# STUDY OF THE INTERACTION BETWEEN FERROMAGNETIC PARTICLES IN A ROTATING CONSTANT MAGNETIC FIELD

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A rotating magnetic field produces in a magnetic colloidal suspension a friction torque which is equal to the energy of dipole attraction between particles, which increases as the surface forces of repulsion decrease, and which is by a few orders of magnitude greater than the effect of intrinsic rotation of particles (the Tsvetkov effect).

When a magnetic field acts on a colloidally dispersed ferromagnetic substance, the particles agglomerate into chains [1, 2]. In a rotating field the particles follow the field and, as a result, there appears a friction torque due to the interaction between particles. This study was concerned with the effect of the frequency $\omega$ and of the field intensity on the friction torque in colloidal suspensions of magnetite $Fe_3O_4$ and of metallic iron. A field was produced by rotating an electromagnet energized from a direct-current source through slip rings. The friction torque was measured by the twisting of a cylindrical vessel containing 4 $cm^3$ of the colloidal substance and suspended on an elastic Nichrome thread. It had been shown earlier in [3] that the friction torque

$$M = 2n\bar{m}^2r^{-3} + p\varphi_{ev}\eta\omega$$

represents the sum of friction torque $M_n = 2n\bar{m}^2r^{-3}$ due to interaction between particles and friction torque $M_\omega = p\varphi_{ev}\eta\omega$ due to the intrinsic rotation of particles [4]. For particles with a constant magnetic moment (single-domain particles) $\bar{m} = mL(mH/kT)$, where $L(mH/kT)$ is the Langevin function with k denoting the Boltzmann constant and T denoting the temperature. An analogous expression can be derived for a rotating electric field.

One usually, without justification, disregards the effect of interaction between particles on the magnitude of M [5-7], assuming that $M = M_\omega$, since $\lim\limits_{\omega\to 0} M \equiv 0$. The friction torques measured in a magnetic B-field and shown in Fig. 1 indicate, however, that $M \neq 0$ when $\omega = 0$, i.e., that, according to (1), $\lim\limits_{\omega\to 0} M = M_n$.

It is evident from the graphs that, at moderately high frequencies, $M_n$ is often by a few orders of magnitude greater than M, the latter being taken into account only in a few known studies on this subject [5-11]. Over the entire tested range of field intensity (100-1200 Oe) and frequency $\omega$ (0 to $2\pi\cdot 40$) the torque $M_\omega$ is proportional to $\omega$.

The increase in $M_n$ observed after NaCl has been added to aqueous suspensions and $C_2H_5OH$ has been added to toluene suspensions of colloidal ferromagnetic substances is a result of smaller repulsion forces, i.e., of a smaller distance (r) between particles in the chains.

The magnitude of a rigid magnetic dipole (m) and the saturation magnetization $I_s = mn$ are determined by measuring the magnetization of sols: for a colloidal magnetite suspension in water $m = 2.2\cdot 10^{-16}$ erg/Oe and $I_s = 0.37$ G, for a colloidal magnetite suspension in toluene $m = 2.0\cdot 10^{-16}$ erg/Oe and $I_s = 0.98$ G, for a colloidal iron suspension in toluene $m = 2.0\cdot 10^{-16}$ erg/Oe and $I_s = 0.036$ G.

From these data and measured values of the twisting torque one can calculate the equilibrium distances between particles in chains and the corresponding surface forces of repulsion between particles, on the basis of the equilibrium condition, i.e., the equality of these forces and the dipole attraction forces.

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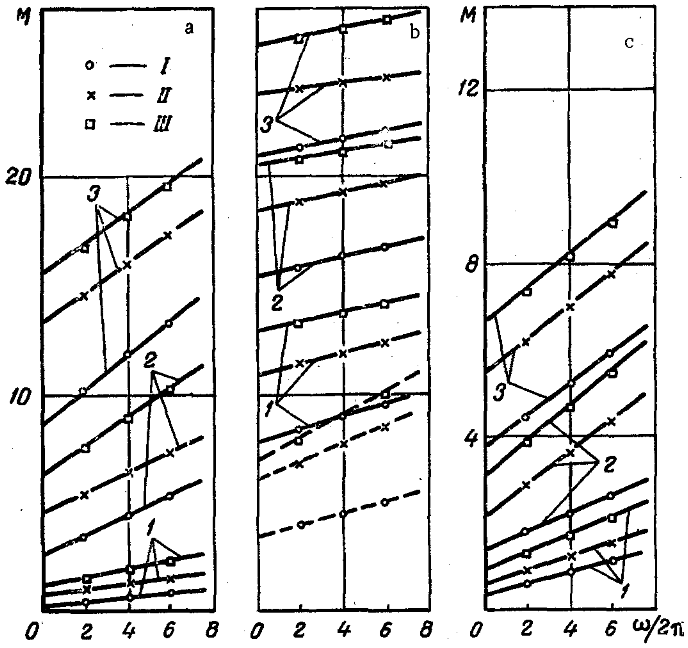


Fig. 1. Twisting torque (M, dyn/cm$^2$) in a rotating field, as a function of the frequency and of the field intensity, for: a) water suspension of colloidal $Fe_3O_4$; b) toluene suspension of colloidal $Fe_3O_4$; c) toluene suspension of colloidal Fe. Field intensity: I) 400 Oe; II) 800 Oe; III) 1200 Oe. Concentration of coagulators and colloidal ferromagnetic substances: a) coagulator NaCl: 1) 0 mole/liter; 2) 0.2 mole/liter; 3) 0.35 mole/liter; b) coagulator ethanol: 1) 0 mole/liter; 2) 2.5 moles /liter; 3) 5.4 moles/liter; dashed lines indicate traces of water; c) coagulator ethanol: 1) 0 mole/liter; 2) 1.6 moles/liter; 3) 2.8 moles/liter. Frequency $\omega/2\pi$, sec$^{-2}$.

In a water suspension of $Fe_3O_4$ the distances decrease from 500 to 210 Å as the NaCl concentration is increased from 0 to 0.4 mole/liter; in a toluene suspension of $Fe_3O_4$ the distances decrease from 330 to 270 Å as the $C_2H_5OH$ coagulator concentration is increased from 0 to 5.4 moles/liter; in a toluene suspension of Fe the distances decrease from 230 to 110 Å as the $C_2H_5OH$ concentration is increased from 0 to 2.8 moles/liter.

The insignificant traces of water present in the toluene suspension of magnetite cause the repulsion forces between particles to become greater and the equilibrium distances between particles to increase from 330 to 350 Å.

## NOTATION

$n$ is the number of particles per unit volume;
$\bar{m}$ is the mean magnetic moment projected on the field axis;
$r$ is the distance between particles in a chain;
$\varphi_{ev}$ is the effective volume fraction of the dispersed phase;
$\eta$ is the viscosity of the medium;
$\omega$ is the angular frequency of the rotating field;
$p$ is the form factor ($p = 6$ for spheres).

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