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In-line measurement of visco-elasticity by EMS system
EMS システムによる粘弾性のインライン計測

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1. Introduction

The viscosity determining the ultrasonic absorption in homogeneous media is composed of two kinds, those are shear and volume components. For example, two-fifths of the ultrasonic absorption in pure water is due to the shear viscosity and the rest is brought about by the volume one. The shear viscosity of pure water is only 1 mPa·s, and we can easily understand that the ultrasonic decay in more viscous media is seriously affected by the rheological behaviors.

Among various kinds of rheology measurement apparatus, the Electro-Magnetically Spinning (EMS) system has a remarkable feature, that is the remote induction of the driving torque to the rotating viscosity probe immersed in fluid samples.[1-4)] The principle is already shown in our previous papers and here, we give a brief account. A probe is made of conducting metal and the rotating magnets placed around or below the probe induces temporally modulating magnetic field to the probe. Current is then induced in the metal probe and then, the Lorentz interaction between the excited current and the applied magnetic field gives a torque to the probe so that if follows the rotation of the magnetic field. The probe is immersed in the sample and it rotates feeling the viscosity of the surrounding medium. The value of the viscosity is then given from the relation between the rotational speeds of the magnetic field and the probe.

As mentioned above, the EMS system can drive the probe in a non-contact manner, and therefore, it would be used for the remote sensing of the viscoelastic properties in, for example, reactors, reserves and pipe-lines. In this study, we examined the possibility of application of the EMS system to the in-line measurement of rheology.

2. Remote induction of torque

First, in examining the possibility of in-line measurement, let us estimate the spatial decay of the magnetic field generated by the dipole type arrangement of the two magnets. **Figure** 1 shows the arrangement of the magnets actually employed for the disk-type EMS viscometer. A coordinate used for the numerical calculation is shown in the figure. Two rectangular magnets are horizontally set, below which an iron plate is placed. The iron plate shortens the magnetic flux between the N and S poles below the magnets and decreases the magnetic reluctance. The magnitude of the magnetic field above the magnets is thus enhanced. The magnetic potential at the position of $\mathbf{r} = (x, y, z)$ is then given by the integration over the surface area indicated by the surface coordinate of $\mathbf{r}_\mathrm{S}=(x_\mathrm{S}, y_\mathrm{S}, 0)$ as,

$$\phi(\mathbf{r}) = \int \frac{sign(\mathbf{r}_s)}{r} dS,$$

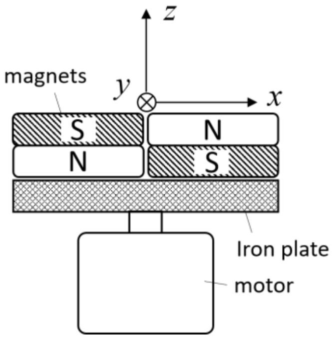

Fig. 1 Schematic view of the driving part of EMS system and the coordinate used for numerical calculation of magnetic field.

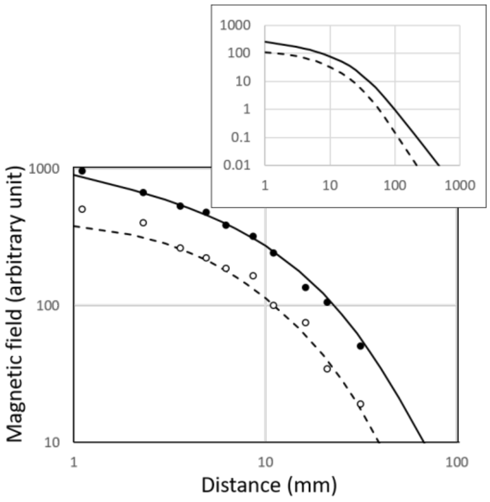

Fig. 2 Magnitude of magnetic field plotted as a function of distance from surface of magnets. Circles indicate the results of experiment.

where $r = \{(x - x_S)^2 + (y - y_S)^2 + z^2\}^{1/2}$ and sign($\mathbf{r}_s$)= +1, or -1 for N and S pole, respectively. The magnetic field is then given by $\mathbf{B}$=-grad $\phi(\mathbf{r})$.

Figure 2 shows the result of the numerical calculation of the magnetic field, obtained with the actual surface size of the magnet of 30 x 60 mm^2. The solid line shows the magnitude of the x-component of the magnetic field above the origin of the coordinate, which give the driving torque for the ancient type sphere probe EMS, and the dashed line indicates the z-component above the surface position of x_S=5 mm and y_S=0 mm. The radius of the probe disk is R=10 mm and the magnitude at R/2 is indicated in the figure, of which magnetic field mainly determine the driving torque. The attached figure shows the result in a wide range of the distance. As the magnetic field is the dipole interaction, the far field dependence is approximated by $\phi \propto r^{-3}$, which is shown as the gradient above r=100 mm.

On the other hand for the near field, the magnitude gradually decreases until the distance approaches the size of the magnet. The magnitude of the magnetic field is actually measured and plotted in **Fig**.2 as circles. As shown, the experimental values well agree with the numerical calculation. When we consider the actual usage under the in-line measurement, the penetration length of the magnetic field should exceed the thickness of the wall of the container, rector or the pipe, and therefore the length of 30 mm is considered as the expected value of the remote distance. Therefore, we designed the test equipment with the surface size of the magnets of 60 x 60 mm^2.

3. Demonstration of remote sensing of viscosity

For the demonstration of the remote sensing of viscosity with the distance larger than 30 mm, we measured the shear viscosity of the pure water in the cooling process. The initial temperature of water was 80 C and was poured into an insulation paper cup. An aluminum disk with diameter of 20 mm and thickness of 0.3 mm is employed as a probe rotor, which floats on the surface of the sample water with buoyancy and surface tension. The driving part shown in **Fig**.1 was set upside above the sample. The distance between the surface of the magnet and the disk probe is 35 mm. The rotation of the probe is observed by a video camera and the viscosity is obtained from the rotational speed determined though the image analysis.

The sample was set in the room temperature and the temporal change in viscosity was measured in the cooling process. The temperature of the sample was monitored by a thermistor. The volume of the sample is 150 mL and it took about 90 minutes for the sample to cool down from 80 to 30 C.

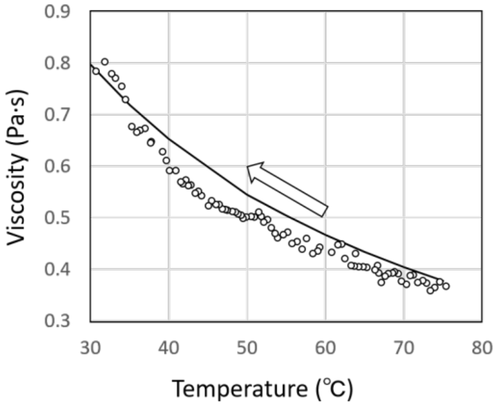

Fig. 3 Remote sensing of water viscosity obtained for cooling process in a paper cup. The arrow shows the direction of the temperature change and the solid line shows the values obtained from the measured temperature and the literature values of the viscosity.

Figure 3 shows the measured viscosity plotted against the temperature. These data were obtained in the direction indicated by an arrow. The solid line shows the expected viscosity obtained from the measured temperature and the literature values of the temperature dependence of the water viscosity. As we can see, remote sensing could detect the viscosity even in the lowly viscous liquid.

Some discrepancy is seen, which would be due to the spatial inhomogeneity of the temperature formed in the non-equilibrium process of cooling, such as the heat conduction and the convection; the floating rotor detects the viscosity in the vicinity of the sample surface, while the thermistor measures the temperature 20 mm beneath the sample surface. Note here that the temperature near the surface is not necessarily lower than that at a deeper position.

In conclusion, a fundamental examination to apply the EMS system to the remote sensing of the rheological properties was carried out. In the presentation, we would propose further result to detect the change of the rheological properties accompanying the proceeding chemical reaction.

References

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