Polarizable particles aggregation under rotating magnetic fields using scattering dichroism

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We used scattering dichroism to study the combined effects of viscous and magnetic forces on the dynamics of dipolar chains induced in magnetorheological suspensions under rotating magnetic fields. We found that the chains adjust their size to rotate synchronously with the field but with a constant phase lag. Two different behaviors for the dichroism (proportional to the total number of aggregated particles) and the phase lag are found below or above a critical frequency. We obtained a linear dependence of the critical frequency with the square of the magnetization and with the inverse of the viscosity. The Mason number (ratio of viscous to magnetic forces) governs the dynamics. Therefore there is a critical Mason number below which, the dichroism remains almost constant and above which, the rotation of the field prevents the particle aggregation process from taking place being this the mechanism responsible for the decrease of dichroism. Our experimental results have been corroborated with particle dynamics simulations showing good agreement.

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I. INTRODUCTION

Magnetorheological (MR) suspensions consist of magnetizable particles suspended in a nonmagnetic fluid. They are a model system for the study of structure formation and dynamics in dipolar suspensions with tunable interaction between the particles. It is well known that when a unidirectional magnetic field is applied, the particles making up the suspension acquire a dipole moment \( \vec{m} = (4\pi/3)a^3\vec{M} \), where \( \vec{M} \) and \( a \) are the particle magnetization and diameter, respectively. Due to dipolar interactions, these particles join to form chain structures in the field direction inducing an optical anisotropy in the sample due to polarization dependent scattering from oriented aggregates. When the size of the scattering objects is comparable to the wavelength of the light (\( \lambda_l \)), the induced dichroism will be bigger than the induced birefringence \( I \). Due to the polarization scattering, scattering dichroism has been shown to be a good technique for the study of these anisotropic structures in MR suspensions at moderate concentration which cannot be readily studied with other optical techniques, such as video microscopy. Using Rayleigh-Debye theory for the scattering of light we can estimate the scattering dichroism generated from a chain \( j \) formed by \( N_j \) particles in the forward direction (\( \phi = 0 \)) to be \( I \):

\[
\Delta n''_j = \frac{2N_j}{k^2} \left( Re \left[ T_2(\phi = 0) \right] - Re \left[ T_1(\phi = 0) \right] \right) ,
\]

where \( k = 2\pi/\lambda_l \) is the wave vector of the laser beam and \( T_i(\phi = 0) \) is a function of \( k, a, \) and the isotropic refractive indexes of solvent and particles. We assume that the scattering dichroism produced from a set of \( N_c \) chains is the incoherent sum of the scattering dichroism produced for each chain, so the total dichroism is proportional to the total number of aggregated particles \( N_a \):

\[
\Delta n'' = \sum_{j=1}^{N_c} \Delta n''_j \propto \sum_{j=1}^{N_c} N_j \equiv N_a .
\]

Recently, we studied the dynamics of MR suspensions under rotating magnetic fields \( I \). We found that the field-induced chains rotate synchronously with the field but lag behind by a constant phase angle. Previous experimental work on magnetic holes \( I \) and liquid crystals \( I \) under rotating magnetic fields report synchronous and non-synchronous regimes depending on the value of the driving frequency. However, as we showed previously \( I \), MR suspensions have the capacity of reducing the size of the structures to decrease their viscous drag while rotating synchronously with the field \( I \). Furthermore, within this synchronous regime, two different behaviors were found below or above a critical frequency. Below this value, the dichroism remains almost constant but above the critical
frequency the viscous drag overcomes the magnetic force and reduces the dichroism following a power law with an exponent -1. The critical frequency was found to increase with the amplitude of the applied field.

In this paper we analyze the interplay between magnetic and viscous forces over the critical frequency separating these two regimes. We have studied the dependence of the critical frequency on the magnetization by applying magnetic fields with different amplitudes on the same suspension. The dependence of the critical frequency on the viscosity of the carrier fluid was analyzed applying a constant field on suspensions with different glycerol concentrations.

A dimensionless parameter that compares these two forces is the well-known Mason number (ratio of viscous to magnetic forces). This number has been defined with different proportionality factors in literature \[8–10\]. The Stokes viscous force acting on two particles in contact which rotate with a field of frequency \(\omega\) is \(F_v = 6\pi\eta a\omega\), where \(\eta\) is the solvent viscosity. The dipolar magnetic force is \(F_m \sim (\pi/2)\mu_0 a^2M^2\), where \(\mu_0\) is the vacuum magnetic permeability. Then, the Mason number is given by:

\[
Ma = \frac{12\eta\omega}{\mu_0 M^2},
\]

where the proportionality factor was chosen to be in agreement with the dimensionless frequency obtained from the theoretical analysis (Section III B).

We found that the critical frequency separating the two regimes increases linearly with the square of the magnetization and decreases with the inverse of the viscosity, so the Mason number governs the dynamics of field-induced dipolar chains under rotating fields. As expected from this result, we obtained a good collapse of the dichroism and the phase lag curves (measured at different magnetic fields and viscosities) with Mason number. The change in behavior of the dichroism and the phase lag occurs at a critical Mason number, \(Ma_c \approx 1\), above which the viscous forces dominate and inhibit the aggregation process. We corroborated our experimental findings through the results obtained from particle dynamics simulations. The simulations show that the average length of the chains decreases with frequency following a power law with an exponent close to -0.5. Furthermore, the simulations also reveal the two different behaviors for the total number of aggregated particles and the phase lag and are in good agreement with the experiments.

II. MATERIALS AND METHODS

A. MR suspensions and procedure

We prepared glycerol suspensions at different concentrations using two water suspensions of polystyrene (PS) polydisperse micro-spheres loaded with iron oxide grains. The aqueous suspensions (M1-180/12 and M1-070/60) were acquired commercially from Estapor-Rhône Poulenc with a solid content of 10%. The particle properties are list in Table I.

The surface of these microspheres is composed of carboxylic acid (-COOH) groups with an added surfactant coating layer of sodium dodecyl sulfate (SDS) to stabilize the suspensions. Since these small magnetite grains are randomly oriented inside the micro-particles, the resulting magnetic moment is zero in the absence of an external magnetic field. Under sufficiently low magnetic fields these particles exhibit superparamagnetic behavior with virtually no hysteresis or magnetic remanence as a result of the orientation of the magnetite grains dispersed in the PS matrix.

Two experimental protocols were used and are summarized in Table II. To study the effect of the magnetic forces on the critical frequency, we diluted the suspension of particles of diameter 1.01 \(\mu\)m (M1-180/12) in glycerol to achieve a solvent volume concentration of 82.5\% glycerol with a volume fraction of \(\phi_v = 0.016\). We will denote the resulting suspension as d-M1-180/12 hereafter. The dilution in glycerol reduced the SDS concentration and additional SDS was added to achieve a concentration equal to the original solution (5gr/liter). The viscosity of the suspension d-M1-10/12 was measured without applying a magnetic field using a Rheometrics Dynamic Analyzer \(RDA\ II\) to be \(\eta = (0.178 \pm 0.002)\ \text{Pa s at 10}^0\ \text{C}\). This set of experiments consists on applying magnetic fields with different amplitudes (from \(H = 6.2\ \text{kA/m}\) to \(H = 24.8\ \text{kA/m}\)) on suspension d-M1-180/12. For high fields, the dipole moment induced on the particles is not directly proportional to the applied field. To determine this non-linear response, we measured the particle magnetization curve with a vibrating sample magnetometer (VSM)-LakeShore 7300 for the range of magnetic fields used in the experiments. The result is shown in Figure II. As expected, the particles show a superparamagnetic behavior with no hysteresis but saturation effects in the magnetization for high fields appeared.

For the second set of experiments we prepared suspensions with volume fraction \(\phi_v = 0.01\) but different glycerol concentrations ranging from 40\% to 80\% in volume. In this case, we used the water suspension M1-070/60 with particles of diameter 0.90 \(\mu\)m. These suspensions are denoted as d-M1-070/60. We also determined their viscosities with the \(RDA\ II\). The effect of the viscous force on the critical frequency was studied by applying a magnetic field
of $H = 3.1 \text{kA/m}$ on the suspensions d-M1-070/60. For this low magnetic field the magnetization is linear with the field $\vec{M} = \chi_{eff} \vec{H}$, being the effective magnetic susceptibility of the particle equal to $\chi_{eff} = 3(\mu_p - \mu_s)/(\mu_p + 2\mu_s) = 1.90$. Here $\mu_p$ and $\mu_s$ are the permeability of the particles and the solvent, respectively \[11\].

B. Experimental setup

To study the dynamics of moderately concentrated magnetic dipolar suspensions (in the range of 1-2 vol%) under rotating magnetic fields scattering dichroism was used. A full description of this experimental technique can be found in Refs. \[3,12\]. A schematic diagram of the optical train used to measure linear dichroism is shown in Figure 2(a) and consists on a He-Ne laser, a polarizer (0°), a photoelastic modulator (45°) and a quarter wave plate (0°). The light is then passed through the sample. The transmitted light, detected by a photodiode, is sent to two phase lock-in amplifiers and then digitized using a 16-bit A/D data acquisition device (National Instruments). With this optical train we can simultaneously measured the time evolution of the dichroism $\Delta n'' = n''_1 - n''_2$, i.e., the difference between the absorption of the incident light in the parallel than in the perpendicular direction to the long axis of the aggregates; and the orientation angle $\theta''$, i.e., the angle between the reference axis of the optical train and the long axis of the aggregates (see Fig. 2(b)). By comparing $\theta''$ with the temporal evolution of the magnetic field direction given by $\omega t$ we found that the structures follow the magnetic field by rotating with the same frequency but with a phase lag that is independent on time for all frequencies measured. Therefore we define the phase lag between the field and the aggregates as $\alpha(t) = \omega t - \theta''(t)$.

The rotating magnetic field was achieved by applying sinusoidal electric signals to two orthogonal pairs of coils by means of two Kepco BOP20-10M power amplifiers, driven by two HP-FG3325A function generators referenced to one another at a phase difference of 90°. In Figure 2(c) we show a sketch of the coils system from the direction of the laser beam. The function generators allowed for control of both the amplitude and the frequency of the rotating magnetic field. These coils are housed in a temperature controlled aluminum cylinder to prevent heating effects. The suspension is placed between two quartz windows held in place by a Delrin attachment with thickness $e = 100 \mu\text{m}$ (see detail of the sample cell on Fig. 2(d)). All experiments were performed at a temperature of $T = 282 \pm 1 \text{K}$ measured on the sample.

III. RESULTS AND DISCUSSION

A. Experimental results

When a rotating field in the plane (X,Y) perpendicular to the optical path direction (axis Z):

$$\vec{H} = H (\cos(\omega t)\hat{x} + \sin(\omega t)\hat{y}),$$

is applied, individual particle chains are observed to continually aggregate and fragment, although after a transient the ensemble achieves a steady state distribution. In the following figures we plot the dichroism and phase lag reached at the steady state, denoted as $\Delta n''_0$ and $\alpha_0$, respectively.

1. Magnetic field effect

In Figure 3(a) the dichroism generated by the suspension d-M1-180/12 (82.5% glycerol, $\phi_v = 0.016$) is plotted versus the magnetic field frequency ($f = \omega/2\pi$) in a log-log form for various magnetic field strengths ($H = 6.2 - 24.8 \text{kA/m}$). As the frequency of the applied field is increased, the dichroism is reduced but not with the same rate. This plot clearly shows two distinct regions for frequencies below and above a critical frequency, $f_c$. Below this critical frequency, the dichroism is essentially independent of frequency and the average number of particles stays almost constant. However, once this frequency is surpassed, the dichroism strongly decreases with frequency, which reveals a diminution of the number of aggregated particles. It is found above 1 Hz that the dichroism drops with frequency with a scaling of approximately $\Delta n''_0 \approx f^{-1}$. For high fields, the change in behavior is moved to higher frequencies, i.e., the critical frequency separating these two regions is shown to increase with the magnitude of the applied magnetic field. At higher fields the particle chains are more able to rotate with higher frequency fields. Since the strength of the interparticle magnetic forces scales with the square of the particle magnetization that dependence is also expected for
the critical frequency. To test this dependence, \( f_c \sim M^2 \), we plot the dichroism curves obtained for different magnetic field strengths versus \( Ma \) number in Figure 4(b) and observe that the curves collapse onto a master curve.

The phase difference between the orientation of the aggregates and the magnetic field, \( \alpha_0 \), versus the frequency of the applied field is plotted in Figure 4(a) for different field strengths. We observe that this phase lag increases with frequency over the whole range of frequencies. However, as we found for the dichroism results, two different responses are observed, depending on the magnitude of the frequency. At low frequencies (below \( f_c \)) the phase difference grows very quickly while at high frequencies the increase of the phase lag is relatively slow. For frequencies larger than the critical frequency, the chains start to disappear so the contribution to the total average phase lag is due to the few small chains that still remain. These small chains lag the magnetic field with larger phase angles since they are close to breaking apart. In addition, a diminution of the phase lag with magnetic field intensity is observed. This behavior is expected since the angular component of the magnetic force, which is the responsible for the rotation of the chain, increases with the amplitude of the magnetic field. These data are replotted versus \( Ma \) number in Figure 4(b) and this also results in a single master curve.

2. Influence of Viscosity

To analyze the influence of the viscosity of the suspending medium, we measured the dichroism induced in the suspensions d-M1-07/60 (with different glycerol concentrations and the same particle volume fraction, \( \phi_v = 0.01 \)) when a field of amplitude \( H = 3.1 \) kA/m is applied. In Figure 5(a) we plot the variation of the dichroism with rotational frequency in a log-log form for solutions with glycerol content ranging from 40% to 80%. Again, two different regimes above or below a critical frequency are observed. As expected, the critical frequency moves to bigger frequencies for low viscosity suspensions because the structures are more free to rotate synchronously with the field. The collapse of those curves with Mason number is presented in Figure 5(b) verifying the dependence of the critical frequency, \( f_c \sim \eta^{-1} \). Note that for low frequencies, \( f < f_c \), the dichroism shows a flatter plateau for solutions with less glycerol content (40-50%) which may be due to the fact that more viscous solutions need more time to reach the steady state.

The steady phase lag measured for these suspensions is plotted in Figure 6(a) versus rotational frequency. We observe that the phase lag variation with the viscosity is much larger than the variation encountered with field strength. As expected, more viscous suspensions show bigger phase lags. The collapse of those curves with Mason number is plotted in Figure 6(b).

These results emphasize the importance of the Mason number in controlling the aggregation phenomena in suspensions of polarizable particles in rotating magnetic fields. The change in behavior for both the dichroism and the phase lag corresponds to \( Ma \approx 1 \) when the viscous forces begin to overcome the magnetic forces.

B. Numerical Simulations

1. Equation of motion

Particle dynamics simulations were conducted that consider the 2D aggregation kinetics of \( N \) dipolar particles of diameter \( 2a \) suspended in a fluid of viscosity \( \eta \) and subjected to rotating magnetic fields of amplitude \( H \) and angular frequency \( \omega \) (see Eq. (3.1)). Two fundamental length scales characterize the formation of chains. The first one is the thermo-magnetic equilibrium distance \( R_1 = 2a \lambda^{1/3} \), where \( \lambda \) is the well-known dimensionless parameter calculated as the ratio between magnetic and thermal energies:

\[
\lambda = \frac{\pi \mu_0 a^3 M^2}{9 k_B T},
\]

where \( \mu_0 \) is the vacuum magnetic permeability, and \( k_B \) is the Boltzmann constant. The second length scale is the average initial interparticle distance, which can be estimated as \( R_0 \approx 2a/\phi_v^{1/3} \). For the experiments presented above \( R_1 > R_0 \) \([13]\), so the application of an external field \( H \) will immediately trigger the magnetic aggregation process. Recognizing this rapid aggregation response, we can neglect the effect of the Brownian motion on the evolution of the structures. Therefore the equation of motion of the \( i \)th particle will be the sum of the following three forces \([14]\):

\[
m \frac{d\vec{v}_i}{dt} = \vec{F}_h(\vec{v}_i) + \sum_{j \neq i} \vec{F}_d(\vec{r}_{ij}) + \sum_{j \neq i} \vec{F}_{hs}(\vec{r}_{ij}),
\]

where
where \( \vec{F}_h (\vec{v}_i) = -6\pi \eta a \vec{v}_i \) is the hydrodynamic Stokes force and \( \vec{v}_i \) is the particle velocity. The dipolar force over particle \( i \)th will be the sum of the dipole-dipole forces exerted by all the other particles over it. The dipole-dipole force between particles \( i \)th and \( j \)th is given by
\[
\vec{F}_d (\vec{r}_{ij}) = \frac{3\mu_0 m^2}{4\pi r_{ij}^4} \left\{ \left[ 1 - 5(\hat{m} \cdot \hat{r}_{ij})^2 \right] \hat{r}_{ij} + 2(\hat{m} \cdot \hat{r}_{ij}) \hat{m} \right\}
\] (3.4)
where \( \vec{r}_{ij} \) is the separation vector between the two center of mass, and we take \( \vec{m} \) to be aligned with the field direction. \( \vec{F}_h \) is a strong repulsive force between the particles to simulate a hard-sphere interaction between them when in contact. This force is calculated from
\[
\vec{F}_h (r_{ij}) = A \frac{3\mu_0 m^2}{4\pi (2a)^4} \exp \left[ -B(r_{ij} / (2a) - 1) \right] \hat{r}_{ij},
\] (3.5)
where we assume \( A = 2 \) and \( B = 10 \). We can normally neglect the inertial term in Eq. 3.3 because the viscous drag term dominates. In the absence of Brownian motion, the strength of the dipolar interactions only influences the coarsening time scale and not the structural evolution [14]. We take the dimensionless length \( A \) where we assume \( B = r/(2a) \) and the dimensionless time \( \tau = t/\beta \) where \( \beta = 12^2 \eta / (\mu_0 M^2) \). This temporal scale leads to a dimensionless rotating frequency equal to \( \Omega = \omega \beta \). This dimensionless frequency is the well-known Mason number with the definition used in Eq. 1.3, \( \Omega \equiv Ma \).

2. Numerical results

We have simulated the first set of experiments using parameters that correspond with suspension d-M1-180/12. The volume fraction \( \phi = 0.016 \) corresponds to an initial average separation between particles equal to \( R_0 / (2a) \approx 3.55 \).

For each magnetic frequency, \( \Omega \), we calculate the experimental observables by averaging their values during the last period of the magnetic rotation after steady state had been reached. As we pointed out previously, \( N_j \) gives us information on the dichroism. In order to calculate the total phase lag, \( \alpha \), we average the phase lag of each cluster, \( \alpha_j \), using the number of particles in each cluster, \( N_j \) as a weighting function.
\[
\alpha = \frac{\sum_j N_j \alpha_j}{\sum_j N_j},
\] (3.6)
where the sum is done for \( j \) with \( N_j > 1 \). The phase lag of each cluster is the difference between the orientation of the magnetic field and the long axis of the chain. To compute the chain orientation we calculate their principal moments of inertia, \( I_j^{max} \), \( I_j^{min} \). Then, the direction of \( I_j^{min} \) gives the orientation of the long axis of the cluster. We also have examined the behavior of the average length, \( \bar{L} \)
\[
\bar{L} = \frac{\sum_j N_j}{\sum_j \frac{1}{I_j^{max}}},
\] (3.7)

To compute these physical quantities we considered straight chains without taking into account the shape of the clusters. To check its effect in our simulations results, we calculated the same quantities but using a weight function \( W_j = N_j s_j \), where \( s_j \) is a shape factor with value 1 for the case of a straight chain, and 0 for a symmetric cluster
\[
s_j = \frac{(I_j^{max})^{1/2} - (I_j^{min})^{1/2}}{(I_j^{max})^{1/2} + (I_j^{min})^{1/2}}.
\] (3.8)

We did not observe appreciable changes in the simulations results using this shape correction. Therefore, we present here the results corresponding to the case without the shape factor.

In Figure 8 we plot the particle positions in the (X,Y) plane for different dimensionless frequencies at one arbitrary time. As we can see in this figure, the size of the structures becomes smaller as the rotational frequency increases. The dimensionless average length versus dimensionless frequency is shown in Figure 8(a). This average length follows a power law behavior with an exponent equal to -0.45. This value is very close to the value (-0.5) predicted by the chain model developed by Martin et al. [16,17] for electrorheological fluids subject to steady shear. Figure 8(b) shows the number of aggregated particles versus dimensionless frequency \( \Omega \). Two different regimes appears, in agreement
with the experimental dichroism. A flat shape for low frequencies, and a strongly decreasing response at frequencies when $\Omega_c \simeq 1$ ($Ma_c \simeq 1$) is surpassed. That means that although the average length is decreasing monotonically with $Ma$, this diminution in length starts affecting the dichroism when the viscous forces dominates over the magnetic forces, i.e., for average chain lengths close to two particles. This is the length associated to the critical Mason number $Ma_c \simeq 1$ (see Fig. 3(b)). For $Ma > 1$ the $N_a$ follows a power law with an exponent close to $-1$, the same value found in the experiments.

These results point out that the number of aggregated particles tracks the dichroism. Therefore we suppose that the theoretical dichroism, computed by the simulations, is a linear function of the $N_a$. In Figure 3(a) the measured dichroism (markers) and the simulated dichroism (solid line) are plotted and show good agreement. We compare in Figure 3(b) the simulated phase lag (see Eq. 3.6) with the experimental values versus dimensionless frequency $\Omega \equiv Ma$. As we can see the theoretical behavior agrees with the experimental results. Below a critical dimensionless frequency $\Omega_c$, the phase lag increases very quickly and above this value the phase lag remains almost constant.

IV. CONCLUSIONS

In this work we used scattering dichroism to analyze the influence of the magnetic and viscous forces on the dynamics of magnetorheological suspensions under rotating magnetic fields. In these suspensions, dichroism arises from the formation of optically anisotropic chains upon imposition of the magnetic field and measure the number of aggregated particles. We found that under rotating fields, these chains adjust their size to rotate synchronously with the field but with a constant phase lag. Two different behaviors for the dichroism and the phase lag are found above or below a critical frequency. We obtained a linear dependence of the critical frequency with the square of the magnetization and with the inverse of the viscosity. This means that the Mason number (ratio of viscous to magnetic forces) governs the dynamics correlating the magnetization and viscosity dependencies of the critical frequency. Therefore there is a critical Mason number below which, the dichroism remains almost constant. Above $Ma_c$, the rotation of the field prevents the particle aggregation process from taking place and hydrodynamic friction forces cause a decrease of dichroism.

Simulations incorporating Stokes friction and dipole-dipole magnetic interaction are able to reproduce the experimental results. According to the simulations, the average length of the chain-like structures decreases when increasing the rotational frequency, scaling as the inverse square root of the Mason number. Furthermore, the simulations reproduce two different behaviors above and below the critical Mason number, $Ma_c$, for the total number of aggregated particles, $N_a$, and the phase lag, $\alpha$, in agreement with the experiments.

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[1] The form dichroism measures the difference between the absorption of the incident light in the parallel and in the perpendicular direction to the long axis of the scattering objects. The form birefringence arises from a spatially anisotropic arrangement of domains with different refractive indexes.

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The values of $\lambda$ that correspond to the results reported here are $181 < \lambda < 712$ for the experiments with the suspension d-M1-180/12 and $\lambda = 322$ for the experiments with suspensions d-M1-070/60.

The same behavior $L \propto M_a^{-1/2}$ is also obtained for a chain model in the case of rotating magnetic fields: J. E. Martin (private communication).

### TABLE I. Properties of the magnetic latex micro-spheres used.

### TABLE II. Summary of the experimental conditions.

FIG. 1. Measured magnetization curve for the particles M1-180/12 in the range of magnetic fields reported in the experiments. The particles show a superparamagnetic behavior with no hysteresis but with saturation effects for high fields.

FIG. 2. Experimental setup. (a) Schematic diagram of linear dichroism optical train which enables one to measure the dichroism, $\Delta n'' = n_1'' - n_2''$, and the orientation angle of the structures, $\theta''$. (b) Definition of the phase lag, $\alpha(t) = \omega t - \theta''(t)$, between the magnetic field and the chains. (c) Sketch of the coils system to generate the rotating magnetic field. (d) Detail of the quartz cell filled with MR suspension.

FIG. 3. Variation of the steady dichroism with rotational frequency (a) and collapse of dichroism with $M_a$ number (b) for different magnetic field strengths in a log-log plot. Measurements for suspension d-M1-180/12 (82.5% glycerol content, $\phi_v = 0.016$). Power law fit with an exponent -1 for $M_a > M_{ac}$.

FIG. 4. Variation of the steady phase lag with rotational frequency (a) and collapse of the phase lag with $M_a$ number (b) for different magnetic field strengths. Measurements for suspension d-M1-180/12 (82.5% glycerol content, $\phi_v = 0.016$).

FIG. 5. Variation of the steady dichroism with rotational frequency (a) and collapse of dichroism with $M_a$ number (b) for suspensions d-M1-070/60 (different glycerol content, $\phi_v = 0.01$) in a log-log plot when a magnetic field of amplitude $H = 3.1$ kA/m is applied.

FIG. 6. Variation of the steady phase lag with rotational frequency (a) and collapse of the phase lag with $M_a$ number (b) for suspensions d-M1-070/60 (different glycerol content, $\phi_v = 0.01$) in a log-log plot when a magnetic field of amplitude $H = 3.1$ kA/m is applied.

FIG. 7. Dimensionless particles position for different dimensionless rotating frequencies, $\Omega \equiv M_a$, at an arbitrary time value. Calculations for suspension d-M1-180/12 (82.5% glycerol content, $\phi_v = 0.016$).

FIG. 8. Dimensionless average chain length (a) and number of aggregated particles (b) versus dimensionless rotational frequency, $\Omega \equiv M_a$, in a log-log plot (markers). The power law fit (solid line) gives an exponent equal to -0.45 for the average chain length and -1 for the $N_a$. Calculations for suspension d-M1-180/12 (82.5% glycerol, $\phi_v = 0.016$).

FIG. 9. Steady dichroism (a) and steady phase lag (b) as a function of the rotating frequency for the experiments (markers) and simulations (solid line). Measurements for suspension d-M1-180/12 (82.5% glycerol, $\phi_v = 0.016$).
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Table 1: Properties of the magnetic latex micro-spheres used.

| Particle properties       | M1-180/12 | M1-070/60 |
|---------------------------|-----------|-----------|
| Mean diameter             | 1.01 µm   | 0.90 µm   |
| Magnetic content          | 13 %      | 62 %      |
| Saturation field          | 11.1 emu/gr | 52.7 emu/gr |
| Surface group content     | 20 µeq/g  | 145 µeq/g |

Table 2: Summary of the experimental conditions.

| Experimental parameters    | Magnetic field effect | Influence of viscosity |
|----------------------------|-----------------------|------------------------|
| Suspension                 | d-M1-180/12           | d-M1-070/60            |
| Glycerol volume content    | 82.5 %                | 40 - 80 %              |
| Volume fraction            | $\phi_v = 0.016$      | $\phi_v = 0.01$        |
| Field strength (kA/m)      | $H = 6.2 - 24.8$      | $H = 3.1$              |