Theoretical Energy Dissipation and Numerical Calculation of Passive Magnetic Fluid Damper

Xiaorui Yang[1], Qingxin Yang[1,2], Lifei Chen[1], Bing Guo[1], and Wenrong Yang[1]

[1] Province-Ministry Joint Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability, Hebei University of Technology, Tianjin 300130, China, wryang@hebut.edu.cn
[2] Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology, Tianjin Polytechnic University, Tianjin 300387, China, qxyang@hebut.edu.cn

Magnetic fluid is a kind of magnetic material. It is a stable colloidal solution mixture that the nano-sized ferromagnetic particles, for example Fe_3O_4, uniformly disperse in the base liquid by surfactant. Magnetic fluid is very stable and has no remanence and coercivity after demagnetization. Magnetic fluid can float the permanent magnet which has a larger specific gravity than the magnetic fluid itself. This phenomenon is known as the second-order buoyancy. Based on this principle, this paper focuses on a kind of passive magnetic fluid damper and builds the comprehensive energy dissipation model considering the magnetic field and liquid flow. The results show that the main factor influencing the damping properties of the damper is the size of the permanent magnet immersed in magnetic fluid. The simulated model is also built. The numerical results present that the flow dissipation has a decisive role in the total energy dissipation in the passive magnetic fluid damper. Because the magnetic fluid will be attracted to the permanent magnet, the magnetic field affects the relative size of the permanent magnets and the container. Passive magnetic fluid damper is sensitive to inertial force and has high reliability, small size, low cost. It can work with no external magnetic field or any other excitation source and is suitable for low-frequency vibration of some longer objects in spacecraft.

***Index Terms*—Magnetic fluid, Second-order buoyancy, Theoretical modeling, Vibration attenuation**

I. Introduction

Magnetic fluid is a kind of magnetic material. It is a stable colloidal solution mixture that the nano-sized ferromagnetic particles, for example Fe_3O_4, uniformly disperse in the base liquid by surfactant. Magnetic fluid presents dual characteristics of magnetism and liquid mobility. It is structurally similar to magnetorheological fluid (for short MRF).The difference between magnetic fluid and MRF is that the ferromagnetic particles in magnetic fluid are nano-sized while the particles in the magnetorheological fluid are micron-sized. The different structures lead to quite different properties between the magnetic fluid and MRF [1-2].

Magnetic fluid is very stable and has no remanence and coercivity after demagnetization. In a gradient magnetic field, the magnetic fluid is subjected to magnetic force. It can float the permanent magnet which has a larger specific gravity than the magnetic fluid. This phenomenon is known as the second-order buoyancy. Based on this principle, the passive magnetic fluid damper is proposed. Much work has been researched in the field of magnetic fluid and magnetic fluid damper [3~5]. However, there is no comprehensive energy dissipation model for this kind of damper. This paper has built the energy dissipation model considering the magnetic field and liquid flow. It is sensitive to inertial force and has high reliability, small size, low cost. It can work with no external magnetic field or any other excitation source and is suitable for low-frequency vibration of some longer objects in spacecraft.

II. Fundamental of Passive Magnetic Fluid Damper

The sketch of the passive magnetic fluid damper is shown as Fig.1, which is composed of a non-magnetic cylindrical container, magnetic fluid and a cylindrical permanent magnet. The container is filled with magnetic fluid and sealed. The permanent magnet immersed in the magnetic fluid is forced not only by buoyancy of liquid but also by the magnetic pressure, which is induced by magnetic field gradient in the radial direction. This magnetic pressure is called second-order buoyancy. Finally, when the magnetic pressure and gravity of the permanent magnet are balanced, the permanent magnet will be suspended in the lower middle of the container [6]. When damper is subjected to an external vibration, due to the inertia, the permanent magnet deviates from the equilibrium position to one side of the container, compressing the magnetic field lines. Then magnetic pressure will be generated towards the equilibrium position. The permanent magnet reciprocates and drives magnetic fluid to viscous flow until it is stable on the equilibrium position again. The viscous flow will absorb vibration energy and ultimately the damper will achieve the purpose of vibration attenuation.

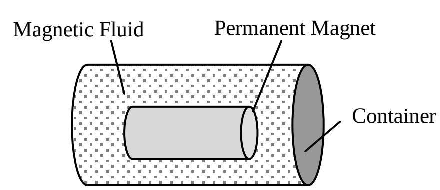

Fig 1. Sketch of the passive magnetic fluid damper.

III. Theoretical Energy Dissipation of the Damper

The flow of magnetic fluid can be regard as laminar flow. Taking a magnetic fluid hollow circular cylinder as the research object, the flow equation of the magnetic fluid can be written as (1).

$$\rho_{\mathrm{f}}(\mathrm{d}\boldsymbol{v} / \mathrm{d}t) = \boldsymbol{f}_p + \boldsymbol{f}_\eta + \boldsymbol{f}_{\mathrm{m}} \quad (1)$$

where $\boldsymbol{v}$ is the velocity of magnetic fluid; ρ_f is the density; $\boldsymbol{f}_p$ is the pressure gradient; $\boldsymbol{f}_\eta$ is the viscous force; $\boldsymbol{f}_m$ is the magnetic field force. As magnetic fluid is incompressible fluid, the expressions of them are as follows:

$$\mathrm{d}\boldsymbol{v} / \mathrm{d}t = \partial \boldsymbol{v} / \partial t + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = 0 \tag{2}$$

$$\boldsymbol{f}_p = -\nabla p = \Delta p / L \tag{3}$$

$$\boldsymbol{f}_\eta = \eta_H \nabla^2 \boldsymbol{v} + \eta_H \nabla(\nabla \cdot \boldsymbol{v}) / 3 = \eta_H \nabla^2 \boldsymbol{v} \tag{4}$$

$$\boldsymbol{f}_m = \mu_0 \boldsymbol{M} \cdot \nabla \boldsymbol{H} = (\mu - \mu_0) H \cdot \nabla H \tag{5}$$

where p is the differential pressure of the two ends of the magnetic fluid; L is length of the permanent magnet; η_H is viscosity in magnetic field. In the gradient magnetic field, the influence of magnetic field on the magnetic fluid is mainly magnetic field force, so the viscosity is considered as constant.

Combining the boundary conditions and the fluid continuity equation, the velocity distribution of the magnetic fluid in the axial direction can be obtained. Based on the velocity of the magnetic fluid, the energy dissipation of the damper in unit time can be calculated. This energy dissipation can be divided into two parts, one part of the flow energy dissipation, as (6), and the other part of the magnetic field loss, as (7).

$$\begin{aligned} W_1 &= 2\pi\eta_H L\left[\dot{x}_m - K_1 \ln\left(R_2 / R_1\right)\right]\left(R_1^{\,2} + R_2^{\,2}\right) \\ &\quad + 8\pi\eta_H L\left\{\left[\dot{x}_m - K_1 \ln\left(R_2 / R_1\right)\right] / \left(R_1 + R_2\right)\right\} \\ &\quad + 2\pi\eta_H L K_1^{\,2} \ln\left(R_2 - R_1\right) \end{aligned} \tag{6}$$

$$\begin{aligned} W_2 &= 2\pi\eta_H \cdot \\ &\int_0^L \mathrm{d}z \int_{R_1}^{R_2} 2\pi\left(\mu - \mu_0\right) / \eta_H \int_{R_1}^{R_2} H_z\left(\mathrm{d}H_z / \mathrm{d}z\right) r \mathrm{d}r F \mathrm{d}r \end{aligned} \tag{7}$$

where τ is the internal friction between the magnetic fluid and the permanent magnet. R_1 and R_2 are the radiuses of the permanent magnet and the container correspondingly. $\dot{x}_m$ is the velocity of the permanent magnet. μ and μ_0 are the magnetic permeability of the magnetic fluid and the vacuum permeability respectively. K_1 and F can be described as (8) and (9).

$$\begin{aligned} K_1 &= \dot{x}_m / \\ &\left\{\left[2R_2^{\,2} / \left(R_2^{\,2} - R_1^{\,2}\right)\right] \cdot \ln\left(R_2 / R_1\right) + \ln\left(R_2 / R_1\right) - 1\right\} \end{aligned} \tag{8}$$

$$\begin{aligned} F &= \left(\mu - \mu_0\right) \int_{R_1}^{R_2} H_z\left(\mathrm{d}H_z / \mathrm{d}z\right) r \mathrm{d}r / \eta_H r \\ &\quad - 2\left\{2r\left[\dot{x}_m - K_1 \ln\left(R_2 / R_1\right)\right] / \left(R_2^{\,2} - R_1^{\,2}\right) + K_1 / r\right\} \end{aligned} \tag{9}$$

IV. Numerical Calculations

In order to research the relationship between the factors and the energy dissipation of the damper, the numerical model of the passive magnetic fluid damper is built. The work liquid is the ester-based magnetic fluid. The density is 1.86 (kg/m^3). The saturation magnetization and dynamic viscosity is 300 (Gs) and 23.2 (mPa*s) accordingly. The diameter and length of the container is 25 (mm) and 55 (mm) accordingly. The remanence of the permanent magnet is 1.5 (T). Fig.2 shows the flow energy dissipation W_1 varies with the size of the permanent magnet in different vibration velocities. Fig.3 shows the shows that the magnetic field loss W_2 varies with the size of the permanent magnet.

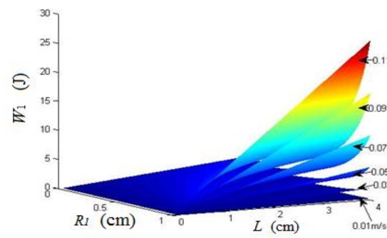

Fig.2 The flow energy dissipation W_1 varies with the size of permanent magnet

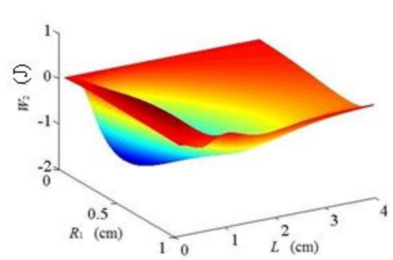

Fig.3 The magnetic field loss W_2 varies with the size of permanent magnet

V. Results and Conclusion

From the Fig.2 and Fig.3, the energy dissipation of the damper is mainly due to the flow energy dissipation of the magnetic fluid. The flow energy dissipation increases with the size of the permanent magnet. The magnetic field loss has little effect on the whole energy dissipation. But the magnetic field will affect the flow condition of the magnetic fluid. In Fig.2, the positive values represent the energy dissipation caused by magnetic field, and the negative values act as lubrication for reducing the energy dissipation in the damper.

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