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Vibration influence on fluid interfaces

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Abstract

This work concerns the vibration influence on the stability and dynamics of fluid interfaces. Resonance phenomena (Faraday ripple, parametric waves under horizontal vibrations, the stability of the interface of liquid and its saturated vapor in the near critical state) are discussed. The thresholds of excitation of parametric resonance are determined and non-linear behavior is investigated. Mean effects of high frequency vibrations with various polarizations on the behavior of planar (terrestrial conditions) and cylindrical interfaces (space conditions) are analyzed. The shape and amplitude of the relief developing on the interfaces after stability loss are defined. The mechanisms of generation of mean flows near a fluid interface by high frequency vibrations are studied. ***To cite this article: D.V. Lyubimov et al., C. R. Mecanique 332 (2004).***

Résumé

Influence des vibrations sur des interfaces fluides. Ce travail concerne l'influence de vibrations sur la stabilité et la dynamique d'une interface fluide. Les phénomènes de résonance (ondulations de Faraday, ondes paramétriques sous vibrations horizontales, stabilité de l'interface d'un liquide et de sa vapeur saturée dans un état proche du critique) sont discutés. On détermine le seuil d'excitation de résonance paramétrique, et on étudie le comportement non-linéaire. On analyse l'influence moyenne de vibrations de haute fréquence, avec différentes polarisations, sur le comportement d'une interface plane (conditions terrestres) et d'une interface cylindrique (conditions de gravité nulle). La forme et l'amplitude des reliefs se développant sur l'interface au-delà du seuil de stabilité sont étudiées, ainsi que les écoulements moyens engendrés près de l'interface par les vibrations haute fréquence. ***Pour citer cet article : D.V. Lyubimov et al., C. R. Mecanique 332 (2004).***

Keywords: Vibrational convection; Interface; Stability

Mots-clés : Mécanique des Fluides ; Convection vibrationnelle ; Interface ; Stabilité

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Même en l'absence de vibration externe, un système hydrodynamique peut être le siège de mouvement périodique et possède un spectre de fréquences propres (ondes gravito-capillaires sur une interface, oscillations propres d'une goutte en suspension dans un liquide, modes oscillatoires d'écoulements convectifs dans un fluide chauffé par en dessous, par exemple). D'une façon générale, en l'absence de champ externe les oscillations propres sont amorties par la viscosité. Par contre l'énergie transmise au système par la vibration peut conduire à une résonance. Mais ce n'est pas le seul mécanisme possible : les vibrations de haute fréquence peuvent aussi supprimer des instabilités, et permettent ainsi d'atteindre des conditions d'équilibre inhabituelles. De plus, dans de nombreuses situations, les vibrations de haute fréquence induisent non seulement des mouvements pulsatoires, mais également des écoulements moyens, dus aux effets non-linéaires et visqueux.

Le présent article est un résumé et une compilation du travail réalisé depuis plus de 10 ans sur le problème des effets des vibrations sur des systèmes hétérogènes. Il a pour but de donner une description synthétique de ces différents mécanismes sur la base d'exemples où des études théoriques et numériques, développées dans des publications précédentes, ont permis de les comprendre.

S'agissant des résonances [4,5], l'excitation d'ondes de résonance sur une interface fluide par des vibrations horizontales est tout à fait différente du cas des 'ripples' de Faraday où la fréquence des ondes excitées est la moitié de la fréquence de forçage. Ici, il n'y a pas de résonance subharmonique et les fréquences des ondes excitées coïncident avec la fréquence de forçage, bien qu'ici la résonance est aussi paramétrique. D'autres particularités intéressantes ont été également trouvées en [4] pour des ondes paramétriques à l'interface entre un liquide et sa vapeur saturée, proche des conditions critiques. Parmi trois mécanismes possibles de dissipation (viscosité, conductivité thermique et changement de phase), l'influence la plus forte sur l'amortissement des ondes est celle de la viscosité.

Lorsque la fréquence de vibration est beaucoup plus grande que l'échelle de temps hydrodynamique, les phénomènes de résonance sont supprimés par la viscosité ; on considère alors les effets moyens. Dans le cas d'une vibration de polarisation linéaire verticale, la théorie développée en [7] montre qu'il existe un domaine de valeurs de l'amplitude (limité par le bas, et par le haut) où l'instabilité de Rayleigh-Taylor peut être supprimée. Dans le cas d'une vibration horizontale, on démontre, sur la base d'équations moyennées [8–10], l'existence d'un relief quasi-fixe à partir d'un certain seuil de la vitesse vibratoire. Dans le cas de couches épaisses, la théorie montre qu'un paramètre essentiel est le rapport de densité des deux fluides superposés. Pour des conditions fortement supercritiques, la majeure partie de l'interface s'oriente perpendiculairement à la direction de vibration (Fig. 1(e)). Cet effet remarquable d'orientation des vibrations de haute fréquence a été trouvé pour la première fois en [12] pour une surface libre, et en [10] pour une interface fluide. Dans le cas de couches minces, des solutions subcritiques de type soliton sont possibles [14]. Dans le cas de deux harmoniques de haute fréquence, de fréquences voisines, en absence de gravité, la vibration crée une élasticité additionnelle à l'interface ; l'interaction non-linéaire conduit à la possibilité d'ondes paramétriques de fréquence égale à la différence des deux fréquences de forçage. Dans le cas de vibrations horizontales de polarisation linéaire, même si la déformation (relief fixe) de l'interface est faible, il existe un écoulement assez intense dans les creux du relief, du côté du fluide le moins dense, généré par un double mécanisme : Schlichting et ondes de surfaces [15]. On a également étudié l'instabilité de l'interface entre deux colonnes liquides concentriques soumises à une rotation et à une vibration axiale de haute fréquence, en absence de gravité [20]. On montre le passage d'une solution correspondant à un relief hexagonal de l'interface à un relief avec cellules carrées ; un effet d'hystérésis a été également mis en évidence [21].

1. Introduction

Vibrations influence the behavior of fluid interfaces in different ways. In many situations, even in the absence of vibrations, a hydrodynamical system is able to perform periodical motion and has a spectrum of eigen-frequencies.

Examples of such a behavior are: capillary-gravitational waves on a free surface or fluid interface, eigen-oscillations of a bubble suspended in a liquid, oscillatory modes of convective flows in a fluid heated from above. If there are no external fields, then, as a rule, the eigen-oscillations are damped due to viscous dissipation. The energy transfer to the system due to vibrations can lead to resonance excitation of oscillations. Vibrations influence equilibrium and flows in hydrodynamical systems with fluid interfaces not only in resonant way. High frequency vibrations can *suppress instabilities* arising in static conditions and lead to the creation of unusual equilibrium configurations. In addition, in many situations, high frequency vibrations induce not only pulsational flows but, due to the non-linear and viscous effects, lead to (comparatively slow) mean flows.

2. Resonances

Although the pioneering work by Faraday [1] on vibrational excitation of capillary-gravitational waves on a free surface appeared in 1831, the question of vibrational excitation of resonance oscillations of fluid interfaces still cannot be considered as completely studied.

The non-linear theory of Faraday ripple correctly accounting for viscosity is developed in [2], where, additionally, the regimes of parametric waves excitation are identified and their stability is investigated.

The parametric instability of a liquid–vapour interface of CO_2 near its critical point has been also investigated by Fauve et al. [3]. Two different symmetries have been observed, with a transition from a wave-pattern formed of squares, to a wave-pattern formed of lines, for a small temperature increase. This transition is attributed to an increase of dissipation near the critical point.

Theoretical investigation of parametric waves on the interface of a liquid and its saturated vapor in near-critical conditions has been described in [4], taking into account: (a) media compressibility; (b) the possibility of phase change; (c) the anomalous values of thermodynamic parameters and kinetic coefficients; and (d) the dissipation due to viscosity and thermal conductivity. The calculations show that among three possible mechanisms of dissipation (viscosity, thermal conductivity and phase change), the strongest influence on wave damping, and therefore on the threshold of excitation of parametric resonance, is from the viscosity.

The excitation of resonance waves on a fluid interface by horizontal vibrations is studied in [5]. It is found that it differs from the Faraday ripple case where the frequency of the excited waves is half the vibration frequency. Here, subharmonic resonances are absent and the excited wave frequency coincides with the frequency of the container vibrations although the resonance is also parametric.

3. Mean phenomena (high frequency vibrations)

When the vibration frequency is large in comparison with the hydrodynamical time scales, resonance phenomena are suppressed by viscosity and mean effects play a dominating role.

3.1. Vertical high frequency vibrations

For vertical high frequency vibrations experiments by Wolf [6] show that the Rayleigh–Taylor instability can be suppressed. The theory of this phenomenon is developed in [7] where it is shown that: (a) stabilization is possible at frequencies higher than a critical value which depends on viscosity; and (b) the range of vibration amplitudes where stabilization takes place is limited both from below and above.

3.2. Horizontal high frequency vibrations

For horizontal high frequency vibrations an interesting phenomenon was discovered in the experiments by Wolf for a two-layer system of immiscible fluids with different densities. In the absence of vibrations, the fluid interface is horizontal. When vibrations are applied, a wave relief arises at the interface. The interface is practically motionless (like a frozen wave); it undergoes just small amplitude oscillations around its mean position, with same order of magnitude as the forcing amplitude, small in comparison with the relief amplitude (with the naked eye these oscillations are invisible). The theory of this phenomenon is developed in [8–10] on the basis of an averaged approach. It is of the threshold type. At low enough vibration intensity the interface remains flat and horizontal. When the critical vibration intensity is attained, the frozen relief arises. Near the instability threshold the relief amplitude increases with the vibration intensity according to a square-root law. The governing parameter is the vibration velocity, $a\omega$, but not the vibration amplitude and frequency separately.

As found in [8], with the decrease of layer thickness H, the minimum of the neutral curve is shifted to smaller wavenumbers and, starting from a certain thickness value, long wavelength perturbations become the most dangerous (Fig. 2).

3.2.1. Deep layers

For deep layers when the instability is cellular, non-linear theory has been worked out and the regimes of quasi-steady relief excitation are determined in [8,9]. It turns out that the parameter responsible for the regime of relief excitation is the density ratio. For a direct bifurcation, the square-root law is found for the dependence of relief amplitude on supercriticality. Experiments [11] and direct numerical simulations [10] of the dynamics of the fluid interface subjected to high frequency horizontal vibrations show that the growth of vibration intensity results in the doubling of the spatial period of relief (Fig. 1(d)). At large supercriticality, the most part of the fluid interface is oriented perpendicularly to the vibration direction (Fig.1(e)). This orientation effect of high frequency vibrations was found for the first time in [12] for a free surface and in [13] for a fluid interface. As shown later in [13], it is a very general property.

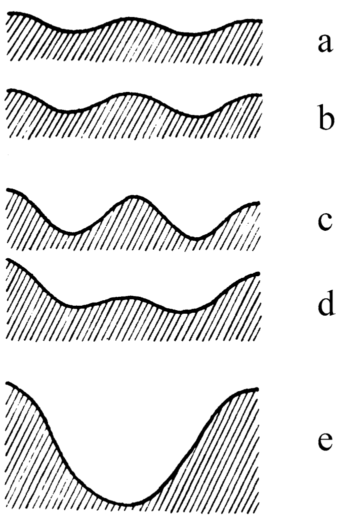

Fig. 1. Interface relief under horizontal vibration; numerical simulation [12]; (a) to (c) illustrate the change of steady relief shape when increasing vibrational parameter B, at small enough supercriticality; (d) and (e) show the doubling of spatial period of relief at higher supercriticality.

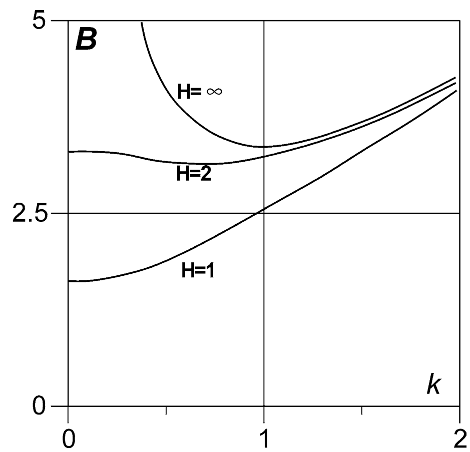

Fig. 2. Dependence of critical vibration parameter $B = a^2\omega^2[(\rho_1 - \rho_2)/\sigma g]^{1/2}$ on the wavenumber k (length scale being the capillary unit $\sigma/[(\rho_1 - \rho_2)g]$), for different thickness of layers.

3.2.2. Thin layers

For thin layers when a long wave instability takes place, the problem of the determination of the relief amplitude is reduced to an ordinary non-linear differential equation by implementing the shallow water approximation [14]. The analysis of this equation shows that subcritical solutions of soliton type are possible. In the supercritical parameter range, the solitons are possible only for small violations of the conditions for long-wavelength instability defined from the linear theory.

3.2.3. Back influence

In the experiments [11], the mean flows near the relief arising on the fluid interface subjected to horizontal vibrations were observed. The mechanisms of generation of these flows are studied theoretically in [15]. It is shown that non-uniformity of the pulsational velocity field along the fluid interface, arising when frozen relief develops, results in the generation of a mean flow (see Fig. 3 where the mean flow streamlines are plotted, x and z being measured in capillary units). The generation of this flow is related to two mechanisms: one is similar to the Schlichting mechanism which generates flows near a vibrating solid wall [16], the other is similar to the mean flow induced by interfacial waves [17,18]. The mean flow intensity is small in comparison with the pulsational flow intensity and it has just a weak influence on the fluid interface shape.

3.3. Cylindrical fluid interface

A cylindrical fluid interface subjected to axial high frequency vibrations and rotation, has been considered in [19,20] for zero-gravity conditions. Effects similar to those observed in [8–10] for a horizontal fluid interface subjected to high frequency horizontal vibrations and gravity field were found.

3.4. High frequency horizontal vibrations of circular polarization

For high frequency horizontal vibrations of circular polarization, which is the combination of horizontal vibrations in two perpendicular directions, an interesting behaviour is found [21]. When the vibration amplitude reaches a critical value, the hexagonal relief arises on the interface through finite-amplitude effects. With an increase of supercriticality, this regime changes to a relief with square cells, again through finite-amplitude effects. With a decrease of vibration intensity, hysteresis phenomena take place (Fig. 4).

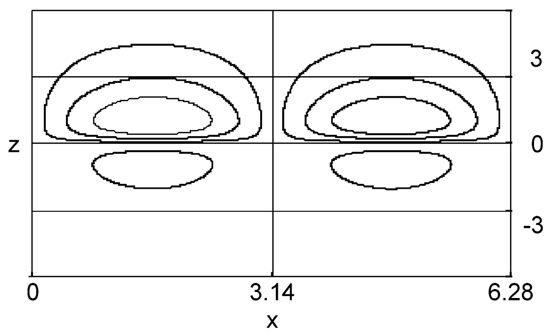

Fig. 3. Mean flow induced by high frequency horizontal vibrations: for the theory, see [15].

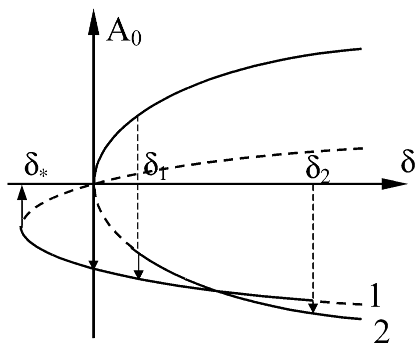

Fig. 4. Amplitude of interface relief A_0 for horizontal vibrations with circular polarization (1 – hexagon cells, 2 – square cells) versus relative supercriticality $(B - B_0)/B_0$, B_0 being the threshold value of the vibration parameter B for square cell excitation.

3.5. Combination of vertical vibrations

For a combination of vertical vibrations with two high frequency harmonics of close frequencies, in zero gravity conditions, it was shown that: (i) high frequency vibrations result in an additional elasticity of the interface, increasing the effect of capillary and gravitational forces; (ii) non-linear interaction leads to the possibility of parametric waves at a frequency equal to the difference in frequencies of the two harmonics.

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References

[1] M. Faraday, On a peculiar class acoustical figures and on certain forms assumed by a group of particles upon elastic surface, Philos. Trans. Roy. Soc. London 121 (1831) 209–318.
[2] D.V. Lyubimov, A.A. Tcherepanov, Non-linear theory of parametrically excited waves on a surface of viscous fluid, in: Some Problems of Fluid Surface Stability, UNC AN SSSR, Sverdlovsk, 1984, pp. 54–76.
[3] S. Fauve, K. Kumar, C. Laroche, D. Beysens, Y. Garrabos, Parametric instability of a liquid–vapor interface close to the critical point, Phys. Rev. Lett. 68 (1992) 3160–3163.
[4] D.V. Lyubimov, A.A. Cherepanov, T.P. Lyubimova, B. Roux, D. Beysens, Parametric resonance at the interface of phase separating media, in: Waves in two Phase Flow, EUROMECH Colloquium 376, Book of Abstracts, Istanbul, 1998, pp. 56–57.
[5] D.V. Lyubimov, M.V. Khenner, M.M. Shotz, Stability of a fluid interface under tangential vibrations, Fluid Dynamics 33 (1998) 318–323.
[6] G.H. Wolf, Dynamic stabilization of the interchange instability of a liquid–gas interface, Phys. Rev. Lett. 24 (1970) 444–446.
[7] N.A. Bezdenezhnykh, V.A. Briskman, A.A. Tcherepanov, M.T. Sharov, Control of the stability of the interface by alternative fields, in: Hydromechanics and Transfer Processes in the Weightlessness, Sverdlovsk, 1983, pp. 37–56.
[8] D.V. Lyubimov, A.A. Tcherepanov, On the development of steady relief on fluid interface in a vibrational field, Izv. Akad. Nauk SSSR, Mekhanika Zhidkosti i Gaza 6 (1986) 8–13.
[9] A.V. Zamaraev, D.V. Lyubimov, A.A. Tcherepanov, On equilibrium shapes of fluid interface in a vibrational field, in: Hydrodynamics and Heat Transfer Processes, UB Acad. Sci. USSR, Sverdlovsk, 1989, pp. 23–28.
[10] D.V. Lyubimov, T.P. Lyubimova, One method for numerical modelling in the problems with deformable fluids interfaces, Model. Mech. 4 (1990) 136–140.
[11] N.A. Bezdenezhnykh, V.A. Briskman, D.V. Lyubimov, T.P. Lyubimova, I.V. Zakharov, A.A. Tcherepanov, The influence of high frequency tangential vibrations on the fluid interfaces in microgravity, in: H.J. Rath (Ed.), Microgravity Fluid Mechanics, Springer-Verlag, 1992, pp. 137–144.
[12] D.V. Lyubimov, M.V. Savvina, A.A. Tcherepanov, On quasi-equilibrium shape of free surface of a fluid in modulated gravity field, in: Problems of Hydromechanics and Heat/Mass Transfer with Free Boundaries, SO AN SSSR, Novosibirsk, 1987, pp. 97–105.
[13] D.V. Lyubimov, A.A. Cherepanov, T.P. Lyubimova, B. Roux, Orienting effect of vibrations on the interface, C. R. Acad. Sci. Paris, Ser. IIb 325 (1997) 391–396.
[14] D.V. Lyubimov, M.V. Khenner, On a long-wave instability of fluid interface under tangential vibrations, Hydrodynamics (Perm) 11 (1998) 191–196.
[15] D.V. Lyubimov, A.V. Perminov, A.A. Tcherepanov, Generation of mean flows near fluid interface in a vibration field, Vibration Effects in Hydrodynamics (Perm) 1 (1998) 204–221.
[16] G. Schlichting, Grenzchicht-Theory, Braun, Karlsruhe, 1951.
[17] M.S. Longuet-Higgins, Mass transport in water waves, Philos. Trans. Roy. Soc. London Ser. A 245 (1953) 535–581.
[18] B.D. Dore, On mass transport induced by interfacial oscillations at a single frequency, Proc. Cambridge Philos. Soc. 74 (1973) 333–347.
[19] V.A. Briskman, D.V. Lyubimov, A.A. Cherepanov, Stability of interface of rotating fluids in axial vibrational field, in: Numerical and Experimental Modelling of Hydrodynamic Phenomena in Weightlessness Conditions, UB AN SSSR, Sverdlovsk, 1988, pp. 18–26.
[20] A.Yu. Lapin, D.V. Lyubimov, T.P. Lyubimova, Numerical investigation of quasi-equilibrium shapes of rotating fluid interface in axial vibrational field, in: Non-Linear Problems of Viscous Fluid Dynamics, Sverdlovsk, 1990, pp. 90–97.
[21] A.A. Tcherepanov, D.V. Shipulin, Behaviour of fluid interface in a vibrational field with circular polarization, in: Convection in Systems of Immiscible Fluids, RAS, Ekaterinburg, 1999, pp. 134–154.