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Experimental investigation of surface instability of a thin layer of a magnetic fluid

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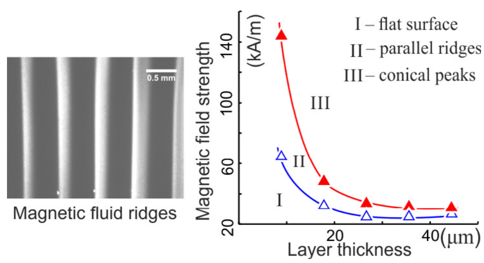
HIGHLIGHTS

- Magnetic fluid flat layer transforms into liquid ridges in a critical tilted field.
- Increase in the field strength leads to the layer breakup.
- Critical magnetic field increases monotonically with the tilt angle.
- Critical magnetic field decreases monotonically with the layer thickness.
- Pattern wavenumber depends on the layer thickness and on supercritical field strength.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present work the instability of a flat horizontal thin layer of a magnetic fluid (the depth of no more than 50 μm) under the action of a uniform magnetic field is studied experimentally. It was revealed that the development of instability under the action of tilted magnetic field can lead to the formation of parallel ridges on a fluid surface; the ridges undergo a transformation into hexagonal system of conical peaks with the magnetic field increasing. The necessary conditions for the formation of these surface patterns are studied. It was found that the development of instability of quite thin layers may result in layers breakup. The dependences of instability wave number on the system physical parameters are obtained. The time for the development of instability is measured. The experimental results are compared with the existing theory and discussed.

1. Introduction

The matters of instability of fluid interfaces and formation of surface patterns under the action of external fields are widely studied and still receive a great deal of attention in the fluid mechanics range of problems. Apart from independent interest, the results of such studies can be useful in the understanding of a number of natural phenomena and in technical applications. Among the problems of fluid instabilities the problem of instability of a free surface of magnetic fluid in a dc magnetic field is widely known. A magnetic fluid is a colloidal suspension of ultra-fine ferro- or ferri-magnetic nanoparticles suspended in a carrier fluid. When the external dc vertical magnetic field reaches some critical value, the horizontal magnetic fluid surface spontaneously deforms into regularly spaced conical peaks, usually distributed on a hexagonal lattice. It is so-called normal field or Rosensweig instability; see [1] for a review. The available theoretical and experimental publications devoted to the Rosensweig instability mainly deal with the case of a deep magnetic fluid layer. At

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the same time the investigations of the instability of layers of the thickness comparable or less than the characteristic linear scale (capillary length) are also important. Periodic structures of pointed drops formed as a result of decomposition of thin layers are of interest in the designing of devices for injecting charged particles with the help of magnetic field [2,3]. The instability of the finite thickness layers in a perpendicular magnetic field has been theoretically considered in some classical works [4,5]. Peculiarities of thin layers instability is also a subject of several recent theoretical researches [6–8]. As to experiments in this area, it seems that only works [9–12] can be mentioned. The dependences of the critical magnetic field strength and critical wave number on the thickness of the magnetic fluid layer have been measured. The supercritical wave number dependences on the magnetic field strength and layer thickness have been obtained [9–12]. It was shown that the thickness dependence of the instability phenomena is the most pronounced in a layer of the thickness below 100 μm. However, the characteristic time for the development of instability has not been analyzed in the existing experiments.

While a wide variety of detailed investigations of the instability of a magnetic fluid surface in a perpendicular magnetic field are available, the data on the behavior of a magnetic fluid surface in a tilted magnetic field are scarce. The presence of a tangential component of a magnetic field changes the character of instability and pattern of a magnetic fluid surface qualitatively. The problem of the magnetic fluid instability in a tilted magnetic field has been studied theoretically in [13–18]. It has been shown that the tangential component of a magnetic field stabilizes a certain range of harmonic perturbations propagating along it, and it leads to the emergence of the surface pattern in the form of parallel stripe-like ridges with axes parallel to the tangential component of a magnetic field. It should be noted that several assumptions with loss of generality have been made in the mentioned theoretical studies.

A first experimental observation of liquid ridges on a magnetic fluid surface in a tilted magnetic field was presented in [19]. However, no further experiments have been reported. More recently, rather more detailed experimental studies of the problem have been attempted [20,21]. It was demonstrated that, when increasing the tilted field strength, the flat surface gives way to liquid ridges, and a further increase results in a transition to a pattern of stretched hexagons. The threshold values of the magnetic field at which these patterns are formed were measured as a function of a tilt angle. The magnetic fluid layers investigated in the mentioned works are quite thick, and it can be considered as if they are of quasi-infinite depth. The dependence of the surface patterns peculiarities on the layer thickness and the wave number of instability in a tilted magnetic field were not examined in the existing experimental works.

In the present work we study the instability of a thin layer of a magnetic fluid in an arbitrary orientated external uniform dc magnetic field. Our experiments were performed with 5- to 50-μm-thick layers.

2. Theoretical background

The problem of the instability of a thin layer of a magnetic fluid in an arbitrary orientated magnetic field has been studied theoretically by Korovin [15]. We will use the results of [15] to analyze our experimental data and to compare the measured results with the theoretical predictions. A layer of a motionless magnetic fluid with a flat free surface on a horizontal nonmagnetic plate immersed in a uniform tilted magnetic field has been studied in [15]. The layer has been considered to be thin in the sense that the condition $h/\lambda \ll 1$ is satisfied. Here h is the layer thickness and λ is the wave length. The case of $\tau_d/\tau_i \ll 1$ was analyzed. Here τ_i is the characteristic time for the development of instability, $\tau_d = h^2/\nu$ is the characteristic time for the diffusion of vorticity across the fluid layer, and ν is the kinematic viscosity of the fluid. Our experimental conditions are in general agreement with the model requirements.

Within the scope of a linear perturbation analysis the following dispersion equation has been obtained:

$$s = \frac{h^3}{3\eta}\left\{-\rho g\left(k_1^2+k_2^2\right)+\frac{\mu_0}{2}\left[M_{03}^2\left(k_1^2+k_2^2\right)^{3/2} - M_{01}^2 k_1^2\left(k_1^2+k_2^2\right)^{1/2}\right]-\sigma\left(k_1^2+k_2^2\right)^2\right\} \quad (1)$$

where s is the imaginary part of the perturbation frequency ω, which is purely imaginary quantity; η is the dynamic viscosity of the fluid; g is the acceleration of gravity; ρ is the fluid density; σ is the fluid surface tension; μ_0 is the magnetic constant; M_{03} is the vertical component of the magnetization of magnetic fluid; M_{01} is the projection of the magnetization of magnetic fluid onto the direction of tangential component of external magnetic field; k_1 and k_2 are the wave numbers of perturbations propagating along the tangential component of magnetic field and perpendicularly to it. The magnetization of magnetic fluid is determined from the experimental magnetization curve $M(H_i)$ (H_i is the magnetic field inside the magnetic fluid). Field strength inside the fluid, H_i, is computed from the externally applied magnetic field H_e by the solution of implicit equations:

$$H_{i3} = H_{e3} - NM_{03}(H_{i3}), \qquad H_{i1} = H_{e1},$$

where N is the demagnetizing factor, which was set equal to unity for the thin flat layer under study. The analysis of Eq. (1) shows that the tangential component of a magnetic field stabilizes the harmonic perturbations propagating along it.

The system of equations

$$\partial s/\partial k_2 = 0, \quad s = 0 \quad (2)$$

is the condition of the instability onset. Having numerically analyzed Eqs. (2) with regard to the magnetization curve taken experimentally, one can determine the critical magnetic field strength and critical wave number.

It should be noted that the rate of a magnetic field rise is an important factor for the surface pattern formation process. When the slowly rising magnetic field reaches the critical value, the surface pattern with critical wave number appears. If the magnetic field increases further the wave number of the pattern will remain nearly the same, only wave amplitude must grow. But the pattern wave number may change if the rate of a magnetic field rise is greater than the instability increment, i.e., if the magnetic field settles down before the surface instability starts developing. Thus, if the magnetic field of the strength greater than critical value is switched on very rapidly the wave number of surface pattern is no longer a constant and depends on the magnetic field strength [9]. For the supercritical magnetic fields only the first equation of the system (2) should be considered to find the wave number of the most unstable perturbations (supercritical wave number).

In the case of the supercritical magnetic field from the dispersion Eq. (1) one can find the characteristic time for the development of the most rapidly growing harmonic (the instability development time) [15]:

$$\tau_i = 2\pi \cdot \left[\max s\left(k_1, k_2\right)\right]^{-1}. \quad (3)$$

The presented Eqs. (1)–(3) will be used to compare our experimental data with the results of calculation. The figures below show, where possible, both experimental and theoretical results.