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Dynamic Viscoelasticity Measurement with Quadruple Electromagnetically Spinning Method

四重極電磁スピニング法による動的粘弾性計測

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1. Introduction

Viscosity is one of the most important properties when we design industrial fluid processes such as transportation and mixing, and accurate measurement of viscosity is indispensable. One of the most popular apparatus for viscosity measurement is the rotational viscometer, in which the sample is deformed by the rotor and the resistant torque is measured. The problem of measurement is that the apparatus should be in contact with the sample.

Recently, to settle the problem, we developed the electromagnetically spinning (EMS) viscometer. In this system, a metal spherical probe is set in a sample and is driven to rotate by a torque remotely applied through the electro-magnetic interaction; rotating magnetic field generates eddy current in the spherical probe and the Lorentz interaction between the current and the magnetic field induces the driving torque to the probe. The sample is confined in a disposable sample tube and, therefore, the system is free from the contamination. It is a remarkable advantage over the previous methods.

When we discuss the flow dynamics of the complex fluids at micellar level, a value of the viscosity obtained at only a certain shear deformation rate is not sufficient and the flow curve or dynamic viscoelasticity is required. In this work, we introduce the measurement of the frequency spectrum of the viscoelasticity using Quadruple EMS system (QEMS). This system applies oscillatory torque to the probe with electromagnets. In this presentation, we will show the result of measurement of viscoelastic relaxation and demonstrate the performance of the method.

2. Measurement of viscoelasticity with EMS method

Here, we briefly explain the principle of the viscoelasticity measurement with the EMS method. An apparently rotating magnetic field is generated by the oscillatory magnetic field, which applies driving torque to a metal probe. A temporally modulated magnetic field produces eddy currents in the probe. The eddy currents **I** satisfies rot $\mathbf{I} = -\sigma\partial\mathbf{B}/\partial t$, where σ is the electric conductivity of the sphere and $\mathbf{B} = (B_x, B_y, 0)$ is the magnetic field. The Lorentz force is given by $\mathbf{F} = \mathbf{I} \times \mathbf{B}$ and the driving torque is given by $\mathbf{T} = \mathbf{r} \times \mathbf{F}$. We can calculate the driving torque with respect to the z-axis as

$$T_B = \frac{2\pi}{15}\sigma R^5\left(B_x\dot{B}_y - B_y\dot{B}_x\right),$$

where R is the radius of the sphere.

For the purpose of measuring dynamic viscoelasticity, two perpendicularly intersecting magnetic fields with different frequencies are applied to the spherical probe. When the magnetic field is written as $\mathbf{B} = (B_1\cos(\Omega_B+\omega)t, B_2\cos\Omega_B t, 0)$, the applied torque is given by

$$T_B \propto B_1 B_2\left[(2\Omega_B+\omega)\sin\omega t + \omega\sin(2\Omega_B+\omega)t\right].$$

Then, when the frequencies are close to each other ($\omega << \Omega_B$), the applied torque is the beating component of these two signals and this can be used for viscoelasticity measurement.

Next, we discuss the resistant torque when a sphere shows the oscillatory rotation in viscous or viscoelastic fluid. Here we consider the diffusion of the momentum. The characteristic diffusion length of momentum is given by $\delta = (2\eta/\rho\omega)^{1/2}$. When the radius of the sphere R is much smaller than the length, the effect of the finite diffusion length can be ignored and the resistant torque is given by

$$T_v = \mathrm{Re}\left[-8\pi\beta\eta^*\Omega_S\right],$$

where the coefficient β is the boundary effect of the bottom and wall and $\Omega_S = i\omega\theta_0\exp(i\omega t)$ is the angular velocity of the sphere.

On the other hand, under the condition of $R >> \delta$, or at high frequency, the momentum of the sample is localized around the probe and the inertia of sample plays a major role to determine the resistant torque.

Therefore $R << |\delta|$ is experimentally important in measuring viscoelasticity. To determine the viscoelasticity we observe the amplitude on the rotating angle of the sphere θ_0 and the phase difference $\Delta\phi$ between the driving torque and the oscillation of the sphere. The modulus G^* can be determined by calculating $G^* = (CT_B/\theta_0)\exp(i\Delta\phi)$ with the coefficient C obtained with a standard sample.

3. Experiment

Figure 1 shows a schematic view of the viscoelasticity measurement system with Quadruple EMS method. An aluminum spherical probe and sample are contained in a sample tube. Two pairs of electromagnets are set vertically to each other below the sample tube and horizontal magnetic field is generated around the spherical probe (Fig. 1(b)).

The motion of the spherical probe is detected by observing the motion of the laser speckle pattern of the scattering light at the surface of the probe. The motion of the speckle pattern following the oscillatory rotation of the sphere is detected by a line image sensor. Flashed light synchronized with the oscillatory driving torque was also detected by the image sensor to determine the phase of the motion. Where the pitch of the line sensor is 10 μm and the distance from the sphere is 50 cm, the resolution of angular displacement is 2×10^{-5} rad. It is equal to the shear of 10^{-4}.

The applied torque is determined by the amplitudes of the two magnetic fields, which is observed by two pickup coils set in front of the electromagnets.

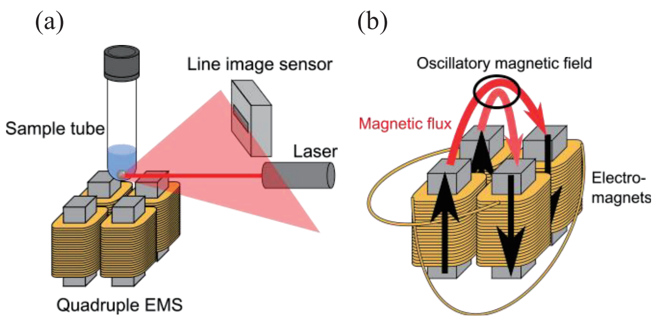

Fig. 1 Schematic view of Quadruple EMS system. (a)Entire view of this system. (b)Generation of oscillatory magnetic field by electromagnets.

4. Results and discussion

Here, we show two results of viscoelasticity measurement. First, we measured Newtonian samples to demonstrate the performance of this method. The sample liquid is silicone oil with a viscosity of 1 Pa·s. The frequency of one magnetic field was fixed to 1 kHz and the other was swept in the range of 1001-1100 Hz. The magnitude of magnetic fields were fixed by controlling the current of 1 A. The driving torque can be estimated from the product signal V_p. **Figure 2** shows the result obtained for the Newtonian sample. The loss modulus G'' of Newtonian is given by G'' = ηω, which is shown by the solid line. The experimental result agrees well with the relation, which shows the validity of the present system.

Next, we show the result obtained for the sample showing typical viscoelastic relaxation, which is called as 'shear thinning' in the field of rheology. The sample is aqueous solution of the surfactant cetyltrimethylammonium bromide (CTAB) 200 mM and the salt sodium salicylate (NaSal) 700 mM, which contains wormlike micelles. **Figure 3** is the relaxation spectrum of this sample. In the range of 1-30 Hz, the spectrum is well fitted by the single viscoelastic relaxation given by

$$G'(\omega) = G_0 \frac{(\omega\tau)^2}{1+(\omega\tau)^2}, G''(\omega) = G_0 \frac{\omega\tau}{1+(\omega\tau)^2},$$

where the shear modulus G_0 is 100 Pa and the relaxation time τ is 1.6×10^{-2} s. At higher frequencies above 30 Hz, we can see the effect of the inertia. As shown, we successfully measured the viscoelastic spectra with the Quadruple EMS method in a non-contact manner.

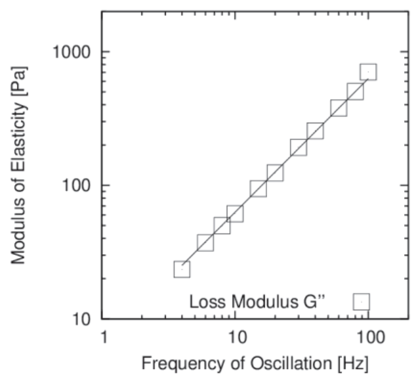

Fig. 2 Dynamic modulus of Newtonian sample and determination of apparatus constant. The loss modulus is proportional to the frequency. The solid line is given by G''= ηω.

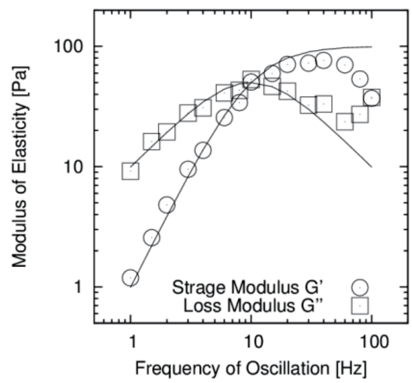

Fig. 3 Dynamic viscoelasticity of wormlile micellar solution. The solid line shows single viscoelastic relaxation.