2. ISUD
2nd International Symposium on Ultrasonic Doppler Methods
for Fluid Mechanics and Fluid Engineering
September 20-22, 1999
Paul Scherrer Insitut, 5252 Villigen PSI, Switzerland

Sloshing Behavior of A Magnetic Fluid in A Cylindrical Container

Y.Ohira[1)], T.Sawada[1)] and M.Tada[2)]

1) Department of Mechanical Engineering, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
2) Tokyo Motor Vehicle Works, Mitsubishi Motors Corporation
10, Ohkura-cho, Nakahara-ku, Kawasaki 211-8522, Japan

1 Introduction

The magnetic fluid is a stable colloidal dispersion of rather small surfactant-coated magnetic particles in a liquid carrier. It is developed in order to control a position of liquid fuel under a gravity-free state. Its characteristics such as strong magnetism and liquidity are paid attention, and fundamental studies have been carried out.

"Sloshing" is a phenomenon that the liquid with a free surface is agitated severely in liquid storage tanks. Zelazo and Melcher[1] studied dynamic behavior of a magnetic fluid in an oscillated container. Dodge and Garza[2] demonstrated a simulation of liquid sloshing in low-gravity by using a magnetic fluid. Omori. et al.[3] analyzed swirling phenomenon as a turning phenomenon of steady-state vibration solution which results from nonlinear coupled vibration.

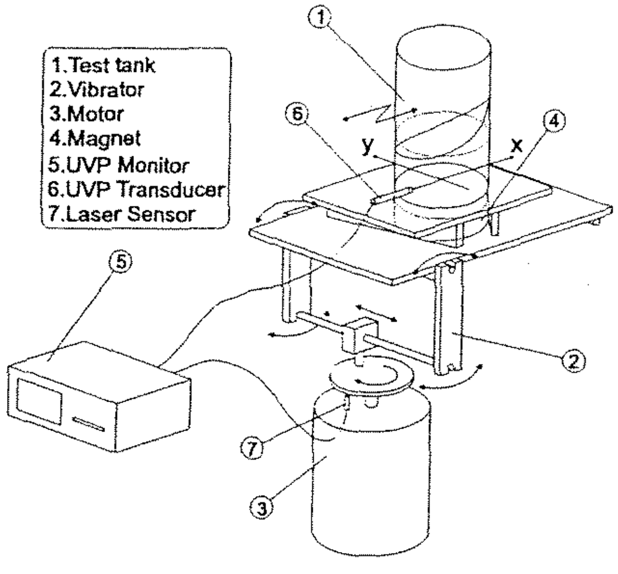

Fig. 1: Experimental Apparatus

The sloshing problem is not easy from a mathematical point of view. Obvious nonlinearities are occurring especially in the vicinity of the resonant frequency. In an axisymmetric container the inner liquid oscillates with rotational movement around the center axis of the container in spite of the lateral excitation. It has been called "swirling phenomenon". The direction of the rotation is not fixed. The direction is changed irregularly. Moreover, the stop of the rotation is sometimes observed. In order to understand and to explain this complex problem, detailed measurement of internal velocity profiles is necessary. However, magnetic fluid is opaque. Thus, optical methods like laser Doppler anemometry or the flow visualization technique like particle image velocimetry can not be applied. We performed an ultrasonic velocity profile(UVP) measurement. It is a method for measuring a velocity profile on a line with respect to the velocity component along this line, which can be applied to opaque fluid. Kikura, et al.[4] measured velocity profile of the Taylor vortex flow of a magnetic fluid using by UVP. Sawada, et al.[5] examined flow behavior of a magnetic fluid sloshing in a rectangular container. In the present experiment, we also used UVP method. We attempt to measure the velocity profile of the magnetic fluid sloshing in order to clarify "swirling phenomenon".

2 Experiments

Figure 1 shows the schematic diagram of the experimental apparatus. The cylindrical container is made of transparent acrylic resin, and its inner diameter and height are 94 mm and 300 mm, respectively. The adjustable crank is mounted on the output shaft of the motor. Rotation of the motor is changed to horizontal motion by crank mechanism. The rotational frequency of the motor is continuously controlled by an inverter, and the shaking table is oscillated sinusoidally. The amplitude of the oscillation is X_0=1.5 mm for all experiments. We used a water-based magnetic fluid W-40 with 27 wt%. The fluid depth is h=47 mm in the present experiment. Magnetic field is applied by a cylindrical permanent magnet whose diameter is 110 mm. We used several permanent magnets in order to change the magnetic field intensity. Since magnetic particles in the magnetic fluid are too small to reflect ultrasonic waves, we add porous SiO_2 powders with a mean diameter of 0.9 μm (MSF-10M, Liquidgas Co., Ltd.). An ultrasonic(US) transducer is fixed on the side wall of the container. Its position is changed in order to measure the horizontal velocity profiles along the same (V_x) and orthogonal (V_y) lines with the direction of the forced oscillation. A nominal diameter of the US transducer is 5 mm, and the measuring volume has a thin-disc shape, ϕ5 mm×0.71

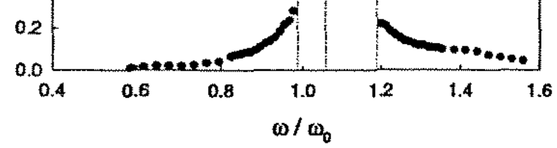

Fig. 2: Frequency responses of the free surface of a magnetic fluid for B=0 mT

mm. The UVP monitor is an Model X-2 manufactured by Met-Flow SA. The basic frequency is 4 MHz. Experiments are carried out changing motor frequencies, magnetic field intensities, and heights of fixed US transducer.

3 Results and Discussions

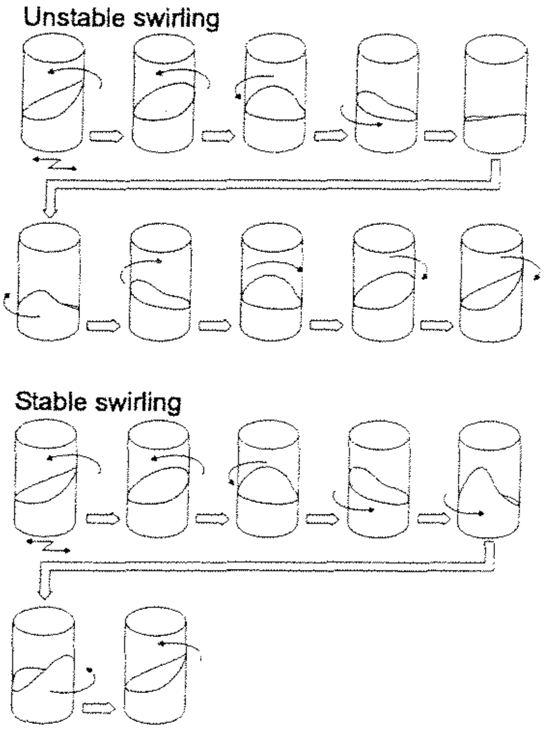

Fig. 3: Unstable swirling and stable swirling

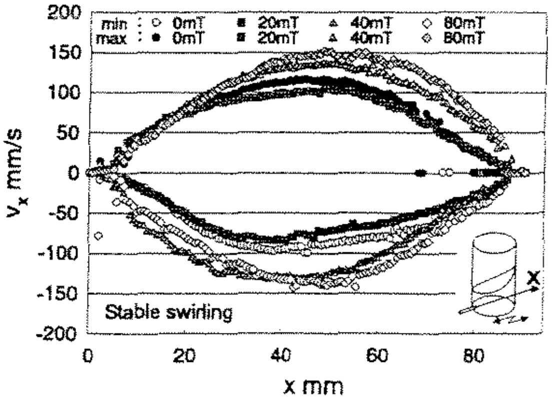

Fig. 4: Maximum velocity profiles for the second resonant angular frequency at h_0=10 mm

Figure 2 shows the frequency response of the free surface of a magnetic fluid when the forcing frequency varies. The surface magnetic field induction at the center of the permanent magnet is indicated by B, η is the maximum free surface elevation at the inner wall and ω_0 is the first resonant angular frequency for B=0. In the region of A, the free surface vibrates with the direction of the forced oscillation. As the forcing frequency increases, the surface elevation also increases until the free surface is intensively shaken near the resonant frequency (border between A and B). At the resonant frequency, the free surface forms the collapse wave, and after the resonant frequency (in the region of B), rotation around the center axis of the container occurs. The direction of the rotation is not fixed, and the direction is changed irregularly. Because of the above phenomena, it has been called "unstable swirling phenomenon"(see Fig.3). As the forcing frequency increases in the region of B, the surface elevation decreases with unstable swirling phenomenon. On the border between B and C, unstable swirling phenomenon changes to stable rotation whose direction is fixed. It has been called "stable swirling phenomenon". In the region of C, the stable swirling phenomenon is kept and its direction depends on the direction of unstable swirling phenomenon on the border between B and C. As the forcing frequency increases, the surface elevation also increases. The surface elevation is maximum on the border between C and D, and the surface elevation rapidly decreases after the border between C and D. In the region of D, the free surface vibrates as well as region A.

UVP measurements were mainly carried out near the second resonant angular frequencies(border between C and D). Figure 4 shows maximum velocity profiles for several applied magnetic fields. There are 128 measurement points along the measurement axis. Here x is the distance from the inner wall where the US transducer is fixed, and h_0 is the position of the US transducer from the bottom wall. When the magnetic field increases, the velocity also increases because of the magnetic force. We can not have data near the opposite inner wall away from the US transducer. We suppose that it comes from the clustering and chaining of the magnetic particles of a magnetic fluid formed under an applied magnetic field. As a result, we suppose that the US echo signal diminishes.

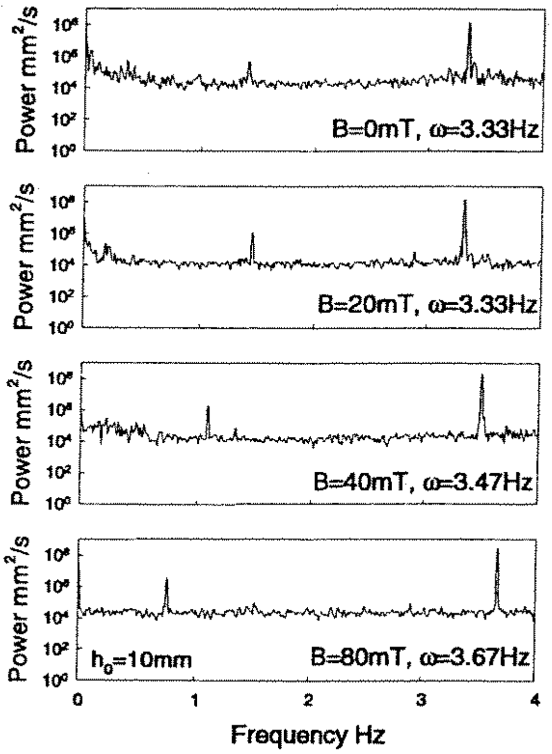

Fig. 5: Power spectra for the second resonant angular frequency over 12.65 mm$\leq x \leq$19.04 mm at h_0=10 mm

From measured velocity data, we calculated power spectra by using a fast Fourier transform in time domain. Figure 5 shows the power averaged over a region of 12.65 mm$\leq x \leq$19.04 mm at h_0=10 mm. The most dominant peak for each applied magnetic field corresponds to the forcing frequency. For each applied magnetic field, the second dominant peak exists. We can not understand what it means, but it is observed that the second dominant peak is shifted to the low frequency region as the magnetic field intensity becomes large. We consider that there is some relation between the second dominant peak and swirling. It is a theme in the future that we carry out detailed experiments for this problem.

This work was partly supported by Grant-in-Aid for Scientific Research (B) of The Ministry of Education, Science, Sports and Culture.

References

[1] R.E.Zelazo and J.R.Melcher, *J.Fluid Mech.* **39** (1969),1.

[2] F.T.Dodge and L.R.Garza, *NASA Tech.Rep.* **9** (1970),1.

[3] H.Omori, T.Matui, K.Kato and K.Hujiwara, *J.Struct.Constr.Eng.* **385** (1988),69.

[4] H.Kikura, T.Takeda and F.Durst, *Expt.Fluids* **26** (1999),208.

[5] T.Sawada, H.Kikura and T.Tanahashi. *Expt.Fluids* **26** (1999),215.