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Dynamics of magnetic fluid drop's shape in rotating and stationary magnetic fields

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Abstract

A drop of magnetic fluid was experimentally studied in a rotating magnetic field H_r with the additional influence of a stationary magnetic field H_s. The conditions of a drop break were studied with different values and directions of intensities between rotating and static magnetic fields. The results of the experiment were theoretically well grounded.

Keywords: Drop of a magnetic fluid; Rotating magnetic field; Stationary magnetic fields

1. Introduction

There are some works dealing with the studies of a magnetic drop's shape in a static [1–3], and rotating [4–6] magnetic field. The researches considered it interesting to conduct similar experiments on simultaneous action of rotating and stationary magnetic fields at different angles to the directions of their intensities.

A drop of magnetic fluid such as magnetite in kerosene with density $1.26 \times 10^3\,\text{kg/m}^3$ was suspended in glycerin in hydro-weightlessness (the inter-phase surface tension for the magnetic fluid/glycerin was $3.7 \times 10^{-2}\,\text{N/m}$).

A glass vessel with drop (1) (Fig. 1) was placed at an equal distance between two pairs of Helmholtz's coils. One pair (2) was mounted on a rotating platform (3). The other one (4) was fixed, the vector of the stationary field intensity H_s being either parallel or perpendicular to the rotation plane of vector H_r.

Since in these fields the drop shape is close to the ellipsoid of revolution, the eccentricity $e = \sqrt{1 - b^2/a^2}$ (where a, b are the major and minor axis) was accepted as a basic parameter. A video camera was employed to record the evolution of the drop made with the obtained data being subsequently processed. The size measurement error was less than 10%.

2. The intensity vectors of both stationary and rotating fields are oriented in the same plane

As found earlier [6], in the absence of constant magnetizing field the eccentricity of the drop remains the same during all the period of the drop rotation, provided that the field rotates with a fixed frequency. In our case (having applied the constant field), we observed fluctuations similar to the fluctuations described in Ref. [7,8] (in Ref. [7,8] the electrical field was applied along with the rotating magnetic field). The $e(t)$ curves resembled ordinary cycloid (Fig. 2). But contrary to the observations of Ref. [7,8], the frequency of the eccentricity oscillation coincided with the frequency of the field rotation, while the amplitude of the oscillation grew as H_s was intensified. Curve 1 in Fig. 2 corresponds to the rotation frequency $\omega = 7\,\text{s}^{-1}$ and the following field intensities: $H_r = 6.4\,\text{kA/m}$, $H_s = 1.2\,\text{kA/m}$. For curve 2, the intensity of stationary field H_s was increased to 2 kA/m(other parameters being the same).

When the stationary field was kept constant the eccentricity decreased as the frequency of the rotating field was increased.

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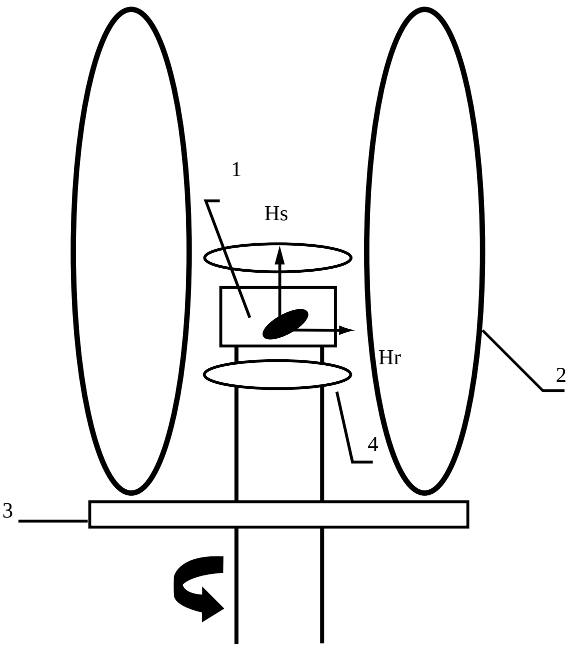

Fig. 1. The experimental installation: (1) glass vessel with drop, (2) the first pair of Helmholtz's coils, (3) rotating platform, and (4) second pair of Helmholtz's coils.

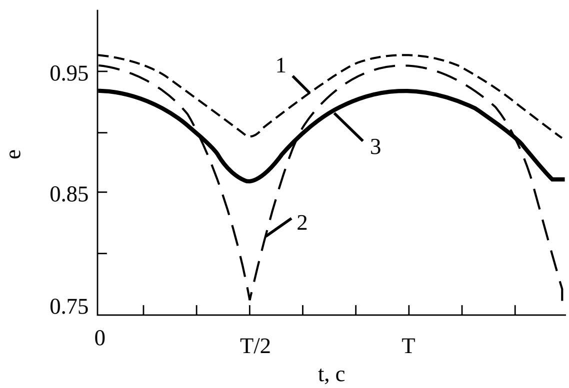

Fig. 2. The dependence of drop's eccentricity from time during one rotation period (rotation frequency was $\omega = 7\,s^{-1}$): (1) $H_r = 6.4\,kA/m$, $H_s = 1.2\,kA/m$, (2) $H_r = 6.4\,kA/m$, $H_s = 2\,kA/m$, and (3) the theoretical curve.

As established earlier [6], the major axis of the drop lags behind the instant direction of the magnetic field H_r. We denote the angle of lag as φ. The value of φ depends on the viscosity of liquid, the rotation frequency and the magnetic field intensity. As we found from our experiments, angle φ did not remain constant during the rotation period of H_r if the additional stationary magnetic field was applied. Its time dependence was defined by intensities ratio of the stationary magnetic field and rotating one. With H_r and the rotation

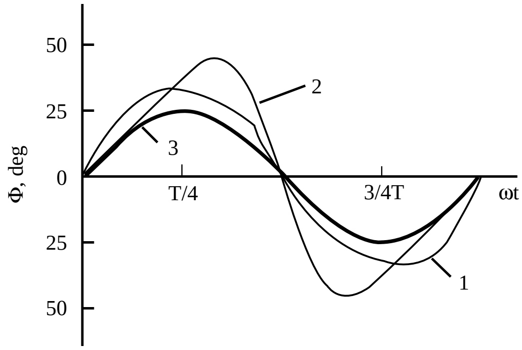

Fig. 3. The dependence of a corner of backlog φ of a drop from the intensity of a rotating field from time: (1) $H_s = 2\,kA/m$, $H_r = 6.4\,kA/m$, (2) $H_s = 2.4\,kA/m$ and the intensity $H_r = 1.3\,kA/m$, and (3) the theoretical curve.

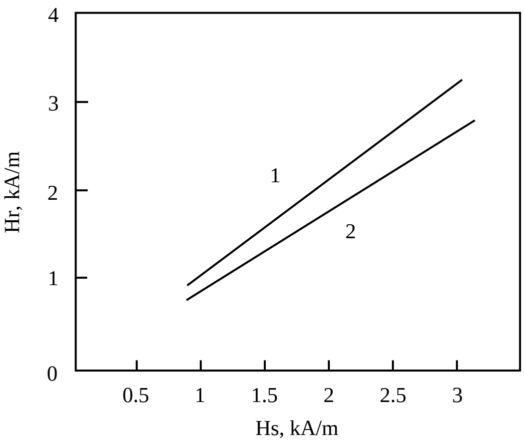

Fig. 4. The dependence the intensity of a rotating field on the intensity of a stationary field at the moment when a drop passed from oscillatory movement to rotary movement: (1) $d = 2.5\,mm$ and (2) $d = 8\,mm$.

frequency being kept constant, the $\varphi(t)$ dependence shifted from a sine-shaped wave to a non-sine function, as H_s was increased (Fig. 3, curves 1 and 2). Curve 1 was obtained at the following intensities: $H_s = 2\,kA/m$ and $H_r = 6.4\,kA/m$; curve 2, at $H_s = 2.4\,kA/m$ and $H_r = 1.3\,kA/m$. The further increase of the stationary field resulted in the termination of the drop rotation. Instead of rotation we observed the fluctuations of drop's major axis about the vector of a stationary magnetic field. We experimentally investigated the $H_r = H_r(H_s)$ dependence at the rotation–oscillation transition. It turned to be linear with the proportionality coefficient being dependent on the size of the drop (Fig. 4). For all the frequencies ($\omega = 0-20\,s$) and field intensities ($H_s = 0-4\,kA/m$, $H_s = 0-9\,kA/m$) tried, the additional stationary field proved to prevent the drop from the break-up as reported in Ref. [6].

3. The intensity vectors of the stationary and rotating fields lie on perpendicular planes

When the H_s vector was directed perpendicularly to the rotation plane of the H_r vector, the superposition of these fields at every moment gave a conical rotary resulting field. Under the latter the magnetic fluid drop deformed and started a precession rotation about the axis through the mass center with the ends of the major axis describing circles on parallel horizontal planes (Fig. 5).

If the intensity of the resulting magnetic field $H = \sqrt{H_s^2 + H_r^2}$ was smaller than some critical value H^*, the increase in the field rotation frequency lead to reduction of deformation of the drop (it approached a spherical shape). The similar phenomenon was observed earlier [6] at zero stationary magnetic field. The H^* value in turn depended on the size of the drop and rotation frequency.

At $H \geqslant H^*$ the deformation of the drop progressed and at a certain frequency of rotation it broke into 2 or 3 unequal drops. The $H^*(H_s)$ dependence at break-up was obtained for different drop sizes intensities from the intensities of stationary field H_s at the moments of drop's break were received. They were obtained for different drop's sizes (Fig. 6, curves 1, 2 and 3 correspond to drop diameters $d = 5$, 6 and 7 mm, respectively). As may be seen from Fig. 6, at the fixed frequency the position of the curves' minim shifted towards higher field intensities, while the drop size decreased.

Introducing angle β between the major axis of the drop and the rotation plane of the H_r vector ($\mathrm{tg}\,\beta = H_s/H_r$), we also obtained the β dependence for the drop rotation frequency at break-up (Fig. 7). The

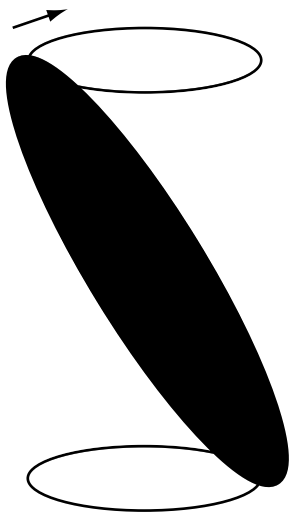

Fig. 5. Precession rotation of a magnetic fluid drop when the intensity of stationary field was perpendicular to the intensity of rotating field.

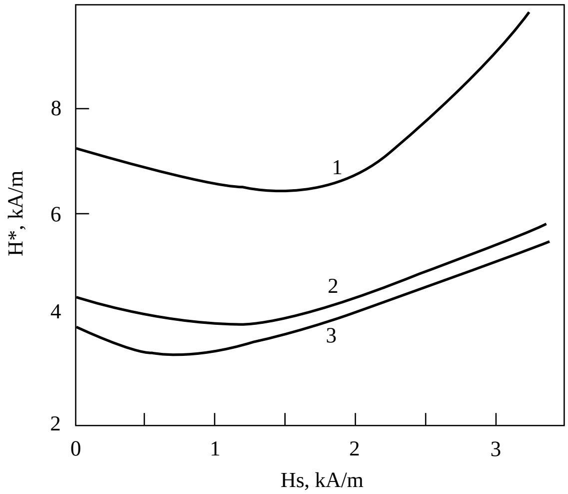

Fig. 6. The dependence of intensity of a magnetic field H* when a drop broke from intensity of a stationary magnetic field: (1) $d = 5$ mm; (2) $d = 6$ mm; (3) $d = 7$ mm.

value of the resulting magnetic field was being kept constant $H = 3.1$ kA/m. Three curves were plotted for various drop diameters d (curve 1 corresponds to $d = 0.55$ sm; curve 2 to $d = 0.7$ sm and curve 3 to $d = 0.8$ sm). At $\beta \geqslant \beta^*$ the drop breaks up, where β^* is the critical angle. If β was kept constant and the resulting field intensity H was varied instead, the H dependence for the rotation frequency at break-up turned to be linear. In Fig. 8 this dependence is presented at different angles β ($d = 0.9$ sm): for curve 1 $\beta = 45°$, for curve2, $\beta = 30°$ and for curve3, $\beta = 0°$.

The theoretical analysis of the observable phenomena is carried out similarly to Ref. [7] using the model of absolutely elastic ellipsoid of revolution. In the present article we only consider the case of the stationary field vector H_s lying in the rotation plane of the vector H_r. The general case will be reported elsewhere.

We analyze the energy of a magnetic fluid drop in a rotating magnetic field. It takes the form

$$W = W_p - W_m - W_r, \tag{1}$$

where W_p is the superficial energy of the drop given as

$$W_p = 2\pi r^2 \sigma (1 - e^2)^{1/3} \left(1 + \frac{\arcsin e}{e\sqrt{1 - e^2}}\right), \tag{2}$$

r is the radius of the unperturbed drop, W_k is the kinetic energy of rotating ellipsoid

$$W_k = \frac{4\pi\rho r^5}{15} \frac{2 - e^2}{(1 - e^2)^{2/3}} \omega^2. \tag{3}$$

W_m is the magnetic energy of ellipsoidal drop,

$$W_m = \chi H^2 V \left(\frac{\cos^2\varphi}{1 + \chi n} + \frac{2\sin^2\varphi}{2 + \chi - \chi n}\right) \tag{4}$$

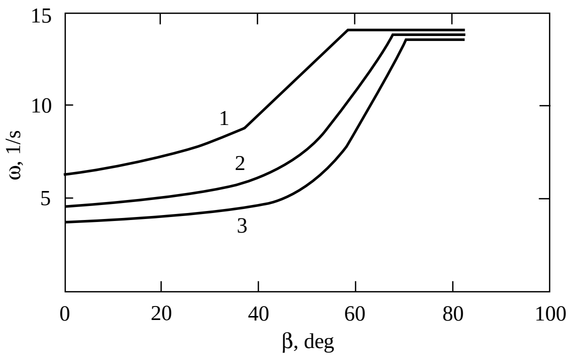

Fig. 7. The dependences of rotation frequency of a drop at the moment of drop's break from a corner β between large axis of a drop and plane of rotation H_r: (1) $d = 5.5$ mm; (2) $d = 7$ mm; (3) $d = 8$ mm.

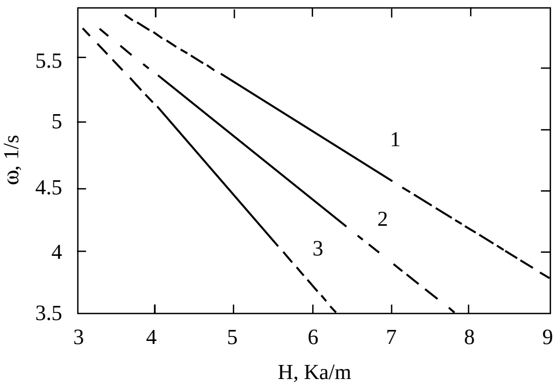

Fig. 8. The dependences of rotation frequency at which the drop was broken off from of intensity of a resulting magnetic field: (1) $\beta = 45°$, (2) $\beta = 30°$; (3) $\beta = 0°$.

with

$$H = \sqrt{H_s^2 + H_r^2 - 2H_r H_s \cos \omega t}. \tag{5}$$

The necessary conditions of the energy minimum for a stable eccentricity may be expressed by the following system of the equations:

$$\frac{\partial W}{\partial e} = 0,$$
$$\frac{\partial W}{\partial \varphi} = K_{mp}. \tag{6}$$

In order to solve system (6) it is necessary to know the eccentricity dependence for the angle of lag, which can be found from the equation

$$K_m \sin 2\varphi - K_t = 0, \tag{7}$$

where K_t is the viscous torque exerted on a drop [9], K_m is the maximal moment of magnetic forces exerted on an ellipsoidal drop, determined by the expression

$$K_m = \mu_0 \frac{VH^2\chi^2(1-3n)}{2(1+\chi n)(2+\chi-\chi n)}. \tag{8}$$

Solving Eq. (7) gives

$$\varphi = \frac{1}{2}\arcsin\frac{K_t}{K_m}. \tag{9}$$

Numerical solution of system (6) gives the time dependence of the eccentricity (curve 3 in Fig. 2). This dependence is close to cycloid with the period equal to the rotation period of the magnetic field, which is consistent with our experimental results (curves 1 and 2, Fig. 2).

Substituting the obtained eccentricity-time dependence into Eq. (9) enables us to derive the time dependence of the angle of lag. From Eq. (7) one can see that the angle of lag fluctuates about zero (curve 3, Fig. 3), if the maximal moment of the magnetic force is not less than the viscous friction torque, which is in a good agreement with the experimental data (curves 1 and 2, Fig. 3). Otherwise, the fluctuations occur about the direction of the stationary magnetic field, which is also in accordance with the experimental evidence.

Thus, our research demonstrated that supervision of the stationary magnetic field enables one to operate the stability of a magnetic drop, in applied rotating magnetic field.

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