Study on the Characteristics of an Oscillating Flat Plate in Iron-Nitride Magnetic Fluid*

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Iron-nitride magnetic fluid has higher magnetization compared with water-based magnetic fluid W-40 or kerosene-based magnetic fluid HC-50 that are usually used. The effects of magnetic field on oscillation characteristics of a flat plate in iron-nitride magnetic fluid are investigated experimentally and compared with the case of other magnetic fluids especially taking into account the viscous effect. It is clarified that the iron-nitride magnetic fluid has relatively large viscous effect on damping characteristics compared with the commercial magnetic fluids.

Key Words: Magnetic Fluid, Oscillatory Flow, Fluid Force, Flat Plate, Magnetic Field, Viscous Damping Coefficient, Added Mass

1. Introduction

Magnetic fluids are functional ones to respond to a magnetic field and widely investigated in the basic and applied fields. In the application of magnetic fluids, many studies for development of magnetic fluid damper, actuator and other various equipments have been conducted[(1)-(9)]. Recently, new magnetic fluid with a high quality has been prepared and its fluid properties are investigated.

Magnetic fluid with iron-nitride particles has a larger magnetization compared to the case of usual magnetic fluid with magnetite particles. Therefore, it is possible to develop new equipment showing higher performance by applying high magnetic force acting on the magnetic fluid. However, the experimental studies have been hardly conducted hitherto in the fields of actual application and its model tests except for the study of basic fluid properties because of the difficult treatment of new magnetic fluid[(10),(11)]. It is, therefore, necessary to clarify the basic flow properties of iron-nitride magnetic fluid in order to develop new application field of magnetic fluid.

In this paper, experimental study on a vibrating flat plate immersed in the iron-nitride magnetic fluid is carried out as a basic study to develop magnetic fluid damper. The flat plate is selected for easiness of analysis. Further, the comparison of iron-nitride magnetic fluid with usual magnetic fluid with magnetite particles (W-40 and HC-50) is conducted on the effect of viscous damping characteristics on the vibrating characteristics of the flat plate in an applied magnetic field.

2. Resistance Force Acting on Flat Plate in a Liquid

2.1 Derivation of resistance force from experimental data

Figure 1 shows an analytical model of a flat pate vibrating in a magnetic fluid. The flat plate ④ is immersed in a magnetic fluid ③ in a vessel ② on a base table ①. The flat plate is connected to the vibrating exciter ⑦ through the supporting rod ⑤ and

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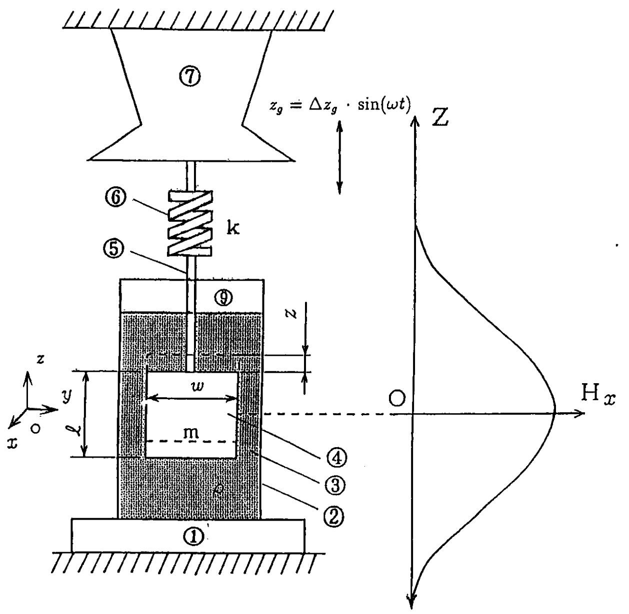

Fig. 1 Schematic diagram of a vibrating flat plate ①Table ②Vessel ③Magnetic fluid ④Flat plate ⑤ Shaft ⑥ Spring ⑦ Vibrating exciter ⑨ Guide

spring ⑥. The flat plate is excited to vibrate in a magnetic fluid in an applied stationary magnetic field as shown in Fig. 1.

The equation of motion of flat plate is expressed as follows[12),(13)].

$$m\frac{d^2z}{dt^2}+k(z-z_g)=D \tag{1}$$

where m: mass of flat plate, z: displacement of flat plate, t: time, k: spring constant, z_g: displacement of vibrating exciter, D: fluid resistance force. The magnetic force term is neglected in Eq. (1) since the effect of magnetic pressure acting on the plate is symmetrical to $z=0$ line and negligible in the case of small amplitude. When the precise measurement of displacement of z and z_g is possible, the resistance force D is obtained from Eq. (1) with substitution of z and z_g. However, in the actual experimental study, the amplitude ratio and phase difference of z and z_g are recorded instead of time-series data of displacement. Therefore, the following process is necessary to obtain the D-values.

In the case of small amplitude, it is possible to describe D as the linear equation of displacement z as

$$D=-C\frac{dz}{dt}-m_A\frac{d^2z}{dt^2} \tag{2}$$

where C and m_A are viscous damping coefficient and added mass which depend only on frequency f and not on time t.

Now, let's consider to express the displacement of exciter and plate as a function of angular frequency $\omega=2\pi f$ and phase difference ϕ as

$$z_g=\Delta z_g\cdot\sin(\omega t) \tag{3}$$

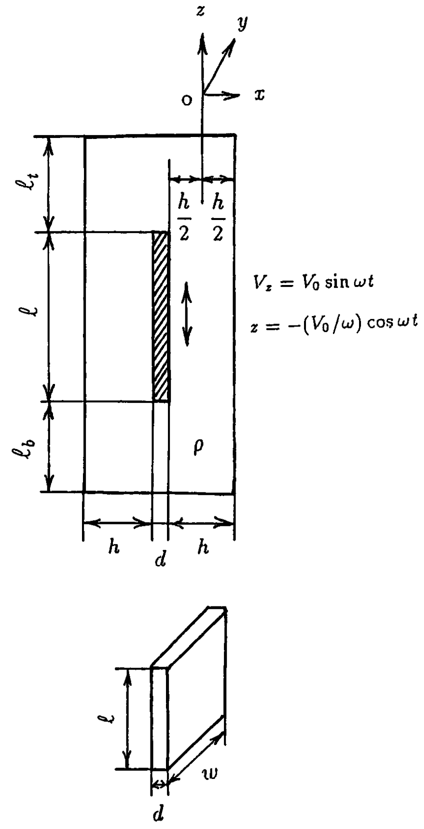

Fig. 2 Vibrating flat plate in a magnetic fluid

$$\omega=2\pi f,$$
$$z=\Delta z\cdot\sin(\omega t+\phi) \tag{4}$$

Substituting Eqs. (2)-(4) into Eq. (1), the following equations are obtained.

$$C=\frac{k}{\omega}\cdot\frac{1}{a}\sin\phi \tag{5}$$

$$m_A=\frac{k}{\omega^2}\left(1-\frac{1}{a}\cdot\cos\phi\right)-m \qquad \left(a=\frac{\Delta z}{\Delta z_g}\right) \tag{6}$$

When the amplitude ratio $a=\Delta z/\Delta z_g$ and phase difference ϕ are obtained, the values of C and m_A are calculated from Eqs. (5) and (6). Also, the mean square values of D is obtained as

$$\frac{\sqrt{\overline{D^2}}}{V_0}=\sqrt{\frac{1}{2}C^2+\frac{1}{2}m_A^2\omega^2} \tag{7}$$

where V_0 is velocity amplitude $(=\omega\Delta z)$.

2.2 Analytical study

Theoretical values of m_A and C are also obtained from analytical study on a fluid flow around a vibrating flat plate. The analytical study is conducted by using a simplified analytical model as shown in Fig. 2 in which the thin flat plate vibrates in a large vessel with infinite length of z- and y-directions with velocity $V_z=V_0\sin\omega t$. The following assumptions are employed

(1) Magnetic fluid is incompressible Newtonian fluid.

(2) Flow is two-dimensional.

(3) Plate and vessel are long enough.
$l \gg h,\ l_t \gg h,\ l_b \gg h$

(4) Flow is a parallel one except for the edge portion of plate.
$u_z = u_z(t, x),\ u_x = 0$
$p = p(t, z),\ \partial^2 p/\partial z^2 = 0$

(5) At the edge portion
$\partial p/\partial x = 0,\ \partial^2 p/\partial z^2 = 0$

In the analytical study, Shliomis formula[14] is used for an apparent viscosity. Also, the effect of particles aggregation is ignored.

The basic equation of plate motion and boundary conditions are then expressed as follows.

Basic equation:
$$\rho\frac{\partial u_z}{\partial t} = -\frac{\partial p}{\partial z} - \eta\frac{\partial^2 u_x}{\partial x^2} \tag{8}$$

Condition of flow continuity:
$$dV_0 \sin \omega t = -2\int_{-h/2}^{h/2} u_z dx \tag{9}$$

Boundary condition:
$$u_z = 0 \text{ at } x = h/2 \tag{10}$$
$$u_z = V_0 \sin \omega t \text{ at } x = -h/2 \tag{11}$$

where η is the apparent viscosity which include the effect of applied magnetic field[14].

We assume velocity u_z and pressure p by using coefficients f_c, f_s, a_c, a_s in Eqs. (12) and (13).
$$u_z(t, x) = V_0[f_c(x)\cdot\cos \omega t + f_s(x)\cdot\sin \omega t] \tag{12}$$
$$p(t, z) = \rho V_0\omega[a_c\cdot\cos \omega t + a_s\cdot\sin \omega t]z + \text{const} \tag{13}$$

The origin of x-coordinate is taken at the center of the gap between plate and vessel wall h as shown in Fig. 2. The coefficients f_c and f_s are expressed as Eq. (14) by dividing into even and odd functions.
$$\left.\begin{array}{l} f_c = f_{c\,\text{even}} + f_{c\,\text{odd}} \\ f_s = f_{s\,\text{even}} + f_{s\,\text{odd}} \end{array}\right\} \tag{14}$$

Substituting Eq. (14) into Eq. (8), then the two-pair simultaneous differential equations are obtained. Concerning the even functions $f_{c\,\text{even}}$, $f_{s\,\text{even}}$ and odd functions $f_{c\,\text{odd}}$, $f_{s\,\text{odd}}$, the following homogeneous solutions are obtained.
$$\cos\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right)\cdot\cosh\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right),$$
$$\sin\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right)\cdot\sinh\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right)$$
and
$$\cos\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right)\cdot\sinh\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right),$$
$$\sin\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right)\cdot\cosh\left(\sqrt{\frac{\rho\omega}{2\eta}}x\right)$$
where W_O is the Womersley number defined as
$$W_O = \frac{h}{2}\sqrt{\frac{\rho\omega}{2\eta}} \tag{15}$$

The solutions of f_c, f_s, a_c and a_s are obtained by determining the coefficients to satisfy the boundary conditions and continuity condition.

Substituting the solutions of f_c, f_s, a_c and a_s into Eqs. (12) and (13), then the solution of u_z and p is obtained. Furthermore, fluid resistance force $D = D_p + D_f$ is obtained by using the solution of u_z and p as a function of W_O, where D_p is pressure resistance force and D_f the viscous resistance force.

Next, substituting D into the left-hand side of Eq. (2) and arranging the equation, the viscous damping coefficient C and added mass m_A are obtained as Eqs. (16) and (17).
$$C(\omega) = \frac{2\eta l w}{h}W_O\left[\left(1+\frac{d}{h}\right)^2 \times \frac{(E+S)\cos W_O\cdot\sinh W_O - (E-S)\sin W_O\cdot\cosh W_O}{E^2+S^2} + \frac{\sinh W_O\cdot\cosh W_O + \sin W_O\cdot\cos W_O}{(\cos W_O\cdot\sinh W_O)^2 + (\sin W_O\cdot\cosh W_O)^2}\right] \tag{16}$$
$$m_A(\omega) = \rho d l w\left[\frac{d}{2h} + \frac{h}{d}\left(1+\frac{d}{h}\right)^2\frac{1}{4W_O} \times \frac{(E-S)\cos W_O\cdot\sinh W_O + (E+S)\sin W_O\cdot\cosh W_O}{E^2+S^2} + \frac{h}{d}\cdot\frac{1}{4W_O} \times \frac{\sinh W_O\cdot\cosh W_O - \sin W_O\cdot\cos W_O}{(\cos W_O\cdot\sinh W_O)^2 + (\sin W_O\cdot\cosh W_O)^2}\right] \tag{17}$$
where
$$E = \cos W_O\cdot\cosh W_O - \frac{(\sin W_O\cdot\cosh W_O + \cos W_O\cdot\sinh W_O)}{2W_O} \tag{18}$$
$$S = \sin W_O\cdot\sinh W_O - \frac{(\sin W_O\cdot\cosh W_O - \cos W_O\cdot\sinh W_O)}{2W_O} \tag{19}$$

Considering W_O as fixed values, the C-values are proportional to the viscosity η. However, W_O includes η in the definition itself. Therefore, in the case of large W_O ($W_O \gg 1$), W_O is proportional to $\eta^{1/2}$.

3. Experimental Apparatus and Method

Figure 3 shows an experimental apparatus. To prevent the degradation of fluid quality, the apparatus is covered by nitride gas within the case made by a transparent acrylic resins plate with thickness of 15 mm as shown in Fig. 3. To measure the displacement of plate by using noncontacting optical displacement meter which measure the movement of index ⑩, the glass plate with the size of 200 mm×200 mm×2 mm is attached to the case for making the light-pass possible. The tested flat plate is made of titanium with the size of 30 mm×30 mm×3 mm. The measuring process is as follows. Magnetic fluid ③ is immersed in the rectangular vessel ② with the size of 50 mm×110 mm×9 mm. The test plate ④ which is connected to supporting rod ⑤, spring ⑥ and vibrating exciter ⑦ is inserted in the magnetic fluid. After applying the

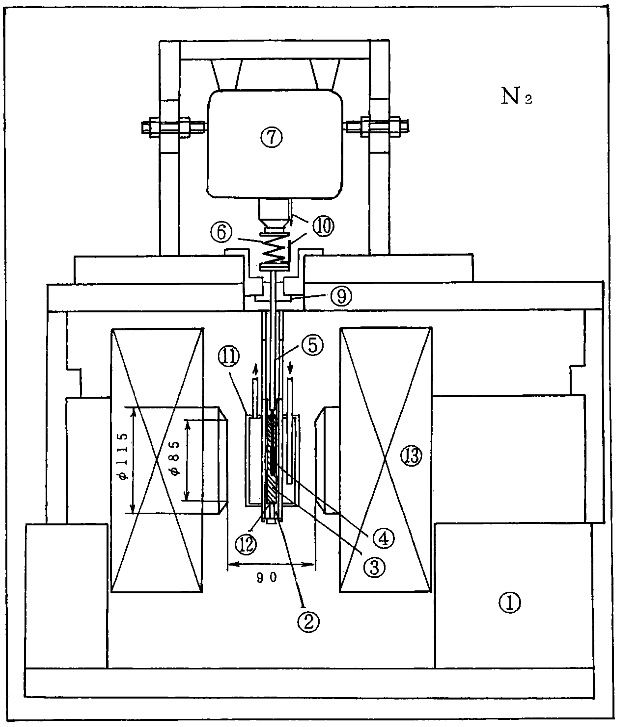

Fig. 3 Experimental apparatus of vibrating flat plate ①Table ②Vessel ③Magnetic fluid ④Flat plate ⑤Shaft ⑥Spring ⑦Vibrating exciter ⑨Guide ⑩ Index ⑪ Constant temperature vessel ⑫ Thermocouple ⑬ Electromagnet

stationary magnetic field by the electromagnet ⑬, the oscillation of plate is started by the vibrating exciter. The displacement of the plate and the vibrating exciter and their phase difference are recorded by the measurement of movement of each index ⑩ and analyzed by FFT analyzer. The measurement of the displacement is conducted in the range of linearity conserved with the consideration of small displacement. The magnetic fluid used here is a kerosene-based with iron-nitride particles (FeN) which shows a high quality and usual commercialized fluids with magnetite particles (water-based (W-40) and kerosene-based (HC-50) fluids).

The values of C and m_A are obtained by substituting the measured values of $a\,(=\Delta z/\Delta z_g)$ and ϕ into Eqs. (5) and (6) because the direct measurement of viscous damping coefficient C and added mass m_A is impossible. However, it is necessary to correct the effect of Coulomb force acting on the supporting rod due to the solid contact with the guide ⑨ in Fig. 3. That is, the Coulomb force is measured in the operating condition of plate oscillation without magnetic fluid. Therefore, the true values of C and m_A is obtained from subtracting the Coulomb force term from the measured values in the case of vibrating plate immersed in a magnetic fluid.

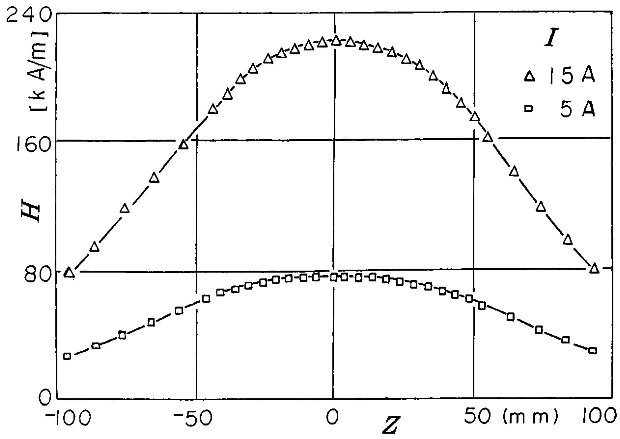

Fig. 4 Distribution of magnetic field strength (I=5 A, 15 A)

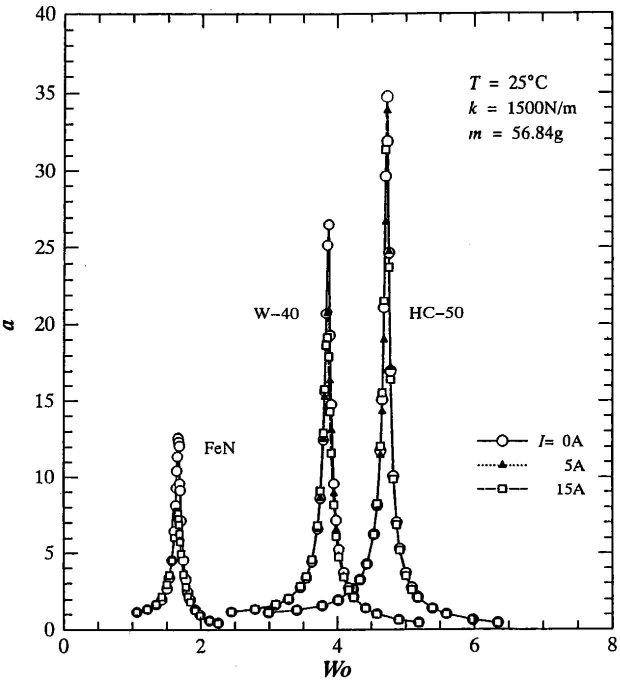

Fig. 5 Vibrating characteristics of amplitude

4. Experimental Results and Discussion

Figure 4 shows the applied magnetic field distribution in which the sign I means a supply current to the coil of electromagnet.

The experimental data in this paper are taken under the conditions of spring constant k=1 500 N/m, mass of plate m=56.84 g and liquid temperature T= 25°C (constant). Figure 5 shows the relation of amplitude ratio $a=\Delta z/\Delta z_g$ to Womersley number W_o. It is clear from this figure that a-values and also W_o number at resonance point decrease in order of HC-50, W-40 and FeN fluids which strongly depends on the fluid viscosity in the case of no magnetic field. Also, the maximum a-values at resonance point

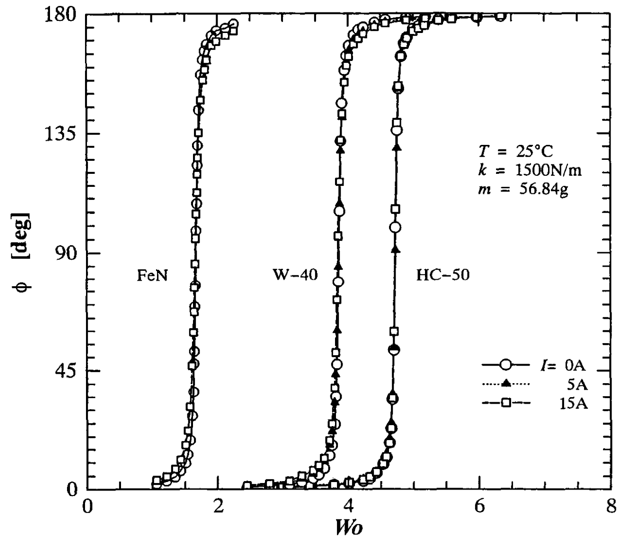

Fig. 6 Vibrating characteristics of phase difference

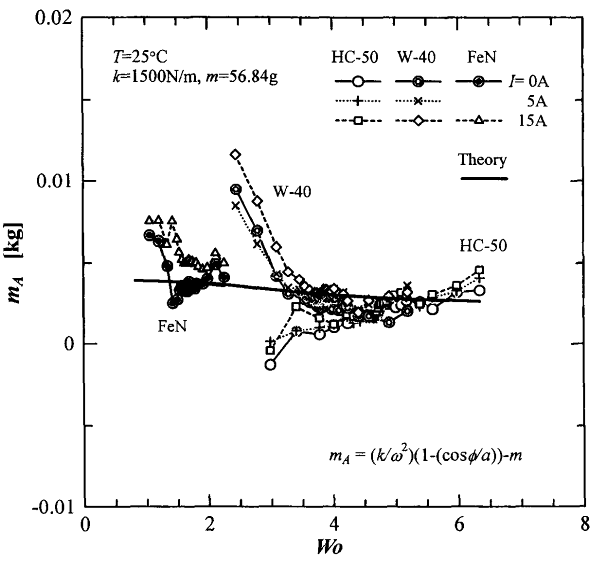

Fig. 8 m_A versus Womersley number

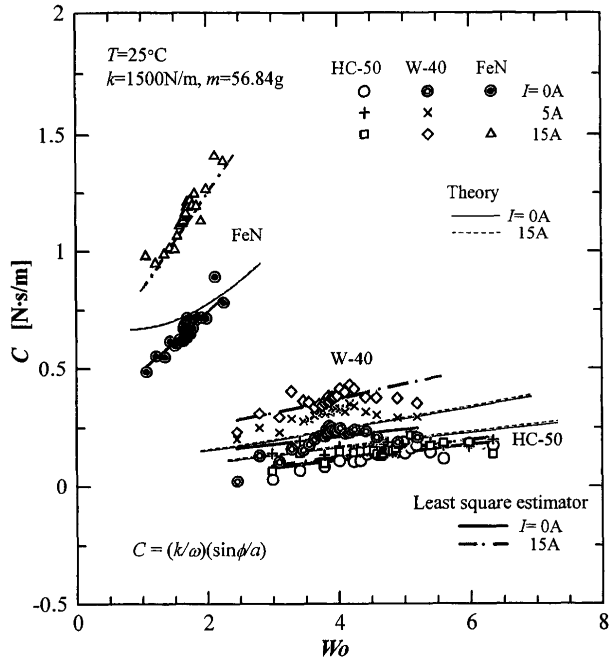

Fig. 7 C versus Womersley number

decrease with increase in the applied magnetic field.

Figure 6 shows the relation of phase difference ϕ to Womersley number W_O. The effect of the applied magnetic field on ϕ is very small and the ϕ-values increase slightly in the range of smaller W_O number than the resonance point and decrease in the range of larger W_O.

Figures 7 and 8 show C and m_A calculated from Eqs. (5) and (6) using measured a- and ϕ-values and corrected by the subtracting the Coulomb effect. The analytical values of C and m_A are also shown in the same figure. Although the increase in the viscosity occurs due to the application of magnetic field, it is not taken into account in the W_O values in Figs. 7 and 8. Although it is necessary to correct the W_O-values considering the viscosity change, the precise evaluation of this correction is difficult since it is impossible to determine the precise values of viscosity increment due to the application of magnetic field.

It is clear from Fig. 7 that the C-values increase with the application of magnetic field in all kind of magnetic fluids. In the case of no magnetic field, there is difference of about 10% between the experimental data and analytical values in all kind of magnetic fluids. In the applied magnetic field case, the experimental data show a large increase in C compared to the case of no magnetic field. On the other hand, the calculated values do not show the effect of applied magnetic field clearly. The reason why such difference occurs is as follows.

1. The effect of particle aggregation on the viscosity change in the applied magnetic field is neglected in the analytical study.
2. The viscosity of based fluid is used in the Shliomis formula[14],[15]. It does not consider the existence of the surfactant.
3. It is difficult to realize parallel flow in the edge portion of the plate in the actual flow condition.

Next, from Fig. 8, it is clear that the added mass m_A increases slightly with the applied magnetic field except for the case of HC-50. However, the increase in m_A is very small compared to the plate mass of $m = 56.84$ g. In analytical solution which is obtained from Eq. (17), the m_A-values are expressed in one line since the density of the magnetic fluids is nearly same.

Concerning the Coulomb friction force, the vibrating state of the supporting rod is differ between plate oscillation with and without a magnetic fluid. Therefore

Table 1 Values of unknown coefficients by least square method

	α [N·s/m]	β [N·s/m]	γ [%]	δ [%]
HC-50	-1.450×10^{-2}	3.162×10^{-2}	11.61	16.44
W-40	7.893×10^{-2}	3.261×10^{-2}	78.62	20.26
FeN	0.2471	0.2474	74.16	7.19

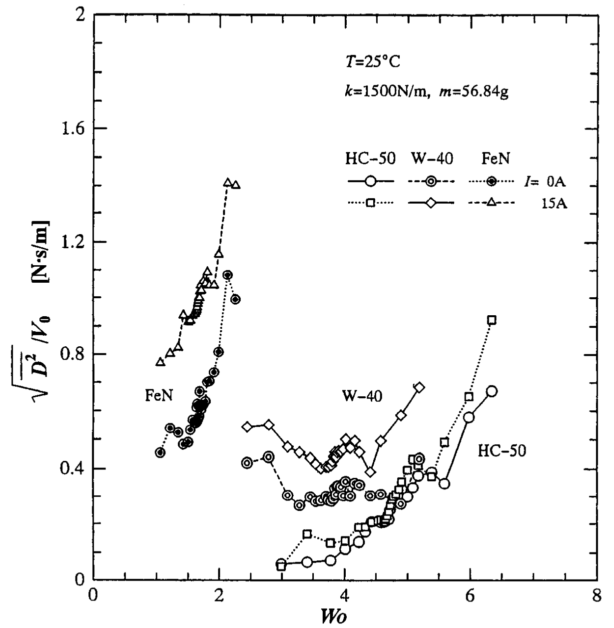

Fig. 9 Fluid resistance versus Womersley number

the experimental values of m_A depend strongly on the W_O-values.

Now let's consider the increasing rate of C with the application of magnetic field. When the increasing rate is directly calculated from the experimental values of C which include several errors, these errors are extraordinary evaluated. Therefore, in this paper, the following approximating process is considered. By using the unknown factors α, β, γ, the viscous damping coefficient C in the cases of supply current of 0 A and 15 A is formulated as

$$C_0^*=\alpha+\beta W_O \quad (20)$$

$$C_{15}^*=(1+\gamma/100)\cdot(\alpha+\beta W_O) \quad (21)$$

where γ is increasing rate of C due to the applied magnetic field.

The data of α, β and γ obtained by a method of least squares with the experimental data are indicated in Table 1, where δ is standard error of increment rate[16]. Minimum square regression line obtained from these data is also shown in Fig. 7.

From Table 1, increasing rate γ in FeN-fluid is 75% which is the same as W-40 fluid and is much

Table 2 Resistance increment with magnetic field of 15 A coil current

	Average [N·s/m]	Standard deviation [N·s/m]
HC-50	0.0423	0.0584
W-40	0.1475	0.0463
FeN	0.3772	0.0476

larger than the case of HC-50 ($\gamma=11\%$). As the viscous damping factor C is nearly proportional to η in the range of $W_O<3$ from Eq. (16), the increasing rate of viscosity in FeN-fluid is evaluated as 75%.

Figure 9 shows mean square values of resistance force obtained from Eq. (7) by substitution of C and m_A. Table 2 shows resistance increment by the magnetic field with 15 A coil current $(\sqrt{\overline{D^2}}/V_0)_{15A}-(\sqrt{\overline{D^2}}/V_0)_{0A}$ and standard deviation. From Table 2, resistance increment is largest in the case of FeN-fluid.

5. Conclusion

Experimental and analytical investigations are carried out to clarify the effect of magnetic field on the dynamic characteristics of an oscillating flat plate immersed in three kinds of magnetic fluids such as commercial water-based and kerosene-based magnetic fluids and magnetic fluid with iron-nitride particles (FeN). The results obtained in this paper are summarized as follows.

(1) Analytical method for evaluation of fluid resistance force acting on the oscillating flat plate immersed in a magnetic fluid is developed by using viscous damping coefficient C and added mass m_A obtained from the experimental data.

(2) The increment of resistance force with the applied magnetic field in the case of FeN-fluid is larger compared to the cases of water-based (W-40) and kerosene-based (HC-50) magnetic fluids.

(3) Increasing rate of viscous damping coefficient in FeN-fluid is the same order as water-based fluid and the increasing rate of apparent viscosity is about 75% in the test range which is estimated from the viscous damping coefficient.

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