Journal of Magnetism and Magnetic Materials 402 (2016) 28–33

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

The dynamics analysis of a ferrofluid shock absorber

Jie Yao [a], Jianjun Chang [a], Decai Li [a,*], Xiaolong Yang [b]

[a] School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] School of Mechanical Engineering, Guangxi University of Science and Technology, Liuzhou, Guangxi 545006, China

ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form
9 November 2015
Accepted 11 November 2015
Available online 14 November 2015

Keywords:
Ferrofluid
Shock absorber
Hydrodynamics
Energy dissipation

ABSTRACT

The paper presents a shock absorber using three magnets as the inertial mass. Movement of the inertial mass inside a cylindrical body filled with ferrofluid will lead to a viscous dissipation of the oscillating system energy. The influence of a dumbbell-like ferrofluid structure on the energy dissipation is considered and the magnetic restoring force is investigated by experiment and theoretical calculation. A theoretical model of the hydrodynamics and energy dissipation processes is developed, which includes the geometrical characteristics of the body, the fluid viscosity, and the external magnetic field. The theory predicts the experimental results well under some condition. The shock absorber can be used in spacecraft technology.

1. Introduction

Both magnetorheological (MR) fluid and ferrofluid, as the liquid magnetic material which can exist in the room temperature, are prospectively used in the field of vibration controls. MR fluid with the micrometre-scale particles greatly increases its apparent viscosity and becomes a viscoelastic solid in the presence of an external magnetic field. Importantly, the yield stress of the fluid can be controlled very accurately by varying the magnetic field intensity. Hence there have been lots of attempts in using the fluid to develop the active damping devices, such as the vibration isolator of a vehicle suspension [1,2]. However, the large decrease of the fluidity of MR fluid in a weak magnetic field will limit its application in these fields where low damping forces and small yield stresses are needed.

Unlike the MR fluid, ferrofluid particles are primarily nanoparticles which are suspended by Brownian motion and generally will not settle under normal conditions. So ferrofluid has an extremely great fluidity and a negligible yield stress in the strong magnetic field compared with MR fluid, which leads to a wider applications [3–5]. Such a relatively 'softer' ferrofluid has also shown lots of advantages in constructing damping devices [6]. Several types of ferrofluid dampers and shock absorbers have been proposed and investigated [7–18].

Some scholars have developed several types of the dampers by means of the viscous properties of the ferrofluid as the energy dissipating medium. Several early viscous dampers used for preventing oscillations of mobile elements are presented in [7–10]. The ferrofluid is inserted in the space between moving parts and stationary parts, being retained by strong magnetic forces. The magnetic field can be generated by the permanent magnet or electromagnet. The ferrofluid may fill or partially fill the damper space, which depends on the influence of the temperature expansion of the ferrofluid. Relative motion between the two parts is damped by the viscous shear force, which reduces oscillations and the extension of the moving parts.

From then on, based on the modes of operation of ferrofluid, these being shear mode and squeeze-flow mode, the active damper and the porous elastic sheet using ferrofluid are proposed in [11,12], respectively. Both of them are the extension of the traditional ferrofluid damper. In recent years, the viscous properties of the ferrofluid are also used in the tuned liquid damper (TLD) to enhance the performance of the TLD [13,14]. The TLD with a ferrofluid as the working fluid is called a tuned magnetic fluid damper (TMFD). The TMFD has a characteristic that the natural sloshing frequency can be changed by the external magnetic field.

Moreover, the unique levitation characteristic of ferrofluid, the self-levitation of an immersed magnet, are already used in shock absorber to eliminate the vibration of a satellite [15–18]. Some characteristics, including the non-linear stiffness, the frequency response of the permanent magnet-ferrofluid element and the surface instability of ferrofluid, in such type shock absorber have been studied in [19–21]. A new type of ferrofluid shock absorber is the best for eliminating the oscillations with small amplitude and small frequency in [15,16]. The action of the ferrofluid is twofold, i.e., it can provide the magnet with a light mobility due to liquid fluidity and it can work as an elastic damping material in the magnetic field. A Lanchester-like passive damper shows a good

* Corresponding author.
E-mail address: dcli@bjtu.edu.cn (D. Li).

http://dx.doi.org/10.1016/j.jmmm.2015.11.040

experimental result in [17]. Another new ferrofluid shock absorber with a simple structure is proposed in [18]. The ferrofluid shock absorber consists of an annular magnet immersed in a cylindrical nonmagnetic body filled with ferrofluid, which is fixed at one end of an elastic plate. However, a large discrepancy between theoretical and experimental results is ineluctable due to the negligence of the magnetic force acting on the vibrating object.

In this paper, a ferrofluid shock absorber with simple structure is presented. The theoretical model based on the shock absorber shows the dependences of the decrement of the oscillations on the geometrical characteristics of the body, the fluid viscosity, and the external magnetic field. The influence of a dumbbell-like ferrofluid structure around the magnets on the energy dissipation is considered in the theoretical model, which predicts the experimental results well.

2. Theoretical analysis

The model of the oscillating system is shown in Fig. 1.

The ferrofluid shock absorber consists of three cylindrical magnets and a nonmagnetic cylindrical body filled with ferrofluid. A stable suspended support force exerts on the cylindrical magnets and retains the magnets location in the center of body. When the magnets move from the initial position under the influence of external vibration, the volume distribution of ferrofluid gradually changes in body, and a magnetic restoring force occurs. Moreover, the flow of ferrofluid will dissipate the oscillating system energy. The performance parameter of the shock absorber is tested by the free oscillations of an elastic plate with one end fixed and the other free. For the damping system with two degrees in free vibration, the equations of motion are:

$$m_1\ddot{x}_1 + C_1\dot{x}_1 + C_2(\dot{x}_1 - \dot{x}_2) + K_1x_1 + F_m = 0$$
$$m_2\ddot{x}_2 - C_2(\dot{x}_1 - \dot{x}_2) - F_m = 0 \quad (1)$$

where m_1 is the equivalent mass of body, ferrofluid and elastic plate, m_2 is the mass of three magnets, x_1 and x_2 are the displacements of the elastic plate and magnets, respectively, C_1 and C_2 are the equivalent damping of the elastic plate and shock absorber, respectively, K_1 is the equivalent stiffness of the elastic plate and F_m is the magnetic restoring force. The main task of the absorber modeling is the calculation of the C_2 and F_m, and the following assumptions are necessary.

(1) Flow in a ferrofluid is laminar and steady-state.
(2) Collinear magnetization and field M//H.
(3) Temperature is constant in time and space.
(4) The change of viscosity of ferrofluid by magnetic field can be neglected.

2.1. Calculation of the equivalent damping C_2

According to hydrodynamics, the boundaries of ferrofluid must coincide with the isobars. In the system containing the ferrofluid, the magnetic force can replace or augment both the surface tension and body force effects. So the solid aggregate is almost consistent with the magnetic equipotential surface. The external vibration induces shear stress on the solid aggregate and forms a shear layer coating with the solid aggregate. If the Reynolds numbers are small, the ferrofluid will only flow along the continuous magnetic equipotential surface under the joint action of the Couette and Poiseuille flow. At this time, there is a critical radius forming at the ends of the magnets, which corresponds to the first continuous magnetic equipotential surface. It is only when the radius of the body exceeds the critical radius, $R_2 > R_c$, the flow occurs. The critical radius $R_c = 10.75$ mm can be determined in Fig. 2 by the place on the line having a same magnetic field

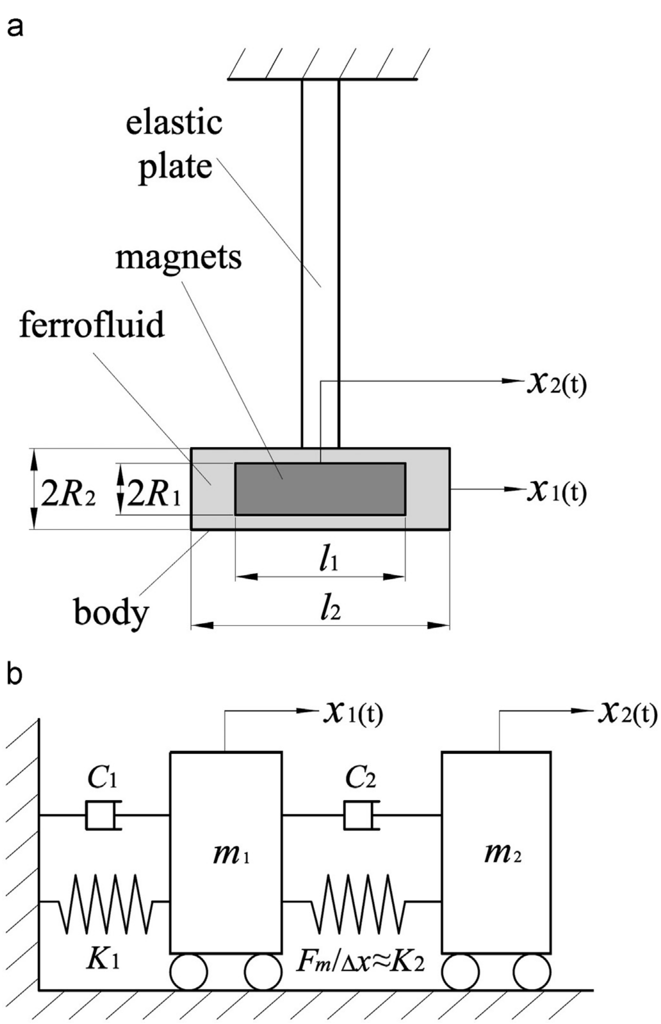

Fig. 1. A scheme of (a) the experimental setup and (b) the model of the oscillating system.

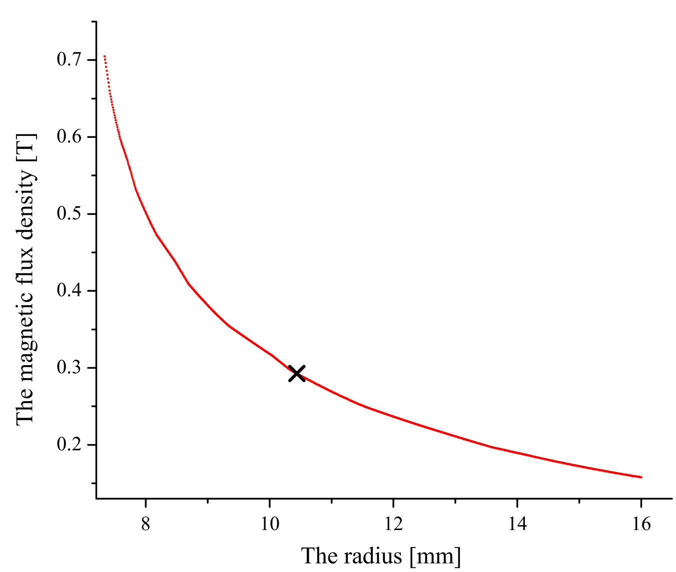

Fig. 2. The determination of the critical radius (line—dependence of the magnetic field strength at the ends of magnets on the radius, dot—the magnetic field strength at the middle of the three magnets with radius $r = R_1$).