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NOVEL CONCEPTS OF INERTIAL ACTUATORS FOR VIBRATION BASED ON MAGNETS AND FERROFLUID

BY

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Abstract. Inertial actuators are widely used in applications requiring vibration generating and control. The purpose of this paper is to investigate new and non-conventional vibration actuators with inertial mass suspended by magneto-elastic forces. The magnetic forces that lead to pseudo elastic effect can be obtained in three ways: the interaction of a non-magnetic body, as inertial mass, and a ferrofluid differentially pre-magnetized by external permanent magnets; self-levitation of a magnet disposed into an enclosure filled with ferrofluid, and a magnetic repulsive arrangement consisting of one or more mobile magnets and two fixed magnets.

Key words: inertial actuator; vibration electromagnetic actuator; vibration damping, magnetic spring.

1. Introduction

Vibration actuators are designed and built given one of three destinations for the vibrations that are generated: *process vibrations*, *vibration testing* and *vibration suppression*. Most vibration actuators, whatever the destination, use the same functional principles, but important distinctions in their design and construction occur depending on the specific destination.

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Process vibrations are for industrial uses such as compacting gravel, transporting materials, cleaning, etc. *Vibration testing* is the process of applying a controlled amount of vibration to a test specimen, usually for the purposes of establishing reliability or testing to destruction. *Suppression vibrations* cause forces in a structure subject to disturbing and harmful vibrations, in which case the applied vibration leads to alleviate or remove unwanted vibration supported by the structure.

A vibrator is an electromechanical device to generate mechanical vibrations for industrial process and vibration testing. Actuators in vibration control provide secondary forces acting on the structure to damp out the unwanted vibration brought on by impulsive disturbances.

Dampers (vibration absorbers or vibration isolation devices, other names that are common in the literature) can be classified into three categories passive, active and semi-active (Megahed *et al*., 2010).

A passive damper is a self-excited device that provides a reaction force to an applied motion (force), and just effective for certain single frequency. Examples of passive damping materials include viscoelastic materials, viscous fluids, magnets, smart materials (piezoceramics, electro-rheological fluids, magneto-rheological fluids, ferrofluids, magnetostrictive materials, shape memory alloys) and high damping alloys. These systems are using the potential energy generated by the structural response to provide the control force.

Semi-active dampers are characterized by their ability to dynamically vary their properties with a minimal amount of power (Housner *et al*., 1997; Spencer *et al.,* 1997).

Active dampers require more power than semi-active damper because it relies solely on external energy, having no passive damping properties as the semi-passive device. Active and semi-active dampers require embedded sensors that monitor the structure vibration and send the information to an external feed-back controller that drives the internal electromagnetic actuator of the damper.

Inertial actuators are widely used in vibrators and dampers with active vibration control. An inertial actuator, or actuator with inertial mass, consists of a suspended mass on a fixed base through an elastic element which is put in vibration by an internal force. This force can be generated through different physical principles. Generally, electromagnetic principle is preferred because electromagnetic devices have a long lifespan compared to piezoelectric and electrostatic devices that suffer from degradation and leakage effect, respectively. Vibration electromagnetic inertial actuators can be with: moving iron (electromagnets), moving coil (voice coil actuators) and moving magnet. Although, moving coil actuators are now the most used in vibration systems, the research on vibration actuators with moving magnets is intense and growing (Winberg *et al*., 2004; Paulitsch *et al.*, 2005; Jiao *et al*., 2012; Yoon *et al*., 2013; Lee *et al*., 2013), many companies commercializing such devices.

In the following, the working principle of vibration electromagnetic actuators with magnetic inertial mass is presented. There are described some new ways to achieve a vibration actuator by use of magnets and ferrofluid, whereas inertial mass can be either a permanent magnet (or two) or a non-magnetic body.

2. Functional Principle of Inertial Actuators with Moving Magnet for Active Vibration Damping

The actuators with inertial mass are based on the principle that the acceleration of the suspended mass lead to a reaction force on the supporting structure. Fig. 1 presents an actuator model with permanent magnet as inertial mass.

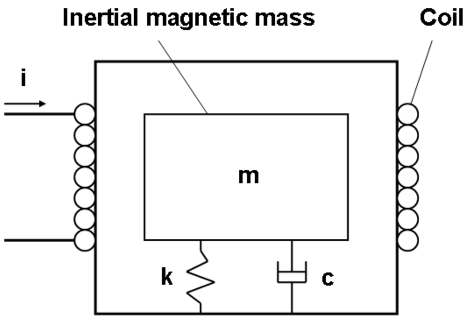


Fig. 1 – Model of actuator with inertial magnetic mass.

Considering a permanent magnet of mass *m* connected to a rigid supporting structure by means of a magnetic spring *k* and a damper *c*, the mass being subjected to a force f_{em} provided by electromagnetic actuator, the transfer function between the applied force and the mass displacement, *x*, is:

$$G_x(s) = \frac{X(s)}{F_{\mathrm{em}}(s)} = \frac{1}{ms^2 + cs + k} = \frac{1}{m\left(s^2 + 2\zeta\omega_n s + \omega_n^2\right)}, \tag{1}$$

where: $\zeta = c/2\sqrt{mk}$ is the damping ratio and $\omega_n = \sqrt{k/m}$ is the natural frequency.

On the other hand, accelerating the mass produces a reaction force on the supporting structure equal to:

$$f = -m\ddot{x} \tag{2}$$

Therefore, the transfer function between the applied force f_{em} and the resulting force *f* is:

$$G_f(s) = \frac{F(s)}{F_{\mathrm{em}}(s)} = \frac{-s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{3}$$

The Fig. 2 illustrates the theoretical transfer function, amplitude-response, between the reaction force *f* at the actuator interface and the current *i* applied to the coil. One can see that the actuator behaves as a force generator for the frequencies above its suspension frequency, for $\zeta < 1$. Therefore, the only design parameters are the desired bandwidth and required control force. The electromagnetic force is expressed as $f_{em} = lBi$, where l and B are the coil winding length and the magnetic flux density in the coil, respectively. Maximum reaction force is obtained at the resonance, near its natural frequency, $\omega_n = \sqrt{k/m}$.

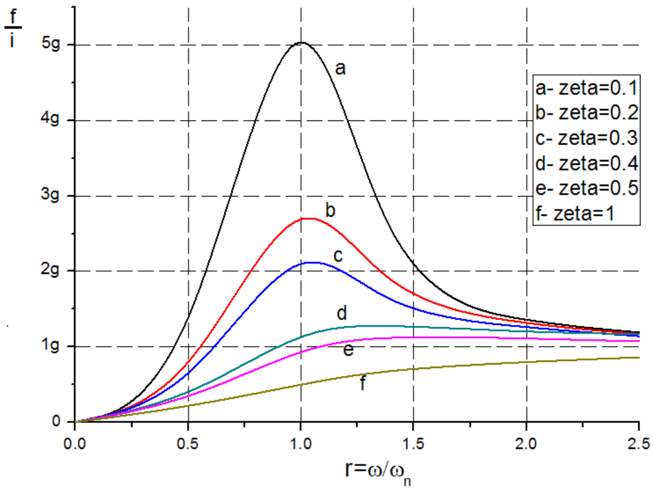


Fig. 2 – Different ζ values amplitude-response graph.

There are several advantages to implement an inertial actuator (as described above) into an active damping system, such as:

a) Generating damping within a structure or machine with an inertial actuator is a non-intrusive process, because no structural modification is need. The actuator is just fixed on the machine and adds damping.

b) Inertial actuators only need to be attached to the structure at a single point, thus enabling them to be connected in parallel with other passive or active dampers, so, damping is an additive process, and *i.e.* more devices can be attached to the structure to get more damping.

c) There is no need for external mechanical link, like it would be the case with classical dampers. Unlike classical dampers that need a physical reference anchor, the inertial actuator has a virtual reference point; it is “hooked to the sky”.

d) The performances of the inertial dampers are not driven by the mass ratio between the structure and the actuator such as with a tuned mass damper. The size of the actuator depends only on the required control force, so an impressive damping ratio has been achieved on a 400 kg structure with only a 20 g actuator.

3. Vibration Actuators with Suspended Magneto-Elastic Inertial Mass

Further, are presented and discussed four original configurations of devices for the generating and/or damping vibrations. Their differences in how to ensure the magneto-elastic suspension of the inertial mass consist mainly of using a non-magnetic body or one or more magnets. All four models of actuators can work both as generator of vibration or as absorber of shock and vibration.

3.1. Damper Actuator Based on the First Order Buoyancy Force in Ferrofluid

The buoyancy force of ferrofluid is constrained to the first and second order buoyancy principles. The first order buoyancy principle refers to the nonmagnetic body levitating in ferrofluid under external magnetic field.

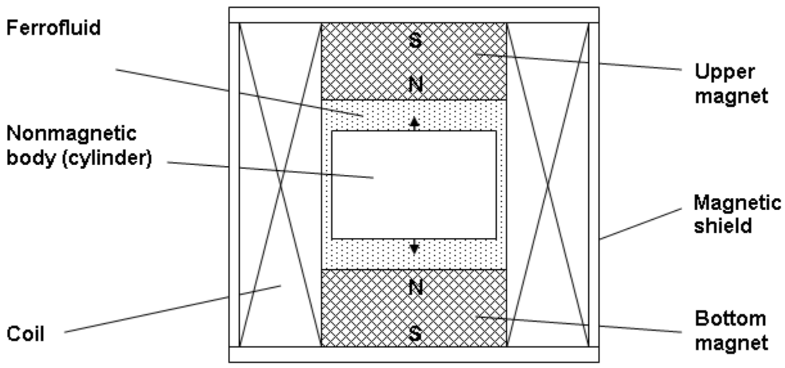


Fig. 3 – Damper actuator with non-magnetic body levitating in ferrofluid.

The implementation of this principle for a vibration semi-active damping with differentially biased magnetic field is illustrated in Figure 3. A ferrofluid differentially magnetized by the two magnets assures stable positioning of the nonmagnetic cylinder in the central position, for zero current in the coil, if gravity force is neglected. In the absence of an electric current through the coil, the damper is passive. Damping force transmitted to vibrating structure is determined by the feedback acceleration of the non-magnetic mass, which is magneto-elastic suspended in ferrofluid. This force has higher values near the resonance frequency of the non-magnetic cylinder in ferrofluid. The damper becomes active if an electric current, supplied by a control system, circulates through the coil that allows adjusting damping forces in a wide range of frequencies.

3.2. Vibrator Based on the Second Order Buoyancy Force in Ferrofluid

In the second order buoyancy force principle of ferrofluid, the magnet is levitating in ferrofluid in the absence of external magnetic field (self-levitating magnet). Based on this principle can be developed a small vibrator, for smart-phones, for example, where the vibrator is the thickest part of of the phone.

A small ring magnet levitates in a ferrofluid that is locked in a volume slightly higher than that of the magnet. Passing an electric current through the two coils connected in series and phase opposition makes the magnet to vibrate in ferrofluid (Fig. 4). The air bubble helps taking small volumes of ferrofluid dislodged during magnet vibration, reducing its viscous damping.

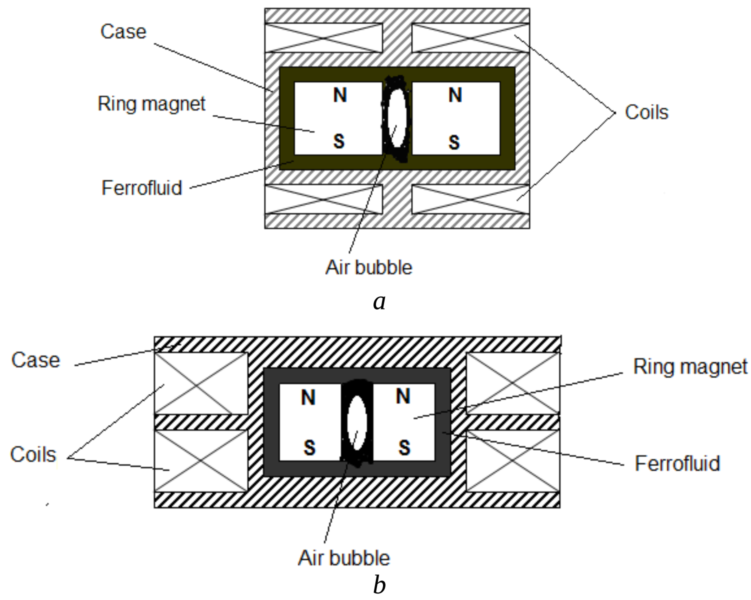
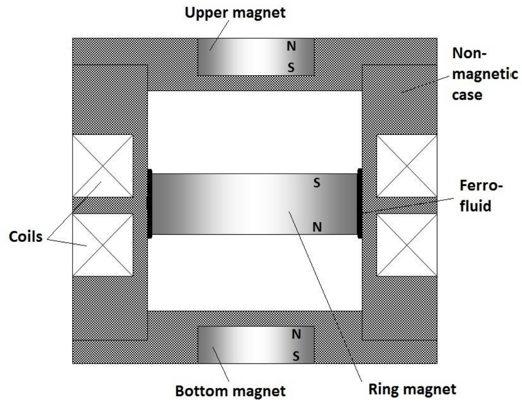


Fig. 4 – Vibration actuator with auto-levitated magnet in ferrofluid: *a* – each coil is positioned in front of a magnetic pole; *b* – coils positioned lateral.

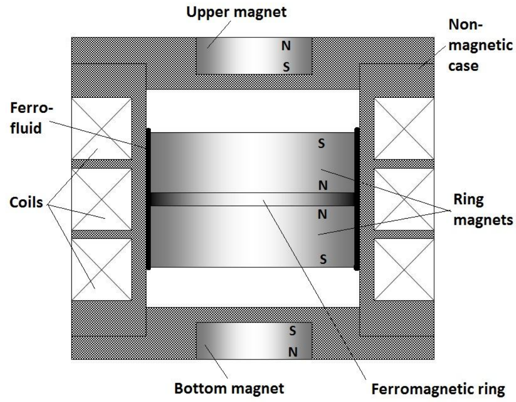
The vibrator, in its two versions, is characterized by an extreme simplicity, high reliability and very low cost.

3.3. Vibration Actuator with Magnetic Springs

Such actuator has the inertial mass suspended by two springs magnetic consisting of the movable magnetic mass and two fixed magnets that provide opposite forces (Fig. 5). In the first version, the simplest, it can use a single mobile magnet (Fig. 5 *a*) and in the second, the movable mass consists of two repulsive magnets between which is placed a ring of ferromagnetic material (Fig. 5 *b*). This second version is better, because the ferromagnetic ring increases the perpendicular magnetic component of magnetic field which crosses the central coil windings. An amount of ferrofluid placed in the circular gap between the movable mass and the non-magnetic case, which is attracted and retained on the lateral surface of the magnet(s) ensures a drastically reduction of friction, so the device can work at different angles from the vertical, even horizontally.



a



b

Fig. 5 – Vibration actuator with magnetic springs: *a* – one movable magnet and two coils; *b* – two movable magnets and three coils.

3.4. Vibration Actuator with Magnet Suspended by Magnetic Springs and a Ferrofluid Subjected to a Magnetic Bias Field

Such an actuator can be obtained with the vibration actuator based on magnetic springs presented above (Figs. 5 *a* and 5 *b*) if the cavity is filled with ferrofluid. The variant with a movable magnet is presented in Fig. 6. As a result, the magneto elastic force of the device and the damping supported by movable magnetic mass are increased. We get a very robust actuator that can work both as vibrator and damper at low frequencies, but also as violent shock absorber.

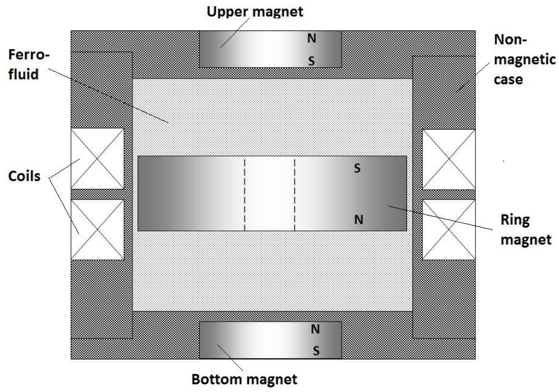


Fig. 6 – Vibration actuator with movable magnet sink in a biased magnetic ferrofluid.

4. Conclusions

This paper presents the working principles and technical solutions of non-conventional vibration electromagnetic actuators, which are distinguished by their magneto-elastic suspension of the inertial mass. Magneto-elastic suspension can be obtained in three ways, using: a ferrofluid that is magnetically polarized and a non-magnetic body as inertial mass; a ferrofluid in which is immersed a permanent magnet; magnetic spring(s) consisting of moving magnet(s) and two fixed magnets. In the latter case, the ferrofluid is applied in two ways leading to two actuator configurations.

From the perspective of their use in systems of vibration, these actuators are of great interest since remove the mechanical elastic elements, such as the springs, subject to wear and defect because of the numerous and lengthy operating cycles.

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CONCEPTE NOI DE ACTUATORI INERȚIALI PENTRU VIBRAȚII PE BAZĂ DE MAGNEȚI ŞI FEROFLUID

(Rezumat)

Actuatorii inerțiali sunt mult utilizați în aplicații ce necesită generarea şi controlul vibrațiilor. Lucrarea de față își propune să investigheze noi actuatori neconvenționali de vibrații cu masă inerțială suspendată datorită forțelor magneto-elastice. Forțele magnetice ce conduc la efecte pseudo-elastice pot fi obținute în trei moduri: interacțiunea unui corp nemagnetic, ca masă inerțială, cu un ferofluid premagnetizat diferențial de către magneți externi; autolevitarea unui magnet dispus într-o incintă umplută cu ferofluid; un aranjament magnetic repulsiv constând din unul sau mai mulți magneți mobili şi doi magneți ficşi.