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STABILITY OF LIQUID BRIDGES. RESULTS OF SL-D1 EXPERIMENT†

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Abstract—An analysis is presented of an experiment aboard Spacelab-D1 on the mechanical stability of long liquid columns between coaxial equal discs. The effect of g-jitter, column slenderness, disc rotation and disc vibration upon the liquid outer shape, is studied.

1. INTRODUCTION

Experiments with cylindrical liquid bridges of 35 mm in diameter and up to 100 mm in length were performed by Payload Specialist Dr Furrer during the Spacelab-D1 mission (November 1985) to investigate the behaviour of long liquid columns when subjected to mechanical disturbances in a microgravity environment, under a wider-scope experimental project which make use of different microgravity platforms (aircraft parabolic flights, sounding rockets and Spacelab) as well as ground tests using the neutral buoyancy technique.

Apart of its own fluid mechanical interest, the behaviour of liquid bridges is of great importance in several well-known applications, among which the floating zone technique of producing high purity single-crystals of semiconductor materials can be pointed out. Even just in the mechanical behaviour of a real floating zone, there are so many factors interplaying (surface tension, gradients in surface tension caused by temperature and concentration fields, sample rotation to uniformize the heating, gravity, vibration induced by the drivers during the processing, etc) that the most suitable approach is to analyze one by one the different factors.

Thus, one tries to get rid of gravity (the dominant factor) by minimizing the Bond number $\mathrm{Bo} = \Delta\rho g R^2/\sigma$, which measures the relative importance of gravity and capillary forces. To this aim, and taking into account that the surface tension of most suitable liquids varies scarcely, one can adopt three possible approaches: to diminish the density difference $\Delta\rho$ in a neutral buoyancy tank (as pioneered by Plateau in the XIX century), to diminish the effective gravity g by an inertial balance (drop tower, parabolic flight of airplanes and rockets, or orbital flight) or to reduce the spatial dimensions of the sample (characterized here by the disc radius R) working with microscopic zones. The latter approach brings so many experimental constrains that have not been pursued under this project.

Experimentation on ground in a Plateau Tank Facility[1] provides a simple accurate mean to perform static experiments to measure shapes and stability[2] and, if a theory for the effect of the outer bath on liquid bridge movements is developed, can also serve to investigate certain dynamic characteristics[3]. However, this method is not suitable to perform experiments on liquid bridge rotation, for instance.

Experimentation in microgravity platforms imposes its own constrains, as can be learnt from the experience in this project of liquid-bridge stability investigations. In 1976, an experiment proposal for SL-1 was accepted. When the nominal procedures were executed in 1983 (SL-1) the liquid went uncontroled after a few seconds from start, due to inertial spreading beyond the intended edges[4]. A more conservative design was then tried in 1984, within the 20 s of microgravity provided by NASA's KC-135 plane in parabolic flight, but the results, though encouraging, were inconclusive due to high g-jitter. Clear success came in May 1985 with an experiment on the TEXUS rocket, where cylindrical liquid columns up to 80 mm long and 30 mm in diameter were repeatedly formed in a few minutes[5]. Finally, the experiments envisaged for SL-1 were successfully carried out in SL-D1 where the only problem found when working with liquid columns up to 100 mm long and 35 mm in diameter was that the residual gravity and g-jitter prevent going any further towards the cylindrical stability limit of length/diameter = π in absence of gravity[6, 7].

2. RESULTS OF SL-D1 EXPERIMENT

The trials performed can be separated to the purpose of analysis (in chronological order) as shown in Table 1.

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Table 1. Summary of trials performed (MET = Mission Elapsed Time)

From MET	To MET	Run	L_{max}[mm]	Ω_{max}[rpm]	Comments
5/23:35:00	5/23:51:41	1	95	0	Broke by volume depletion
6/00:28:23	6/01:07:56	2	95	0	Broke by jet firing from the Shuttle
6/01:09:26	6/01:29:31	3	95	12	Broke by disc spinning
6/03:03:06	6/03:18:46	4	100	10	Broke by disc spinning
6/03:20:31	6/03:30:33	5	90	13	Broke by disc spinning

The data recorded during the experiment consists of photographic images of the liquid bridge, on a 16 mm film (KODAK 2476) shot at 2 s per frame (f/2, 1/20 s), video images, house-keeping data of the Fluid Physics Module used, and auxiliary information (voice track and logbooks).

The analysis has concentrated on the photos because they are best suited to manual handling (the sophisticated automatic image processing needed is not available). Besides, malfunction of the on-board video tape recorded damaged the best part of the video track.

The procedure followed has been: (1) enlarge the 16 mm frames with a microfilm projector and manually draw the outline of the liquid column roughly filling an A4 sheet; (2) input that shape (some 50 points each) to a computer via a digitizing tablet; (3) smooth the shape with a Fourier series expansion (a few terms), and finally analysis the sequences of shapes. The effect of optical distortions, subjective shape-drawing, number of digitized points, number of Fourier terms, etc. has been thoroughly screened. The only artificial correction applied has been an axial compression of the digitized shape to match the known slenderness of the column (the consistent bias to values 2 to 3% larger is attributed to optical defomations in the microfilm projector).

A weak point is that the volume of liquid in the column was not measured and has to be computed from the outer shape of columns that are not perfectly axisymmetric (a characteristic type deviation of 3% has been found).

A description of the trials performed and results obtained follows.

2.1. *Run 1: non-cylindrical breaking*

Bridge formation was achieved by growing a large drop anchored to the feeding disc edge until contact with the opposite disc, situated at 3/4 of diameter apart, occurred (Fig. 1). This procedure was also used in SL-1, but there, either the first spreading wave advancing over the feeding disc, or the later spreading wave over the opposite disc when contact took place, caused the liquid to jump over the disc edge and get uncontroled. This procedure was not used in TEXUS-12, where a cylindrical filling law was followed from the initial zero-separation stage. A big jet firing occurred at this stage in SL-D1, but this short bridge withstood it easily.

Subsequent bridge elongation was performed setting an automatic separation speed of 1 mm/s and instructing the operator to inject liquid from a syringe, manually turning a handle (delivering 3.45 cm^3 per turn) while watching at the bridge to keep it as cylindrical as possible.

The stretching seemed to be too fast and, as soon as the intended length (95 mm) was reached, the bridge disrupted. Image analysis has allowed the reconstruction of the volume-separation history and showed that the minimum volume limit had been transpassed[6].

2.2. *Run 2: axial oscillations*

After liquid recovery, the procedure to establish a long (95 mm) liquid column was repeated (this time at 0.5 mm/s), but when the separation was 31.3 mm big, jet firings from the Shuttle (see Fig. 2) forced the operator to hold for several minutes. After that, he succeeded in applying a 0.93 mm peak-to-peak axial oscillation through one of the disc at frequencies of 0.1, 0.3, 0.7, 1.1 and 1.6 Hz that were predicted to lay near the resonances. Except for the first mode, where no deformation was apparent (over the ambient jitter) the response of the column was as expected.

2.3. *Run 3: disc rotation at 12 rpm*

After liquid recovery and column reforming to 95 mm in length, both discs were spun up at 9 s/rpm up to 12 rpm, slightly surpassing the theoretical speed limit of zero-gravity. Although no visible effect upon the outer shape when spinning up, some tens of seconds after the speed was reached, the necking deepened until breakage. Although the column slenderness in this case was chosen to coincide with the

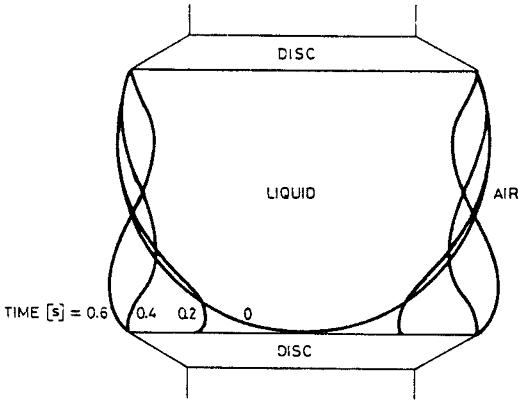

Fig. 1. Four stages in the spreading of the captive drop over the opposite disc (untreated aluminium) used in Spacelab-D1 to establish a liquid bridge (by hand from TV images).

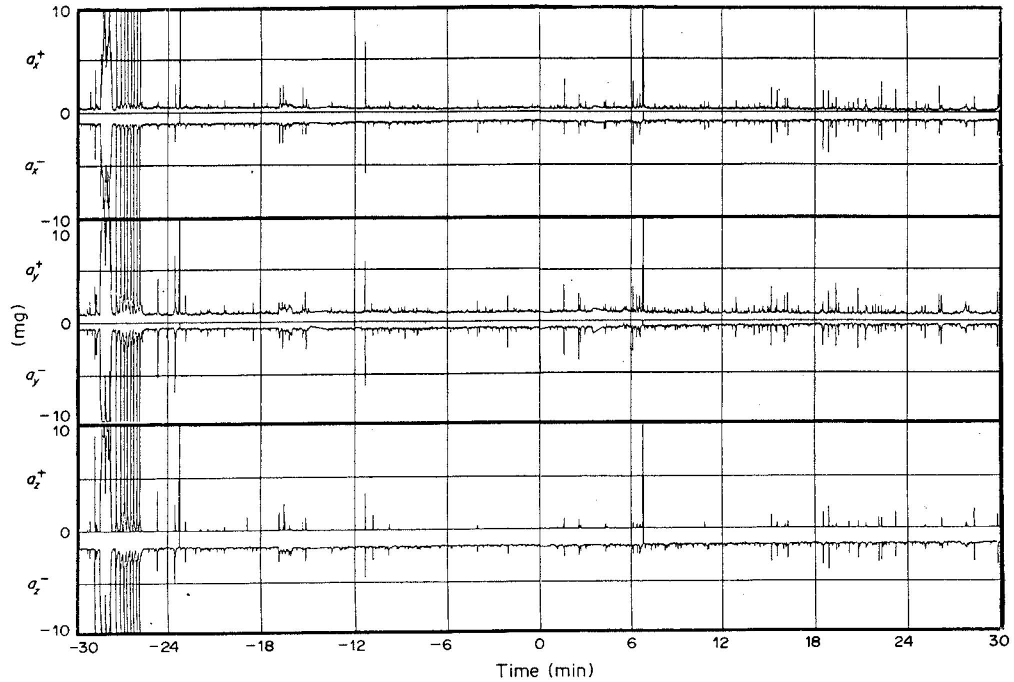

Fig. 2. Signal from accelerometers near the Fluid Physics Module in Spacelab-D1. The maximum value inside a 1 s interval, for each of the six directions, is recorded. The unit m*g* stands for 10^{-3} times Earth gravity. Time origin is Mission Elapsed Time (MET) 6/01:00:00.

separation between anphora-mode and C-mode instabilities at zero-gravity, the residual mean axial gravity forced an anphora-mode deformation both initially and in the subsequent breaking, but the breakage itself was triggered by rotation and not by gravity[8].

2.4. *Run 4: disc rotation at 10 rpm*

A first attempt of this trial had to be aborted because, once the 100 mm long column was established and the spin up started, high *g*-jitter and the announcement of forthcoming maneuvers advised the operator to close and resume one hour later.

When finally this trial was performed, the behaviour of the liquid column was as in Run 3. In fact, has the bias of residual gravity been known, this trial could have been spared, as the outcome is foreseeable. However, being the longest column ever achieved (100 mm), it has provided very valuable data (Fig. 3) on the effect of ambient *g*-jitter at these high slenderness (L/D = 2.857).

A most puzzling finding in this respect is the apparent disagreement between actual response of the liquid column to the residual gravity and predictions, as presented in the following reasoning. From Figs 3b and c it can be concluded that the neck and ridge oscillate relative to mean values of 1.09 and 0.90 respectivley. For that geometry, a cylindrical volume ($V = \pi R^2 L$) and that deformation, theory indicates the need of a Bond number Bo = 0.010. However, from the accelerometer data (Fig. 3g) a mean value of Bo = 0.017 is deduced, that, besides being quite distinct, is beyond the maximum Bo for stability with that geometry and assumed volume, $Bo_{cr} = 0.015$.

If the accelerometer data is discarded, the observed behaviour is easily explained as follows: a cylindrical column 100 mm long between discs of 35 mm supports a mean residual axial acceleration equivalent to Bo = 0.010 that, in absence of any other perturbation, would given an outer shape as in Fig. 4 (Bo = 0.010). From Mission Elapsed Time (MET) 6/03:10:40 to 6/03:13:00 what is seen is that due to the effect of stopping bridge stretching, a wide oscillation was superimposed that caused the shape to nearly reach the limiting deformation (see Fig. 4).

But the above explanation assumes a cylindrical volume, what means in this case $V/R^3 = 17.95$. As said before, no record of the amount of liquid volume manually injected was kept. The results of volume computation form film frames is shown in Fig. 3a, where the corresponding cylindrical value is also plotted for reference. From MET 6/3:11 to 6/3:14 this assumption seems justified (the mean value of these 90 shapes is 99.8% of the cylindrical one), but if the average is taken from MET 6/3:11 to 6/3/17 (180 shapes) a value of 98.9% of the cylindrical value is obtained, what, although close to it, make big changes to the reasoning above, now, instead of the limit Bond number being 0.015, the smaller volume would reduce the limit to Bo = 0.012, which corresponds to a neck radius $Y_{neck}/R = 0.85$, and the question arises, how could the necking observed at

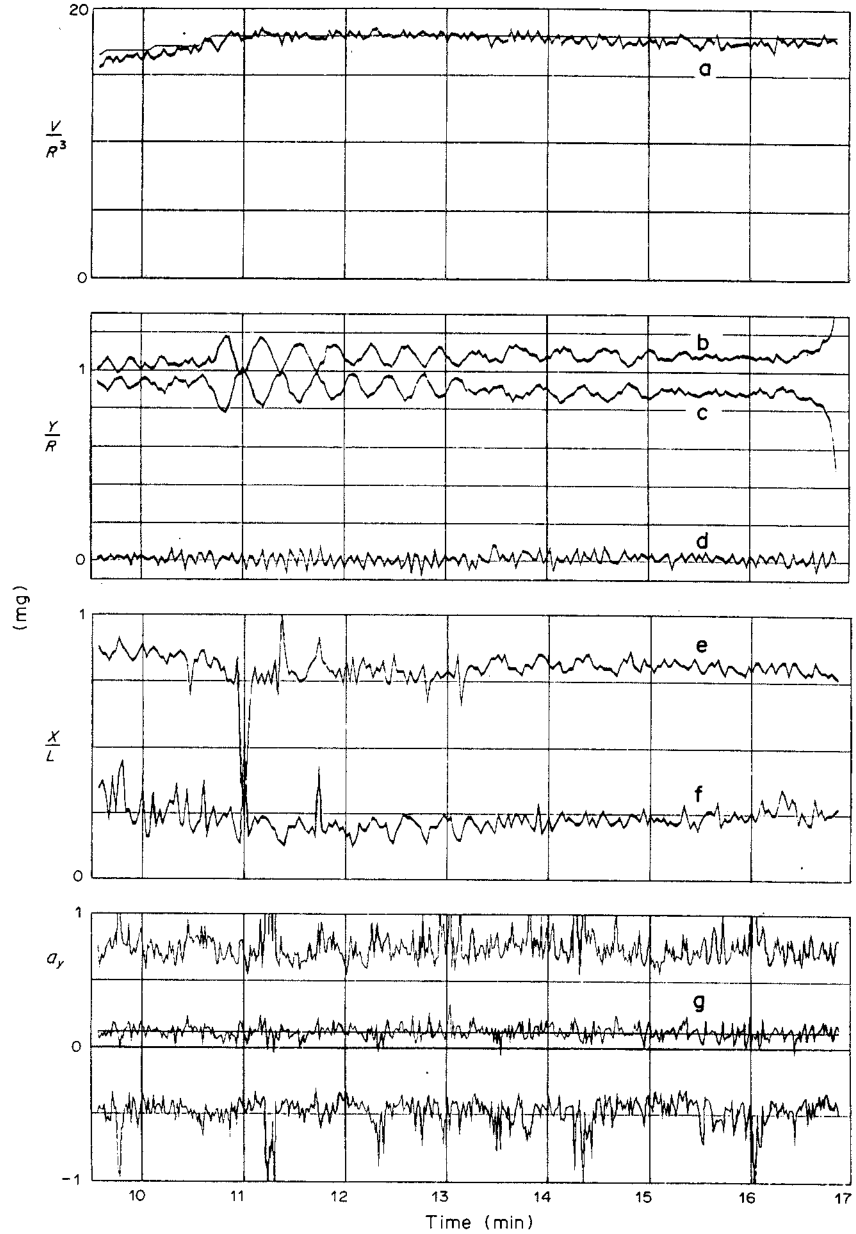

Fig. 3. Some results on time evolution of a long nearly-cylindrical liquid column. Origin is at Mission Elapsed Time (MET) 6/03:00:00. (a) Liquid volume computed from the pictures compared with the scheduled one (cylindrical volume means $V/R^3 = 17.95$). (b) and (c) Radius at 3/4 and 1/4 of the column length, respectively (they nearly correspond to the maximum bulge and neck). (d) Deformation of the column center-line at mid length (natural frequency is about three times that of (b). (e) and (f) Position of maximum bulge and neck along the column, respectively. (g) Accelerometer data in the axial direction, mean value and averaged mean (m*g* stands for 10^{-3} times Earth gravity).

MET 6/03:10:49 (see Fig. 3b) go beyond that limit without breaking?

2.5. *Run 5: disc rotation at 13 rpm*

With a disc separation of 90 mm and (as before) cylindrical volume, the discs were spun to 13 rpm. Image analysis shows that even before the speed was reached, a necking started that finally ended in bridge disruption, also in the amphora-like mode, contrary to theoretical predictions fore zero-gravity at this slenderness. The residual gravity seems to be the explanation, shifting the transition from C-mode to amphora-mode to a lower slenderness.

Unfortunately, a final trial at a length of 75 mm and 16 rpm, which would have shown C-mode instability, was not performed on SL-D1 for time constrains.

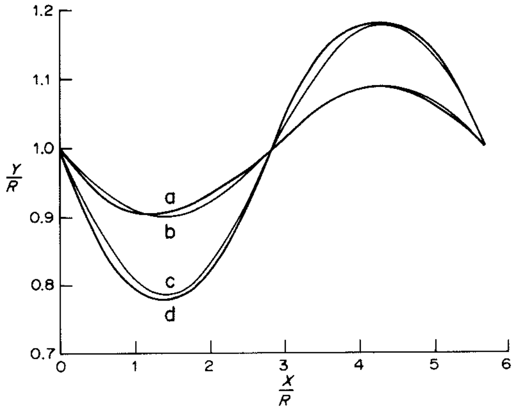

Fig. 4. Experimental (a and d) and theoretical (b and c) shapes of liquid bridges with $L/D = 2.857$ and a cylindrical volume. From MET 6/03:10:40 to 6/03:13:00 the shape shows damped oscillations around shape a, going from a nearly cylindrical form to shape d. For that slenderness and volume, the maximum axial gravity allowed would correspond to a deformation as c. Thus, if the mean axial gravity were 7.10^{-4} m/s^2 (Bo = 0.010), the equilibrium shape would have been b and the oscillations up to the limiting c shape quite understandable, but the accelerometers give nearly double value (see Fig. 3).

3. CONCLUSIONS

1. SL-D1 has provided very valuable experimental data (some of it still to be analyzed) on the mechanical behaviour of long liquid columns in a real microgravity environment.

2. Residual acceleration in SL-D1, of the order of $10^{-4} g$ (g = Earth gravity) is still so high that prevents experimentation with cylindrical liquid columns beyond 9/10 of the theoretical zero-gravity stability limit. Future Space Station environments are not expected to perform any better on that.

3. Platform maneuvers easily break long liquid bridges, but do not damage short ones. This conclusion and the former came out after SL-D1, where columns lengths of 91% of the stability limit were handled, because earlier experience in SL-1 with columns up to 54% of the limit were little sensitive to residual accelerations (in fact, the effect of a Shuttle maneuver, a gentle push on the column, was the only noticeable event on that respect).

4. Volume computations from the liquid outer shape seem to point out a slight decrease of nearly 1% over a period of 6 min where it should be constant according to schedule. This teaches that redundancy in data collection during rare experimental occasions must be increased.

5. Observed natural oscillation of the liquid column (Fig. 3b) indicate a period of some 21 s for the first axial mode and nearly a third of that for the first transversal mode. These values support the thesis[3] that the volume level was near cylindrical and not so close to instability as the 98.9% value (referred to above) would imply.

6. A discrepancy is found between the residual axial gravity that would theoretically cause a deformation as the mean value of oscillating shape in Fig. 3b (see Fig. 4), and the accelerometer readout.

7. Apart the latter, in all cases analyzed, the behaviour of long liquid columns in a real microgravity environment has been in agreement with theory up to the accuracy reached (−1%).

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