Stability of a ferrofluid layer on a liquid substrate

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Abstract. The stability of a horizontal magnetic fluid layer located on a liquid substrate in the alternating magnetic field orthogonal to the surface is experimentally investigated. Kerosene-based magnetite liquid stabilized with oleic acid (ferrofluid) and perfluorooctane (to create a liquid substrate) were chosen as working fluids. The presence of a free surface and interface in the magnetic fluid layer determines the influence of spatial characteristics of the system, such as the diameter of the cell and the thickness of the liquid layer, on the resonant frequency. The stability of the ferrofluid layer in an orthogonal stationary magnetic field is investigated, and the dependence of the critical field strength on the layer thickness is obtained. The dependences of intensity amplitude on the alternating magnetic field frequency are depicted for the ferrofluid layers of various initial thicknesses. The obtained stability curves show that the low frequency field (1–4 Hz) destabilizes the system, while the high frequency one (from 4 Hz and above) has a stabilizing effect.

1. Introduction

The free surface of magnetic fluid (MF) layer of finite depth is propagated by the gravity-capillary waves, and in the presence of the magnetic field – by the magnetic capillary waves. The waves on the MF surface arise due to the fact that the pressure within the fluid is proportional to the magnetic field intensity [1]. The periodic change in the magnetic field causes the periodic motion on the free MF surface [2]. This movement acquires a resonant character when the characteristics of the surface wave, excited by the magnetic field, coincide with the temporal and spatial characteristics of the driving force [3, 4].

The parametric generation of a standing wave on the liquid’s free surface by means of vertical oscillations leads to the classical Faraday instability [5]. The initially flat free surface of the liquid becomes unstable at a certain intensity of vertical vibrations of the entire system. Faraday's magnetic instability consists in the excitation of parametric waves by means of ponderomotive forces under the action of alternating magnetic field [6]. The action of oscillating magnetic field was previously considered in the vertical [7], horizontal [8] and inclined [9] directions with respect to a thick layer of magnetic fluid located on a solid substrate.

Particularly, subharmonic standing waves were observed on the MF surface in the vertically oscillating magnetic field [7]. It was shown [2] that the wave number of perturbations near the edge of the container is similar to the observed phenomenon of surface instability in a static field. In the alternating horizontal
magnetic field, the isotropy of the system is violated, and instability is observed in the form of parallel standing waves oriented perpendicular to the magnetic field [3, 8]. The alternating magnetic field oriented at an angle to a continuous ferrofluid layer provokes the appearance of the so-called drifting instability, which can be used as an MF pump [9].

The use of liquid substrate for the ferrofluid layer is associated with various types of equilibrium instability and fluid flow in systems with free surface and interface [10]. In the uniform vertical magnetic field, the MF layer with two deformable boundaries disintegrates into an ordered system of drops [11]. The critical field strength at which the ferrofluid layer disintegrates on a liquid substrate is lower than on a solid one.

This work is devoted to the experimental study of the stability of the horizontal MF layer located on the liquid substrate in spatially uniform magnetic field oscillating in the vertical direction. A low-frequency range of exposure was used to avoid the non-equilibrium nature of the ferrofluid layer magnetization.

2. Experimental technique

In the experiment, a glass cell (1) of circular cross-section with diameters $D_1 = 59.4$ mm and $D_2 = 42.8$ mm (Figure 1) was placed on a horizontal platform in the center of Helmholtz coils (2) with the average radius of the windings $R = 135$ mm (the non-homogeneity of the magnetic field in the measurement zone did not exceed 2%). The coils were powered by a Mastech DC Power Supply HY3010E-2 source (3). In order to organize linearly polarized alternating magnetic field, the Helmholtz coils were connected to a signal generator of special shape (4) through an Emotiva A-300 amplifier (5). The output signal from a small resistor (8), connected in series with the coils, was fed to the input of the analogue-to-digital converter ADC LA-I24 USB (9) and processed using the standard software kit (10).

![Figure 1. Experimental setup](image)

Figure 1. Experimental setup: 1 – a circular-section cuvette with two-layered liquid system; 2 – Helmholtz coils; 3 – DC power supply; 4 – specialized signal generator; 5 – amplifier; 6 – video camera; 7 – circular light source; 8 – measuring resistor; 9 – ADC; 10 – computer

The image of the MF layer was recorded by a digital video camera (6) from the from above of its free surface. In order to provide better contrast for hills and troughs on the layer surface and to analyze quantitatively the characteristics of travelling waves, visualization of the layer relief was performed using a circular LED light source (7). The obtained experimental data on the relief of the initially continuous layer, the behavior of the boundaries of a stable rupture, and the evolution of spatial structures were further processed using the Comef and Virtual Dub software package.
Magnetite in kerosene stabilized by oleic acid was used as the magnetic fluid (called also ferrofluid) with the following physical and chemical properties: density $\rho_1 = 1.45 \text{ g/cm}^3$, surface tension $\sigma_1 = 27.0 \text{ mN/m}$, kinematic viscosity $\nu_1 = 4.2 \text{ cSt}$, initial magnetic susceptibility $\chi_0 = 72$, particle concentration $n = 1.58 \times 10^{23} \text{ m}^{-3}$, diameter of magnetic particles $d = 9.8 \text{ nm}$, average magnetic moment $<m> = 3.25 \times 10^{-19} \text{ A} \cdot \text{m}\) [12]. Perfluorooctane C$_8$F$_{18}$ (density $\rho_2 = 1.76 \text{ g/cm}^3$, surface tension $\sigma_2 = 15.8 \text{ mN/m}$, kinematic viscosity $\nu_2 = 0.8 \text{ cSt}$) was chosen as a transparent immiscible liquid substrate, since it has higher density and lower surface tension compared to MF [10].

Two-layer liquid system filled a cuvette in the form of a short vertical cylinder made of borosilicate JENAerGLAS glass. The thickness of the ferrofluid layer was determined as $h = m/\rho S$, where $m$ was the mass of the liquid, and $S = (\pi D^2)/4$ was the area of the initial (continuous) MF layer, which was assumed to be flat, $D$ was the inner diameter of the cuvette. The measurement of the liquid's mass and, accordingly, the layer’s thickness was carried out by weighing the syringe with the ferrofluid before and after pouring it into the cuvette using an electronic scales Vesta VM 2202 with a measurement accuracy of 0.01 g. In the experiments, the thickness of the ferrofluid layer varied from 1 to 5 mm, while the thickness of the liquid substrate was several times greater than the MF layer, ranging from 5 to 20 mm.

The ambient temperature for the experiments was kept at $(25 \pm 1) ^\circ\text{C}$. The measurements were carried out in a quasi-stationary mode, i.e., after changing the field oscillations frequency the surface relief was photographed only after a pause that significantly exceeded the viscous time $\tau$ of the ferrofluid layer ($\tau = hD/2\nu$ [11]). The perturbations, associated with the transient process, decayed during this time, while perturbations, close to the system’s characteristic wavelength, were amplified by the magnetic field.

3. Experiment results
It was shown earlier [11], that the stable two-layered system "ferrofluid – perfluorooctane" becomes unstable at a critical vertical magnetic field strength $H^*$, constant in time and space (uniform). The relatively small thickness of the layer and the absence of special damping of the experimental setup serve for the emergence of perturbations in the form of gravity-capillary waves on the MF free surface and interface. The uniform vertical magnetic field enhances these disturbances and leads to the formation of a relief in the form of penta- or hexagonal cells on the free surface of a ferrofluid layer (Fig. 2a) similar to the static Rosenzweig instability [13].

The same relief, but with a different spatial period, appears on the interface with perfluorooctane. In this case, the deformation of the layer’s lower boundary is significantly higher, since the difference in the density and the interfacial tension are three times less than on the free surface. As a result, since the total amplitude of disturbances of both surfaces exceeds the layer thickness, it disintegrates into an ordered system of drops (Fig. 2b) at the critical magnetic field strength $H^*$.

![Figure 2](image)

**Figure 2.** Deformation of a ferrofluid layer of the thickness $h = 2.8 \text{ mm}$ under the action of a uniform vertical magnetic field of the strength $H$, kA/m: 3.2 (a); 3.3 = $H^*$ (b)

The dependence of the critical field strength $H^*$, at which the layer decomposed into an ordered system
of drops, was obtained for several MF of various thicknesses (from 1 to 5 mm) in cuvettes of different diameters (Fig. 3) under the action of regular uniform magnetic field. The critical magnetic field strength $H^*$ depends on the initial layer thickness $h$ and on the MF initial magnetic susceptibility $\chi_0$. At the same time, the value of $H^*$ weakly depends on the diameter of the cell [11].

![Figure 3. Critical magnetic field strength $H^*$ versus the thickness $h$ of the MF layer of different initial magnetic susceptibility $\chi_0$: 2.0 (3); 7.0 (1, 2)](image)

It is known that the magnetic pressure in the MF is proportional to the magnetic field strength [14]. Therefore, the MF free surface, being a surface of constant pressure, will form a system of hills and troughs corresponding to the maximum and minimum of the magnetic field. Periodical change in the field strength $H(t) = H_m \cos (2\pi \nu t)$ will expose the MF layer surface to periodical oscillations due to the action of a periodically varying ponderomotive force. Since the demagnetization factor of the MF layer in the near-wall zone is lower in comparison with the centre of the cuvette, the meniscus is involved in the vibrational motion earlier than the rest of the layer. In addition, the tangential stresses caused by the field non-uniformity are distributed in the region near the cell boundary [15]. With this configuration, the oscillating meniscus turns out to be the source of waves in the form of concentric circles travelling along the surface of the MF layer. When the oscillation frequency of the external magnetic field increases, the travelling wave becomes a standing wave (see Fig. 4a). In this case, the length of the formed standing wave decreases with an increase in the frequency of magnetic field oscillations.

It was found that the two-layered liquid system passes from the standing wave regime to the state of instability at some values of the amplitude $H_m$ and the frequency $\nu$ of the magnetic field strength. This transition is accompanied by the decomposition of the ferrofluid layer continuity into droplet structures (Fig. 4b), similar to the observed droplets in the case of uniform stationary magnetic field.

![Figure 4. Oscillations of the MF layer free surface of thickness $h = 3.5$ mm under the action of alternating magnetic field with an amplitude $H_m = 3.5$ kA/m and frequency $\nu = 5$ Hz (a), $H_m = 5.0$ kA/m and $\nu = 5$ Hz (b)](image)
The study in an alternating magnetic field was carried out for the MF layers of thicknesses $h = 3.5\div4.5$ mm, corresponding to the stability criterion of two-layered liquid systems in the absence of external influences [10]. The regions, highlighted in Figures 5 and 6, correspond to the range of the amplitude $H_m$ of the alternating magnetic field equal to the intensity $H^*$ of the stationary magnetic field for the selected thicknesses of the MF layers (Figure 3).

Figure 5. Stability maps, showing the dependence of the amplitude $H_m$ of the alternating magnetic field on its frequency $\nu$, at which the MF layer of the thickness $h$ experiences instability in cuvettes with a diameter $D$, mm: 42.8 (a); 59.4 (b)

The stability maps show that the MF layer instability occurs at the values $H_m < H^*$, which indicates the destabilizing field effect in the frequency range 1–3 Hz. The layer loses its stability at values $H_m \approx H^*$ in the frequency range of 3–5 Hz. Further increase in the frequency leads to the decay of the MF layer at values $H_m > H^*$, i.e., a stabilizing effect of field oscillations on the stability of the entire system is observed. The instability of the ferrofluid layer occurs in a threshold manner because it is affected by many factors, such as the presence of perfluorooctane film on the MF layer’s free surface, external vibrations, etc. These causes also affect the uncertainty of measurement results especially in less stable range of parameters $H_m$ and $\nu$. The stability maps obtained for two cuvettes of different diameters have similar dynamics, especially in the region above the critical one. In this case, the geometry of the working area has a noticeable effect in the pre-critical and critical areas.

It is necessary to note that at certain parameters of the investigated two-layered liquid system some new regimes were observed under the influence of vertically oscillating magnetic field. Among these regimes are the formation of a ferrofluid cumulative jet, oscillations of peaks on the free surface of droplet structures, as well as wave interference and alternation of wave patterns on the free MF surface. These modes will be the subject of our further research.

4. Conclusion

In the vertically oscillating magnetic field, the free surface of horizontal ferrofluid floating layer undergoes several modes: the travelling waves, the standing waves and the disintegration of the layer’s continuity. The transition between these modes is defined by the magnetic field strength amplitude $H_m$ and frequency $\nu$. In various cuvettes, the MF layers of different initial thickness are described by similar $H_m(\nu)$ dependencies except for the low-frequency range (due to the stronger influence of eigen frequency compared to frequency of forced oscillations). The stability curves show that the effect of low frequency field (1–3 Hz) destabilizes the system, while high frequency fields (from 5 Hz and above) cause a
stabilizing effect.

The obtained results expand the concept of multilayered magnetic fluid systems, and their evolution within the magnetic field, including those cases of strong deformations. The obtained experimental data will help verify mathematical models describing the dynamics of MF layer with two free boundaries under the action of gravity and magnetic field.

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