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대변형 진동전단유동 하에서의 전자기 유변유체의 구조변화

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Microstructural change of electrorheological fluids in the large amplitude oscillatory shear

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Introduction

Electrorheological (ER) fluids are a suspension of nonconducting or weakly conducting particles dispersed in an insulating liquid. They show dramatic changes in the rheological properties upon the application of electric fields. Apparent viscosity can increase by several orders of magnitude upon the application of electric fields of the order of 1 KV/mm. This behavior is related with the microstructural change of ER fluids. As the process takes place very fast in milliseconds and is reversible, the ER fluids can have applications for the devices that require precise control of stress transfer, such as shock absorbers, engine mounts, clutches, brakes, actuators, control valves and robotic devices etc.

However despite much effort over the last ten years, there are few commercial devices available yet. This may be due to the lack of effective fluids as well as of understanding the mechanism. The fluids require high yield stress, resistance to sedimentation, thermal stability, and so on. The development of effective ER fluids will accompany our understanding the mechanism. And it will be important to understand the rheological properties under the flow environment that is similar to the flow situation of ER devices. As the ER devices usually operate in a dynamic mode with large deformation, the behavior under large amplitude oscillatory shear (LAOS) is of particular importance among the rheological properties.

The LAOS behavior of ER fluids has not been studied extensively and our understanding is still lacking. Recently Parthasarathy and Klingenberg studied the LAOS behavior of ER fluids both theoretically and experimentally. By using the particle-level simulation method that is based on the electrostatic polarization model, they could predict a lot of important nonlinear behavior observed in the experiments, including the maximum of the effective loss modulus at intermediate strain amplitude, a dog-bone-like behavior in the Lissajous plot (stress vs. strain), and the viscoplastic behavior, for example. They also pointed out that the nonlinearity first arises from the slight rearrangement of unstable structures and then proceeds further with the overall rupture of percolating clusters between the electrodes.

The purpose of this paper is to investigate the LAOS behavior of ER fluids. By using the particle-level simulation method developed earlier, we probe the microstructural change of ER suspensions in a three-dimensional flow cell. To precisely analyze the stress signal that becomes complicated at large deformation due to the higher harmonic contributions, the Fourier transformation analysis will be carried out. The characteristics of the higher harmonic contributions to the stress as well as some microstructural analysis will be given.

Mathematical modeling

ER suspensions are treated as neutrally buoyant, hard, uncharged dielectric spheres immersed in a dielectric Newtonian liquid. When electric field is applied, the sphere experiences electrostatic interaction, hydrodynamic drag, and short-range repulsion. Hydrodynamic interaction, colloidal and Brownian forces are neglected. Details of simulation method can be found elsewhere (1), and only the dominant forces are listed below

$$\mathbf{F}_{ij}^{el}\left(R_{ij},\theta_{ij}\right)=F_s\left(\sigma_i\ \sigma_j\right)\left(\frac{R_{\min}}{R_{ij}}\right)^4\left[\left(3\cos^2\theta_{ij}-1\right)\mathbf{e}_r+\sin 2\theta_{ij}\mathbf{e}_\theta\right]$$

where $F_s\left(\sigma_i\ \sigma_j\right)=\frac{3}{16}\pi\varepsilon_0\varepsilon_c\beta^2E_0^2\left(\sigma_j^2\frac{16\lambda_{ij}^3}{\left(1+\lambda_{ij}\right)^4}\right)$

$$\mathbf{F}_i^{hyd}\left(\mathbf{R}_i\right)=-3\pi\eta_c\sigma_i\left(\frac{d\mathbf{R}_i}{dt}-\mathbf{u}^\infty\left(\mathbf{R}_i\right)\right)$$

$$\mathbf{F}_{ij}^{rep}\left(\mathbf{R}_{ij}\right)=F_s\left(\sigma_i\ \sigma_j\right)\exp\left(-\kappa\frac{R_{ij}-R_{\min}}{R_{\min}}\right)\mathbf{e}_r$$

$$l_{scale} = \sigma_0, \quad F_{scale} = \frac{3}{16}\pi\varepsilon_0\varepsilon_c\sigma_0^2\beta^2E_0^2, \quad t_{scale} = \frac{16\eta_c}{\varepsilon_0\varepsilon_c\beta^2E_0^2}$$

Results and Discussion

One thousand spherical particles were randomly generated in a three-dimensional simulation box. Upon the application of electric fields, the spheres tend to agglomerate to the direction of the electric field and form clusters. The volume fraction is 5 percents and the perspective view is shown in Fig. 1. With this aligned configuration, dynamic test was carried out. At low frequency of 0.1, the storage modulus shows strain thinning, while the loss modulus shows an overshoot followed by strain thinning as shown in Fig. 2. This behavior is qualitatively the same as in 2-D ER simulation. Similar behavior is often observed in some suspensions, emulsions, surfactant solutions, and biopolymer solutions.

As there exist higher harmonic contributions at large deformation, Fourier transformation (FT) analysis is necessary for precise understanding of the complex behavior at large deformation. The intensities of FT analysis are shown in Fig. 3. The first harmonic increases with slope one at small strain and then slightly decreases at large strain amplitude, while the higher harmonic contributions increase with much steeper slope. The behavior of higher harmonic contributions at small strain amplitude is a numerical artifact, which can be verified with a controlled FT analysis with larger number of data points. In addition, the study with a controlled configuration like a string reveals that the ER system has a slope n for n-th harmonics. The Lissajous curves are shown in Fig. 4. At small strain, the curve is elliptic which is typical for most viscoelastic materials. At large strain, it changes to a dog-bone like shape, which is observed in experiments too. Detailed results will be reported (2).

References

1. Parthasarathy M. and D.J. Klingenberg, J.Non-Newtonian Fluid Mech., 81, 83 (1999).
2. Sim H.G., S.H.Kim, K.H.Ahn, and S.J.Lee, in preparation (2002).

Acknowledgement

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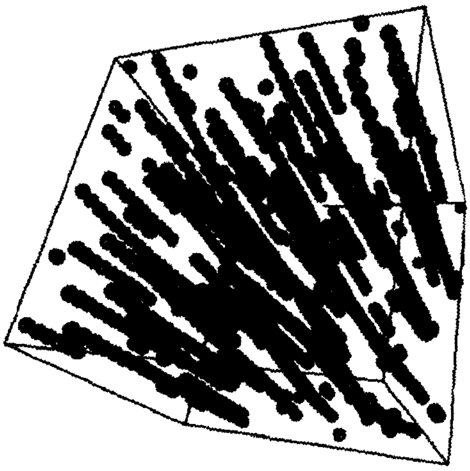

Fig.1. 3-D perspective of ER fluid under the electric field.

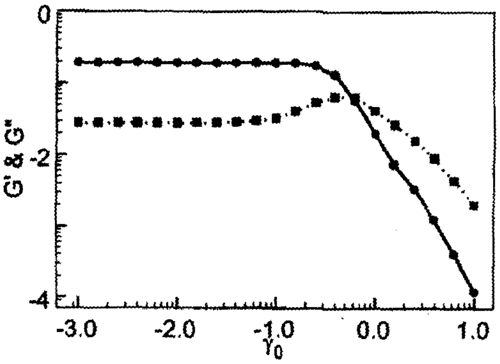

Fig.2. Effective storage and loss moduli as a function of strain.

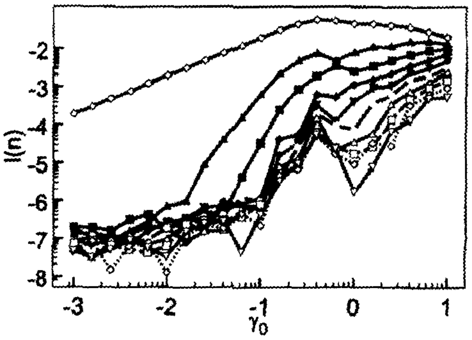

Fig.3. Intensities of higher harmonics.

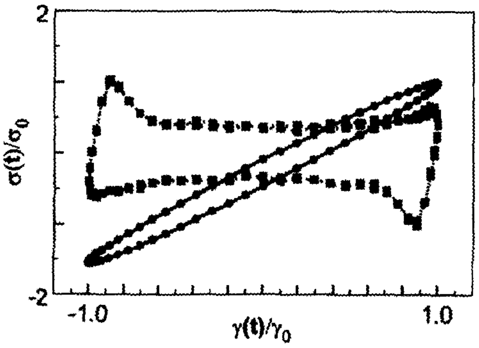

Fig.4. Lissajous curves at small (0.01) and large (6.31) strain amplitude.