart" materials are MR elastomers. Devices based on them have the ability to work in all vibration isolation modes (passive, semi-active and active mode). In this work we consider a construction of a damper based on the MR elastomer and the experimental research results of the damper in semi-active vibration isolation mode.

Keywords: Vibration protection; vibration isolation; actuator; damper; magnetorheological elastomer; vibration transfer coefficient;

1. Introduction

It is widely known that the vibrations are always present in the daily life. They can be both useful and harmful. Vibrations from neighboring equipment and transport transmit through the foundation and have a significant impact on the characteristics of a modern research and technological equipment. At present electronic devices such as integrated circuits manufacturing are at present reached the minimum feature size of 10 nm. It is particularly important to protect the technological equipment from vibrations. An external vibration can lead to defects in microlithography process products [1]. The magnitude of vibrations in city buildings can be up to 200 μm [2].

Vibration protection systems are commonly used to reduce the vibration exposure to the equipment.

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2. Vibration isolation

The most effective method of vibration protection is the vibration isolation. Its main object is reduction the interconnection between the source of vibrations and the protected equipment. Vibration isolation reduces the dynamic effects of vibrations on the protected object [3]. Vibration isolation is usually divided into three types: passive, semi-active and active systems.

A passive vibration isolation systems example is massive heavy granite platforms and equipment foundation. Springs of a cars and a railway transport are the passive vibration isolation systems. However, these systems work effectively under vibrations of high frequencies and low magnitudes.

Active vibration isolation systems are most effective at low frequencies and large amplitudes of vibrations. The active vibration isolation systems reduce and compensate disturbing force (or vibration displacement) by the additional energy source (or actuator). These systems are usually used positioning mechanisms (actuators). These actuators compensate vibration displacement due to closed-loop control system with feedback.

Semi-active vibration isolation is intermediate between active and passive. In this system damper change the vibration absorption properties (damping properties) according to the characteristics of external vibrations. An example of such a system is a car shock absorber with MR-fluid [4].

Obviously, it is necessary to combine systems of passive and active vibration isolation for the effective damping and compensation of the frequency spectrum of vibrations 0.2 ... 200 Hz of production factories and research laboratories and its magnitudes of up to 200 μm [2].

3. Actuators

There is some types of actuators, which can potentially be used in equipment active vibration isolation systems. Actuators are divided into groups depending on the physical principle of their action [5].

Electromechanical actuator is based on the conversion of electrical energy into kinetic energy of actuator movement. Typically, it consists of a motor and transmission gears (worm, belt, screw-nut etc). A transmission gear converts movement from the motor into the necessary movement of the actuator. The main electromechanical actuators disadvantages is the long kinematic chains that leads to the low performance (high response time) and high positioning error (more than 1 μm).

Hydraulic and pneumatic actuators transform the energy of compressed fluids and gases in the kinetic energy of motion of the piston. Main hydraulic and pneumatic actuators advantage is high load capacity (more than 10 kN) and a large actuator travel range, limited only by the length of the hydraulic cylinder. However, they have low accuracy (~ 50 μm) and performance (response time is 500 ms) because of the presence of the inertia elements (valves, slide valves, membranes, etc.).

Currently, large widespread actuators are devices based on smart-materials. These is piezoelectric, magnetostrictive, shape memory alloys materials, and MR- and ER-fluids and elastomers.

The operating principle of piezoelectric actuator based on the inverse piezoelectric effect. The piezoelectric actuator advantages are a very low positioning error (~ 0.1 nm) and a small response time (~1 ms). Disadvantages it is a small load capacity limited by the properties of ceramics, and a small range of motion, which requires multiplying mechanisms as well as the temperature dependence of the piezoelectric properties.

Magnetostrictive actuator is similar to the piezoelectric. This actuator works on the magnetostriction effect. Magnetostrictive materials (Terfenol-D) change its shape and dimensions under the external magnetic field. This actuator advantages and disadvantages are similar to the piezoelectric actuator. However, magnetostrictive properties do not strongly depend on temperature.

A MR-actuator is a hydraulic actuator with the MR-fluid. MR-fluid properties are controlled by external magnetic field. This field influences directly on MR-fluid to avoid applying inertial elements. MR-actuator has low positioning error (0.1 μm) and response time (100 ms) [6].

MR-fluid is a suspension of magnetic particles (reduced iron, pure iron, cobalt, carbonyl iron, nickel, chromium dioxide) of 10...30 μm in the carrier fluid like organic mineral oil.
MR-elastomer is a solid-state analog of the MR-fluid. It consists of magnetic particles powder and a silicone rubber. Magnetic powder is magnetite (Fe₃O₄) with a particle size of 0.2...0.3 μm and iron with a particle size of 1...5 μm [11]. The elastomer may include both soft and hard magnetic particles.

Previous researches have shown, that elastomer has a number of properties: a magnetorheological effect, magnetodeformative effect, magnetostrictive effect, the shape memory effect, magnetoresistive effect and additive change of electric conductivity under external magnetic field and mechanical stress [9]. In particular, this material may elastically deform and change their viscoplastic properties under external magnetic field.

Investigation at the late 20th century [12] exhibits that the shear strength of MR-materials could vary from 2…3 kPa to 100 kPa under applying an external magnetic field varying from 0 to 0.3 T [10]. Experimental research have demonstrated, that an external magnetic field of 0.8 T causes a change of the elastic modulus of the MR-elastomer up to 60% of no-field modulus [13]. Calculations using finite element method have shown that for typical MR-elastomers the increasing of shear modulus due to particle dipole magnetic interaction is about 50% of no-field modulus.

Many materials, especially polymers show viscoelastic properties. Viscoelasticity can be either linear or nonlinear. MR-fluids can show as linear as nonlinear viscoelastic properties depending on the level of shear stresses in fluid and applied external magnetic fields. MR-elastomers are normally operated in pre-yield regime in the linear viscoelastic region with small deformation [13].

Viscoelastic properties of elastomers depend also on particles sizes, its orientation in silicon matrix. There are usually distinguish two types of elastomers, depending on the orientation of the particles: homogeneous and aligned [13]. The dynamic testing of homogeneous and aligned MR-elasomer has shown that in the absence of an external magnetic field the elastic modulus is much higher for the aligned material in the chain direction than for the homogeneous material with the same particles volume fraction [15].

4. Mechanism based on MR-elastomer

An external magnetic field control visco-plastic properties and elongation of the samples of the MR-elastomer [7]. This effect is successfully used to create precise actuators and active vibration isolation dampers [12, 14]. Damping is a process of dissipation of oscillation energy in a vibrating system. MR-elasomer damping devices is viscous type of vibration control.

The paper proposes to apply for vibration damping device based on homogeneous MR-elastomer with a random distribution of soft magnetic particles. The work-body of the proposed damper is a membrane elastomer (diameter – 100 mm, thickness – 15 mm), based on silicon rubber and 5 μm spherical soft magnetic particles.

Proposed damper (fig. 1) [8] consists a membrane of the MR elastomer with moving plate 5, the electromagnetic coil 3, magnetic conductor rings 4, the magnetic core 2. The air gap 6 is formed between the membrane and the core. A control current in the electromagnetic coil produce closed magnetic field in the damper magnetic circuit. Under this field membrane moves axially within the air gap. Furthermore the membrane deforms and changes its stiffness and elastic modulus depending on the applied external magnetic field.

![Fig. 1. The design of the damper based on MR elastomer: 1 - foundation, 2 – magnetic core, 3 – electromagnetic core, 4 - magnetic conductor rings, 5 - membrane of the MR elastomer, 6 - air gap](image-url)
Thus, damper carries out semi-active and active vibration isolation. Without the control current damper operates as a passive vibration isolation system. MR-elastomer absorbs vibration energy due to its elastic properties. The proposed damper has the following dimensions: height - 50 mm, diameter – 130 mm.

5. Investigation of damper vibration isolation transfer coefficient in semi-active mode

The experimental investigation allows determining the dependence of the vibration isolation transfer coefficient of the frequency of external vibrations.

External vibrations produced by an electrodynamic vibration machine 12MVE-2/50-010. Low-frequency generator set parameters of the external vibration of vibration machine. Low-frequency generator is capable to produce signals from 10 Hz to 10 MHz. The typical external vibration magnitude given by vibration machine was 150 μm. The vibration magnitude measured by a capacitive displacement sensor. A sensor has sensitivity up to 0.01 μm and its maximum measured displacement is 500 μm. Analog signals from the sensor are converted into digital form by laboratory analog-to-digital converter NI USB-6009 and recorded in a personal computer by means of control program.

An experimental dependence of the vibration isolation transfer coefficient of the frequency of external vibrations is shown in fig. 2.

![Fig. 2. Experimental diagram of dependence of the vibration isolation transfer coefficient from the frequency of external vibrations](image)

6. Conclusions

Application of active and semi-active vibration isolation based on MR-materials can improve the efficiency of the precise equipment vibration protection. The dampers based on the MR-elastomers can operate in passive, semi-active and active mode of vibration isolation. The maximum efficiency of the damper in semi-active vibration isolation mode is achieved by control current 1.4 A (vibration isolation transfer coefficient - 0.36 ... 0.4) at low frequencies from 10 to 18 Hz.
Acknowledgement

This work is supported by the Ministry of education and science of the Russian Federation under the project part of the State job No. 9.462.2014/K in the sphere of scientific activity.

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