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Stabilization of axisymmetric liquid bridges through vibration-induced pressure fields

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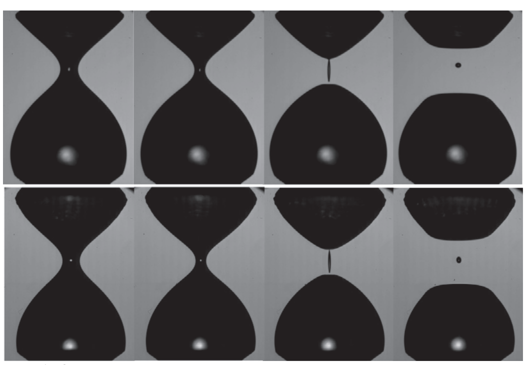
GRAPHICAL ABSTRACT



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ABSTRACT

Previous theoretical studies have indicated that liquid bridges close to the Plateau-Rayleigh instability limit can be stabilized when the upper supporting disk vibrates at a very high frequency and with a very small amplitude. The major effect of the vibration-induced pressure field is to straighten the liquid bridge free surface to compensate for the deformation caused by gravity. As a consequence, the apparent Bond number decreases and the maximum liquid bridge length increases. In this paper, we show experimentally that this procedure can be used to stabilize millimeter liquid bridges in air under normal gravity conditions. The breakup of vibrated liquid bridges is examined experimentally and compared with that produced in absence of vibration. In addition, we analyze numerically the dynamics of axisymmetric liquid bridges far from the Plateau-Rayleigh instability limit by solving the Navier-Stokes equations. We calculate the eigenfrequencies characterizing the linear oscillation modes of vibrated liquid bridges, and determine their stability limits. The breakup process of a vibrated liquid bridge at that stability limit is simulated too. We find qualitative agreement between the numerical predictions for both the stability limits and the breakup process and their experimental counterparts. Finally, we show the applicability of our technique to control the amount of liquid transferred between two solid surfaces.

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1. Introduction

Liquid bridges occur and play a relevant role both in nature [1,2] and in many industrial applications, such as materials engineering [3], powder granulation [4] and flow in porous media [5]. When the solid supports are surfaces parallel to each other, the liquid bridge becomes a relatively simple configuration, commonly used as a testbed to study surface tension-driven phenomena. The complex dynamics of the liquid meniscus formed next to the slipping triple contact lines may significantly affect the liquid bridge behavior. The problem is simplified when the solid surfaces are disks of the appropriate size, so that the contact lines anchor to their sharp edges. This specific configuration has turned nowadays into a model system to study complex phenomena on free surfaces.

There are numerous interfacial phenomena that can be studied using liquid bridges. A good example is the instability of a constrained capillary surface under different types of perturbations [6]. It is well known that the maximum length of a weightless cylindrical bridge supported by two disks of the same diameter equals the disk circumference (the Plateau-Rayleigh stability limit) [7]. The gravitational force deforms the liquid column overcoming the resistance offered by the surface tension, which reduces the maximum slenderness (length in terms of the disk diameter). In addition, the magnitude of the gravitational force relative to that of the surface tension force scales with the disk diameter squared, which limits the disk size too. As a consequence, the volume of liquid bridges with slendernesses greater than unity cannot exceed on earth some tens of cubic millimeters. This limitation is of importance in a number of practical problems, including the classical floating zone technique used for crystal growth and purification of high melting-point materials [8], printing processes [9], and capillary feeders [10].

Liquid bridges can be stabilized if the effect of gravity is somehow compensated for. A number of methods have been proposed to this end. A simple possibility is to immerse the liquid bridge in a density-matched liquid bath (the Plateau-tank technique) so that the stability problem becomes fully equivalent to that of a liquid bridge under microgravity conditions. Using this configuration, the Plateau-Rayleigh stability limit has been overcome by enclosing the liquid bridge between elliptical disks [11], or by applying axial electric fields [12,13]. This stability limit has also been suppressed by controlling the bridge shape with the radiation pressure of an ultrasonic wave [14] or the optical-radiation pressure of a continuous laser wave [15]. Non-Newtonian effects can also enable the formation of stable liquid columns with lengths well in excess of the supporting disk circumference [16]. Small pressure gradients along the interface due to the slight imbalance between the densities of the liquids can be cancelled if the outer bath moves upwards at the appropriate speed [17,18]. A similar effect is produced by a closed-flow in both the encapsulating liquid and the bridge [19].

Both the linear and non-linear dynamics of the Plateau-tank configuration is considerably different from that of a liquid bridge in air due to the non-negligible contribution of the surrounding liquid bath. Different methods have been considered to reduce the effect of the gravitational force on a liquid bridge suspended in air. A simple alternative is to make the liquid drop rest on a lower supporting disk of diameter smaller than that of the upper one [20]. In this way, the triple contact line anchorage produces a deformation opposite of that caused by gravity, which increases the maximum slenderness. Paramagnetic liquid bridges with slendernesses very close to the Plateau-Rayleigh stability limit were formed using magnetic levitation [21,22]. Pure and leaky dielectric liquid bridges surrounded by air can be stabilized beyond that limit in the presence of an electric dc field [23]. The growth of the axisymmetric capillary mode responsible for the breakup of liquid bridges in low gravity was suppressed with both acoustic radiation pressure [24] and active electrostatic stabilization [25]. Interestingly, the stabilization caused by an axial outer liquid stream [17,18] cannot be produced by a gas current. In this case, a recirculation cell appears in the bulging part of the liquid bridge, which has a destabilizing effect independently of the gas stream direction [26,27]. A similar effect is caused by the thermal (Marangoni-buoyant) convection in liquid bridges with high Prandtl numbers [28].

Very recently [29], a method has been proposed to stabilize liquid bridges in air and close to the Plateau-Rayleigh stability limit. In this method, the upper disk is vibrated at a frequency f much higher than the inverse of the capillary time t_0, and with an amplitude a much smaller than the supporting disk radius R. In the limit $(ft_0)^{-1}, a/R \ll 1$, the effect of the disk vibration reduces to a pressure field that straightens the free surface shape. If the vibration frequency or amplitude is appropriately adjusted, the Plateau-Rayleigh stability limit can be reached for non-zero Bond numbers.

The primary goal of the present paper is to show experimentally that the method described above can indeed stabilize liquid bridges under normal gravity conditions. In Ref. [29], an analytical study was conducted for liquid bridges asymptotically close to the Plateau-Rayleigh stability limit [29]. Here, we extent that analysis to arbitrary axisymmetric shapes from numerical simulations of the Navier-Stokes equations. In addition, we describe both numerically and experimentally the breakup of vibrated liquid bridges.

2. Theoretical model

The configuration considered in this work (Fig. 1) consists of an isothermal mass of liquid of volume $\mathcal{V}$, held by the surface tension force between two parallel and coaxial disks of radius R which are placed a distance L apart. The liquid bridge density, viscosity and surface tension are ρ, μ, and σ, respectively. The surrounding gas density and viscosity are much smaller than those of the liquid, so that they do not significantly affect the liquid bridge dynamics. The liquid is subjected to the action of the axial gravitational force of magnitude g per unit mass. The upper disk is vibrating harmonically with an amplitude a and frequency f.

We use the disk radius R and the capillary time $t_0 \equiv (\rho R^3/\sigma)^{1/2}$ as the characteristic length and time, respectively. The problem can be characterized in terms of the following dimensionless parameters: the slenderness $\Lambda \equiv L/(2R)$, the reduced volume $V \equiv \mathcal{V}/(\pi R^2 L)$ (defined as the ratio of the physical volume $\mathcal{V}$ to the volume of a cylinder of length L and radius R), the Bond number $B \equiv \rho g R^2/\sigma$, the Ohnesorge number $\mathrm{Oh} \equiv \mu(\rho\sigma R)^{-1/2}$, the upper disk vibration amplitude $A \equiv a/R$, and frequency $\Omega \equiv 2\pi f t_0$. These last two quantities can be grouped into the dimensionless number $W \equiv \Omega A$, which measures the relative importance of the pressure due to the upper disk vibration versus the capillary pressure.

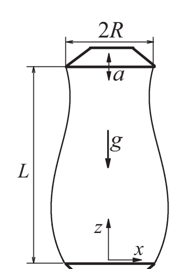

Fig. 1. Geometry and coordinate system for the liquid bridge.