Experimental study on damping characteristics of the tuned liquid column damper with magnetic fluid

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Abstract. A magnetic fluid is a smart, colloidal, and strongly magnetizable fluid, and is composed of a base liquid, ferromagnetic particles, and a chemically adsorbed surfactant. A tuned liquid column damper (TLCD) — devised for vibration mitigation of high structures — is a passive damper categorized as a dynamic absorber. Using a magnetic fluid as the working fluid of a TLCD can improve and change the TLCD into a novel semiactive damper. The natural frequency of a TLCD with a magnetic fluid can be changed via a magnetic field. This novel damper can be used as an effective vibration suppression mechanism for building structures. In this study, we investigate the effect of the magnetic field on the natural frequency of a TLCD with a magnetic fluid. In addition, using the experimental results, we demonstrate the relationship between the setting positions of an electromagnet, the strength of the magnetic field, and the changes in the natural frequency.

1. Introduction
The recent development in lightweight high-strength materials and associated construction techniques permits the building of high-rise structures. These structures are very sensitive to wind excitations and long-period seismic waves because of their small structural damping and low natural frequencies. Therefore, low-frequency vibration in high-rise structures is a critical design issue, and the development of an effective vibration suppression mechanism is often necessary. A tuned liquid column damper (TLCD) can mitigate vibrations in high-rise structures and is categorized as a passive damper. Since its introduction by Sakai et al. [1] in 1989, a TLCD has been investigated by many researchers for setting structures [2-4]. It can suppress wind excitations and earthquake-induced vibrations in structures such as tall buildings by absorbing the energy via the motion of the liquid mass in a tube-like container. A TLCD is a reliable and low-cost application. In addition, it yields a simple analyzable motion because it follows a simple mechanism. It consists of a container partially filled with a liquid (water in most cases).

The natural frequency of a TLCD is significant because the oscillation can only be suppressed in a narrow range around its natural frequency. Therefore, it is necessary to control the damping characteristics of a TLCD by using a simple additional mechanism. The semiactive damper is a controllable passive damper. Several researchers have proposed various semiactive TLCDs including a semiactive TLCD with an active orifice, where damping can be controlled by the
orifice opening [5,6], and a magneto-rheological tuned liquid column damper (MR-TLCD), which was designed by Wang et al. [7]. An MR-TLCD consists of a magneto-rheological fluid and an orifice, where damping can be controlled by a magnetic field.

In this study, we design a novel semiactive damper using a magnetic fluid as the working fluid. This damper is called the tuned liquid column damper with a magnetic fluid (MF-TLCD). A magnetic fluid is a smart fluid that can be strongly magnetized in the presence of a magnetic field. In addition, it is attracted to magnets strongly depending on the strength of the magnetic field. Because of this attribute, the damping characteristics of an MF-TLCD, especially its natural frequency, can be controlled by the magnetic field. We conduct experiments to analyze the effect of the magnetic field on the natural frequency of the MF-TLCD. We also discuss the relationships among the setting positions of an electromagnet, the strength of the magnetic field, and the changes in the natural frequency.

2. Theoretical approach

2.1. Magnetic fluid column oscillation in a U-pipe in the presence of a magnetic field

Let us consider the magnetic fluid motion in a U-pipe with an electromagnet, as shown in figure 1. Assuming a magnetic fluid is inviscid and incompressible, the equation of motion of a liquid column oscillation in the presence of a magnetic field is

$$\rho Al \ddot{\eta} + 2 \rho A g \dot{\eta} + F_{mag} = 0$$

(1)

where $\rho$ is the density of the magnetic fluid, $A$ is the cross sectional area of the U-pipe, $g$ is the gravitational acceleration, $l$ is the length of the liquid column, $\eta$ is the displacement of the free surface of the magnetic fluid from the rest position, and $F_{mag}$ is the force generated by the magnetic field. In the absence of the magnetic field, i.e., $F_{mag} = 0$, the natural frequency of this liquid column vibration $\omega_f$ is

$$\omega_f = \left(\frac{2g}{l}\right)^{1/2}$$

(2)

In the presence of a magnetic field, the magnetic fluid is attracted to the magnet, and the additional pressure $p_{mag}$ appears as follows:

$$p_{mag} = \mu_0 \int_0^{H(s)} MdH'$$

(3)

![Figure 1. One degree of freedom model of magnetic fluid column oscillation.](image)
where $\mu_0$ is the magnetic permeability in vacuum, $M$ is the magnetization, and $H'$ is the magnetic field, and $H(s)$ is the magnetic field intensity where the position is $s$. In weak magnetic fields, we can assume that $M = \chi H$, using the susceptibility $\chi$ and equation (3) is written as

$$\mu_0 \int_0^H M dH' = \mu_0 \chi \int_0^H H' dH'$$

$$= \frac{1}{2} \mu_0 \chi H^2$$

(4)

Considering a coordinate system $s$ as shown in figure 1, the magnetic force $dF_{mag}$ acting on a small line element $ds$ can be written as

$$dF_{mag} = Adp_{mag} = A\mu_0 \int_{H(s)}^{H(s+ds)} MdH'$$

$$= \frac{1}{2} A\mu_0 \chi \left[ \left( H(s+ds) \right)^2 - \left( H(s) \right)^2 \right]$$

$$= \frac{1}{2} A\mu_0 \chi \left\{ \frac{d}{ds} \left( H^2 \right) \right\} ds$$

(5)

Since the electromagnet placed on one side of the U-pipe, the magnetic field effects on only one side column part ($h \leq s \leq (l - b)/2$). Integrating equation (5) yields

$$F_{mag} = \frac{1}{2} A\mu_0 \chi \int_{\eta}^{(l-b)/2} \left\{ \frac{d}{ds} \left( H^2 \right) \right\} ds$$

$$= \frac{1}{2} A\mu_0 \chi H^2 \bigg|_{\eta}^{(l-b)/2}$$

(6)

where $b$ is the distance between two fluid columns. Equation (6) indicates the summation of the magnetic force acting on the magnetic fluid column. According to equations (1) and (6), the

![Figure 2. Two degrees of freedom model of the structure with MF-TLCD.](image-url)
The equation of motion of the magnetic fluid column oscillation in the U-pipe in the presence of a magnetic field is

\[
\rho Al\ddot{\eta} + 2\rho Ag\dot{\eta} + \frac{1}{2} A\mu_0 \chi \left[ \{ H(\eta) \}^2 - \left\{ H \left( \frac{l-b}{2} \right) \right\}^2 \right] = 0 \tag{7}
\]

The magnetic field distribution in a solenoidal coil is given by

\[
H(\eta) = \frac{NI}{2L} \left[ \frac{\eta + h + L/2}{\left( \eta + h + L/2 \right)^2 + r_{em}^2}^{1/2} - \frac{\eta + h - L/2}{\left( \eta + h - L/2 \right)^2 + r_{em}^2}^{1/2} \right] \tag{8}
\]

where \( N \) is the number of coil turns, \( I \) is the supplied electric current, \( L \) is the length of the solenoid coil, \( r_{em} \) is the inner radius of the solenoid coil, and \( h \) is the displacement of the center of the solenoid coil from the free surface of the magnetic fluid.

### 2.2. Motion of the structure with MF-TLCD

Figure 2 shows two degrees of freedom model of the structure with an MF-TLCD. From equation (7), the equation of motion of the structure with an MF-TLCD is given by

\[
\begin{bmatrix}
\rho Al & \rho Ab \\
\rho Ab & \rho Al + m_s
\end{bmatrix}
\begin{bmatrix}
\ddot{\eta} \\
\ddot{x}
\end{bmatrix}
+ \begin{bmatrix}
c_f & 0 \\
0 & c_s
\end{bmatrix}
\begin{bmatrix}
\dot{\eta} \\
\dot{x}
\end{bmatrix}
+ \begin{bmatrix}
2\rho Ag & 0 \\
0 & k
\end{bmatrix}
\begin{bmatrix}
\eta \\
x
\end{bmatrix}
+ \begin{bmatrix}
A\mu_0\chi/2 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\{ H(\eta) \}^2 - \left\{ H \left( \frac{l-b}{2} \right) \right\}^2 \\
0
\end{bmatrix} = 0 \tag{9}
\]

where \( x \) is the displacement of the structure, \( m_s \) is the mass of the structure, \( c_f \) is the viscous damping coefficient of fluid motion, \( c_s \) is the viscous damping coefficient of the structure, and \( k \) is the spring constant. In equation (9), we consider that the viscous damping of liquid column vibration works as damping of vibration.
3. Experiment

3.1. Experimental setup

Figure 3 illustrates a schematic diagram of the experimental apparatus. The magnetic fluid is placed in the U-pipe container. A detailed cross section of the U-pipe is shown in figure 4. By applying a virtual instrument (VI) LabVIEW, the frequency of the actuator can be controlled. The sine wave vibration is provided by the actuator and is transferred to the structure through the spring and the vibration base between the two smooth slider mechanisms. The vibration amplitude is 0.4 mm. Two laser sensors were used to measure the displacements of the structure and the vibration table, as well as the phases of their vibrations. The pressure of the magnetic fluid in the U-pipe was measured using a pressure transducer. Instead of the displacement of the magnetic fluid’s free surface, we monitored the frequency response of the time-dependent pressure. We confirmed that the pressure change corresponds to the free-surface displacement. We used a kerosene-based magnetic fluid, whose characteristics are shown in table 1.

3.2. Arrangement of an electromagnet

An electromagnet was mounted on one side of the U-pipe as shown in figure 4. When the magnetic field was applied, the magnetic fluid was attracted to the electromagnet, and the position of the still free surface changed. As a result, a revised parameter $h_c$ was introduced as shown in figure 4.

3.3. Magnetic field distributions

We measured the spatial distributions of both $r$ and $z$ components of the magnetic field by using a Gauss meter. The intensity of the magnetic field was calculated by using these experimental

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Table 1. Characteristics of magnetic fluid.

| Characteristic                  | Value              |
|--------------------------------|--------------------|
| Density ($25^\circ$C)          | 1350 kg/m$^3$      |
| Viscosity ($25^\circ$C)        | 5.34 mPa·s         |
| Saturation magnetization       | 48 ± 5 kA/m        |
magnetic field components. Figures 5 and 6 show the axial and radial distributions of the magnetic field intensity for a 1.0 A electric current, respectively. The magnetic field intensity reaches a maximum value at \( z = 0 \) mm, and decreases as \(|z|\) increases. Thus, figures 6 and 7 indicate that the magnetic field intensity depends on \( z \) rather than \( r \).

4. Results and discussions

Figure 7 shows the frequency responses of the the structure with an MF-TLCD; \( a_s \) is the amplitude of the structure; \( f \) and \( a_0 \) are the excitation frequency and amplitude of the actuator, respectively. The frequency response varies for according to different values of \( H_0 \), which is defined as the reference magnetic field intensity obtained at the center point \((z = 0 \) mm, \( r = 0 \) mm) of the electromagnet.

Figure 8 shows the relationship between the natural frequency \( f_n \) and the magnetic field intensity. These frequency responses correspond to the time-dependent pressure waves obtained from the pressure transducer. Here \( f_0 \) is the natural frequency in the absence of a magnetic field. The natural frequency is defined as the frequency where the frequency response is minimal as shown in figure 7. When \( h \) is smaller than 0 mm, the natural frequency increases with \( H_0 \). In contrast, when \( h \) is larger than 0 mm, the natural frequency decreases in the presence of weak
magnetic fields and increases in the presence of strong magnetic fields. Thus, the position of the electromagnet plays an important role in the transition of the natural frequency.

Figure 9 shows the distributions of the natural frequency with \( h \) for various values of \( H_0 \). The experimental results are compared with those obtained from numerical simulation. The symbol and full line of the same color indicate experimental and numerical results, respectively. We numerically solved equation (7) using the 4th-order Runge–Kutta method. Comparing these results, the experimental and numerical results are found to be qualitatively coincident. Therefore, it is verified that equation (7) expresses the motion of the magnetic fluid column oscillation in a U-pipe in the presence of a magnetic field.

The still magnetic fluid level changes when the magnetic field is applied and \( h \) varies according to the magnetic field. Subsequently, we replace \( h \) with the revised parameter \( h_c \) as shown in figure 4. Figure 10 shows the relation between natural frequency and \( h_c \), and compares the experimental and numerical results. Figure 10 is the revised version of figure 9. When \( h_c \) is smaller than approximately \(-8\) mm, all experimental values of \( f_n \) are larger than \( f_0 \). On the other hand, when \( h_c \) is larger than approximately \(-8\) mm, all values of \( f_n \) are less than \( f_0 \). Thus,
it is determined that $h_c$ is a vibration characteristic of the MF-TLCD under the presence of a magnetic field. However, the zero-cross point in the numerical results is larger than $-8$ mm.

Figure 11 shows the total magnetic attraction force acting on the magnetic fluid in the entire U-pipe in the presence of various magnetic fields. These results are obtained from the static experiment. We measured the equilibrium position of both magnetic fluid surface levels in the U-pipe with and without a magnetic field. A numerical simulation was carried out ignoring the first term of equation (7). The value of the magnetic force is maximum when $h_c$ is $-9$ mm, where the natural frequency hardly changes. The electromagnet has a specific position. When the electromagnet is located in this specific position, the natural frequency does not change despite the applied magnetic fields. These experimental results indicate whether the change in the natural frequency is positive or negative, and consequently, estimate their approximate values.

Comparing experimental and numerical results, there exist some differences in $h_c$ for the maximum peak points. The experimental $h_c$ values are smaller than those obtained by numerical simulation. These differences increase with $H_0$. It is considered that these differences are

![Figure 9. Distributions of the natural frequency with $h$ for various values of $H_0$.](image1)

![Figure 10. Distributions of the natural frequency with $h_c$ for various values of $H_0$.](image2)
caused by the curvature of the free surface of the magnetic fluid. In numerical simulation, we assumed that the surface of the magnetic fluid is flat in the U-pipe. However, in reality, this is not the case because of the radially distributed gradient of the magnetic field, which results in a surface curvature for the magnetic fluid. This causes $h_c$ to be somewhat different from that in the numerical model, as shown in figure 4. Therefore, it is necessary to consider the radial distribution of the magnetic field to calculate the total magnetic attraction forces more accurately.

5. Concluding remarks
We devised a novel TLCD using a magnetic fluid. It can suppress structural vibrations and change its damping characteristics by changing the magnetic field. Our experimental results showed that the natural frequency was dependent on the position of the electromagnet. These results are in good agreement with those obtained numerically via the 4th order Runge–Kutta method. It is also demonstrated that the natural frequency changes can be estimated from the experimental results.

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