DESTABILIZATION OF THE FILM-COATED SURFACE OF AN ELECTRICALLY CONDUCTING FLUID IN AN ALTERNATING FIELD EXPOSED TO IRRADIATION WITH LIGHT

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We examine and analyze the appearance of a surface nonuniformity in a conducting fluid under the action of an alternating electric field.

In recent years continuing interest [1-3] has been shown in the question of mechanical stability of the surface of a conducting fluid in a constant electric field. Disruption of this stability is caused by the negative pressure acting on the fluid surface in an electric field [4]. However, if the field is alternating, the surface may also lose stability parametrically, since in a uniform electric field the pressure is distributed uniformly over a uniform fluid surface [5]. If the surface is nonuniform (for example, if the surface contains inclusions that are chemically diverse, oxide films, adsorption materials, etc.), on imposition of an electric field the pressure over the surface is not distributed uniformly, as a consequence of which the surface is distorted in a constant electric field, while an alternating electric field may generate surface waves [6]. However, if the surface films are uniform (or if the nonuniformities are extended), in an alternating electric field we may find the possibility of a parametric loss of surface stability [7]. How can one disrupt the uniformity of such a surface? Most simply, by changing, in one way or another, the electrophysical properties of the film. For example, by means of light it is possible to achieve photoelectric transfer of the charge from the film to the ambient medium, i.e., to the outside or to a conducting fluid (and vice versa). The possibility of photomechanical excitation of waves in Langmuir films was studied in [8, 9]; here we find an examination of wave excitation by means of light directly within films of an anisotropic structure (a type of "Langmuir forest"), but no consideration was given to the possibility of generating corresponding motion in the substrates. It is the purpose of this paper to study the wave motion of a conducting fluid coated with a dielectric (poorly conducting) film, with application to the fluid of a variable potential under conditions of inducing a nonuniform surface charge in the film through a photoeffect. Simultaneously, this will allow us to clarify the frequency of the electric field necessary for the profile of the surface-vibration amplitudes most exactly to correspond to the relief of the induced charge (the surface relief) or, in other words, to ascertain the adequacy of such recording.

Thus, let the conducting fluid be covered with a film [exhibiting dielectric permittivity $\varepsilon(\omega_0)$]. A potential of frequency ω_0 is imposed on the conductor, and the value of the field strength $E = E_0 \cos \omega_0 t$ (outside of the film) is inadequate [7] to cause the parametric destabilization of the surface or to result in Tonks–Frenkel' instability. In this case no wavelike motion of the surface is excited. At some instant of time, let light be incident on the surface, with the distribution of light intensity over the surface in the form of $I(x, y)$ (x, y are coordinates along the surface). Under conditions of linear photoeffects, in proportion to this intensity and to the time a charge $q(x, y, t)$ begins to accumulate within the film. If the irradiation is pulselike in nature, with the duration of the pulse small in comparison with the characteristic times of the wave processes at the surface (or small in comparison with ω_0^{-1}), we can assume that the light instantaneously imparts a nonuniform relief to the surface, which subsequently does not change with time. Let us limit ourselves precisely to this case; the kinetics of accumulation (and saturation) of the charge in the film under conditions of prolonged irradiation is an independent problem.

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If q(x, y) is the distribution of the charges in the film per unit area at various points on the surface, an additional pressure acts on the surface: $p_q = E_0 q(x, y) \operatorname{Re} \exp(i\omega_0 t)/2\varepsilon(\omega_0)$. Description of surface destabilization by means of the surface waves is achieved by a well-known method [10] (see also [7, 11]). Solutions for the Navier–Stokes equations and for the equations of continuity are chosen in the form:

$$v_x = a \exp(-i\omega_0 t + ik_x x + k_x z) + b \exp(-i\omega_0 t + ik_x x + Kz);$$

$$v_z = c \exp(-i\omega_0 t + ik_x x + k_x z) + d \exp(-i\omega_0 t + ik_x x + Kz);$$

$$p = p \exp(-i\omega_0 t + ik_x x + k_x z); \quad K = k_x \sqrt{1 - i\omega_0/\nu k_x^2};$$

ν is the kinematic viscosity of the fluid which may depend on the frequency ω_0, with consideration of the relaxation properties of the fluid (see [12, 13]).

The z axis is directed perpendicular to the surface of the fluid from without. The solutions are substituted into the conditions for the stress-tensor component in the fluid at the film surface [14]:

$$\rho_f h \frac{\partial^2 \xi}{\partial t^2} + \frac{h^3 E_f}{12(1-\mu^2)} \Delta^2 \xi + (\sigma_{zz} + \Delta p) = 0$$

and the components of the velocity v_x at the surface of the film are equal to zero. Here $\Delta^2 = k_x^4$, $\xi = v_z/(-i\omega_0)$;

$$\sigma_{zz} = \left(-p + 2\eta \frac{\partial v_z}{\partial z}\right)\Big|_{z=0}; \quad \eta = \rho\nu; \quad \Delta p = -\gamma \frac{\partial^2 \xi}{\partial x^2} + p_k;$$

where γ is the effective coefficient of surface tension in the field: $\gamma = \gamma_1 + \gamma_2 - (2k)^{-1} \cdot E_0/4\pi$ (γ_1 and γ_2 are the coefficients of surface tension at the boundaries between the film and the ambient medium and the fluid, respectively). In Δp, in terms of p_k, we denote the corresponding Fourier expansion factor p_q over the plane waves along the fluid surface; let us limit ourselves for the sake of simplicity to the case:

$$p_q(x, y) = p_q(x) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} dk_x \exp(ik_x x)\, p_k(k_x).$$

As a result of solving the system we find the values for the coefficients:

$$a = -\frac{k_x \omega_0}{\rho F} p_k; \quad c = -ia; \quad b = -a;$$

$$d = i\frac{k_x}{K} a; \quad F = \omega_0^2 - \frac{\gamma_e k_x^3}{\rho} \frac{K - k_x}{K};$$

in which case

$$\gamma_e = \gamma + k_x^{-2}\left(-\rho_f h \omega_0^2 + \frac{h^3 E_f}{12(1-\mu^2)} k^4\right).$$

The expressions that we have obtained for these coefficients allow us to determine the wavelike motion of a surface covered with a film for arbitrary distributions of the induced charges. For this we have to sum, respectively, the values of v_x, v_z, and p, treating them as Fourier components. Let us write out the expression for the displacement of the surface elements:

$$\xi(x, t) = (2\pi)^{-\frac{1}{2}} \int_{-\infty}^{\infty} dk_x \frac{v_z|_{z=0}}{-i\omega_0} =$$

$$= \frac{\exp(-i\omega_0 t)}{-i\rho\sqrt{2\pi}} \int_{-\infty}^{\infty} dk_x \left(\frac{K - k_x}{K} k_x \frac{1}{F}\right) p_k \exp(ik_x x).$$

Obviously, if the expression in the parentheses in the last integral for some region of change in k_x depends weakly on the values of the latter (for example, it is independent or linearly dependent), then for $p_q(x)$, whose distribution corresponds to such k_x, the function $\xi(x)$ is simply associated with $p_q(x)$. Thus, if $p_q(x)$ corresponds to $p_k(k_x)$ so that at a frequency ω_0 we find satisfied the inequality $\omega_0 \gg \nu k^2$, $\omega_0^2 \gg \frac{\gamma_e k_x^3}{\rho}\frac{K-k_x}{K}$, then $F \simeq \omega_0^2$, $|K| \gg k_x$, and the expression in parentheses under the integral in $\xi(x, t)$ equal to k_x, and therefore

$$\xi(x, t) = \rho^{-1}\exp(-i\omega_0 t)\frac{\partial}{\partial x}p_q(x).$$

By means of the last expression with respect to the distribution $\xi(x)$ it is easy to restore $p_q(x)$ and, consequently, $q(x)$.

Let us note that equality $F = 0$ represents a dispersion relationship for determination of the spectrum of surface waves in a conducting fluid, where that surface is covered with an elastic film and subjected to an alternating electric field [7]. Since F serves as the denominator in the expressions for all coefficients, the largest destabilization amplitudes correspond to the minimum values of $|F|$. Moreover, naturally, the effect of surface-wave destabilization will be all the more pronounced, the larger the Fourier component p_k, i.e., if dimensions (geometric) of charge nonuniformities are commensurate with the excited wavelengths.

Let us present characteristic estimates, using the data of [8, 9]. For the intensity $I = 10^3$ W/cm² of the optical radiation ($h\nu \simeq 2\cdot 10^{-12}$ erg) with a pulse duration of ~ 1 µsec we have the specific charge at the surface $q \simeq 0.5\cdot 10^{10}$ e/cm² (with a quantum photoeffect yield $f = 10^{-2}$ and an absorption efficiency from the film surface of $\varkappa = 10^{-4}$).

Let the characteristic length of the change in the intensity of the light field along the surface be equal to 1 mm. Then for the field E = 1 kV/cm applied to the surface at a frequency of 50 Hz, we will estimate the amplitude of the surface vibrations to be on the order of 0.1 mm.

NOTATION

ε, dielectric permittivity; ω_0, frequency; E, E_0, electric-field strengths; p, p_q, pressure; v_x, v_z, velocity components; k_x, wave number; ρ_f, E_f, μ, h, density, modulus of elasticity, Poisson coefficient, film thickness; ξ, surface displacement; ν, η, ρ, kinematic and dynamic viscosities and the density of the fluid; p_k, Fourier pressure component; a, b, c, d, coefficients of the solution; σ_{zz}, stress-tensor component.

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