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Friction torque reduction by ultrasonic vibration and its application to EMS viscometer

超音波加振を用いた摩擦トルク低減効果と EMS 粘度計への応用

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1. Introduction

Viscosity is one of the most important properties for understanding fluid dynamics. In the rotational viscometer, which is one of the most popular methods of viscosity measurement, the relation between the rotational speed of the rotor and the applied torque gives the viscosity. The lower limit of viscosity measurement is restricted by the friction at the actuator and torquemeter, which causes an error in the viscosity measurement.

We recently developed the Electro-Magnetically Spinning (EMS) viscometer[1] whose principle is schematically shown in **Fig. 1**. In this system, a metal spherical probe is set in a sample and rotates by the electromagnetic interaction between the metal probe and the appried rotating magnetic field. The rotational speed of the probe gives the viscosity of the sample. The driving torque is given by $T_B = (2\pi/15)\sigma B^2 R^5(\Omega_B\text{-}\Omega_S)$, where σ is the electric conductivity of the sphere, B is the rotating magnetic flux density, R is the radius of the sphere, and Ω_S and Ω_B are the angular velocity of the sphere and the magnetic field. The resistant torque for viscosity is given by $T_r = 8\pi\beta\eta R^3\Omega_S$, where η is the viscosity, and β is a coefficient that is of the order of unity for the effect of the wall and bottom of the cell. The resistant torque for friction is given by $T_f = (8\pi/9)\mu\Delta\rho g R^3 r$, where μ is the friction coefficient, $\Delta\rho$ is the difference between the densities of the sphere and the sample, g is the gravity acceleration, and r is the radius of the contact area between the sphere and the bottom of the cell. Low viscosity measurement is possible if the friction between the probe and the bottom of the sample cell is satisfactorily low.

However, the friction torque causes an error in the low viscosity measurement around 1 mPa·s in the conventional method with permanent magnets. Under the conditions of $\eta \geq 10$ mPa·s and $\Omega_B \approx 100$ rad/s, $T_B >> T_f$ holds, on the other hand, T_r is close to T_f under 1 mPa·s because $\Omega_S \approx \Omega_B$, and the friction torque cannot be ignored. In the quadrupole EMS (QEMS) with electromagnets, Ω_B is about 10^4 rad/s and $T_B >> T_f$ holds (Fig. 1). However, under such conditions, a vortex flow is generated and the sphere cannot rotate stably.

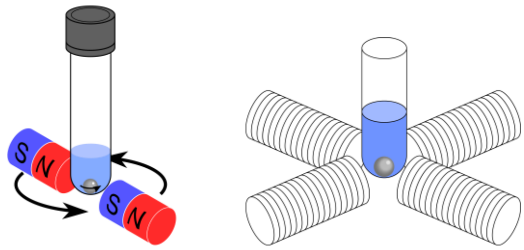

Fig. 1 Schematic drawing of EMS and QEMS.

The friction force reduction by ultrasonic vibration has been well known[2]. According to the Coulomb's law, the friction is given by $F = \mu N$, where N is the normal force. When an object is moving at the constant velocity v_c on the substrate vibrating at the velocity $v(t) = v_0\cos\omega t$, the average friction force is given by

$$F_R = \frac{1}{T}\int_0^T F(\mathrm{t})\,\mathrm{dt},$$

where $F(\mathrm{t})$ is the instantaneous friction force given as $F(\mathrm{t}) = \mu N \mathrm{sgn}(v_c - v(\mathrm{t}))$. Therefore F_R can be calculated to

$$F_R = \frac{2}{\pi}\mu N \sin^{-1}\left(\frac{\mathrm{v}_c}{\mathrm{v}_0}\right).$$

Here $\mu_1 = (2/\pi)\sin^{-1}(v_c/v_0)$ is the coefficient of friction reduction. In this work, the effect of the friction reduction was applied to EMS viscosity mesurement.

2. Experiment and result

In this work, we used QEMS. The angular velocity of the magnetic field is 6.0×10^3 rad/s. The sample liquid is the silicone oil with η = 48 mPa·s, and the radius of the probe sphere is 0.5 mm. **Figure 2** shows a schematic view of the ultrasonic vibration system. The two piezoelectric actuators vibrate the sample tube and the sphere has motion relative to the bottom of the tube.

This system can apply constant driving torque to the sphere because Ω_B is large enough, and, therefore we can determine the friction torque by obtaining the rotational speed of the sphere under constant driving torque.

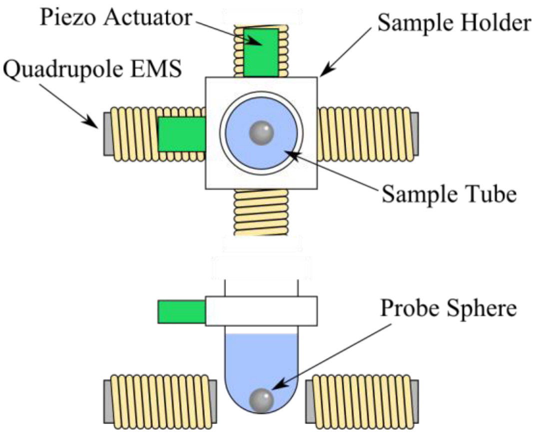

Fig. 2 Schematic drawing of ultrasonic vibration system.

First, we determined the viscous torque. The driving torque is known, and the resistant torque is given by $T_f + T_r = T_f + K\Omega_S$. We determined K from the gradient of the relation between T_B and Ω_S, and the value of the coefficient K was determined to

$$K = 1.06\times10^{-10}\ \mathrm{N\cdot m\cdot s}.$$

Next, we measured the rotational speed of the sphere Ω_S under the constant driving torque of 2.43×10^{-10} N·m, controlling the amplitude of the piezoelectric actuators within $0.03-0.5\ \mu\mathrm{m}$ at the frequency of 22 kHz. The phase difference of two actuators was $\pm\pi/2$, and the direction of revolution of the sample tube was the same as or the reverse to the spin of the sphere. For both directions, the rotational speed of the sphere increased with the increasing vibration amplitude (**Fig. 3**). We measured the rotational speed ten times and calculated the average and the standard deviation of the friction torque T_f, which is shown in **Fig. 4**. For both directions, we can see that both of the average and the standard deviation of the friction torque decreased. This result shows that the EMS measurement becomes more accurate by the application of ultrasonic vibration. Under 1 mPa·s, the accuracy of the measurement is improved from 10% to 3%.

In conclusion, we found the ultrasonic reduction of friction would be effective also for the viscosity measurement system. Some more quantitative comparison with the conventional friction reduction would be given in the presentation.

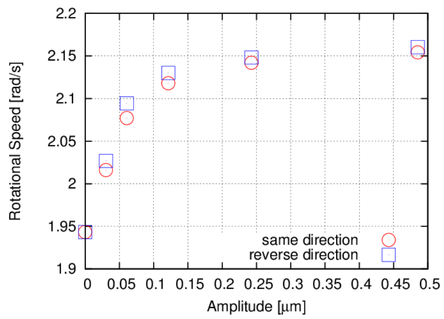

Fig. 3 Relation between amplitude of piezoelectric actuators and rotational speed of the sphere.

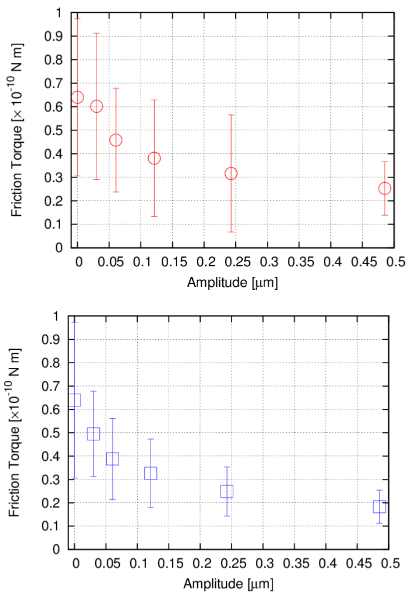

Fig. 4 Relation between amplitude of piezoelectric actuators and friction torque. The top is the same direction and the bottom is the reverse direction. In any case, the standard deviations are 50%.

References

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2. W. Littmann, H. Storck, J.Wallaschek, Arch. Appl. Mech. **71** (2001) 549-554.