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Analysis of a resonance liquid bridge oscillation on board of the International Space Station

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HIGHLIGHTS

- We studied a resonance liquid bridge vibration aboard the International Space Station.
- Two small amplitude vibrations appeared tens of seconds before the vibration.
- We reconstructed numerically the motion which took place in the experiment.
- Tiny perturbations may produce significant vibrations which survive long periods.
- We have characterized the lateral oscillation mode of viscous liquid bridges.

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ABSTRACT

We study the singular event which took place when conducting an experiment with a liquid bridge aboard the International Space Station. The liquid bridge vibrated unexpectedly for several tens of seconds with an oscillation amplitude larger than 15% of its radius. At first glance, the analysis of the mass force measured by the accelerometer during the oscillation did not show any significant perturbation. However, our study reveals the existence of two small-amplitude vibrations of the experimental setup with practically the resonance frequency of the first lateral mode. These vibrations occurred a few tens of seconds before the liquid bridge oscillation reached its maximum amplitude, produced a mass force with a magnitude of the order of $10^{-5}g$. The numerical integration of the non-linear Navier–Stokes equations reproduces remarkably well the free surface oscillations measured in the experiments. It allows us to reconstruct the three-dimensional liquid bridge motion which took place in the experiment. The present study illustrates the sensitivity of liquid bridges in a microgravity environment, where tiny perturbations may produce significant vibrations which survive over long periods of time.

1. Introduction

A liquid bridge is a mass of liquid held by surface tension between two solid supports. It can be regarded as an excellent test bench to analyze varied fluid-dynamic phenomena driven by the capillary force [1–5]. Among those phenomena, the thermocapillary (Marangoni) convection has been frequently studied both theoretically and experimentally over the past two decades, in part because of its relationship with the liquid configuration appearing in the floating zone technique [1,3]. Experiments conducted on earth are inevitably altered by natural convection, and limited by the instability of the liquid bridge equilibrium shape. For this reason, experiments have been carried out on board of the International Space Station (ISS) in several occasions (see, e.g., [6–8]).

Liquid bridges under microgravity conditions enjoy much greater stability, which allows one to grow liquid columns with sizes on the centimeter scale. However, the Ohnesorge numbers (the ratio of the viscosity to the capillary force) characterizing those bridges are much smaller than those of the terrestrial ones. As a consequence, perturbations with frequencies close to the resonance ones are greatly magnified by the liquid column, producing large oscillations. Besides, viscous damping is so weak that those oscillations can survive over a stretch of time. For this reason, g-jitter becomes a dangerous phenomenon on board of the ISS, and can lead to intolerable free surface vibrations, or even to the liquid bridge breakage.

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A very interesting example of g-jitter effects aboard the ISS is the one that took place in the experiment *Dynamic Surf* conducted on April 23th 2013 in the Fluid Physics Experiment Facility of the Japanese Experiment Module (Kibo). Large free surface oscillations were observed over several minutes before the experiment started. The analysis of the accelerometers mounted on the same experimental rack did not reveal the existence of any perturbations whose magnitude could justify the liquid bridge response.

In this paper, we will examine such a singular event considering the body forces measured by the accelerometers not only within the time window when the analyzed oscillation occurred, but also a few tens of seconds back in time. As will be shown, there were two time intervals about 1 min long in the liquid bridge history when a small-magnitude (on the order of $10^{-5}g$) perturbation developed. That perturbation had almost the resonance frequency of the first lateral mode. It triggered the liquid bridge oscillations, which grew over time and reached their maximum amplitude within the observation time window. The integration of the full Navier–Stokes equations will allow us to recreate the three-dimensional (3D) liquid bridge vibration. The resonance character of liquid bridges in space has been described in previous works (see, e.g., [9]). However, these analyses have restricted themselves to the comparison between the observed frequencies and the theoretical predictions for the resonance ones, leaving aside both the calculation of the oscillation amplitude from the measured perturbations, and the comparison of this quantity with the corresponding experimental values. To the best of our knowledge, this comparison is done for the first time in the present paper.

Both the fluid configuration and the governing equations are described in Section 2. We also present in that section some theoretical results for both the linear and non-linear regimes. The singular event which took place on board of the ISS is described and examined in Section 3. This section also shows a comparison between the theoretical and experimental results. The paper closes with some conclusions in Section 4.

2. Theoretical background

Consider the fluid configuration sketched in Fig. 1. It consists of an isothermal mass of liquid of volume $\mathcal{V}$ held by the surface tension force between two parallel and coaxial circular supports of radius R placed a distance L apart. One assumes that the liquid anchors perfectly to the edges of those supports, and therefore the triple contact line remains fixed. The effects of the ambient and the constant residual gravity can be neglected. The liquid properties are the density ρ, viscosity μ, and surface tension σ. The axisymmetric free surface equilibrium shape is given by the function $F_0(z)$, which measures the distance between a surface element and the z axis.

The perturbations are considered through the mass force (per unit mass) $\mathbf{g} = g\mathbf{e_g}$, whose magnitude g and direction $\mathbf{e_g}$ depend on time. The resulting velocity $\mathbf{v}(\mathbf{r}; t) = U(r, \theta, z; t)\mathbf{e_r} + V(r, \theta, z; t)\mathbf{e}_\theta + W(r, \theta, z; t)\mathbf{e_z}$ and pressure $p(r, \theta, z; t)$ fields are described in terms of the cylindrical coordinate system $(\mathbf{e_r}, \mathbf{e}_\theta, \mathbf{e_z})$. The free surface evolution is given by the function $F(\theta, z; t)$, which measures the distance between a surface element and the z axis at the instant t. Fig. 1 also illustrates the meaning of the quantity $X_{\max}(t) = \max[F(\theta, 0; t)\cos\theta]$, which corresponds to the maximum value of the projection onto the axis x of the liquid bridge contour at $z = 0$.

In what follows, all the spatial and temporal quantities are made dimensionless using the liquid bridge radius R and the capillary time $t_c \equiv (\rho R^3/\sigma)^{1/2}$ as the characteristic length and time, respectively. In this way, the following dimensionless parameters are obtained: the slenderness $\Lambda \equiv L/(2R)$, the dimensionless volume $\widehat{V} = \mathcal{V}/(\pi R^2 L)$, the capillary number (defined as the square root of the Ohnesorge number) $C \equiv \mu(\rho\sigma R)^{-1/2}$, and the (dynamic) Bond number $\mathbf{B} = \rho\mathbf{g}R^2/\sigma = B_x\hat{\mathbf{x}} + B_y\hat{\mathbf{y}} + B_z\hat{\mathbf{z}}$.

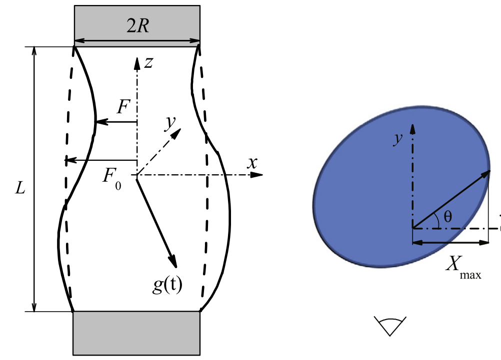

Fig. 1. (Left) Liquid bridge configuration. The dashed and solid lines represent the equilibrium and oscillating free surface shape, respectively. (Right) The liquid bridge section at $z = 0$.

The liquid bridge motion is governed by the (incompressible) Navier–Stokes equations [10,11]

$$\frac{(rU)_r}{r} + \frac{V_\theta}{r} + W_z = 0, \tag{1}$$

$$U_t + UU_r + \frac{V}{r}U_\theta + WU_z - \frac{V^2}{r} = B(\mathbf{e_g}\cdot\mathbf{e_r}) - p_r + C\left[\frac{(rU_r)_r}{r} + \frac{U_{\theta\theta}}{r^2} + U_{zz} - \frac{U}{r^2} - \frac{2V_\theta}{r^2}\right], \tag{2}$$

$$V_t + UV_r + \frac{UV}{r} + \frac{V}{r}V_\theta + WV_z = B(\mathbf{e_g}\cdot\mathbf{e}_\theta) - \frac{p_\theta}{r} + C\left[\frac{(rV_r)_r}{r} + \frac{V_{\theta\theta}}{r^2} + V_{zz} - \frac{V}{r^2} + \frac{2U_\theta}{r^2}\right], \tag{3}$$

$$W_t + UW_r + \frac{V}{r}W_\theta + WW_z = B(\mathbf{e_g}\cdot\mathbf{e_z}) - p_z + C\left[\frac{(rW_r)_r}{r} + \frac{W_{\theta\theta}}{r^2} + W_{zz}\right], \tag{4}$$

where the subscripts stand for the partial derivative with respect to the corresponding variable. These equations are integrated considering the kinematic compatibility [12]

$$F_t - U + \frac{F_\theta}{F}V + F_zW = 0, \tag{5}$$

and equilibrium of both normal and tangential stresses

$$p - \frac{2C}{C_n^2}\left\{U_r + F_z(F_zW_z - U_z - W_r) - \frac{F_\theta}{F} \times \left[-\frac{F_\theta}{F^2}(U + V_\theta) + \frac{U_\theta}{F} + V_r - \frac{V}{F} - F_z\left(V_z + \frac{W_\theta}{F}\right)\right]\right\} = \nabla\cdot\mathbf{e_n}, \tag{6}$$

$$-\frac{C}{C_nC_t}\left\{2F_z(U_r - W_z) + (1 - F_z^2)(W_r + U_z) - \frac{F_\theta}{F} \times \left[V_z + \frac{W_\theta}{F} + F_z\left(\frac{U_\theta}{F} + V_r - \frac{V}{F}\right)\right]\right\} = 0, \tag{7}$$

$$-\frac{C}{C_n^2C_t}\left\{\frac{2F_\theta}{F}\left[U_r - (1 + F_z^2)\frac{U + V_\theta}{F} + F_z(F_zW_z - U_z - W_r)\right] + \left(1 + F_z^2 - \frac{F_\theta^2}{F^2}\right) \times \left[\frac{U_\theta}{F} + V_r - \frac{V}{F} - F_z\left(V_z + \frac{W_\theta}{F}\right)\right]\right\} = 0 \tag{8}$$