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**Short Communication**

# Spectrum Features of Forced Oscillations of Microdroplet Aggregates in Magnetic Fluids

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We have studied the discrete spectrum of the forced oscillation of microdroplet aggregates in magnetic fluid in magnetic field $H(t) = H_0\sin\omega t$ with the frequency of 0,01-100 Hz.

Keywords: Magnetic fluid, Microdroplet aggregate, Forced oscillations, Fourier analysis.

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## 1. INTRODUCTION

Magnetic fluids are artificial magnetizing nanodispersive environment, combining fluidity with the ability to be magnetized. Microdroplet aggregates are included in some of the samples of magnetic fluids type «magnetite in water» [1] and «magnetite in kerosene» [2], represent a field outside a spherical drop of highly concentrated magnetic fluid with size of about 1 µm in the magnetic fluid of low concentration. High sensitivity microdroplet aggregates to the magnetic field is associated with high for artificial liquid medium values of magnetic permeability (~ 50) unique and low values of interfacial tension at the interface of microdroplet – ambient magnetic fluid ($\sigma \sim 10^{-7}$N/m). In a weak alternating magnetic field at $\sigma < 10^{-6}$ N/m possible forced oscillations of both the small and large amplitude [3]. The relevance of the study of oscillations of microdroplet aggregates are associated with a non-contact determination of physical properties of individual units in the parameters of oscillations and the search for effective ways to control the properties of the samples containing the magnetizable ensembles of interacting micro-objects. Deformation [1] and oscillations [3] of microdroplet aggregates in a magnet field are of a hysteresis character, which changes the shape of the aggregates correspond to the critical fields of a strong stepwise elongation with increase of the field threshold ($H_1$) and abrupt reductions in elongation with decreasing field ($H_2$), and $H_2 < H_1$. In this article we consider the discrete spectrum of forced oscillations of microdroplet aggregates in the field $H(t) = H_0\sin\omega t$ when $H_0 > H_1$. The characteristic time of deformation $\tau_0 \sim \eta R_0/\sigma$ for the studied samples is a few seconds, so the period change of the external field $T$ in the frequency range 0,01 Hz $\leq f \leq$ 100 Hz can be more or less $\tau_0$. Were previously studied forced oscillations, mainly during $T >> \tau_0$ and $T << \tau_0$.

Less studied are the forced oscillations at frequency 1-2 Hz when $\tau_0 \sim T$ and a change in the nature of oscillations from hysteretic to anhysteretic.

## 2. DESCRIPTION OF THE OBJECT AND METHODS OF INVESTIGATION

In this article we investigate discrete spectrum of forced oscillations, the contribution of higher harmonics in the oscillations, as well as the applicability of the previously developed systems computer simulation [4] to describe the oscillations, when $\tau_0 \sim T$. Research methods based on field and numerical experiments.

Experimental setup and methodology is described in [3]. Images of isolated microdroplet aggregates were obtained at high magnification with a microscope, and change their form in an alternating magnetic field were investigated by recording the light transmitted through the sample. In an alternating magnetic field changing the shape of the aggregates during oscillations lead to periodical changes of the luminous flux, passed through the slit diaphragm, on which was projected the image of the boundary between aggregates and the surrounding liquid. Luminous flux (signal PMT) and the signal proportional to the alternating magnetic field were recorded using a dual beam oscilloscope. Samples for testing consisted of a magnetic fluid type «magnetite in kerosene», were containing microdroplet aggregates with a size of ~ 1 µm. Interfacial tension did not exceed $4\cdot10^{-7}$ N/m, the permeability of the aggregates was ~ 50.

The magnitude of the external field $H(t) = H_0\sin\omega t$ experimentally selected so as to obtain a stepwise elongation of the aggregates, when the instantaneous value of the field exceeded the critical field stepwise elongation $H_1$, at the same time, the consolidation of aggregates into larger isn't occurred.

Oscillations microdroplet aggregates in the frequency range of 0.01-100 Hz can be divided into three types: steady state oscillations in $T >> \tau_0$ the transition mode when T~ $\tau_0$ and steady-state mode when $T << \tau_0$.

Steady state oscillations at $T >> \tau_0$, described in the work [5], characterized by the fact that during the period of oscillation the ratio of the semiaxes of units $\lambda(t)$ changes to the order from the value $\lambda(t) = 1$ corresponding spherical shape to the value $\lambda(t) > 10$ which corresponds to the needle-like shape of the aggregates. Such variations are of a hysteresis character, occurring when the frequency of the external field $f$ changes from 0.01 to 0.1 Hz.

The transition mode oscillations ($T \sim \tau_0$) obtained when $f \sim 1$ Hz. This mode corresponds to the transition from hysteretic nature of the oscillations to anhysteretic. Periodic curves corresponding to the luminous flux associated with the deformation of the shape of droplets are non-sinusoidal in nature. Oscillations occur relatively elongated shape and the restoration of spherical shape does not occur. The shape of the curves of the light flux in the transition regime ($T \sim \tau_0$) not stable in amplitude and resembles the letter «M».

## 3. ANALYSIS OF THE RESULTS OF THE EXPERIMENT

For oscillation analysis used a decomposition of the signal in the Fourier series ($F$), and wavelet transform of this signal using the wavelet Daubechies of the 4th order ($G$). The spectrogram resulting from a wavelet transformation $|G_k|$, and the Fourier transformation $|F_k|$ see Figure 1(*a*).

Figure 1 (*b*) shows a graph of the analyzed signal $S_i$ and the points obtained by the inverse wavelet transform $AG_i$.

From the obtained results it follows that the contribution of harmonics of the frequency $f$ and the $2f$ in the transitional regimes are close in magnitude, an appreciable contribution to the oscillations also make 3 and 4 harmonics. Wavelet transform in the analysis of forced oscillations can be used to detect the transition, as for other modes of oscillation the contribution of the wavelet functions are negligible.

Steady state oscillations at $T \ll \tau_0$ characterized by the fact that the forced oscillations are relatively highly elongated needle-like shape and are reduced to fluctuations of the pointed ends, while the oscillations are of anhysteretic in nature [6]. At low values $\sigma \sim 10^{-7}$ N/m and high values of magnetic permeability

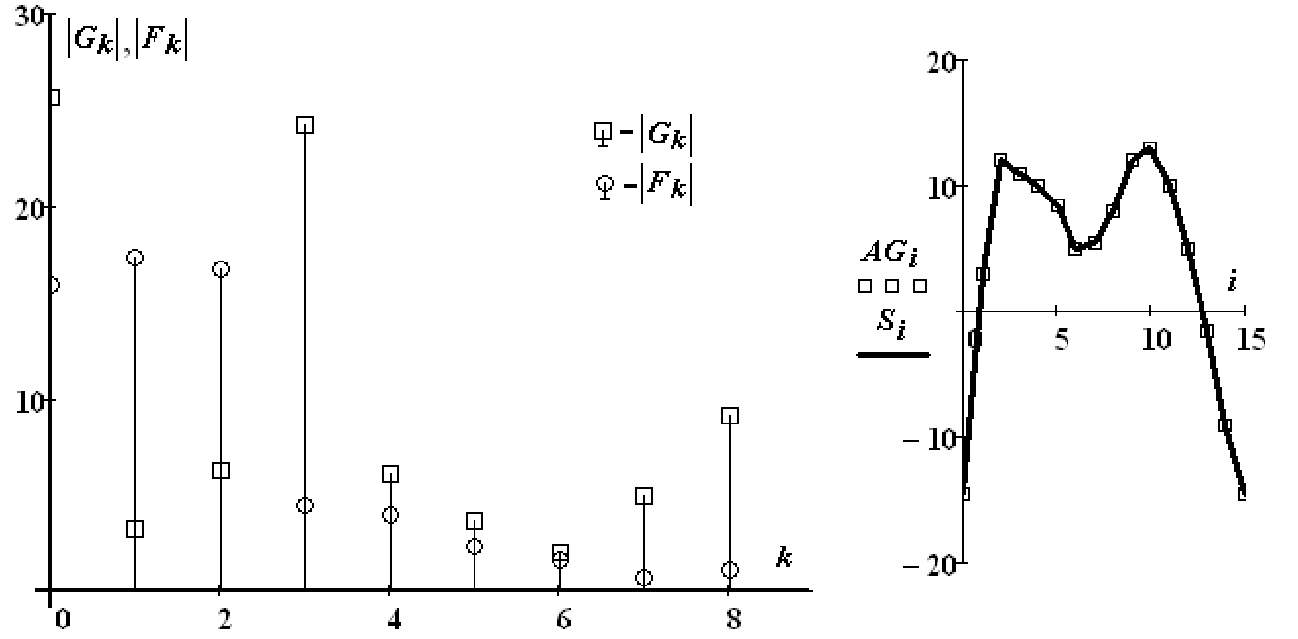


**Fig. 1** – Results of Fourier and wavelet analysis of a signal: a) Spectrogram of the direct Fourier transform $|F_k|$ and a direct wavelet transformation $|G_k|$, b) recovered as a result of the inverse wavelet transformation $AG_i$ of the analyzed signal $S_i$

oscillations are not completely terminated when the frequency of the external magnetic field $f > 20$ Hz and you may receive small vibrations of the ends of highly elongated aggregates, despite the fact that during visual observations with a microscope the aggregates seem to be fixed. For harmonic components of the discrete spectrum the coefficients $k_i = A_i/A$, representing the relationship of effective values of the harmonics ($A_i$) to the effective value of the whole curve ($A$) where $i$ – the number of the harmonic were calculated. The dependences of the calculated values $k_i$ from the frequency are presented in Figure 2. Curve 1 corresponds to the fundamental oscillation. The frequency of the fundamental harmonic of oscillations coincides with the frequency of driving force ($2f$). Curve 2 corresponds to the harmonic, the frequency of which coincides with the frequency of the external field $f$ and is equal to half the frequency of the fundamental harmonic. Values $k_i$, obtained at $i = 3$, are shown by circles, at $i = 4$ – triangles, at $i = 5$ – stars.

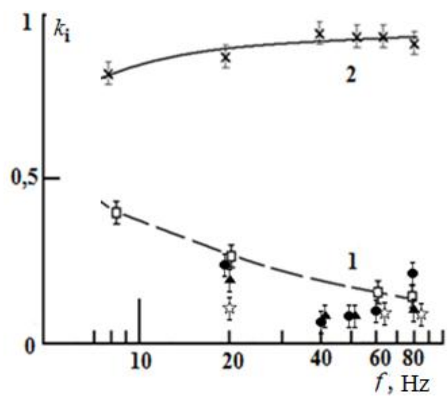


**Fig. 2** – Dependence $k_i = A_i/A$ from the frequency to the harmonic frequency $2f$ (curve 1) and frequency $f$ (2)

## 4. CONCLUSION

From the obtained results it follows that for strongly elongated aggregates with increasing frequency the contribution of the harmonic frequency $f$ to the current value of the signal is increased, and the fraction of the harmonic of frequency $2f$ decreases.

On changing the external field frequency from 10 to 80 Hz, the relative fraction of higher harmonics is significantly lower than the fraction of harmonic frequency $f$. The relative fraction of the harmonic frequency $2f$ in oscillations of strongly elongated ends at $f > 60$ Hz is less than 0.17 and the harmonic frequency $2f$ is merged into the noise.

Thus, the pointed ends of the microdroplet aggregates can make the forced oscillations in the frequency range from 20 to 80 Hz, which are characterized by the presence mainly in the discrete spectrum of harmonic frequency $f$. Therefore, for highly elongated microdroplet aggregates in a weak alternating field the assumption of the linear nature of the magnetization, which should lead to a doubling of the oscillation frequency, is not performed.

Computer simulation of forced oscillations of microdroplet aggregates [4] on the basis of mathematical model and systems computer simulation, constructed under the assumption about the linear nature of the magnetization and ellipsoid shape of aggregates can adequately describe the variation in $T >> \tau_0$, and $T << \tau_0$. When $T \sim \tau_0$ to obtain a non-sinusoidal periodic curves corresponding time dependences of the ratio of the semiaxes $\lambda(t)$ it wasn't possible. At the same time, the shape of the curves $\lambda(H)$ corresponding to dependence of $\lambda$ on the instantaneous field values corresponds to the shape of the experimental curves of the dependence of intensities of anisotropic scattered light on the instantaneous field values for the samples of magnetic fluids type «magnetite in kerosene» containing microdroplet aggregates [2]. Since the oscillations of the aggregates lead to fluctuations in intensity of scattered light, a system of computer simulation [4] can be useful in the analysis of oscillation regimes when $T \sim \tau_0$.

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