STABILITY OF LONG LIQUID COLUMNS IN SPACELAB-D1

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ABSTRACT

An updated analysis of Experiment FPM-04-FLIZ, carried out aboard Spacelab-D1 mission in November 1985, is given. An account of the activities performed, problems found, raw data obtained, method of analysis and results achieved, is presented.

Keywords: microgravity, capillarity, stability, experiment, liquid bridge, floating zone, space operations, telescience.

1. INTRODUCTION

The configuration of experiment WL-FPM-04,"FLIZ" (Floating Liquid Zones) consisted of a near cylindrical volume of liquid held by surface tension forces between two equal in diameter coaxial solid discs at whose borders the liquid is attached. Discs were made of aluminium, with a 30° receding sharp edge to avoid liquid spreading, the discs radius being $R = 0.0175$ m ($D=0.035$). Working liquid was a low viscosity dimethyl silicone oil (viscosity $\nu = 5 \times 10^{-6}$ m^2/s^1, density $\rho = 920$ kg/m^3 and surface tension $\sigma = 0.02$ N/m) with tracers (Eccospheres of 0.15 mm in diameter and concentration of 0.1 kg/m^3) to enhance inner motion visualization.

The nominal experiment sequence envisaged [1] basically consists of: liquid injection, disc vibration and rotation of both discs, and was similar (slightly reduced) to the one tried on Spacelab-1 (SL-1) in 1983 where wetting and spreading problems with the nominal configuration allowed only partial success [2]. There, although the much wanted C-mode deformation of the liquid column was indeed finally excited by rotating a large liquid bridges with a length to mean diameter ratio of 1.7, most of the time the liquid went out of control beyond the small mechanical and chemical (anti-spread coating) barriers. As on that occasion, the interest here was to check the liquid bridge response against available theories, mainly concerning its stability limit, a problem of practical importance in crystal growth by the floating zone technique [3].

The preparation, performance and early results of this experiment has been described in earlier papaers [4-6]. The same Fluid Physics Module (FPM), but with corrected end-discs (more protruding and cut back) and a manually operated syringe for liquid injection was used. A small video-camera and a 16 mm cine-camera, the later shooting a frame every 2 seconds for "hot" phases of the experiment and every 92 seconds for the rest of time, were the main source of data for later analysis (this odd figure was chosen to simplify manual settings).

After SL-1 and before SL-D1, some other trials were performed on the sounding rocket TEXUS-12 (May 1985) with big success [7]. Long (80 mm) cylindrical liquid bridges were established in less than a minute, demonstrating that sounding rocket flights (lasting 6 minutes) can be used to perform experiments in microgravity with large liquid masses.

The overalll performance of FLIZ experiment was excellent: in particular, a large liquid mass was accurately positioned in the test chamber, well anchored to the sharp edges of coaxial discs. Long cylindrical liquid columns of slenderness (length/diameter) 2.86 were easily established several times (the limit for no gravity being π). A long cylindrical liquid column subjected to specified axial vibrations showed deformations with as many nodes (1, 2, 3, 4 and 5) as predicted by theory for each case. Several (four) long cylindrical liquid columns were made to rotate at increasing rates and all them destabilized near the theoretical limit. The breaking of long cylindrical liquid bridges when subjected to perturbations beyond the stability limit gave way to two separate drops with relative volumes as predicted by theory [8].

It is a pity that the big time-constraint in SL-D1 did not allow to finish the sequence of rotation trials and the much wanted C-mode instability could not be realized this time.

2. EXPERIMENT EXECUTION

For this research, Payload Specialist (PS) Dr. Furrer was in charge of the in-flight experimentation. The nominal time allocation was from Mission Elapsed Time (MET) 5/22:48:00 to 6/00:49:00 (two hours). Actual start time was 5/23:21:00 (FPM

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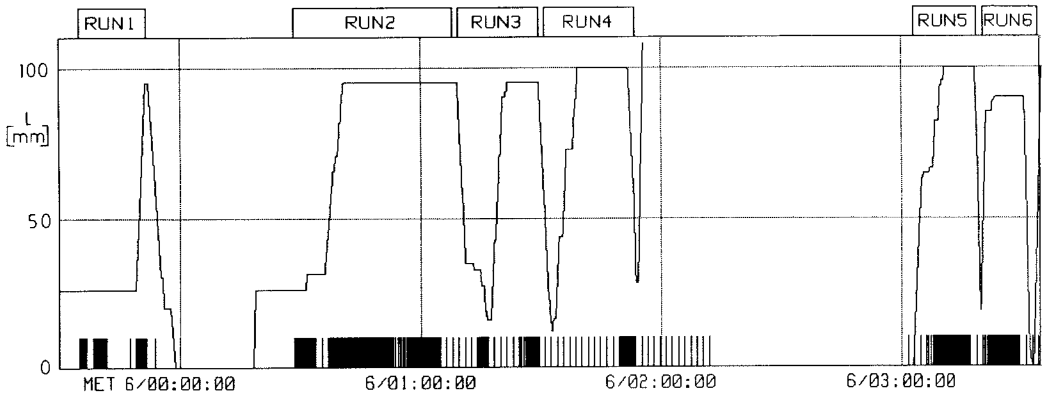

Fig. 1. Actual disc separation L versus time during the SL-D1 experiment FLIZ. Vertical lines at the bottom indicate when photos were taken (sparse lines have 92 s interval, whereas filled areas correspond to packed lines at 2 s interval).

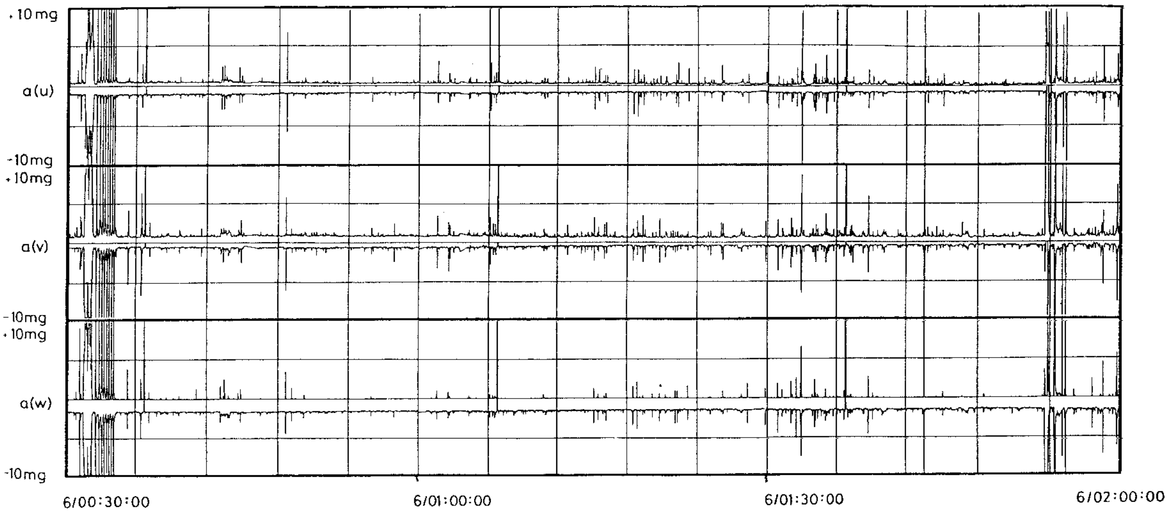

Fig. 2. Signal from accelerometers near the Fluid Physics Module in Spacelab-D1. The maximum value inside a 1 s interval, for each of the six directions, is recorded. The unit mg stands for 10^{-3} times Earth gravity.

power up), and the first good picture (it was frame number 45, but the previous were over-exposed) was taking 14 minutes later, already showing a liquid drop formed on the feeding disc (FD). There was no air/ground link at the time.

After all the problems of handling the working liquid in SL-1, there was no foreseen breakage of the liquid column until late in the experiment sequence. However, it turned out that the intended overpassing of the rotational stability limits always ended in bridge disruption. Fortunately, the PS had great dexterity in recovering back and start anew, what has served to divide the experiment in "Runs", as shown in Fig. 1, that group all trials ended in disruption of the liquid bridge; a total of 6 such Runs have been recorded, a detailed description of which can be found in Table 1 of Ref. [5].

The most peculiar finding during SL-D1 was the effect of g-jitter, much higher than in SL-1 and TEXUS-12. The accelerometer data from SL-1 and SL-D1 show similar levels of g-jitter, namely 10^{-3}g (10^{-2}m/s^2) high frequency peaks, with a 100 μg averaged mean (Fig. 2), but the liquid column behaves widely differently (in SL-1 interfacial deformations caused by noise were unnoticeable). The explanation found is due to the increased stability of low slender columns (1.7 in SL-1 against 2.86 for SL-D1, the stable limit (for zero gravity) being π; a steady linear theory predicts 20 to 30 times larger deformations for the same stimuli).

In spite of the fact that the PS asked the other crew-members to keep quiet and was granted from the Shuttle pilot a no-maneuvers period, the long columns achieved in SL-D1 were trembling (slowly) and this noisy ambient may have contributed to premature breaking of the column. Although these breakings demanded extra crew-time for liquid recovery, they have provided additional source of information to check theoretical results on breaking dynamics [8].

3. **RESULTS AND ANALYSIS**

RUN 1: The aim was to establish a long cylindrical column by manual liquid injection (turning a syringe handle) while the disc separation was being automatically increased. First, a short liquid bridge was obtained by slow injection of liquid through a 6 mm filling hole in the FD (35 mm in diameter) which remained anchored at the disc edge, growing until it came in contact with the rear disc (RD) that was 26 mm apart. At that time, some major Shuttle maneuvers happened to take place, widely deforming the bridge (which would have certainly brake, had it occurred at larger slendernesses).

During the cylindrical stretching, the PS did not manage to fill liquid at the pace the discs were separating, to achieve a cylindrical evolution, following instead the path shown in Fig. 3, that eventually became unstable and the column broke in two spherical drops. This unforeseen circumstance has furnished an unexpected verification of the validity of the stability analysis of non-cylindrical liquid bridges in a real microgravity environment (this limit had been tested earlier using neutral buoyancy simulation [9]).

At that time, direct video link was available and thus, instead of some experiment sequence, a close view of the operator's hand thoroughly cleaning the rear disc to start a new trial was seen. This, in fact, was a good demonstration for the safety team, who had cast doubts (and establish some hard rules) on the possibility of cleaning the FPM test chamber in flight.

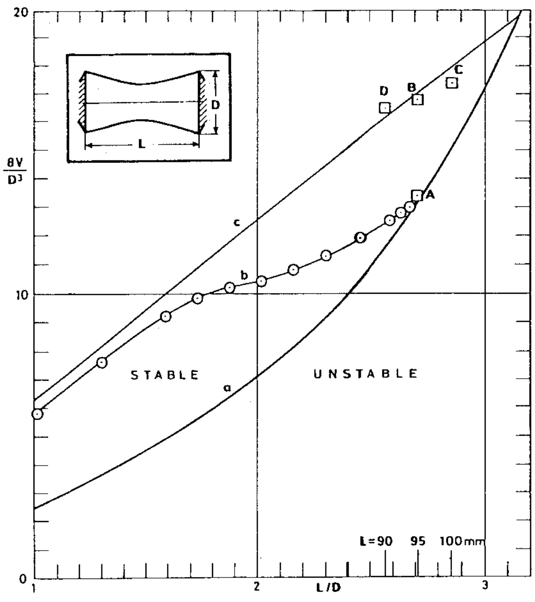

Fig. 3. Actual path in the stability diagram followed by liquid column in the Run 1. It is seen how it deviates from the cylindrical evolution and gets unstable.

RUN 2: After cleaning, injecting liquid to form a 26 mm bridge as above and sligthly stretching to 31 mm, the Payload Specialist started a long talk (with video coverage) with the investigator on ground, concerning liquid visualization and ambient noise. This remote interactive research is a good example of the novel telescience approach.

After a carefull column stretching (with some safety pauses) the 95 mm length was achieved and the oscillation trials performed. The RD was set to a sinusoidal axial oscillation of 0.93 mm pick to pick at selected frequencies of 0.1, 0.3, 0.7, 1.1 and 1.6 Hz, roughly corresponding to the first natural frequencies predicted by theory for a cylindrical liquid column of such a slenderness. During the 3 minutes at 0.1 Hz, the PS could not distinguish any privileged movement of the liquid (neither it is apparent on the photographs), but for the rest, standing waves with 2, 3, 4 and five inner nodes, respectively, were found, as expected.

The oscillation stopped at 6/01:03:46, but then the liquid column unexpectedly broke. The PS was not looking at it and only the "safety" recording of 1 frame every 92 seconds was on. The accelerometer readout does not show any special event (the pick at MET 6/01:06:44 was just for calibration).

RUN 3: The breaking in Run 2 left two drops well attached to the edges of the discs and thus the PS tried to approach the disc and merge the drops to re-establish the bridge. One of the most intriguing findings of this experimentation has been the fact that the two drops could not be merged, no matter how much the PS pressed one against the other by squeezing the supporting discs (rotation of the discs did not help). The only way out he could find was to remove the liquid on the FD back to the syringe and then get the FD in contact with the drop at RD (the spreading over the wet solid FD was easy and a bridge established).

In this Run the first rotation of the column beyond the theoretical stability limit was performed and, even when the PS stopped rotation after some 30 seconds, the liquid shape deformation inevitably grew until bridge disruption. Figure 4 shows hte points tried in the stability diagram, whereas Fig. 5 presents the response of the liquid column.

RUN 4: The same process of drop merging of Run 3 was followed here to re-establish a bridge after the former rupture. The PS started rotation of a 100 mm column at 10 rpm, but the announcement of coming Shuttle manouvers forced him to recover back and abort the trial. The time allocation for FLIZ was by now exhausted, but the highly motivated PS managed to continue it during his spare time.

RUN 5: The start was one hour later with a dry test-chamber and the objective was to try again Run 4. The random oscillation in this column (100 mm long) were so pronounced, even when the PS managed from the Shuttle crew to have a free drift period, that at some instances it seems the column is going to break (although it stood like that for

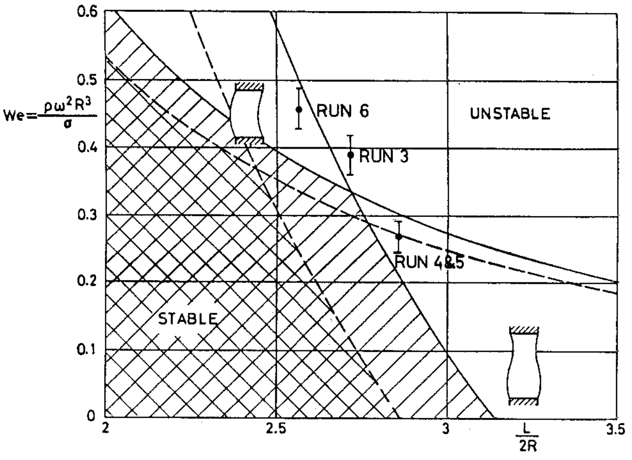

Fig. 4. Points in the rotation-slenderness stability diagram for cylindrical liquid columns, exercised during SL-D1. Dashed line indicates the effect of an axial residual gravity on the rotational stability limit.

5 minutes). When subjected to 10 rpm of rotation, the column broke (Fig. 6) in an amphora-shape mode, as expected.

An important point to note is that the mean residual acceleration computed after the mean shape-deformation from the film is [6] around 70 μg, whereas the mean value from the accelerometers is 120 μg. This discrepancy is atributed to the zero-point uncertainty of the sensors (they were six, one measuring in each direction, with a range from 10^{-2}g to 10^{-5}g and a resolution of 10^{-6}g (1 μg).

RUN 6: The goal of this Run was to excite a C-mode deformation in a liquid column 90 mm long. When the stability limit was surpassed at 13 rpm, the column deformed in an amphora-like mode instead of in C-mode. The explanation now given is as follows. As above mentioned, the accelerometer data indicate a residual axial acceleration of some 100 μg which tends to promote the amphora-like instability above the C-mode one by shifting the rotational stability limit to lower slendernesses, as sketched in Fig. 4.

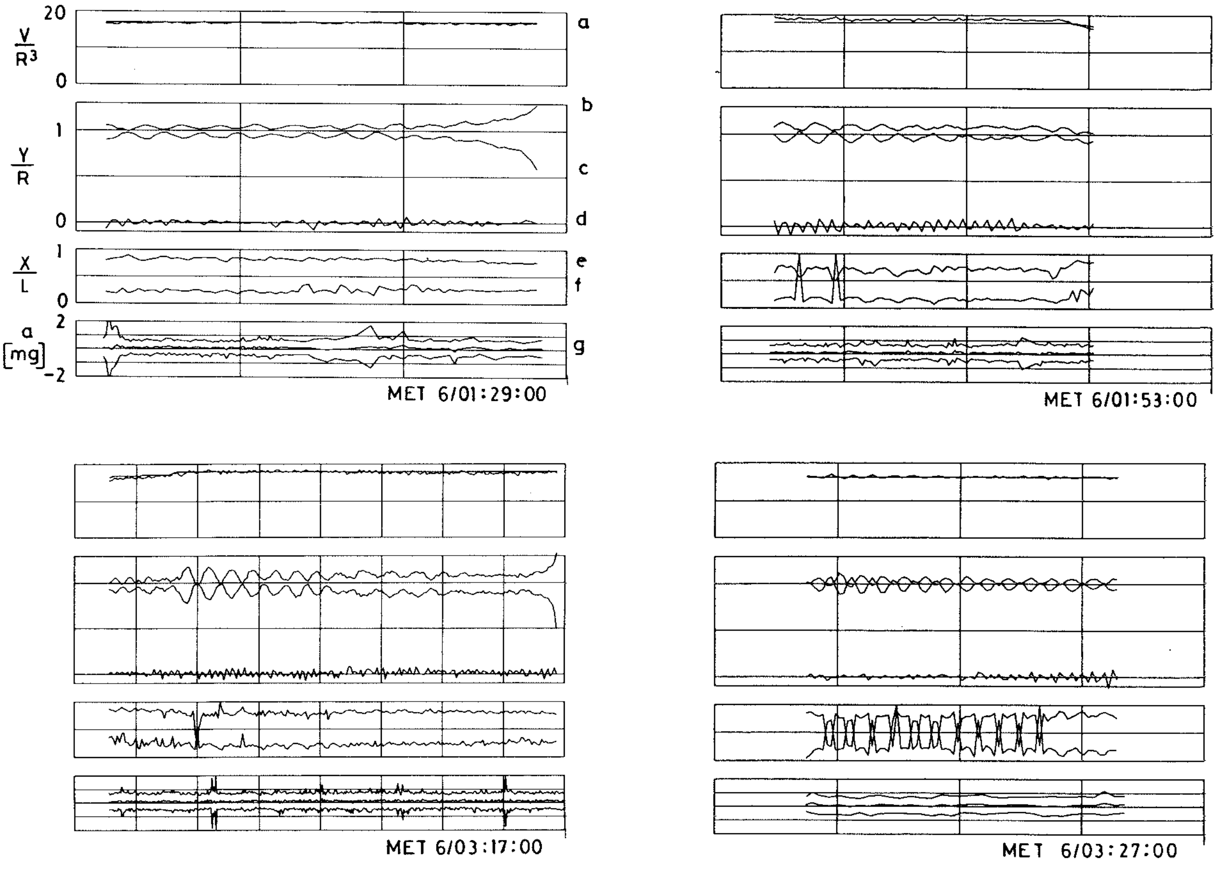

Fig. 5. Some results on time evolution of long nearly-cylindrical liquid columns (for the 4 cases with rotation). Time origin is marked in each case, and grid spacing is always 60 seconds. **a)** Liquid volume computed from the pictures compared with the scheduled one. **b)** and **c)** Radius at 3/4 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.

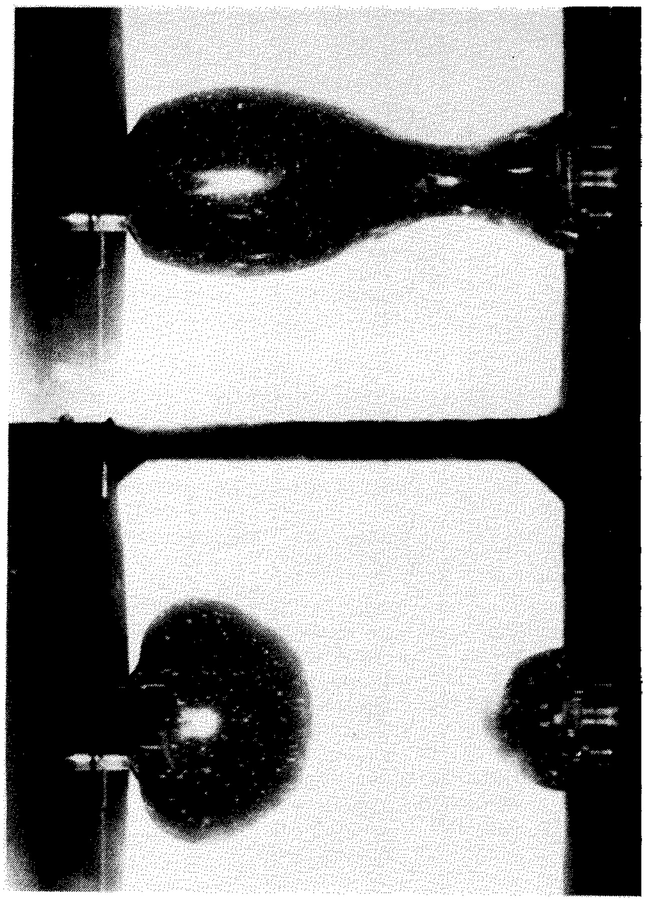

Fig. 6. Two consecutive film frames (at 2 s interval) showing the breaking of a 100-mm-long cylindrical liquid column.

By that time, experiment FLIZ had used resources (mostly crew-time) over and above initial allocation and was concluded. Unfortunately, the only Run remaining in the nominal procedures was a last rotation trial at 16 rpm with a column of 75 mm which would have clearly shown a C-shape disruption mode.

4. LESSONS LEARNT

The details compiled here concern marginal problems ocuured during Spacelab flight and are irrelevant to the results of the investigations, but their inclusion will help future users and managers of research facilities in space to better plan their task.

A first logistic problem arose during the setup: a background mask-sheet, intended to enhance visualization and ulterior data analysis from the images, was not found by the PS. It was properly labeled, but, in order to avoid profusion of small containers, was decided to be included in an already available envelop which belonged to another FPM user. The ESA support team and the investigators knew these details (it seems they escaped the PS attention), but during the flight, when the PS asked for assistance to find it, the investigator (who had to talk to the PS through two or three intermediate relay personnel) realized that the short allocated time was running out and instructed the PS to forget about the plastic sheet. This multi-relay voice link caused more waste of time than the already said above. Sometimes the PS sent a message to the investigator on ground, who correctly received it and was prompt to answer, but another member in the link did not catch it and asked the PS to repeat the message or clarify some point on it. Besides, the PS was constantly requested from ground during the scarce voice-link periods to take messages for other business, what distracted him and prevented a more interactive operation.

Another weak point was connected with liquid volume recording. The FPM reservoir used in SL-1 was awkward to control, but its settings were automatically recorded every second. The small manual syringe specially designed for SL-D1 was much more handy, and helped a lot the PS to control the liquid supply and removal, but it was not connected to the data acquisition system. Training on ground was unrealisticaly optimist; once up there, the PS was so busy coping with a highly sensitive liquid column, that he had no time to keep on top a detailed logbook of the syringe counter. Besides, when at some point the PS measured the syringe counter it was for instance 25.2 handle turns, instead of the 26.1 expected for a cylindrical column of that length, an error beyond normal experience on ground trials. Thus, all volumes had to be estimated from the shape on the images.

Concerning data retrieval, D1 mission was much better than SL-1, but still an entangled job far from being satisfactory. The problem is that the investigator does not know before hand how much data will be needed because it all depends on the actual development of the experiment. Besides, a major impact on data requirement in these pioneering space research is the relaibility of the data sources (problems with FPM cine-camera, malfunction of on board video-tape recording, possible errors in data acquisition, etc). For example, when the PS selected (according to the procedures) 12 rpm synchronously for both discs, the printout shows unrelated scatter from 11.2 to 12.7 in disc rotation rates (in contrast to an FPM resolution of 0.1 rpm). Even when reliable data is available, it is difficult to handle; for instance, the bulky printout of FPM housekeeping and accelerometer data. Major steps will be needed if an automated data acquisition (and image processing) capability is wanted in future (presently, the outline of some 500 enlarged pictures have been manualy digitized).

Contrary to the above drawbacks, the incorporation of a frame counter to the FPM housekeeping data for SL-D1 has represented a great improvement with respect to SL-1 (the FPM camera does not yet record time on film).

5. CONCLUSIONS

The purpose of this experiment was to study the mechanical stability of long liquid columns under real microgravity conditions and the aim has been achieved with success.

Apart of minor details as those described on the last section, everything worked as expected: the liquid column was vibrated at the frequencies foreseen in the procedures, and the influence of rotation on the maximum stable length of the liquid bridge was checked through three different rotation tests (another rotation trial was not performed due to lack of time, in spite of the generous time extensions granted to this experiment). In particular:

1. A large liquid mass was accurately positioned in the test chamber, well anchored to the sharp edges of coaxial discs 35 mm in diameter and up to 100 mm apart.
2. Long cylindrical liquid columns of slenderness (length/diameter) 2.86 were easily established several times.
3. Present values of residual acceleration for the Shuttle in free-shift (some 70 μg, measured from the liquid bridge response) prevent any further increase in column slenderness.
4. Volume computations from the liquid outer shape seem to point out a slight decrease of nearly 1% over a period of 6 minutes where it should be constant according to schedule (this teaches that redundancy in data collection during rare experimental occasions must be increased).
5. The breaking of long cylindrical liquid bridges when subjected to perturbations beyond the stability limit gave way to two separate drops with relative volumes as predicted by theory.
6. Observed natural oscillation of the liquid column (Fig. 5) 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 are in good agreement with theoretical predictions for cylindrical bridges [10].

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