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The Effect of Interface Tension on Forced Oscillations of Elongated Microdroplet Aggregates in Magnetic Fluids

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Changes in the shape of microdroplet aggregates exposed to an alternating magnetic field with frequency from 0.01 to 1 Hz are investigated both experimentally and using a computer simulation. Microdroplet aggregates are spherical droplets of a highly concentrated magnetic fluid with a radius from one to several tens of microns dispersed in a liquid with a low concentration of magnetic particles. For values of interfacial tension $\sigma > 2 \cdot 10^{-6}$ N/m small oscillations in a weak alternating field could not be obtained, but periodic forced oscillations were obtained at strong elongations. Oscillations of elongated microdroplet aggregates are of a periodical nonsinusoidal type with higher harmonics and subharmonics in the spectrum.

Keywords: Magnetic fluid, Forced oscillations, Interfacial tension, Microdroplet aggregate.

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1. INTRODUCTION

Application and research of liquid magnetizable nanodisperse systems known as magnetic fluid (MF), started over 50 years ago. MF are the stabilized colloids of magnetic particles of size ~ 10 nanometers in different non-magnetic host liquids. The combination of fluidity with the possibility to be magnetized in weak magnetic fields is still attracting the attention of engineers and researchers. Complex heterogeneous systems that are based on the MF, in particular, microemulsions and MF containing microdroplets are promising new materials for defectoscopy. The properties of boundary between heterogeneous magnetic phases are unique in having both low values of interfacial tension values $\sigma \sim 10^{-7}$ H/m and high values (for liquid artificial media) of permeability units. In the absence of external field, microdroplet aggregates have a spherical shape; in a weak field, they can be strongly deformed assuming the shape of needles oriented along the field. The static deformation of suspended MF" droplets and microdroplet aggregates is well studied experimentally and theoretically [1, 2]. Deformation of microdrops under weak magnetic field corresponded closely to the model that uses assumptions about the linear nature of the magnetization and ellipsoidal shape of the aggregates. When using energy approach equilibrium forms of microdrops can be obtained from the Lagrange equations

$$\frac{d}{dT}\frac{\partial T}{\partial \dot{\lambda}} - \frac{\partial T}{\partial \lambda} = -\frac{\partial E_\sigma}{\partial \lambda} - \frac{\partial E_m}{\partial \lambda} - \frac{\partial \dot{E}_\eta}{\partial \dot{\lambda}},$$

where T – total energy, E_σ – surface energy, E_m – magnetic energy, $\dot{E}_\eta$ – viscous dissipation rate, λ – the ratio of the major and minor axes of the ellipsoid. From the equation (1) it follows that deformation of aggregates in magnetic field has a hysteresis nature.

When the magnetic field strength is lower than critical value H_1 the microdrop takes the shape of prolate ellipsoid of revolution oriented along the field with the axes ratio $a / b < 2$. At $H > H_1$ a jumpwise elongation of a microdrop occurs and it acquires the form of a body of revolution with tapered ends and the axis ratio $a / b > 10$. When the external magnetic field strength decreases, the transition from highly elongated aggregates to the aggregates with ratio $a / b < 2$ take place in the critical field $H_2 < H_1$. In an ac magnetic field $H_0\sin(\omega t)$ microdrops can make as small oscillations close to sinusoidal and nonlinear large-amplitude oscillations [3]. At the same time, the influence of the alternating field on the form of microdrop and large-amplitude oscillation has been insufficiently studied.

2. DESCRIPTION OF THE OBJECT AND METHODS OF INVESTIGATION

We have studied both experimentally and using a computer simulation not previously discussed effect of the interfacial tension on the nature of the oscillations of elongated aggregates. The changes in the shape of microdrops were studied by the optical method with registration of light transmitted through sample. Using a microscope, the boundary between a microdrop and surrounding fluid was projected on a cathode of photomultiplier through a slit diaphragm placed in parallel to the oscillation axis. The experimental set-up is described in [3].

The experimental samples were magnetic fluids of the «magnetite in kerosene» type containing microdroplets. The interfacial tension values σ differ by one order of magnitude and varies between $2 \cdot 10^{-7}$ H/m and $3{,}7 \cdot 10^{-6}$ H/m. For exciting forced oscillation, the root-mean-square value of ac magnetic field $H(t) = H_0\sin(\omega t)$ exceeds the critical value H_1. At the same time, the value H_0 was experimentally chosen so that the aggregates are not merged into a larger ones under the influence of the magnetic field, and the disperse composition of the fluid during oscillation is not changed.

3. EXPERIMENT

In a weak alternating sinusoidal field $H(t) = H_0\sin(\omega t)$ at frequency $f = \omega / 2\pi$ when 0.01 Hz $< f < 0{,}1$ Hz for a period microdrops have time to take strongly elongated shape and return to equilibrium (spherical) shape during period. Oscillations of elongated microdroplet aggregates are of a periodical

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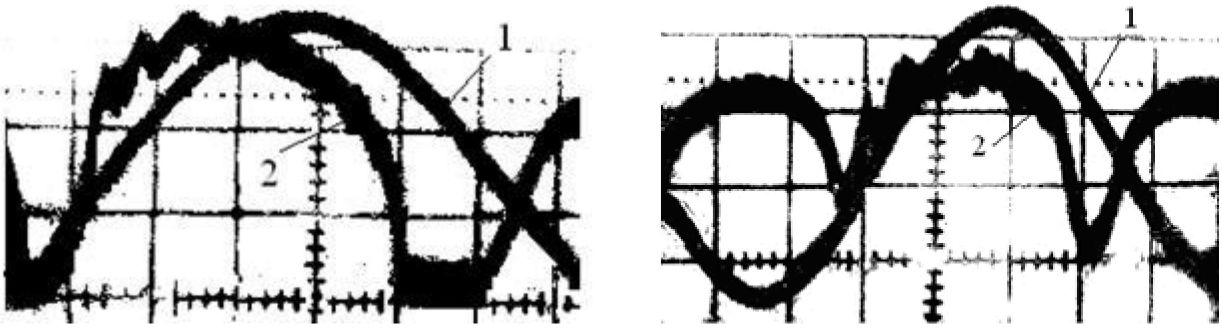

a b

Fig. 1 – Photographs of the oscillograms: f = 0,2 Hz – a; f = 0,3 Hz – b

nonsinusoidal type with period equal to period of the driving force which has sinusoidal character with frequency 2 f (proportional to $H\nabla H$).

Figure 1 shows photograph of the oscillograms, in which two curves are presented. The curves 1 correspond to magnetic field $H(t) = H_0 sin(\omega t)$, the curves 2 corresponds to changes in the light flux.

As the frequency increases, and the ratio T_{el}/T_0 increases reaching $T_{el}/T_0 \to 1$. T_0 is period of oscillation and T_{el} is the residence time of droplets in an elongated state. Figure 2 shows the dependence of T_{el}/T_0 on the ac field frequency when $\sigma = 3{,}7 \cdot 10^{-7}$ N/м, H_0 = 373 A/м.

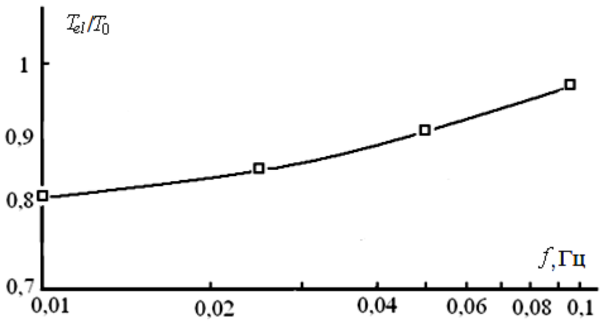

Fig. 2 – The ratio T_{el} / T_0 versus frequency

To analyze the character of the microdrops oscillation, periodic nonsinusoidal curves that corresponded to the light flux were expanded into Fourier series. For harmonic components of the discrete spectrum, we calculated coefficients $k_i = A_i/A$, represent the ratios of root-mean-square values of harmonics to the effective value of the entire curve, which was determined without the constant component. The frequency of fundamental harmonic (k = 1) of oscillations of microdroplets coincides with the frequency of driving force (2f). The subgarmonic (k_s) has frequency f which coincides with the frequency of external magnetic field. It was shown in [3] that contribution of subgarmonic to the effective value of the light flux signal increases with the frequency, and the fraction of fundamental harmonic decreases.

The distinctive property of samples which have $\sigma \geq 2 \cdot 10^{-6}$ N/m is that it is impossible to obtain small-amplitude oscillation due to strong damping. But with strong elongations for these samples the forced oscillation were obtained in an ac field which efficient value is greater than H_1. Elongation of microdroplet aggregates during the forced oscillation is composed of a fixed part, which does not coincide with the equilibrium shape, and a variable part, which is caused by oscillations sharpened end. At $\sigma = 3{,}7 \cdot 10^{-6}$ N/m and f = 0,5 Hz we obtained k_1 = 0,75 and when f = 1 Hz we obtained k_1 = 0,67. A further increase in frequency is accompanied by the fact that the fraction of the fundamental harmonic decreases and the fraction of the subgarmonic increases and character of frequency dependence of k_1 and k_s for samples which have $\sigma \geq 2 \cdot 10^{-6}$ N/m corresponds to that obtained previously at lower values of the interfacial tension.

The surprising thing is that we obtained forced oscillation of microdroplets which have $\sigma \geq 2 \cdot 10^{-6}$ N/m. To explain this fact, we performed numerical calculations.

4. COMPUTER SIMULATION

To compare the effects of viscosity, surface and magnetic forces on microdroplets oscillation at high elongations the computer modeling were performed. For this purpose, equation (1) is represented as:

$$\frac{d^2\lambda(t)}{dt^2} - f_1(\lambda(t)) \cdot \left(\frac{d\lambda(t)}{dt}\right)^2 + f_2(\lambda(t)) \cdot \frac{d\lambda(t)}{dt} + f_3(\lambda(t)) \cdot \lambda(t) + f_4(\lambda(t)) \cdot \lambda(t)$$

where $f_1(\lambda(t)) = \dfrac{\lambda(t)^2 + 2}{\lambda(t) \cdot \left(2\lambda(t)^2 + 1\right)}$; $f_2(\lambda(t)) = \dfrac{60 \cdot \eta}{\left(\rho + \dfrac{\rho_1}{2}\right) \cdot R^2} \cdot \dfrac{\lambda(t)^{2/3}}{\left(2\lambda(t)^2 + 1\right)}$;

$$f_3(\lambda(t)) = \frac{45 \cdot \sigma \cdot}{4R^3 \left(\rho + \dfrac{\rho_1}{2}\right)} \cdot \frac{\lambda(t)^2}{\left(2\lambda(t)^2 + 1\right) \cdot (\lambda(t)^2 - 1)} \left(\frac{\lambda(t)^2 - 4}{\sqrt{\lambda(t)^2 - 1}} \arcsin\left(\frac{\sqrt{\lambda(t)^2 - 1}}{\lambda(t)}\right) + \frac{2}{\lambda(t)^2} + 1\right);$$

$$f_4(\lambda(t)) = \frac{45\mu_0(\mu_i-\mu_e)^2 H(t)^2\left(\lambda(t)^2-1\right)^2}{2R^2\lambda(t)\cdot\left(\rho+\frac{\rho_1}{2}\right)\left(\lambda(t)^{-8/3}+2\lambda(t)^{-2/3}\right)}\times$$

$$\times\frac{\left[\left(\ln\left(2\lambda(t)^2+2\lambda(t)\sqrt{\lambda(t)^2-1}-1\right)-2\sqrt{1-\lambda(t)^{-2}}\right)\cdot\left(2\lambda(t)^2+1\right)\left(\lambda(t)^2-1\right)^{-3/2}-2\lambda(t)^{-1}\right]}{\left(\lambda(t)\left(\mu_i/\mu_e-1\right)\left(\ln\left(2\lambda(t)^2+2\lambda(t)\sqrt{\lambda(t)^2-1}-1\right)-2\sqrt{1-\lambda(t)^{-2}}\right)+2\left(\lambda(t)^2-1\right)^{3/2}\right)^2}.$$

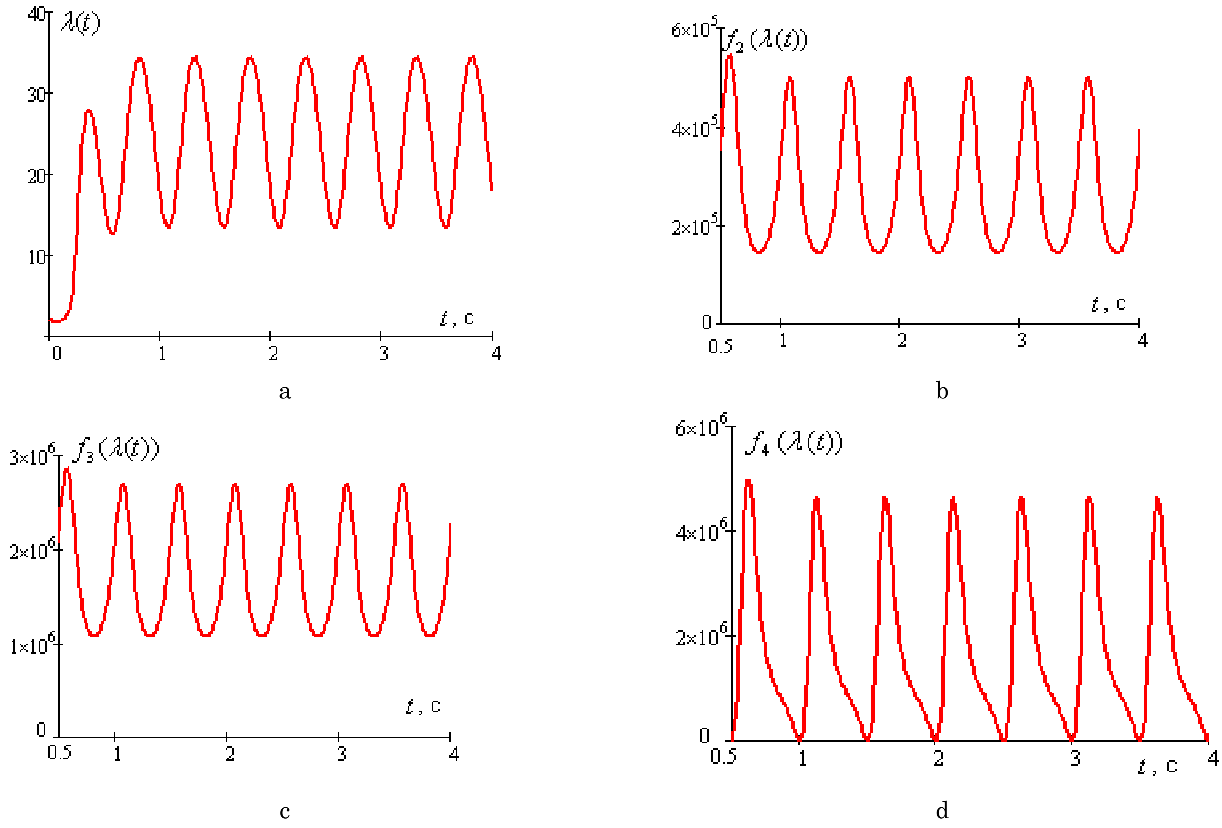

Fig. 3 – Functions of time: ratio $\lambda(t)$ – *a*, viscous forces $f_2(\lambda(t))$ – *b*, surface forces $f_3(\lambda(t))$ – c, magnetic forces $f_4(\lambda(t))$ – d

Numerical calculations performed by the Runge-Kutta methods, allow us to compare the contribution of inertia $f_1(\lambda(t))$, viscous $f_2(\lambda(t))$, surface $f_3(\lambda(t))$ and magnetic $f_4(\lambda(t))$ forces in the process of oscillation. In the calculations the following parameters were used: interfacial tension between microdroplet aggregate and the surrounding fluid $\sigma = 3{,}7\cdot10^{-6}$ N/m, viscosity $\eta = 0{,}068$ Pa·s; permeability unit $\mu_i = 60$; permeability of surrounding fluid $\mu_e = 2$; density of microdroplets $\rho = 1900$ kg/m³ density of the surrounding fluid $\rho_1 = 1360$ kg/m³, $H_0 = 440$ A/m, $f = 1$ Hz. The results are presented in Figure 3.

5. CONCLUSION

From the calculation results, we can conclude that for samples with $\sigma \geq 2\cdot10^{-6}$ N/m the effect of viscous dissipation forces less pronounced than the surface and magnetic forces. Near the sharpened end a dominant influence on the deformation and oscillation can exert magnetic forces.

Therefore, oscillations of strongly elongated aggregates at $H > H_1$ in contrast to small oscillations at $H < H_1$ are not suppressed by surface forces.

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