DYNAMICS IN MR SUSPENSIONS SUBJECT TO ROTATING FIELDS

Sonia Melle[1,2], Gerald G. Fuller[2], and Miguel A. Rubio[1]

1) Dpto. Física Fundamental, UNED, Senda del Rey 9, Madrid 28040, Spain
2) Dpt. Chemical Engineering, Stanford University, Stanford, CA 94305-5025, USA

ABSTRACT

The orientation of field-induced structures in magneto-rheological (MR) suspensions subject to rotating magnetic fields have been studied using different optical methods: video-microscopy, small angle light scattering (SALS), and scattering dichroism. When a rotating field is imposed the field-induced aggregates rotate with the magnetic field frequency but with a retarded phase angle for all the rotational frequencies measured. The size of the aggregates decreases always with frequency. However two different regimes are found below or above a critical frequency. During the first regime (low frequency values) the size of the aggregates remains almost constant while for high frequencies this size becomes shorter.

KEYWORDS: MAGNETORHEOLOGICAL SUSPENSIONS, ROTATING FIELDS, COLLOIDAL DYNAMICS

INTRODUCTION

MR suspensions are essentially suspensions of micron-sized, magnetizable particles in a non-magnetic fluid. Under normal conditions, a MR fluid is a free-flowing liquid, but exposure to a magnetic field can change dramatically the mechanical properties of the fluid in milliseconds. Just as quickly, the fluid can be returned to its liquid state with the removal of the field. This reversible change in the viscosity make MR suspensions specially useful for their applications in mechanical systems such as dumpers, brakes and clutches [1]. An understanding of the dynamics of field-induced structures in MR suspensions is fundamental to controlling their rheological response and modelling the behaviour of MR devices.

Magnetic fluids subjected to unidirectional external fields become optically anisotropic due to the orientation of string-like aggregates of the colloidal particles in the direction of the field [2]. Optical techniques including video microscopy, light transmission and light scattering have been used to characterize the kinetics of field-induced structures formation in MR fluids [3-8]. In this paper we report the structural evolution of MR suspensions under the application of a rotating magnetic field by means of different optical techniques. In previous works it has been found interesting dynamic behaviours when polarizable systems consisting of many elongated objects were submitted to rotating electric or magnetic fields [9-10].
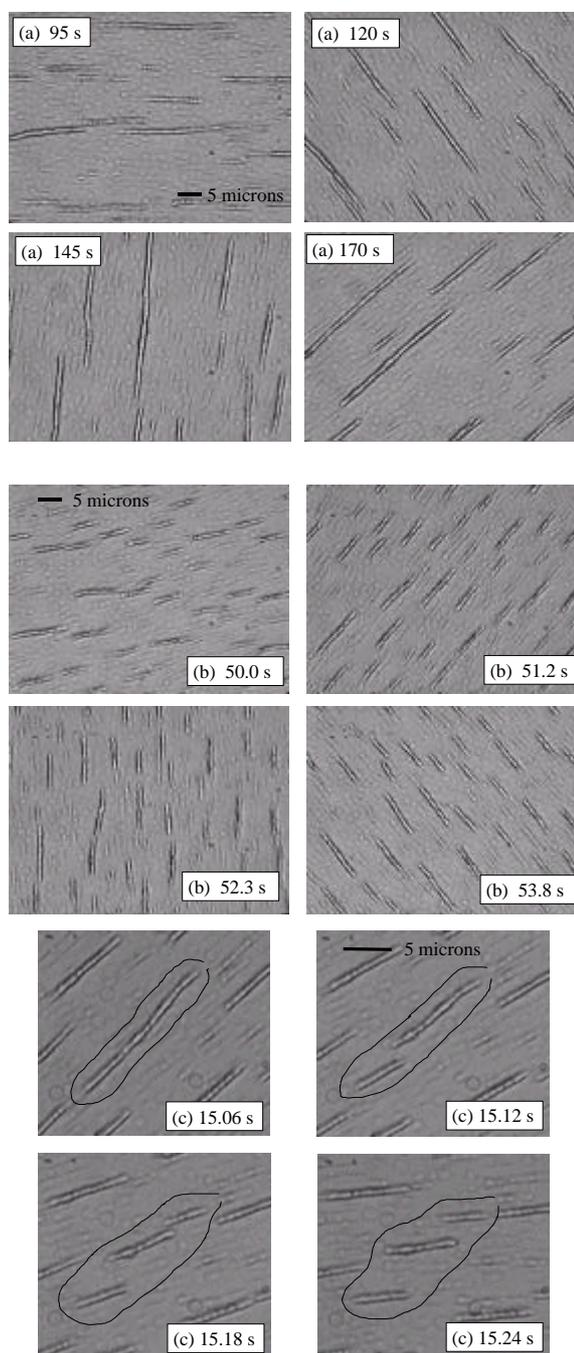

Figure 1. Video-microscopy images showing the time evolution of the chain-like structures for a magnetic field H=12.4kA/m, volume fraction $\phi = 0.0005$ and different rotational frequencies: **(a)** f=0.005Hz clockwise rotation, **(b)** f=0.1Hz counter clockwise rotation, and **(c)** detail of the S shape for f = 0.05 Hz clockwise rotation.

EXPERIMENTAL RESULTS AND DICCUSSION

The experiments were performed using suspensions of super-paramagnetic polystyrene micro-spheres loaded with iron oxide grains, manufactured by $R\hat{h}\hat{o}ne - Poulenc$. Because the techniques we are using here need optical transparency, the fluid sample was sandwiched between two circular quartz windows held in place by a delrin attachment and separated by an annular delrin spacer $100\mu m$ thick (along the Z axis). The sample is surrounded by two orthogonal pairs of coils that generate rotating magnetic fields: $\vec{H}(t) = H\cos(\omega t)\vec{u}_x + H\sin(\omega t)\vec{u}_y$ with strengths $9 < H < 25$ kA/m. We investigate here rotational frequencies ranging from 0.001 Hz to 10 Hz.

Video-microscopy experiments

To study the dynamics governing low volume fraction suspensions we performed video microscopy experiments by applying rotating magnetic fields to a suspension of particles of diameter $0.87\mu m$ with a volume fraction $\phi = 0.0005$. The images were recorded with a CCD video camera and then digitalized on a computer for their subsequent analysis.

In Fig. 1 video microscopy images shows the temporal evolution of the chain-like structures induced in the suspension when a magnetic field of H=12.4 kA/m was applied for different rotational frequencies: (a) f = 0.005 Hz, (b) f = 0.1 Hz, and (c) f = 0.05 Hz.

At low volume fractions the dipolar interaction induce aggregation into linear chains. Under these conditions, two torques act on the induced aggregates: a magnetic torque that rotates the chain-like structures due to dipolar interaction among the particles orientated in the direction of the magnetic field, and a hydrodynamic torque which explains the rotational friction of the structures in the suspending fluid.

For the range of frequencies measured here, the chains remain rotating synchronously with the field but are able to break up to decrease their viscous drag. The average length of the structures decreases with the rotational frequency. The first steps of break up process goes as follow (see Fig. 1(c)): the chain is bent, it develops as S shape the branches of which moves faster to follow the field [11]. Lately the chain breaks up into smaller ones. As a result the domain of synchronous rotation is enlarged compared to the case of solid chains. Break up and recombination processes are observed for all the frequencies measured. Studying the temporal evolution of the average length of the chains we found that this average length is enlarged for low rotational frequencies (around 0.001 Hz) compares to the case of unidirectional magnetic fields.

Scattering Dichroism and SALS experiments

To study the orientation dynamics of more concentrated systems scattering dichroism technique was used. The dichroism is the anisotropy of the imaginary part of the refractive index and is a measurement of the difference between the absorption of the incident light in the parallel and in the perpendicular direction to the long axis of the aggregates [12]. A full description of this experimental technique can be found in Refs [13,14].

For these experiments we used a solution of 82.5% glycerol in water with particles of diameter $1.01\mu m$ and a volume fraction of $\phi = 0.016$. The viscosity of this solution without applying an external magnetic field was

measured using a Rheometrics Dynamic Analyzer (RDA) to be $\eta = (0.975 \pm 0.003)$ Poises at $22^0 C$.

In Fig. 2 (a) we observed the temporal evolution of SALS patterns generated by the suspension in the presence of a rotating magnetic field. Particles chain along the magnetic field causing scattering pattern to appears orthogonal to the field. A qualitative interpretation of such patterns indicates that the induced structures follow the magnetic field rotating with the same frequency. In order to quantitatively analyse this behaviour we have simultaneously measured the time evolution of the dichroism and the orientation angle of the structures $\theta''(t)$ (defined in Fig. 2 (b)). By comparing $\theta''(t)$ with the rotation of the magnetic field direction, given by ωt, it can be observed (see Fig. 2 (c)), that the structures follow the magnetic field rotating with a phase lag independent on time for all frequencies measured. Therefore the average phase lag between the field and the aggregates is $\alpha(t) = \omega t - \theta''(t)$.
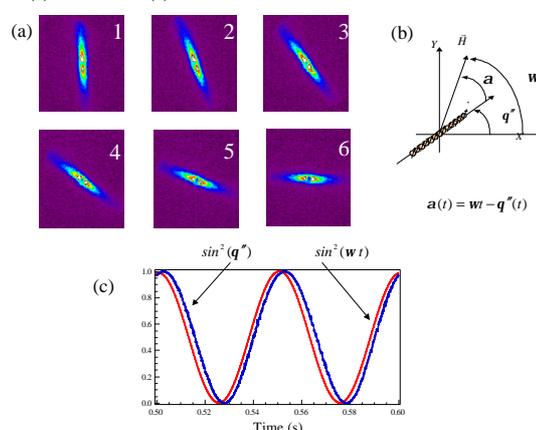

Figure 2. **(a)** Time evolution of SALS patterns during a $\pi/4$ counter clockwise rotation of the field. **(b)** Definition of the phase lag between the magnetic field and the chains. **(c)** Experimental signals of the temporal evolution of the magnetic field direction and the aggregates direction for a field strength of H = 12,4 kA/m, and f = 10 Hz.

In Fig. 3 (a) the dichroism generated by this solution is plotted as a function of f in a log-log form for various field strengths. As the frequency of the applied field is increased, the dichroism is strongly reduced, which indicates that hydrodynamic friction forces can overcome the dipolar magnetic forces. This plot shows clearly two distinct regions for frequencies below and above a critical frequency near to 0.3 Hz. Below this critical frequency, the dichroism is essentially independent on frequency and therefore the aggregates size is also independent on frequency. However, once this frequency is surpassed, the dichroism decreases with frequency, which reveals the diminution of the aggregates size. The critical frequency separating these two regions increases with the magnitude of the applied magnetic field, as expected since the strength of the interparticle magnetic forces scales with the applied field. It is found above 1 Hz that the dichroism drops with frequency with a scaling of approximately $\Delta n'' \approx f^{-1}$.
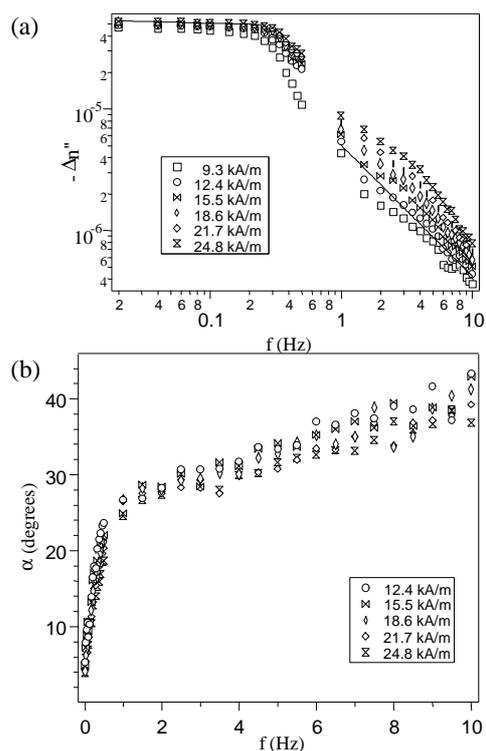
(a)

(b)

Figure 3. (a) Dichroism as a function of magnetic field frequency for a range of magnetic field strength in a log-log plot. **(b)** Phase lag as a function of magnetic field frequency. Two behaviours are found above or below a critical frequency around 0.3 Hz.

The phase difference α between the orientation of the aggregates and the magnetic field versus the frequency of the field is plotted in Fig. 3 (b) for different field strengths. We see a decrease of the phase difference with increasing magnetic field intensity as expected because the magnetic torque increases with the magnetic field strength. We observe that this phase difference is increasing with frequency over the whole range of frequencies. The longer the aggregates are, the higher is their phase lag. However, as we found for the dichroism results (see Fig. 3(a)), two different responses are seen depending on the frequency value. At low frequencies (below the critical frequency) the phase difference growths very quick while at high frequencies the increase of the phase difference is relatively slow**.**

REFERENCES

1. Carlson J.D. and Weis K.D., *Machine Design* (1994) 61; *Proc. 5th Int. Conf. On ER Fluids, MR Suspensions, and Associated Technology*, edited by W. A. Bullough (World Scientific, Singapore, 1996).

2. Scholten P.C., *IEEE Trans. Magn. MAG-11* (1975), pp.1400.

3. Fermigier M. and Gast A.P., *J. Colloid Interface Sci.* 154 (1992), pp. 522.

4. Wirtz D. and Fermigier M., *Phys. Rev. Lett.* 72 (1994), pp. 2294.

5. Lemaire E. et al., *J. Phys. II France* 2 (1992), pp. 359.

6. Hwang Y.H. and Wu X-l., *Phys. Rev. E* 49 (1994), pp. 3102.

7. Silva A.S. et al., *Phys. Rev. E* 54 (1996), pp. 5502.

8. Martin J.E. et al., *Phys. Rev. E* 59 (1999), pp. 5676.

9. Zheng C. and Meyer R.B., *Phys. Rev. E* 55 (1997), pp. 2882.; Migler K.B., and Meyer R.B., *Phys. Rev. E* 48 (1993), pp. 1218.

10. Sandre O. et al., *Phys. Rev. E* 59 (1999), pp. 1736.

11. Martin J.E. et al., *J. Chem. Phys.* 104 (1996), pp 4814 where this shape was also reported for a chain subject to shear in the direction perpendicular to the field.

12. Van de Hulst H.C., *Light Scattering by Small Particles*, (Dover P., New York, 1981).

13. Fuller G.G., *Optical Rheometry in complex fluids*, (Oxford University Press, 1995); Fuller G.G., *Annu. Rev. Fluid Mech.* 22, (1990), pp 387.

14. Melle S. et al., *Phys. Rev. E* 61 (2000), pp. 4111.