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Nonlinear dynamics of confined liquid systems with interfaces subject to forced vibrations

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ABSTRACT

A review is presented of the dynamic behavior of confined fluid systems with interfaces under monochromatic mechanical forcing, emphasizing the associated spatio-temporal structure of the fluid response. At low viscosity, vibrations significantly affect dynamics and always produce viscous mean flows, which are coupled to the primary oscillating flow and evolve on a very slow timescale. Thus, unlike the primary oscillating flow, mean flows may easily interact with the surface rheology, which generates dynamics that usually exhibit a much slower timescale than that of typical gravity–capillary waves. The review is made with an eye to the typical experimental devices used to measure surface properties, which usually consist of periodically forced, symmetric fluid systems with interfaces. The current theoretical description of these systems ignores the fluid mechanics, which could play a larger role than presently assumed.

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1. Introduction

Isolated, static (steady) systems are an idealization that rarely holds up under strict scrutiny. Parameters that are assumed to be constant in the mathematical formulation (the gravitational acceleration, for example) can drift slowly in time, exhibit rapid oscillations, or both. Rapid fluctuations are unavoidable due to ambient noise and perturbations whose magnitude may be significant in some cases. For instance, crew maneuvering and on-board machinery produce time dependent mechanical forcing (g-jitter [1]) in space laboratories that persists in the absence of an effective damping mechanism. Time dependent perturbations introduce dynamics into the system that may or may not significantly change the system state, depending on the associated timescales and the sensitivity of the system. For instance, g-jitter may produce significant effects on on-board material processing and experiments [2] involving confined fluid systems with interfaces, which are very sensitive to time dependent mechanical forcing because, except at very small size (the scope of microfluidics) and very large vibrating frequencies, ordinary liquids exhibit very small viscous damping. The

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effects of vibrations on fluids are important in a wide range of other scientific and engineering applications such as liquid storage, mixing, convection, pattern formation, and the study of basic fluid instabilities.

Ambient vibrations are generally broad band and exhibit time dependent amplitude and direction. However, these oscillations are transmitted to the fluid system through the natural modes of the support structure and the container, meaning that the actual forcing experienced by the fluid usually peaks at some well defined frequencies, amplitude, and directions. Hence, the case of monochromatic oscillations, with fixed amplitude and direction, is a good idealization that provides considerable insight into the relevant physical mechanisms and the subsequent response of the fluid system.

In many important situations, the response of the system occurs on a lengthscale that is small compared to the extent of the system. Distinct excitation patterns may then compete with one another, leading to complex dynamical behavior and pattern selection phenomena. Extended pattern forming systems of this type occur throughout physics, chemistry, and biology, as well as fluid dynamics, and much effort has gone to understanding the factors that determine the nature of the selected states: regular or irregular, steady or periodic, delicate or robust under perturbations, etc. An important distinction can be made between those aspects of the pattern that depend on detailed physical properties, and those which result more generally from its symmetries. Also, due to the different phenomena involved, the effects of vertical and horizontal vibrations are considered separately.

The paradigmatic example of vertical periodic forcing is the Faraday system [3], in which a container of fluid is shaken in periodic fashion to provoke surface waves. Although Faraday himself explored both vertical and horizontal shaking, subsequent attention has overwhelmingly favored the vertical case, now recognized as a classic example of parametric instability [4]. The Faraday system is relatively compact, evolves on a convenient time scale, and is conducive to simple controlled experiments. It also yields a tremendous variety of patterns [5–8], depending on the applied forcing function and fluid properties. The theoretical analysis of Faraday waves can be greatly simplified by assuming a perfectly flat horizontal surface undergoing perfectly vertical vibrations. The forcing is uniform and, in a comoving frame, acts simply as an amplitude modulation of the gravitational force, a purely parametric forcing mechanism. The flat surface solution persists in the presence of this forcing despite its eventual loss of stability at critical forcing amplitude. Despite their central role in the analytical treatment of the vertically forced Faraday problem [9], the twin assumptions of a flat horizontal surface subjected to purely vertical shaking are, in many situations, restrictive. Both assumptions will fail, at some level, for any realistic experiment due to the influence of surface tension, which dominates at small scales and under microgravity conditions, and produces capillary (or meniscus) waves near the boundaries. Although these can be suppressed through careful control of boundary conditions [5,10], such synchronous, spatially nonuniform disturbances are a generic feature of vibrated fluids in most configurations. This observation can be used to argue that, although more resistant to theoretical analysis, horizontally or obliquely vibrated systems may be more relevant to the question of general fluid behavior than the more popular vertically forced Faraday system.

Horizontal forcing leads to a range of interesting new phenomena, some of which were noted by Faraday [3], who observed 'a series of apparently permanent ridges projecting outward like the teeth of a coarse comb' from the edge of a submerged vibrating plate [11]. These ridges can be identified with the subharmonic waves known as cross-waves, which are produced by a wavemaker (namely, a horizontally vibrating plate or similar device used to excite traveling waves on the surface) in a semi-infinite container; see [11] and references therein. Cross-waves are observed in a variety of wavemaker experiments [12], and can display complex behavior, including chaotic dynamics and slow modulations resembling solitary waves [13]. Not only is the cross-wave instability dramatic (quickly overwhelming the underlying synchronous waves in many cases) and easily observed across a broad range of fluid configurations and forcing, but it arises from a parametric instability [14] at the boundary (wavemaker), making it the localized counterpart of the usual Faraday wave instability that has produced so many intriguing patterns. Horizontal vibrations in rectangular containers that are only moderately large allow for interaction between the vibrating endwalls that, unlike standard cross-waves in larger containers, produces patterns that are neither perpendicular to the vibrating end-walls nor strictly 2:1 subharmonic. Instead, these subharmonic waves are oblique, as recently observed experimentally [15] and confirmed theoretically with good agreement in [16], where the dynamics have been shown to be quasiperiodic; some of the results in [16] will be anticipated in the present review. It is to be noted that, unlike the Faraday system, former analyses of horizontally vibrated containers concentrated either on small containers [17–20] (in which the instability only involves a few modes) or fully nonlinear behavior, using modal expansions [21–23] and finite differences [24], which provide simulations but do not allow for extracting more useful knowledge about the associated dynamics. A deeper analysis, similar to the one already performed for the Faraday system is lacking in the literature.

Vibrations always induce viscous mean flows, which had been seen as a byproduct of the oscillating flow in early studies but were more recently shown by some of the authors to be coupled with the primary vibrating field [25]. This leads to new attractors and dynamical phenomena that are due to the interaction with the mean flow. Viscous mean flows rely on localized viscous effects but, surprisingly enough, they produce an overall circulation in the bulk fluid that does not disappear as viscosity goes to zero [26]. Also, these flows are slowly varying (compared to the primary oscillating field) at low viscosity, which facilitates interaction with slow interfacial phenomena, such as Marangoni elasticity [27].

Some experimental devices [28] used to measure non-steady rheological properties involve (very slow) oscillations of surfactant monolayers over a fluid promoted by horizontal oscillations of two parallel barriers, which move in counterphase in a symmetric way. The barriers are only slightly immersed in the fluid, with the intent of minimizing the fluid dynamics of the bulk phase. The question of whether the fluid dynamics can legitimately be ignored has not been addressed in the literature to our knowledge; a preliminary analysis will be provided at the end of the paper. On the other hand, the oscillations are so slow that coupling to capillarity–gravity waves produced by external forcing is unlikely. The question remains whether coupling with fluid dynamics is possible due to slower dynamical effects and mean flow is a good candidate to enhance such coupling. Furthermore, the experimental devices usually possess symmetries that can affect the expected dynamics. As an alternative to current experimental devices, rheological properties can also be measured using much faster mechanical vibrations combined with a good theoretical model that simulates the system [29]. This, however, requires a good understanding of the fundamentals of the dynamics of vibrating fluid systems with interfaces, which is the purpose of the present paper. Specifically, this review explains in simple terms the differences between direct and parametric forcing, as well as the different behaviors that are to be expected from vertical and horizontal excitations. The review concentrates on the small viscosity limit, which is the relevant one for ordinary liquids, and focusses on the effect of symmetries and nonlinearity in the response of the system. In addition, the role of viscous mean flows is illustrated, showing that it couples with the primary surface waves and promotes coupling of the fluid dynamics with surface viscosity, which fundamentally affect the system response. Coupling of the fluid dynamics with surface rheology is further emphasized with a preliminary analysis of the dynamics of compressed–expanded monolayers over a liquid layer.

With this general context in mind, we continue with the formulation of the problem in terms of the Navier–Stokes equations (Section 2) and then consider the forcing mechanisms (Section 3), the viscous mean