2Pa2-5

Extension of remote distance of Electro-Magnetically Spinning viscometer

電磁駆動式粘弾性測定における遠隔駆動範囲拡張機構の開発

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1. Introduction

The most characteristic feature of the electro-magnetically spinning (EMS) viscometer is the remote sensing of the viscosity and/or elasticity of soft materials. It is a kind of rotational viscometer, in which a mechanical probe is rotating in the sample and the viscosity is determined from the ratio between the rotational speed and the applied torque to the probe.

In all of the conventional rotational viscometers except the EMS type, the torque to drive the rotor is transmitted through a driving shaft, which mechanically connects a motor and the rotor. A most troublesome problem common to the rotational viscometer derives from the mechanical contact between the rotor and motor. One is the sealability. It necessarily requires a finite gap in between the rotor and the sample container. Actually, in a practical use of a rheometer, that is most commonly used for the viscosity measurement of volatile liquid samples, the evaporation cannot be ignored from a slight lateral gap of 0.1 mm between the disk rotor and a substrate below. It is of course possible to close the gap by employing a rotatable seal, however, we cannot expect an accurate measurement of low viscosities since the mechanical friction at the seal cannot be ignored. Actually the viscous torque applied to the disk with a radius of 10 mm rotating at 60 r.p.rm is only 10^{-8} Nm. Pollution from/ to the sample is also a serious problem in treating bio hazardous materials. The EMS method is free from this problem.

To enhance this advantage of remote sensing, the extension of the remote distance would be useful for the further application of the EMS system; the rheology measurement in extraordinary environments, such as at high and low temperatures, high pressure and in explosionproof equipment. In this report, we introduce a new apparatus to remarkably extend the remote distance of EMS method.

2. Remote sensing of viscosity by EMS method

In our previous paper, we investigated the possible distance of the remote driving of the probe rotor. Here, we briefly explain the principle of the EMS measurement. In the simplest configuration shown in Fig.1, a couple of magnets rotates underneath the sample, which applies a rotating magnetic field around the probe rotor made of paramagnetic metal. Then currents are induced in the rotor and the Lorentz interaction between the magnetic field and the induced currents drives the rotor to follow the rotation of the magnetic field. The intensity of the applied torque is proportional to the delay of the rotor from the magnetic field, while the shear deformation rate linearly depends on the rotational speed of the rotor. Viscosity is then determined as the ratio between the applied torque and the shear deformation rate.

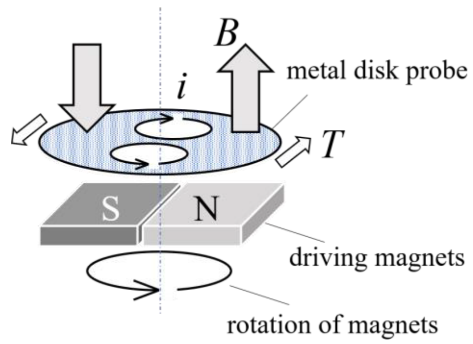

Fig.1 Principle of Electro-Magnetically Spinning method of rheology measurement.

In the previous work, the spatial distribution of the magnetic field is obtained experimentally and the torque applied to the rotor is calculated as a function of the distance from the driving magnets. The distance of the remote sensing was extended to about 40 mm by employing a couple of magnets having wide aperture of 60 x 60 mm^2. It means the distance of the remote sensing is almost the same as the size of the aperture of magnets, which is also examined by the numerical calculation.

The achieved remote distance is, however, not satisfactorily enough for the measurement, for example, in a high-pressure vessel, a vacuum chamber, and high temperature furnace, since their wall thickness might exceed 100 mm. It is not realistic to employ magnets larger than 100 mm.

Our previous method has another problem. The intensity of the driving torque rapidly decreases with the distance as its fourth power. A small fluctuation of the probe position leads to large error in measuring the viscosity.

3. Remote distance extender

To solve these problems, we newly developed an extender of the remote distance of the driving torque. Figure 2 shows the schematic image of the extension of the driving distance. The extender is composed of two permanent magnets, which are set on a rotation table. The table is supported by a bearing mechanism and can be freely rotates. The extender is set in the sample container, which is arranged above the driving magnets rotating in the main body of the EMS apparatus. Magnets of the extender are magnetically connected to the main driving magnets and they rotate at the same speed when the main magnets are driven by a motor.

Hereafter, we discuss the magnitude of the driving force as a function of the remote distance for both cases of direct driving and driving via an extender. In our previous paper, we estimated the magnitude of the driving torque by regarding the couple of magnets as a magnetic dipole. The magnetic flux B generated by a dipole is given by,

$$B \sim \frac{1}{r^3}\left[\mathbf{p} - 3(\mathbf{p}\cdot\mathbf{r})\frac{\mathbf{r}}{r}\right],$$

where **p** and **r** are the dipole and position vectors, respectively. In the experimental condition, where **p** and **r** are almost perpendicular, the magnetic flux penetrating the disk rotor decreases as r^{-3}, and the driving torque decays as r^{-6}.

Next, we calculate the driving torque applied to the extender as a function of the remote distance. The driving magnets are regarded as a couple of positive and negative magnetic charges M and $-M$ set at the positions of $\mathbf{r}=(D/2,0,0)$ and $(-D/2,0,0)$, respectively. On the other hand, the magnets of the extender can be expressed as magnetic charges m

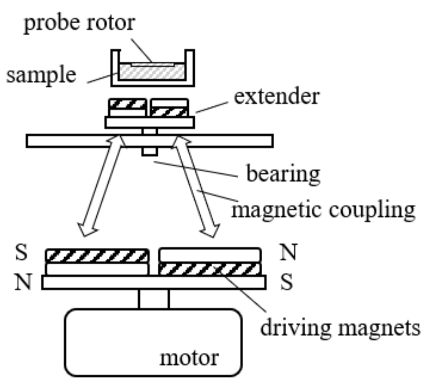

Fig.2 Schematic view of remote distance extender of EMS system,

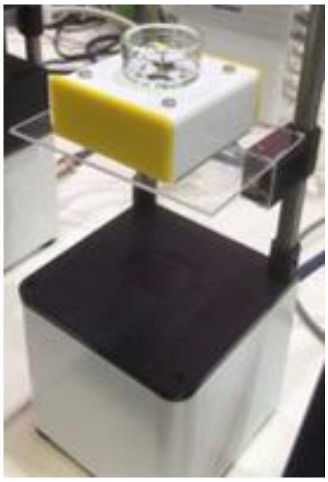

Fig.3 Photo of EMS viscometer and the remote distance extender set 100 mm above the torque driver.

and $-m$ set at $\mathbf{r}=(d\cos\theta/2,\ d\sin\theta,\ h)$ and $(-d\cos\theta/2,\ -d\sin\theta/2,\ h)$, respectively. Here the angle θ is the retardation of the extender to the driving magnets. Then the potential energy can be calculated to,

$$\varphi = \left(h^2 + \frac{L^2}{4} + \frac{l^2}{4}\right)^{-3/2} lL\cos\theta,$$

at the limit of $h^2 >> lL$. The driving torque applied to the extender is given by the differentiation of eq.(1) with respect to θ. The driving torque takes a maximum value when the directions of magnetic dipoles are perpendicular. The magnitude of driving torque decreases approximately as the third power of the remote distance h.

As shown, the distance of the remote sensing of viscosity can be extended by using the extender. Figure 3 shows the photo of the extender in operation. In the photo, a white box with a black top board contains the main driving magnets and the white and yellow box set above is the extender, on which a cell including liquid sample and a probe rotor is set. The remote distance between the top of the main driver and the sample is larger than 120 mm, which would be enough for almost all of the thick wall of environmental devices. In the presentation, we would show the video movie of the working extender.

References

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