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AIAA-2001-5093 7 pgs

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PASSIVE AND ACTIVE STABILIZATION OF LIQUID BRIDGES IN LOW GRAVITY

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Abstract

Tests are planned in the low gravity environment of the International Space Station (ISS) of new methods for the suppression of the capillary instability of liquid bridges. Our suppression methods are unusual in that they are not limited to liquid bridges having very special properties and may impact a variety of low-gravity and earth-based technologies. There are two main approaches to be investigated: (1) Passive Acoustic Stabilization (PAS) and (2) Active Electrostatic Stabilization (AES). In PAS, the suppression of the mode growth is accomplished by placing the bridge in an acoustic field having the appropriate properties such that the acoustic radiation pressure automatically pulls outward on the thinnest portion of the bridge. In AES, the bridge deformation is sensed optically and counteracted by actively adjusting the electrostatic Maxwell stresses via two ring electrodes concentric with the slightly conducting bridge to offset the growth of the unstable mode. While the present work emphasizes cylindrical bridges, the methods need not be restricted to that case. The methods to be explored are relevant to the suppression of capillary instabilities in floating zone crystal growth, breakup of liquid jets and columns, bubbles, and annular films as well as the management of coolants or propellants in low-gravity.

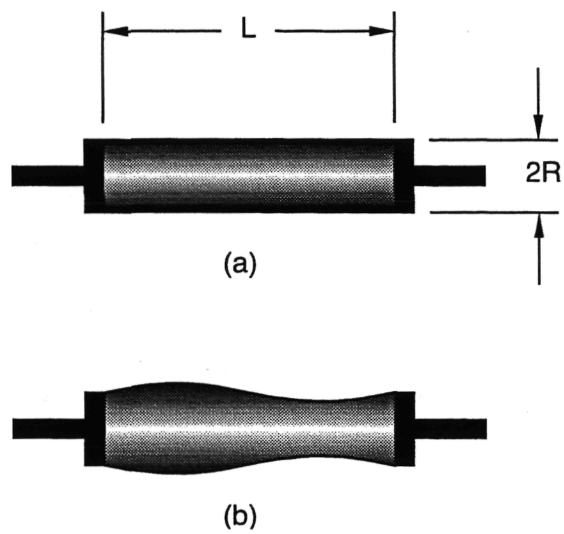

Figure 1. A typical cylindrical bridge is shown supported at the ends in (a) with a length L and radius R. When $L/2R$ exceeds π, the (2,0) mode is unstable, and the bridge deforms as shown in (b) before breaking.

Introduction

Capillary forces have a major influence on fluid-fluid interfaces when the Bond number ($B = (\rho_i - \rho_o)\, g_e R^2 / \sigma$) is small in magnitude. The stability of a weightless column of liquid (or liquid bridge) between identical circular supports is ordinarily governed by capillary forces. When the volume of liquid is constrained to be that of a circular cylinder between coaxial supports and the Bond number vanishes, the column first becomes unstable when its length L exceeds $2\pi R$ where R is the radius of the supports. This stability limit is known as the Rayleigh-Plateau (RP) limit. The RP limit can be expressed in terms of the length to diameter ratio, $S = L/2R$, which is termed the slenderness, and the RP limit then occurs for a slenderness value of π. Figure 1(a) shows a liquid bridge of length L and radius R. When S exceeds π, the (2,0) mode of the bridge becomes unstable, and the bridge takes the form shown in Figure 1(b) before breaking. In this double-index notation the first number is the *axial index* while the second gives the *azimuthal index*. For modes that are symmetric around the axis the azimuthal index vanishes. The (3,0) mode (next unstable) first becomes unstable at $S = 4.49$ when the liquid volume is that of a true cylinder.[1-4]

Applications

One motivation for numerous investigations of the stability of liquid columns in (real or simulated) low gravity[5-7] is the importance of liquid columns to crucible-free purification and crystallization of materials. In normal gravity, float-zone melting is widely used for purification, as in the case of silicon for semiconductor applications.[8] Large-area semiconductor radiation detectors are a related application. The normal procedure is to melt a polycrystalline silicon rod by 3-5 MHz induction heating in Argon gas at a pressure $\approx$ 1 atm. The weight of the liquid in the column affects the stability, though other forces are relevant including surface tension, electromagnetic stresses, convection, and thermocapillarity.[9] The Rayleigh-Plateau instability restricts the aspect ratio of the melted zone achievable in the growth of silicon and GaSb in microgravity.[10] Other factors being similar, shorter melted zones are ordinarily associated with larger thermal gradients and Marangoni stresses.[11] Suppression of the Rayleigh-Plateau instability should facilitate microgravity float-zone crystallization for parameter regions not otherwise achievable. It is also plausible that our control methods may assist crystal growth or purification in normal gravity. The active control of the Maxwell stress distribution may also prove to be applicable to stabilizing or damping modes of inductively heated liquid bridges that are subjected to inward-directed Maxwell stresses by the applied RF *magnetic* field.[12]

Some other situations where the Rayleigh-Plateau instability is important are summarized below. Surface tension plays a major role in the breakup of low-speed jets and nanojets.[13-15] It is plausible that the control methods to be investigated by us could be used to suppress or alter such breakup. There is an analogous process in the breakup of long cylindrical bubbles into spherical bubbles at small Weber and Bond numbers[16] which could be suppressed using the proposed methods. In situations where liquid layers coat the outside or the inside of a long circular cylinder[15] the Rayleigh-Plateau instability contributes to the break up of the layer. One example pertains to the management of coolants in low gravity. One design of the Satellite Test of the Equivalence Principle (STEP) experiment[17] involves the coating of the outside of a cylinder by (what is intended to be) a uniform layer of liquid helium. The concern is that the bunching of the liquid (driven at least in part by surface tension) could cause gravitational gradients resulting in a false signature of an equivalence-principle violation. While there appears to be other means for suppressing such a signature, application of our proposed active feedback methods to coolant management should not be ruled out. There are other situations where surface tension affects propellant and coolant management in low gravity.[18-22] It may be shown that with suitable electrode configurations, in the AES approach the liquids to be controlled may be pure dielectrics.

Because the following examples may not be well known in the field of fluid mechanics, the relevance of the Rayleigh-Plateau instability is noteworthy. A fabrication method for ceramic fibers is to solidify a jet of molten ceramic. The surface-tension induced axisymmetric mode of the liquid jet has a deleterious effect on the quality of the solid fibers produced by this process.[23] The stability and rupture of molten-metal bridges formed by electric arcs are relevant to the physics of high power electrical relays.[24]

While our methods for controlling the Rayleigh-Plateau instability and for actively inducing damping may not be applicable to all situations of interest, we anticipate that our direct approach will provide results beneficial to researchers concerned with the effects of capillary forces on the stability and oscillations of liquid masses. A distinguishing feature of our experiments based on the control of Maxwell stresses is that, unlike electrostatic methods based on axial fields[25-27] which do not involve active control, our methods should apply to electrically conducting and semiconducting bridges. Fortunately, for our AES electrode configuration, it may be shown[1] that the requirements on the electrical conductivity of the liquid σ_e are not very restrictive: $\sigma_e \gtrsim SC_e/2\pi R\tau \approx 10$ μS/cm where $C_e \approx 200$ pF is the electrode capacitance.

Passive Acoustic Stabilization

The Passive Acoustic Stabilization (PAS) method uses a standing acoustic field to stabilize the liquid bridge. Figure 2 shows the transducer and reflector used to produce the acoustic field. The capillary bridge is positioned such that the bridge's axis is located at a pressure nodal plane of an appropriately chosen ultrasonic standing wave. The effect of the acoustic radiation pressure on the bridge is such that the sound field tends to squeeze more on a portion of the bridge that has a larger diameter. So, if the bridge tends to bulge in one place, the sound field automatically squeezes more in that location preventing the instability from leading to bridge breakage. Analysis indicates that this method should be able to stabilize all axial modes of instability.[28,29] The sound field, however, causes the bridge to have an elliptical cross-section rather than a circular cylindrical shape. The degree of ellipticity is a function of the acoustic field strength.

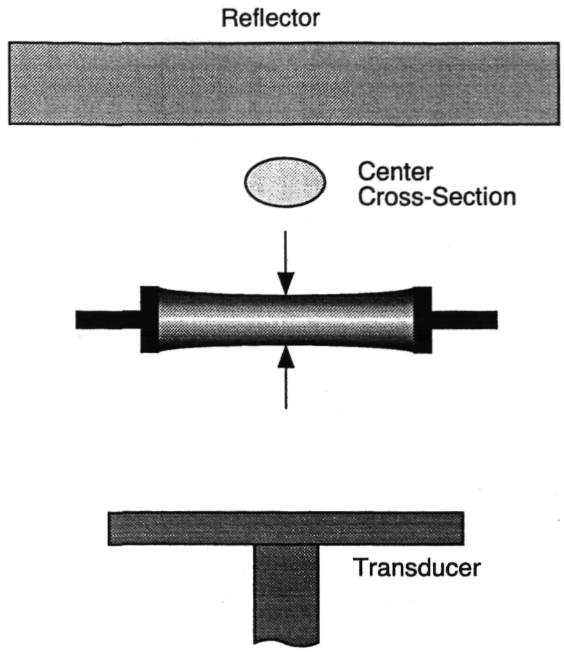

Figure 2. A liquid bridge suspended between circular supports at the pressure nodal plane of an ultrasonic standing wave established between an acoustic transducer (a vibrating plate) and a reflector.

Passive Acoustic Stabilization in air has been observed on several flights by our group on NASA's KC-135 reduced gravity aircraft.[28,29] The sound field is generated by a compact ultrasonic transducer consisting of a resonant bar/plate driven by piezoelectric disks. A standing wave is produced between the plate surface and a reflector (see Figure 2). The liquid column is formed rapidly in the nodal plane of the sound field by injecting liquid through a hole in one of the solid support disks and simultaneously retracting the support disks at the correct rate to maintain a cylindrical volume as the slenderness is increased. The bridge deployment apparatus, transducer/reflector assembly and a CCD camera with back-lighting are all contained in a rack which is freely-floated within the aircraft to reduce vibrations during the low-g maneuvers. Heavier instrumentation and a computer to control the bridge formation and sound field parameters are located in a rack fixed to the aircraft floor and connected by an umbilical to the free-float rack. The free-float rack has a 3-axis accelerometer mounted on it to monitor the effective gravity.

Figure 3 shows a bridge with radius R = 0.162 cm stabilized to S = 4.5 in an acoustic field of frequency f = 29.41 kHz, giving kR = 0.87. In this sequence, the bridge liquid was an aqueous solution of 44.0 wt %

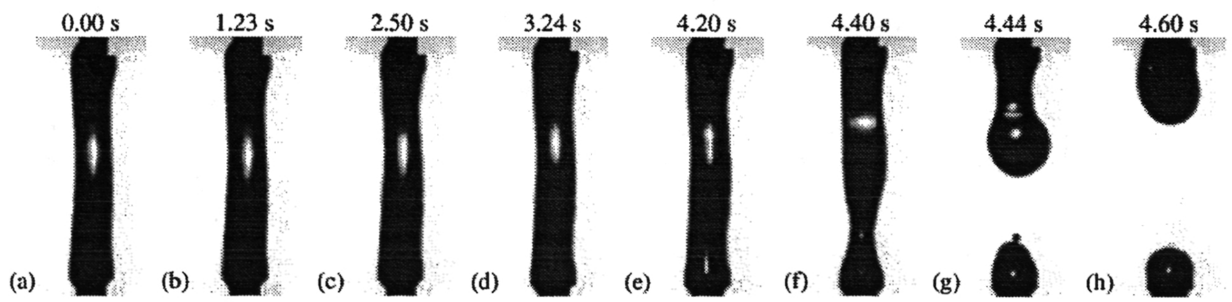

Figure 3. A sequence of images of a bridge stabilized on the KC-135. In frame (a), the bridge has been extended to S = 4.3 and is stable at that length for 2.5 s, at which time the bridge is extended to S = 4.5 starting in frame (c). The bridge is held at S = 4.5 for approximately 1 s, and is then extended to S = 4.7 starting in frame (e). This causes the bridge to become unstable and break. in frames (f) – (h).

glycerol with a viscosity of 4 cS at 20° C. The breakup of the bridge in this case is caused by extending the bridge beyond $S = 4.5$. Control experiments show that without any acoustic field, the bridge breaks in less than a second after extending S even slightly beyond π. Stabilized bridges extended beyond π are observed to break rapidly when the sound is turned off.[28,29]

The limited duration and level of g-jitter onboard the KC-135 prevent the complete validation of the theoretical predictions of the PAS model. In particular, predictions of maximum stable length and bridge oscillation frequency versus sound pressure level require the long-term, low g-jitter, microgravity environment onboard the International Space Station. A flight investigation is currently in the design stages to utilize the Microgravity Science Glovebox facility on the ISS. Figure 4 shows a schematic of the proposed flight hardware. This design is based on the experience gained during the KC-135 flights. Most of the hardware is similar in concept to the current aircraft hardware. The major difference is the clean-up system employed when the bridge breaks in a constant microgravity environment.

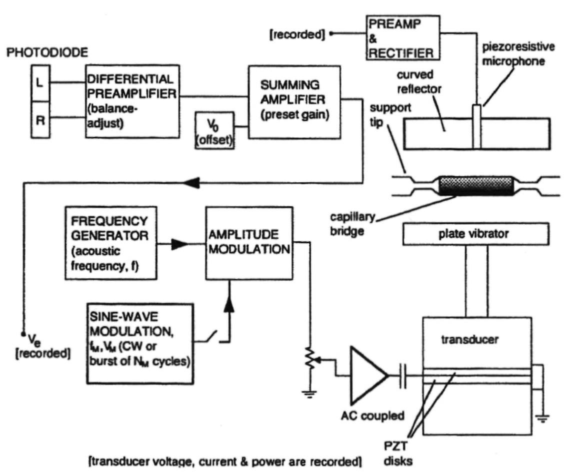

Figure 4. Diagram of proposed PAS experiment. The ability to modulate the transducer drive frequency is employed to oscillate the bridge to verify damping characteristics. The photodiode is used to observe the small amplitude bridge motion and is also used in the AES feedback mechanism.

Active Electrostatic Stabilization

The Active Electronic Stabilization (AES) method uses Maxwell radial surface stresses to stabilize the bridge. Figure 5 shows the electrodes used to create the electric fields that produce the surface stresses. The

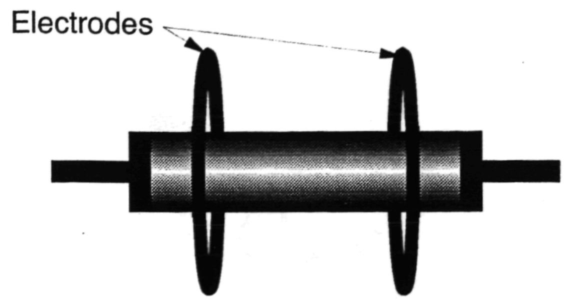

Figure 5. A profile of the liquid bridge suspended between circular supports with concentric electrodes. The supports are grounded and applying a voltage to an electrode results in Maxwell stresses that pull the fluid to that electrode.

Maxwell stresses result in bridge attraction to the activated electrode. The asymmetry signal from a optical detector is used to control the voltage to the electrodes. Voltage is applied to the electrode on the thin side of the bridge, attracting the bridge to the electrode. The applied voltage level is a function of the magnitude of the bridge asymmetry. Stabilization by optically sensing the bridge deformation and actively adjusting the interfacial stresses to offset the growth of the first unstable mode was originally demonstrated in Plateau tanks using acoustic radiation stresses[30] and electrostatic stresses.[1]

In the AES method an error voltage proportional to the amplitude of the unstable bridge mode is generated by an optical system. This signal is generated by illuminating the bridge with a low-power, expanded laser beam and by detecting an asymmetry in the light reaching a pair of photo-detectors as shown in Figure 6. The principle of operation is that if the left side of the bridge becomes rotund and the right side thins, the optical power detected by the photodiode viewing the left decreases while the power into the right diode increases. This imbalance is used (with the aid of a differential amplifier) to produce the error voltage which may be either positive or negative (depending on which end of the bridge is rotund).

The error voltage is processed and used to adjust the potentials of a pair of ring electrodes that are concentric with the axis of the cylinder with one electrode near each end of the bridge. The circular metal disks on each end of the bridge are held at ground potential. The electrical conductivity of the bridge liquid is taken to be sufficiently large so that the bridge liquid (to a good approximation) is maintained at ground potential. Sufficient electrical conductivity for the bridge is

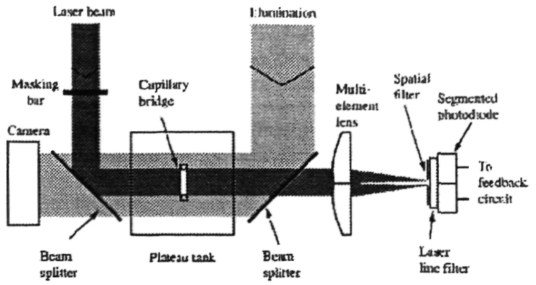

Figure 6. The bridge is illuminated with an expanded laser beam focused onto the segmented photodiode by a two-element lens that projects half of the bridge on each photodiode segment. The difference in signal between the two segments is then a measure of the (2,0) mode deformation.

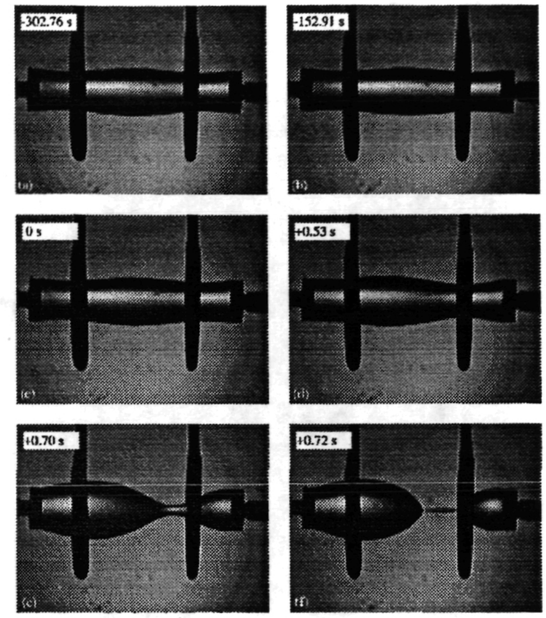

Figure 7. A time sequence showing a bridge with slenderness 4.48 in a Plateau tank actively stabilized using the square-root feedback algorithm. Frames (a) – (c) show the bridge being stabilized for about 5 min. In frame (c) the feedback control is turned off. Frames (d) through (f) show the subsequent growth of the (2,0) mode and bridge breakage which occurs less than a second after control is turned off.

attained by adding some sodium chloride to a mixture of water and glycerol. When a positive or negative potential is applied to a ring electrode, a radial electric field is produced between the bridge surface and electrode. This in turn produces an outward radial electrostatic stress on the surface of the liquid column. Thus, when the bridge begins to neck down on one side, this is detected optically and a potential is applied to the ring electrode on that end of the bridge to pull the liquid back to that half and prevent pinch-off.

In ground-based tests using the AES Plateau-tank method[1,28] stabilization was demonstrated for periods of at least 30 minutes. Liquid bridges have been stabilized to slenderness values of 4.48 (42% beyond RP limit), as shown in Figure 7. This is essentially the slenderness at which the next capillary mode becomes unstable and therefore stabilization beyond about 4.49 would require 3 electrodes and the appropriate modal amplitude detector.

The dynamics of liquid bridges in air is significantly different from that in a Plateau tank.[1,30] The damping of the (2,0) capillary mode is significantly reduced. This makes stabilization more challenging and requires shorter delay times in the feedback system. Stabilization of liquid bridges with the active electrostatic method has been successfully demonstrated on many KC-135 flights with our apparatus. Liquid bridges in air have been stabilized to slenderness values of about 4.4, 40% beyond RP limit.[28]

Complete validation of the theoretical predictions of the AES model require the long-term, low g-jitter, microgravity environment onboard the International Space Station. Predictions of maximum stable length, bridge oscillation frequency, and bridge oscillation damping as a function of the feedback gain will be tested. Our analytical results indicate that with the active application of stresses, it is possible to increase the effective damping of the most unstable mode of short liquid bridges so as to suppress a bridge's response to g-jitter. Figure 8 shows a schematic of the

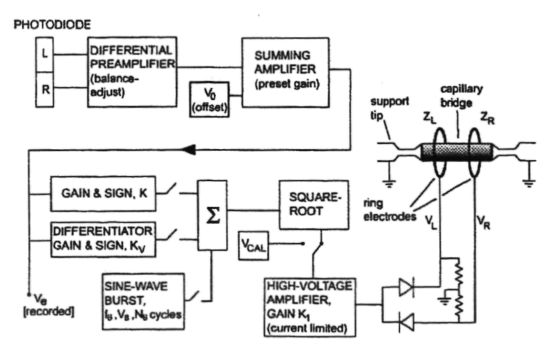

Figure 8. Diagram of proposed AES experiment. The photodiode detector shown in Figure 6 is used to detect the amplitude of the (2,0) mode disturbance and control the voltages of the electrodes to counteract the mode growth.

proposed flight hardware.

Conclusions

The Rayleigh-Plateau instability of liquid bridges is a fundamental instability that affects many earth- and space-based processes. An investigation employing the International Space Station Microgravity Science Glovebox is planned to study new methods to suppress this instability. These suppression methods are unusual in that they are not limited to liquid bridges having very special properties. One method passively stabilizes the instability utilizing a standing ultrasonic acoustic wave to suppress all unstable modes. A second, active method employs Maxwell stresses on the fluid to suppress the (2,0) mode growth, but could be extended to suppress higher modes. Both of these methods have been investigated in ground-based studies, allowing liquid bridges to be stabilized out to S of at least 4.3. However the long-duration, microgravity environment onboard the ISS is needed to validate the theoretical models and test the limits of the stabilization methods, a necessary step to applying them to real problems. Both methods could prove useful in applications involving liquid jets as well as liquid bridges.

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