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STABILIZATION AND LOW-FREQUENCY OSCILLATION OF CAPILLARY BRIDGES WITH MODULATED ACOUSTIC RADIATION PRESSURE

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I. Introduction

Liquid bridges between two solid surfaces have applications in low gravity such as the solidification of floating zones. It has been known since the research of Plateau (1866) and Rayleigh (1879) that a cylindrical liquid bridge will become unstable when it is longer than a critical length. Long bridges naturally become unstable to a symmetric mode by bulging near one end while the opposite end thins. For a cylindrical bridge in low gravity of radius R and length L, the slenderness $S = L/2R$ has a natural (Rayleigh) limit of π beyond which the bridge breaks. In the presence of gravity (which causes a static distortion of a bridge from a cylindrical shape) the critical length is known to be even shorter. This instability places practical limitations on the management of liquids in low gravity and on the earth. For example, stabilization of liquid bridges may facilitate a reduction of temperature gradients in the float-zone method of crystallization. Various methods have been investigated for overcoming the Rayleigh-Plateau (RP) instability, however the methods studied by other researchers may turn out to have limited value for fluids applications of general interest. These include effects of electric fields on dielectric bridges [1], magnetic fields on bridges of high electrical conductivity [2], and hydrodynamic stabilization due to flow of a viscous fluid parallel to a bridge [3]. The objectives of the current research effort are to utilize modulated acoustic radiation pressure to stabilize bridges against breakup and to obtain quantitative information about the frequency and decay time of bridge oscillations.

In the work reported here it is demonstrated that acoustic radiation pressure may be used in simulated low gravity to produce stable bridges significantly beyond the Rayleigh limit with S as large as 3.6. The bridge (PDMS mixed with a dense liquid) has the same density as the surrounding water bath containing an ultrasonic standing wave. Modulation was first used to excite specific bridge modes [4]. In the most recent work reported here the shape of the bridge is optically sensed and the ultrasonic drive is electronically adjusted such that the radiation stress distribution dynamically quenches the most unstable mode. This active control simulates passive stabilization suggested for low gravity [5]. Feedback increases the mode frequency in the naturally stable region since the effective stiffness of the mode is increased.

II. Acoustic Stabilization Methods

The first step in the investigation of acoustic stabilization was to demonstrate the selective excitation of bridge modes in a Plateau tank using the radiation pressure of modulated ultrasound. Results demonstrating that objective were already published [4]. The next step was Marston's analysis [5] of the effect of a selected radiation pressure squeezing of a bridge on the natural frequency and stability of an inviscid bridge. It was assumed that the acoustic radiation pressure $<p_r>$ could be increased with increasing local bridge radius R in such a way that the sound field (on the average) squeezed harder on the fat portions of the bridge than on the slender portions. The control is expressed in terms of an *acoustic parameter*

$$q = (R^2/\sigma)\, d<p_r>/dR \qquad (1)$$

where σ denotes the surface tension of the bridge. The analysis is equally applicable to the situation of passive feedback as it is in the active control case. In the passive case, the acoustic field is designed such that the radiation pressure automatically squeezes more on the fatter parts of the bridge even without active adjustment of the acoustic field. Results are summarized subsequently in the discussion of Fig. 2.

In the next stage of development measurements were made of the natural frequency of the most unstable bridge mode for a bridge in a Plateau tank both with and without active stabilization. Figure 1 shows a diagram of the apparatus. The instantaneous left-right asymmetry of the bridge was sensed by detection of an optical signal with a split photodetector. The resulting voltage difference Vd represents an error signal which is multiplied by a gain constant k and used to control the frequency of the high-frequency oscillator used to excite the ultrasonic transducer. The typical acoustic frequency is 120 kHz. The transducer was designed in such a way that shifting the frequency of the drive shifts the left-right asymmetry of the radial component of radiation pressure on the bridge. The natural frequency of oscillation was measured by superposing on the error signal a weak low-frequency modulation which could be used to excite the N = 2, m = 0 (left/right asymmetry) bridge mode which is the most unstable mode. The frequency of the modulation was adjusted to maximize the response of the desired mode. The measurements of the increase in natural frequency due to active stabilization were carried out with the same kind of silicone-oil/TBE bridge mixture for a neutral density bridge in water as described in [4].

III. Results

A. Frequency Measurements of the Most Unstable Mode

Figure 2 shows an example of the normalized frequency data (as a function of the slenderness S = L/2R) for an experiment where the feedback "gain level" k was set to three different values. The data for the case k = 0 is shown as the squares. The corresponding theory curve is calculated from the one-dimensional inviscid slice (ODIS) approximation applied by Marston [5]. Here $\bar{\omega}$ is a normalized frequency as described in [4]. The theory curve intercepts $\bar{\omega} = 0$ at the Rayleigh-Plateau natural limit of π and the data, which could be taken up to S = 3, follow the curve.

The circles correspond to data taken with k = 4 which is the appropriate feedback sign to increase the stability of the bridge. In each case the natural frequency of the bridge is increased indicating that the "spring" of the bridge mode oscillator has been "stiffened" by the feedback. This is exactly what is required for enhanced stability. The curve labeled q = 0.2 was obtained by adjusting the value of the acoustic parameter q to fit the data. Here q is the parameter in Eq. (1). The fit suggests that with the strength of feedback achieved, it would be possible to extend the bridge to the modified slenderness limit of $S_L \approx 3.5$

which is significantly greater than π. The triangles were taken with k = -4 which correspond to the sign of feedback to reduce the stability of this mode. The frequency is reduced in comparison to the no-feedback (k = 0) values. The corresponding curve shows the case of q = -0.2 which reduces the slenderness limit to 2.86, below the natural value of π.

B. Acoustic Stabilization Beyond the Rayleigh Limit

The next stage of the research was to demonstrate acoustic stabilization as described in the abstract [6]. Several experimental improvements were made to facilitate this objective including (a) improved stability and control of the liquid deployment system and (b) greater bandwidth of the amplifier in the electronic feedback system (Fig. 1). With those improvements, stabilization up to a slenderness S of 3.7 has been achieved. Figure 3 shows frames from a CCD camera video record showing deployment and active acoustic stabilization of a bridge with S = 3.6. Figures 3(a) - (d) show the initial bridge deployment and extension to a length of S = 3.5. In (e) the supports are set and left at S = 3.6 and the bridge volume is adjusted to give a circular cylinder. The bridge length L and diameter D are 15.8 mm and 4.32 mm. The active control of the ultrasonic drive based on an optical error signal (Fig. 1) is implemented throughout the sequence except at the end as explained below. Note that (e) is at an elapsed time of 19 seconds as displayed on the counter. The bridge remains stable until (j), elapsed time of 42 seconds, where the sound field is turned off. The bridge becomes unstable and breaks in less than 1 second in (k) and (*l*). The viscosity of the bridge liquid was small, only 5 cs, so viscous dissipation was not an important stabilization mechanism. While the stabilization sequence in Fig. 3 is less than 1 minute in duration, similar observations show that S = 3.6 may be maintained for an arbitrarily long time. Comparison with results of an investigation of viscous flow-induced stabilization of capillary bridges [3] indicates that the acoustic stabilization method is superior even at this early stage of development.

IV. Conclusions

The research described here has demonstrated that modulated acoustic radiation pressure can be coupled to the natural oscillation modes of a capillary bridge. This effect has been used both to excite these modes in order to measure the natural frequency and damping characteristics of the modes as well as to modify these characteristics in order to enhance the stability of the bridge. Stabilization has been demonstrated to a slenderness ratio of 3.7 using active feedback control of the acoustic field. This is a significant increase in the slenderness ratio over the natural limit of π.

Acknowledgment

This research was supported by NASA Grant NAG3-1622.

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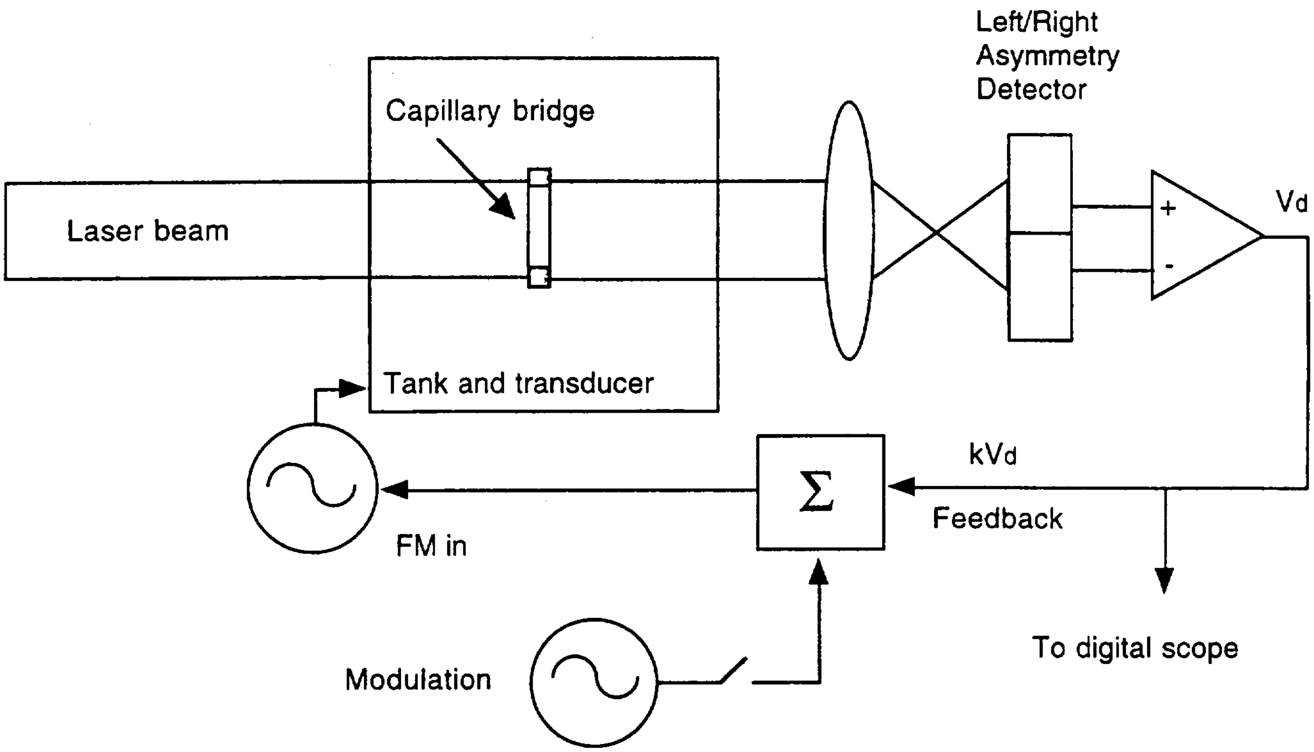


Figure 1. Apparatus to actively stabilize and measure the frequency of maximum response of a capillary bridge.

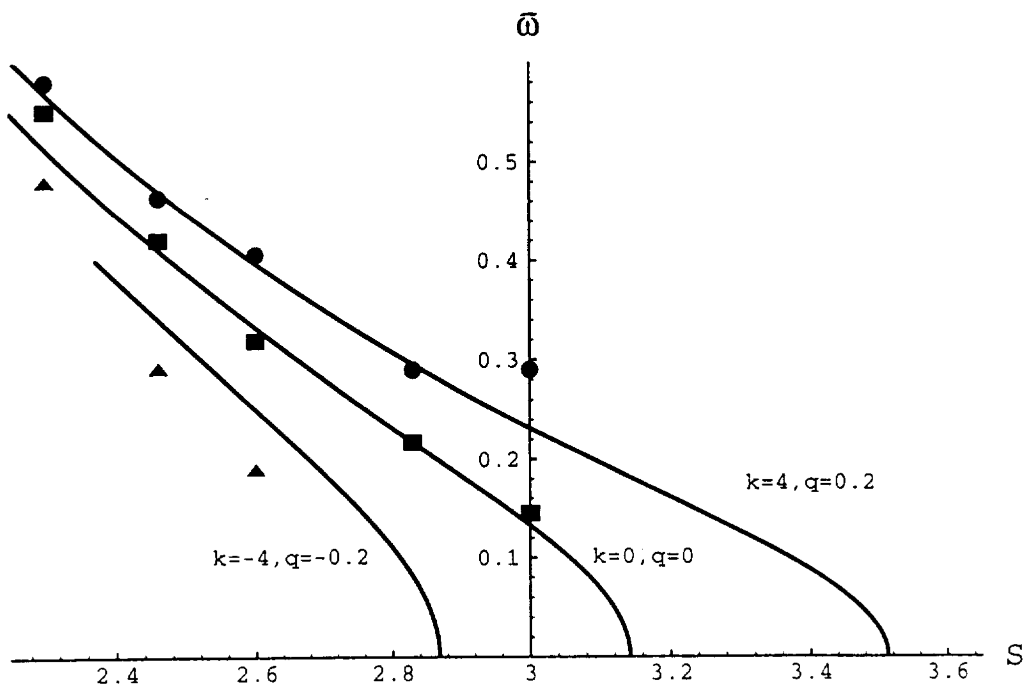
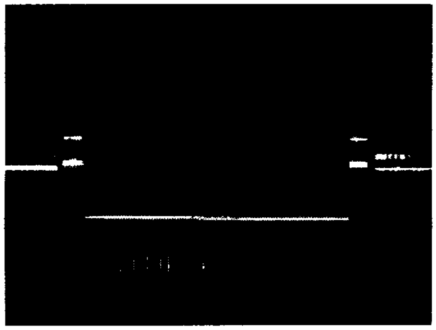
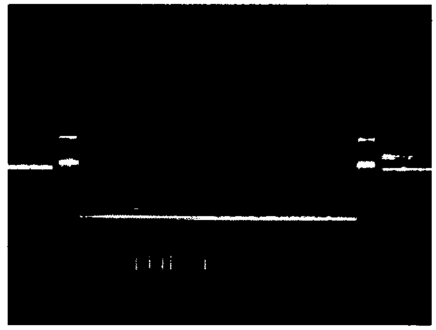


Figure 2. Normalized natural frequency vs. Slenderness ratio.

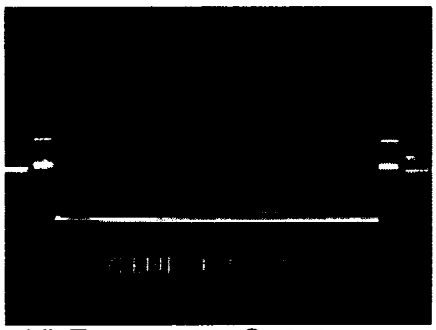


(a) Frame 0, S=2.8

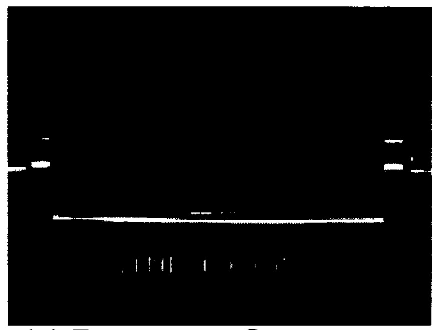


(b) Frame 100, S=3.0

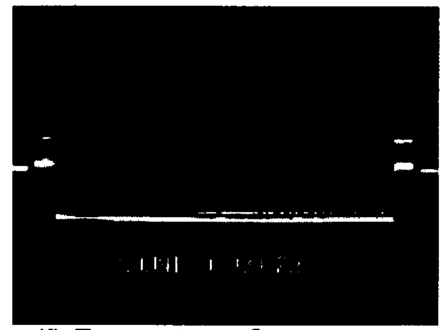
(c) Frame 200, S=3.3



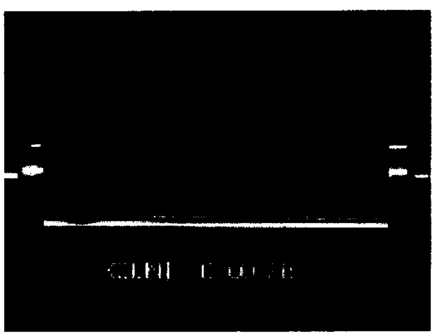
(d) Frame 300, S=3.5



(e) Frame 400, S=3.6

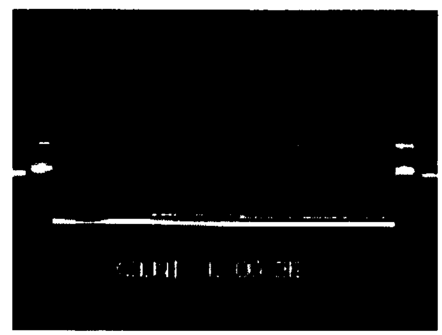


(f) Frame 500, S=3.6

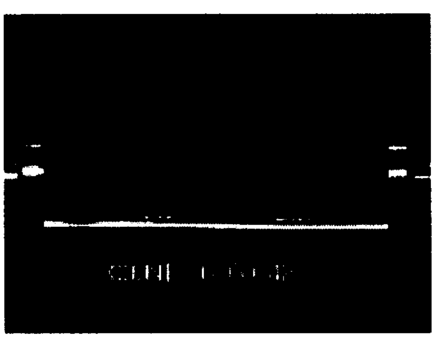


(g) Frame 600, S=3.6

(h) Frame 700, S=3.6



(i) Frame 800, S=3.6



(j) Frame 952, S=3.6
Sound field turned off.

(k) Frame 960, S=3.6
~.3 sec after (j).

(l) Frame 962, S=3.6
~.1 sec after (k).

Figure 3. Sequence of CCD images of the evolution of a stabilized capillary bridge.