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Optimal design of a tuned liquid damper using a magnetic fluid with one electromagnet

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Abstract
Characteristics of a tuned magnetic fluid damper are examined. The optimal depth of a magnetic fluid in a cylindrical container is calculated using a linear analysis of a magnetic fluid sloshing. In order to avoid swirling in lower depth fluids, several experiments using greater fluid depths are carried out and a good damping range is obtained.

1. Introduction

Various types of dampers are used in order to dampen oscillations of buildings, bridges and the like. One type of damper that is commonly used is a tuned liquid damper (TLD). The TLD is a passive mechanical damper that contains water as a working liquid. The TLD uses sloshing hydrodynamic force to dampen oscillations by tuning the sloshing natural frequency to the system oscillation frequency. The TLD has been used effectively to reduce vibrations of tall buildings, long span bridges and offshore structures subjected to earthquakes, wind, and waves.

Modi and Munshi [1] performed a parametric study focused on enhancing the energy dissipation efficiency of a rectangular TLD through introduction of a two-dimensional obstacle. They obtained a significant increase in energy dissipation. Sun *et al* [2] measured liquid motion in shallow TLDs, including rectangular, circular and annular tanks, subjected to harmonic base excitation. Using a tuned mass damper (TMD) analogy, they calibrated the TLD parameters from experimental results. Olson *et al* [3] analysed a sloped-bottom tuned liquid damper using a nonlinear stiffness and damping model. Their results indicate that the stiffness of 30° angle slope is softening while stiffness of 0° angle slope is hardening. They also concluded that the tank frequency should be slightly higher than the fundamental natural frequency of the structure.

Unfortunately, these types of TLDs generally cannot be actively controlled. In order to enhance the performance of the TLD using active control, functional fluids are used rather than water or other liquids and electric or magnetic forces are used as external forces to actively control the functional fluids. Abe *et al* [4] proposed an active TLD using a magnetic fluid (called a tuned magnetic fluid damper, TMFD, herein) and the TMFD's performance was verified experimentally using a two-storey building model. Ohira *et al* [5] demonstrated the further potential of a TMFD using four electromagnets beside a cylindrical container and by applying various kinds of magnetic field. The damping effect of this TMFD was considered to be due to the direct damping of the magnetic force. Horie *et al* [6] measured the magnetic force, and carried out a simulation of a TMFD based on this idea. Horie *et al* concluded that the magnetic force does not dampen oscillations directly and the change in the damping characteristic of the TMFD is effected by the natural frequency change caused by the effective mass change when the magnetic field is applied. In particular, the effective mass means the part of the sloshing fluid mass that is involved in generating hydrodynamic force.

In the present paper, we examine the damping characteristic of the TMFD and determine the optimal number and position of electromagnets and the depth of the magnetic fluid and show the resulting damping effects experimentally.

2. Damping characteristic

The unique damping characteristic of the TMFD is related to the ability to change the natural frequency of sloshing of the magnetic fluid. Because of this characteristic, the TMFD is a damper whose natural frequency can be controlled.

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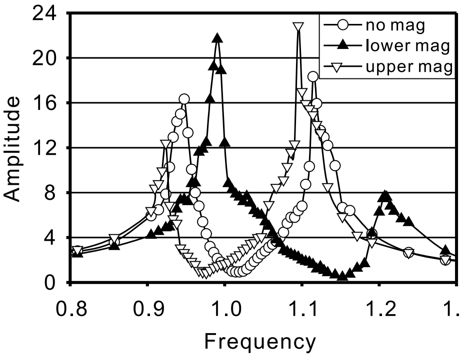

Figure 1. Example effect of TMFD.

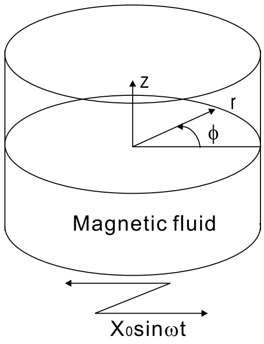

Figure 2. Analytical model of a sloshing magnetic fluid.

An example of the frequency response of the TMFD under different magnetic fields is shown in figure 1. It shows that effective damping can be obtained over a wide frequency range by controlling sloshing behaviour. Thus, it is important to know how the sloshing natural frequency of the magnetic fluid changes on the basis of the magnetic field applied. Initially, a linear analysis is done in order to obtain the sloshing natural frequency.

The sloshing natural frequency is obtained from an unsteady irrotational Bernoulli equation for the magnetic fluid and a continuity equation. If the cylindrical container is used as the magnetic fluid container and excitation of amplitude X_0 is added to the container in the horizontal direction as shown in figure 2, the equations are written in the following form:

$$\rho\frac{\partial\phi}{\partial t}+\frac{1}{2}\rho|v|^2+p+\rho gz-\mu_0\int_0^H M\,\mathrm{d}H$$
$$=\rho X_0\omega^2 r\sin\omega t \quad (1)$$

$$\frac{\partial^2\phi}{\partial r^2}+\frac{1}{r}\frac{\partial\phi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\phi}{\partial\theta^2}+\frac{\partial^2\phi}{\partial z^2}=0 \quad (2)$$

where ρ is the density, ϕ is the velocity potential, v is the velocity, p is the pressure, g is the gravitational acceleration, z is the displacement from a free surface, μ_0 is the magnetic permeability of vacuum, M is the magnetization, H is the magnetic field and ω is the angular frequency. If the magnetization and magnetic field are assumed to be parallel and the susceptibility of the magnetic fluid is assumed to be constant, the magnetic term of equation (1) becomes

$$\mu_0\int_0^H M\,\mathrm{d}H=\mu_0\int_0^H \chi H\,\mathrm{d}H=\frac{\mu_0}{2}\chi H(z)^2$$
$$=\frac{\mu_0}{2}\chi {H_0}^2\,\mathrm{e}^{-2\alpha(z+h)} \quad (3)$$

where χ is the susceptibility, h is the depth of the magnetic fluid, H_0 is the average magnetic field intensity at the bottom of the container ($z=-h$), and α is a constant determined from experimental measurements of the magnetic field. Here α represents the attenuation rate of the magnetic field. The sign of α corresponds to the direction of the magnetic field. The natural frequency of the magnetic fluid calculated from equations (1)–(3) is given by

$$f_{mn}=\frac{1}{2\pi}\sqrt{\frac{\varepsilon_{mn}g^*}{R}\tanh\frac{\varepsilon_{mn}h}{R}} \quad (4)$$

where f_{mn} is the natural frequency, ε_{mn} is the zero of the differential of the Bessel function of first kind, R is the radius of the container and the subscripts m and n indicate oscillation modes. Here m and n correspond to horizontal and rotational oscillations, respectively. g^* is the apparent gravitational acceleration and is given by

$$g^*=g+\frac{\alpha\mu_0\chi {H_0}^2\,\mathrm{e}^{-2\alpha h}}{\rho}. \quad (5)$$

Here $H_0\,\mathrm{e}^{-\alpha h}$ is the magnetic field intensity at a free surface of the magnetic fluid in the container. Thus equations (4) and (5) show that the natural frequency changes with change in the magnetic field intensity at the surface of the magnetic fluid.

The sloshing natural frequency of the magnetic fluid changes on the basis of equations (4) and (5). From these equations, the factor that is changing the sloshing natural frequency is the magnetic field. Moreover, it is necessary to generate the magnetic field in a vertical direction to change the natural frequency. Since the damping characteristic of the TMFD can be adjusted by changing the natural frequency, the proper control of a vertical magnetic field can produce an optimal damping effect for various types of vibrations.

3. Basic design

The TMFD device can be formed as a rectangular shape, a cylindrical shape or other shape. In this paper, a cylindrical container is used as the TMFD container because the electromagnet is round and the TMFD is set above or under the electromagnet.

If the electromagnet is above the TMFD container, a lower natural frequency of the sloshing can be obtained. However, the effect of using an upper electromagnet is often much smaller than that of using a bottom electromagnet (below the TMFD container) because the distance between the magnetic fluid surface and the upper electromagnet is longer and the magnetic field intensity at the surface is smaller. When using a bottom electromagnet, there is another method for reducing the sloshing natural frequency. As shown in equation (4), decreasing the depth of the magnetic fluid also provides a lower sloshing natural frequency. In this experiment, one electromagnet is provided under the TMFD container and is used to increase the natural frequency while the fluid depth is lowered to decrease the initial value of the sloshing natural frequency.

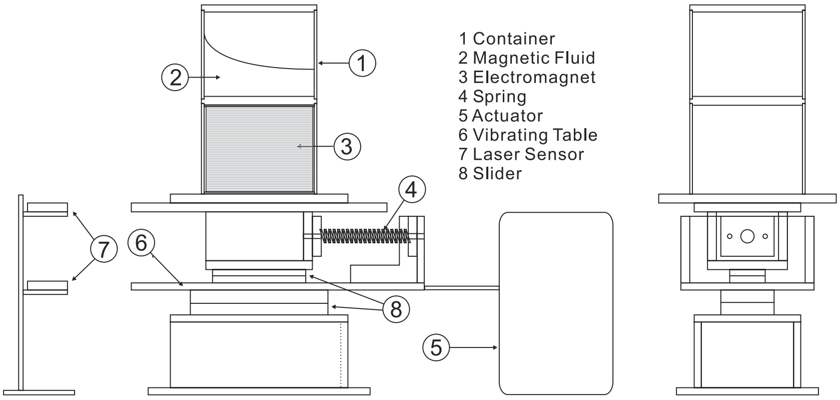

Figure 3. Experimental apparatus.

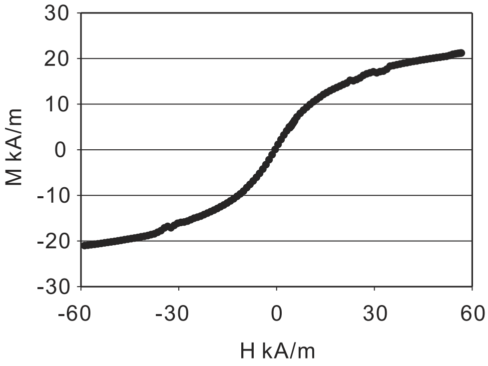

Figure 4. Magnetization curve of EXP01052.

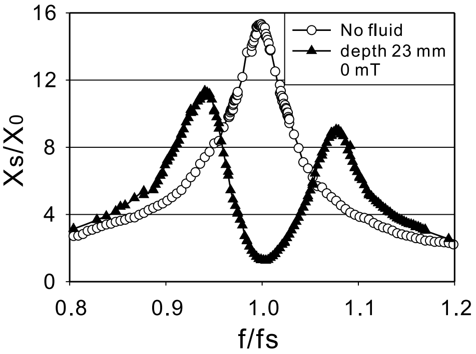

Figure 5. Frequency responses with no fluid and with fluid at depth 23 mm with 0 mT.

4. Experiment

In equation (3), the susceptibility of the magnetic fluid χ is assumed to be constant for convenience even though it is not constant in reality. A value for the susceptibility χ must be obtained by experiment and is obtained from the change of the natural frequency of the TMFD.

A schematic diagram of the experimental apparatus based on the basic design is shown in figure 3. The cylindrical container has an inner diameter of 123 mm. The cylinder contains a kerosene-based magnetic fluid EXP01052 produced by Ferrotec Corporation and having a magnetization curve as shown in figure 4. An electromagnet is placed on the bottom of the TMFD container such that the magnetic field can only be applied to the magnetic fluid from the bottom. The electromagnet and TMFD container are placed on a roller table which is supported on a vibrating table. The total mass of the TMFD device and the roller table, which are considered as a single structure, is 12.38 kg. The vibrating table is moved by an actuator and the excitation force is applied to the roller table by a spring between the vibrating table and the roller table. Displacements of the roller table and the vibrating table are measured by laser displacement transducers.

The vibrating table is oscillated at the amplitude of $X_0 = 0.20$ mm. The exciting frequency is varied from 1.0 to 3.0 Hz and the frequency interval is not constant. The current supplied to the electromagnet is changed from 0.0 to 3.0 A, measuring every 0.5 A. The magnetic field intensity is changed with the current intensity linearly. The maximum magnetic field intensity at the barycentric position of the magnetic fluid is 54 mT. The attenuation rate of magnetic field α is 23.31. The natural frequency without the magnetic fluid is 2.05 Hz.

5. Results and discussion

5.1. Frequency response

Figure 5 shows that the TMFD can be effective as a simple TLD, by comparing the frequency response with no magnetic fluid with that with a magnetic fluid of depth of 23 mm but with no magnetic field. Here f is the exciting frequency. f_s and X_s are the natural frequency and the oscillatory amplitude of the structure, respectively. When the structure is intensively vibrated in a region around the natural frequency f_s, the displacement of the structure is clearly suppressed by using the magnetic fluid. The suppression is particularly strong near the natural frequency f_s. Notably, there are two almost symmetrical peaks that occur on opposite sides of f_s. These two peaks are small in comparison with the peak for the result without a magnetic fluid. Thus, there is a large damping effect achieved when using the magnetic fluid in the structure model even when there is no magnetic field applied.

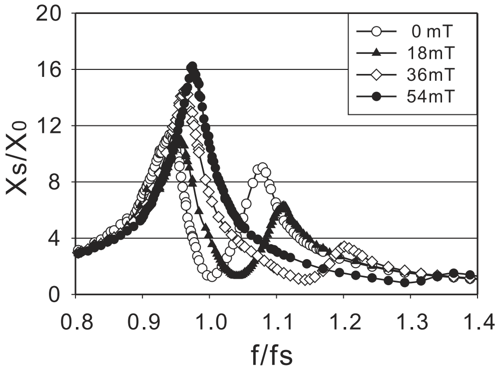

Figure 6. Frequency responses with fluid at depth 23 mm.

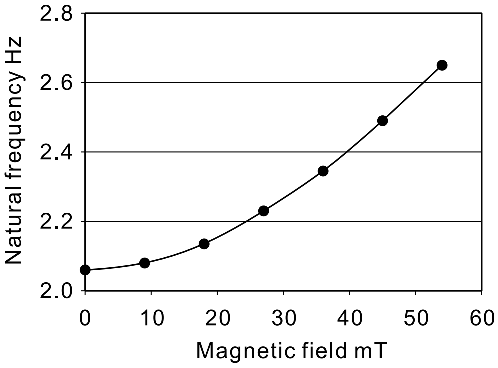

Figure 7. Change of natural frequency at depth 23 mm.

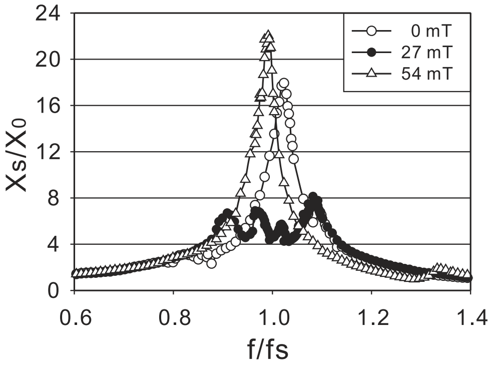

Figure 8. Frequency responses at depth 16 mm.

The frequency responses of the TMFD for several magnetic fields are shown in figure 6. The maximum damping point moves to a higher frequency region with increasing magnetic field intensity. This increase corresponds to the change of the natural frequency of the TMFD as shown in figure 7. Because the maximum magnetic field is 54 mT in this case, the maximum natural frequency corresponds to $f/f_s = 1.14$. This means that an effective damping range for a depth of 23 mm is $1.0 < f/f_s < 1.14$. When the fluid depth decreases, the effective damping area moves to a lower frequency region.

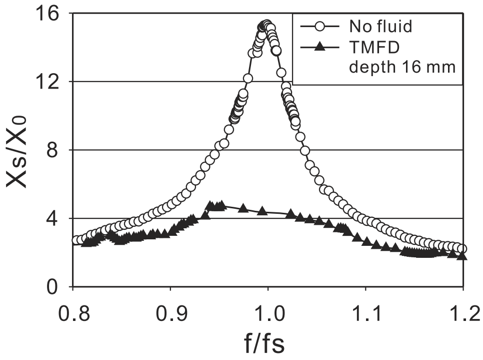

Figure 9. Minimum amplitudes at depth 16 mm.

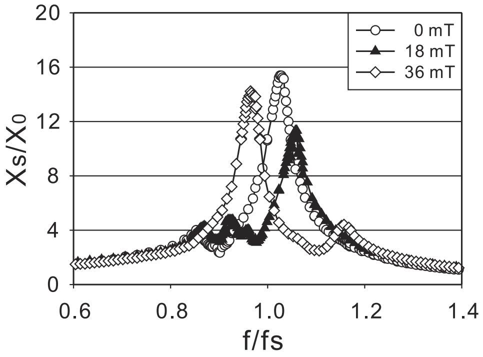

Figure 10. Frequency responses at depth 18 mm.

5.2. *Optimal fluid depth*

From equations (4) and (5), the maximum and minimum natural frequencies are respectively given by

$$f_{\min} = \frac{1}{2\pi}\sqrt{\frac{\varepsilon_{mn} g}{R}\tanh\frac{\varepsilon_{mn} h}{R}} \quad (6)$$

$$f_{\max} = \frac{1}{2\pi}\sqrt{\frac{\varepsilon_{mn}}{R}\left(g + \frac{\alpha\mu_0\chi H_{\max}{}^2\,\mathrm{e}^{-2\alpha h}}{\rho}\right)\tanh\frac{\varepsilon_{mn} h}{R}} \quad (7)$$

where $H_{\max}$ is the maximum value of H_0. $f_{\min}$ is the natural frequency in no magnetic field. In order to obtain the optimal fluid depth, the middle point of the variable range of the natural frequency is tuned to the natural frequency of the structure. That is, we calculate the fluid depth h, satisfying $f_s = (f_{\min} + f_{\max})/2$. Then we obtain $h = 14$ mm. However, because this fluid depth is too small, a swirling effect occurs. Swirling is defined as free surface rotation around the central axis of the container in a specific forcing frequency range. It is necessary to use a fluid depth greater than $h = 14$ mm to avoid swirling. The frequency response for $h = 16$ mm is shown in figure 8. Figure 9 shows minimum amplitude obtained from figure 8 at each frequency and indicates that the TMFD has good damping ability. The minimum amplitudes are very small over a wide frequency range. Interestingly, the shape of the frequency response for 27 mT has a strange curve as shown in figure 8. This disturbance appears to be caused by swirling. When the maximum magnetic field is 36 mT, the optimal fluid depth is $h = 18$ mm. In this case, the frequency responses and minimum amplitudes are shown in figures 10 and 11. From

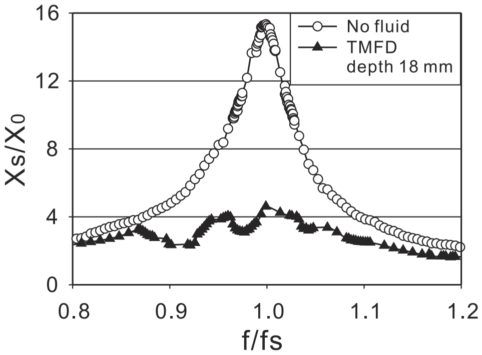

Figure 11. Minimum amplitudes at depth 18 mm.

figure 10, the disturbance caused by the swirling is reduced. The magnetic field range is smaller than that for $h = 16$ mm but a good damping effect is indicated in figure 11.

6. Concluding remarks

The characteristics of a TMFD are examined experimentally. In these experiments, only one electromagnet, placed under the magnetic fluid container, is used effectively to change the response of the TMFD. The range of damping frequencies can be changed by varying both the fluid depth and the applied magnetic field. The optimal depth of the magnetic fluid is calculated from the sloshing natural frequency, which is calculated by using a linearized approach. When the optimal fluid depth is small, there may be additional complications from the swirling phenomenon. The experiments indicated that, even if the optimal fluid depth is not used to avoid swirling, a good damping effect can be obtained.

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