FLOATING LIQUID ZONES IN MICROGRAVITY

D1-WL-FPM 04

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ABSTRACT

The preparation, performance and results of an experiment carried out in Spacelab D1, to study the mechanical stability of long liquid columns held by surface tension between two coaxial disks, are described. The working slenderness (length/diameter) was up to 2.86. Results are in good agreement with previous theory, in spite of the relatively high level of ambient g-jitter. Some lessons learnt on logistics are summarized at the end.

1. INTRODUCTION

The experiment Floating Liquid Zone ("FLIZ") WL-FPM 04), dealing with the behaviour of long liquid bridges under mechanical disturbances in a low gravity environment, was carried out during the Spacelab D1 Mission in November 1985.

The configuration of FLIZ experiment consisted of a near-cylindrical volume of liquid held by surface tension forces between two equal diameter coaxial solid disks at whose borders the liquid is attached (Fig. 1). Disks were made of aluminium, with a 30° receding sharp edge to avoid liquid spreading, the disks radius being $R_0 = 0.0175$ m. Working liquid was a low viscosity dimethyl silicon oil (viscosity, $\nu = 5\times10^{-6}\ m^2\cdot s^{-1}$, density, $\rho = 920\ kg\cdot m^{-3}$ and surface tension $\sigma = 0.02 N\cdot m^{-1}$) with tracers (Eccospheres, 0.15×10^{-3}m in diameter and 0.1 $kg\cdot m^{-3}$ of concentration) to enhance inner motion visualization.

The nominal experiment sequence envisaged [1] basically consists of: liquid injection, disk vibration and rotation of both disks, and was similar (slightly reduced) to the one tried on Spacelab 1 in 1983 where wetting and spreading problems with the nominal configuration allowed only partial success [2]. Although the much wanted C-mode deformation was indeed finally excited by rotating a large liquid bridge 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 was to check the liquid bridge response against available theories, mainly concerning its limit of stability, a problem of practical importance in crystal growth by the floating zone technique [3].

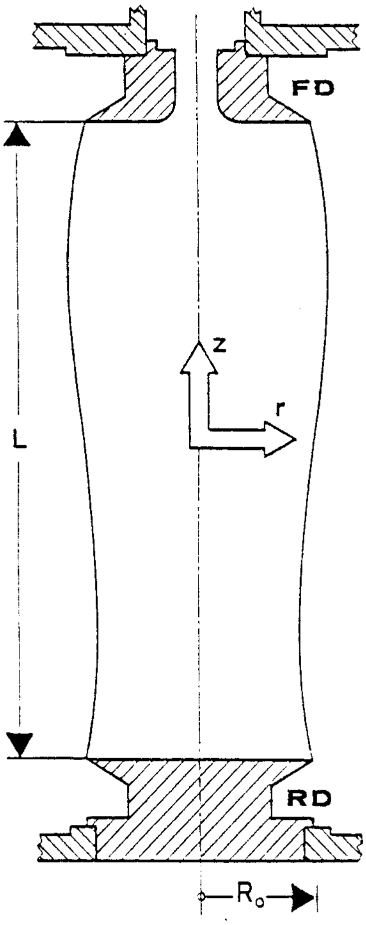


Fig. 1: Sketch of the configuration used, with details of the disk shape. FD= Front Disk (used to feed the liquid and to vary the separation L), RD= Rear Disk (used to vibrate the liquid).

The same Fluid Physics Module, but with corrected end-disks (more protruding and cut back) and a manually operated syringe for liquid injection (see Fig.2) was used. A small video-camera and a 16mm cine-camera shooting a frame every 2 seconds were the main source of data for later analysis.

In the two years that separate both Spacelab flights, besides continuous effort in theoretical, numerical and ground-based experimentation, we had the opportunity to perform microgravity experiments on aircrafts in parabolic flight (NASA KC-135) and sounding rockets (German TEXUS program), in two occasions each. The short microgravity period on KC-135 (25sec) and its poor microgravity

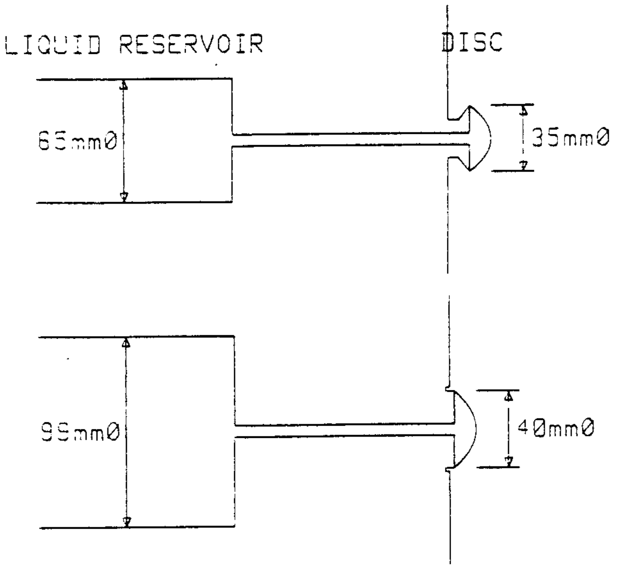


Fig. 2: Difference in hardware used in Spacelab D1 (1985) and Spacelab D1 (1983).

level (low frequency bumps of some 10^{-1} m.s $^{-2}$) render it useless for accurate work in FPM, although it was a great help in testing initial phase operations and for crew training. After a mechanical problem prevented any experimentation in TEXUS-10 (May 1984), the trials on TEXUS-12 (May 1985) were a big success [4]. Long (80mm) cylindrical liquid bridges were established in less than a minute, thus, demonstrating that sounding rocket flights (6min.) can be used to perform experiments in microgravity with large liquid masses.

This last achievement put more confidence in the experimentation during Spacelab D1 in November 1985. An initial assessment of the performance of FLIZ experiment [5] showed that most of the goals had been accomplished; in particular: a large liquid mass was accurately positioned in the test chamber, well anchored to the sharp edges of coaxial disks. 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 axial vibrations showed a deformation with as many nodes (1,2,3,4 and 5) as predicted by theory. 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 [6].

Nevertheless, it is a pity that the big time-constraint in Spacelab flights did not allow to finish the sequence of rotation trials and the much wanted C-mode instability could not be realized this time.

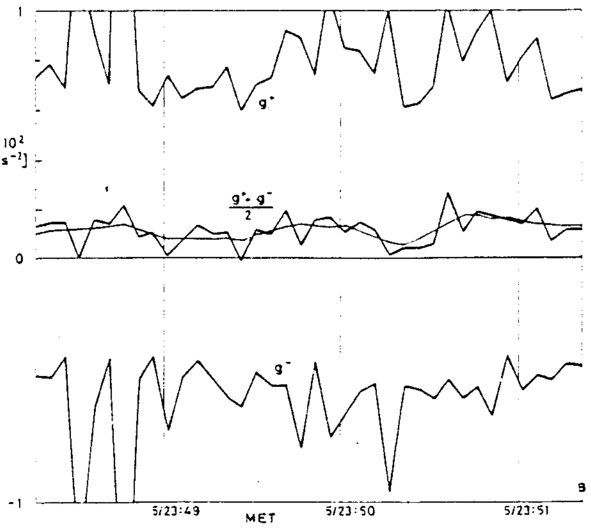
2. EXPERIMENT EXECUTION

For this research, Payload Specialist (PS) Dr. Furrer was in charge of the inflight experimentation. Besides his training on the operation of the FPM, he closely worked with the investigators, simulating this experiment in a neutral buoyancy tank at their premises, and reviewing all the tests and results in connection with previous Spacelab, KC-135 and TEXUS flights.

Actual start time of FLIZ experiment was Mission Elapsed Time (MET) 5/23:21:00 (FPM power up), and the first picture inside the test chamber was taken 14 min. later, already showing a liquid drop formed on the Feeding disk (FD). After all the problems of handling the working liquid in Spacelab 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" that group all trials ended in disruption of the liquid bridge; at total of 6 such runs have been recorded, a detailed description of which can be found in table 1.

The most peculiar finding during Spacelab D1 was that g-jitter was much higher than Spacelab 1 and TEXUS 12 experience had shown. The accelerometer data from Spacelab 1 and Spacelab D1 show similar levels of g-jitter, namely 10^{-2} m.s^{-2} high frequency peaks, with a 10^{-3} m.s^{-2} averaged mean (Fig. 3), but the liquid column seemed to behave with a widely different sensititivy: in Spacelab1 interfacial deformations caused by noise were unnoticeable. The explanation may

Fig. 3: Mean value of the readings (at 5sec interval) of some accelerometers near the FPM (in the axial direction of the liquid column). Pick values have a fluctuation one order of magnitude larger. Because the characteristic response time of the liquid column is of the order of 20sec, the average of five centred samples is also shown (smoother curve).



MET	L [mm]	Ω [rpm]	Frame	DESCRIPTION
5/23:35:00	26.0	0	45	**Start of RUN 1.** After lead tail, first frame already shows a liquid drop on FP. Meridian plane illumination. Tracers visible.
5/23:35:11	26.0	0	51	Bridge formation by liquid feeding.
5/23:36:31	26.0	3	77	Start low isorotation to see all around. Barrel bridge.
5/23:36:46	26.0	3	83	Shuttle jet firings start. The experiment is paused.
5/23:48:56	26.0	3	183	Filming restart. Liquid removal to get a cylindrical bridge, followed by disc separation and simultaneous liquid injection for a cylindrical stretching.
5/23:51:16	95.0	3	253	End of disc separation. Spindle shape. Close to instability.
5/23:51:21	95.0	3	255	Breaking of the liquid bridge.
5/23:51:41	95.0	3	264	End of scene. Direct TV shows operator's hand cleaning on site the disc at RP.
6/00:28:23	26.0	3	265	**Start of RUN 2.** Drop at FP.
6/00:29:09	26.0	3	288	Drop at FP contacts RP and forms a bridge.
6/00:31:21	26.0	3	354	Start of disc separation.
6/00:31:36	31.3	3	361	Separation stops. Crewman and investigator talk. Direct TV link for some 15 min. Illumination system trials.
6/00:33:23	31.3	3	412	From here to end, both meridian plane and background plane illumination are on.
6/00:35:56	31.3	3	418	Disc separation and simultaneous liquid injection for a cylindrical stretching.
6/00:40:51	95.0	3	544	Disc separation stops. Cylindrical shape with a small random vibration.
6/00:49:11	95.0	0	794	After some 9 min of jitter, disc rotation (for visualization purpose) is stopped.
6/00:53:06	95.0	0	911	Overexposed frame to mark the start of disc oscillation experiments.
6/00:56:21	95.0	0	914	RP oscillation experiments at frequencies 0.1, 0.3, 0.7, 1.1 and 1.6 Hz (starting in frame 914, 1007, 1059, 1092 and 1117, respectively). Amplitude is 0.465 mm and frame interval 2 s.
6/01:03:51	95.0	0	1139	End of oscillation experiments (Amplit.=0).
6/01:06:21	95.0	0	1167	Liquid bridge breaking (unexpected). The 1 min 35 s prior to rupture are not filmed. Larger drop at FP.
6/01:07:56	95.0	0	1168	End of scene.
6/01:09:26	86.6	0	1169	**Start of RUN 3.** First, some liquid is removed from the (larger) FP drop. When both drops are equal, the discs are approached for merging.
6/01:11:01	39.1	0	1170	Both drops touching, but not merging (even when disc rotation is activated).
6/01:14:01	32.6	3	1172	Both drops heavily deformed by pushing against each other, but not merging. Small isorotation of the discs to see all around.
6/01:14:36	32.6	0	1189	End of rotation. Merging impossible. All the liquid from the FP drop is removed and the discs approached.
6/01:16:46	15.9	0	1254	The RP drop spreads over the FP disc. After that, disc separation starts, combined with liquid injection to keep a cylindrical bridge.
6/01:26:36	95.0	0	1273	After reaching the working slenderness, isorotation experiments start. Rotation starts.
6/01:28:39	95.0	12.3	1340	Maximum rotation rate reached by the discs (the ramp was 9 s/rpm). At this time, the operator stops both disc rotation.
6/01:28:52	95.0	0	1346	Liquid bridge breaking.
6/01/29:31	95.0	0	1360	End of scene. Change of onboard videotape 6 to 7.
6/01:31:01	50.6	0	1361	**Start of RUN 4.** Two drops. The one at FP is removed and the discs are approached to spread the RP drop over the FP.
6/01:32:36	16.0	0	1362	Bridge formed. Cylindrical stretching until L=100 mm, followed by a prolonged pause.
6/01:50:47	99.9	1.5	1414	Start of isorotation experiment.
6/01:51:48	99.9	8.0	1444	Unexpected start of disc approaching and liquid removal (the operator tries to avoid a breaking). Rotation speed still increasing.
6/01:52:06	91.9	10.0	1453	Rotation rate reached.
6/01:53:39	34.5	10.0	1499	End of scene. Filming is stopped before liquid bridge breakage. Crew reporting two minutes later.
6/03:03:06	9.2	0	1513	**Start of RUN 5.** About one hour with operator off duty. No liquid in the test chamber. Start liquid injection. Repetition of previous experiment.
6/03:04:41	56.7	0	1514	Bridge formed at this point, followed by cylindrical stretching.
6/03:10:41	100.0	0	1605	Disc separation stops. Cylindrical shape with large random oscillations. In frames number 1609 and 1636, the liquid column is near to break.
6/03:13:56	100.0	0.5	1703	Start of isorotation experiment.
6/03:16:26	100.0	10.0	1778	Rotation rate reached.
6/03:16:46	100.0	10.0	1788	Disc rotation stopped.
6/03:16:53	100.0	0	1791	Liquid bridge breaking.
6/03:18:46	82.6	0	1802	End of scene.
6/03:20:31	50.5	0	1803	**Start of RUN 6.** Disc separation and liquid injection until a cylindrical column is achieved at this point.
6/03:23:45	90.0	0	1857	Disc separation stops.
6/03:26:11	90.0	1.7	1930	Disc isorotation starts.
6/03:27:56	90.0	12.7	1982	Rotation rate reached. Operator reports.
6/03:28:51	90.0	12.7	2010	Disc isorotation stopped.
6/03:29:01	90.0	0	2015	Liquid bridge breaking.
6/03:30:33	90.0	0	2035	End of scene. Operator reports ten minutes later.

Table 1: Description of FLIZ experiment as executed. Time (MET), column length L, rotation rate Ω and corresponding frame in the 16mm film, are given.

be due to the increased stability of low slender columns (1.7 against 2.86 for Spacelab D1, the stable limit being 3.14; 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 got from the shuttle crew a no-maneuvers period, the long columns achieved in Spacelab 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.

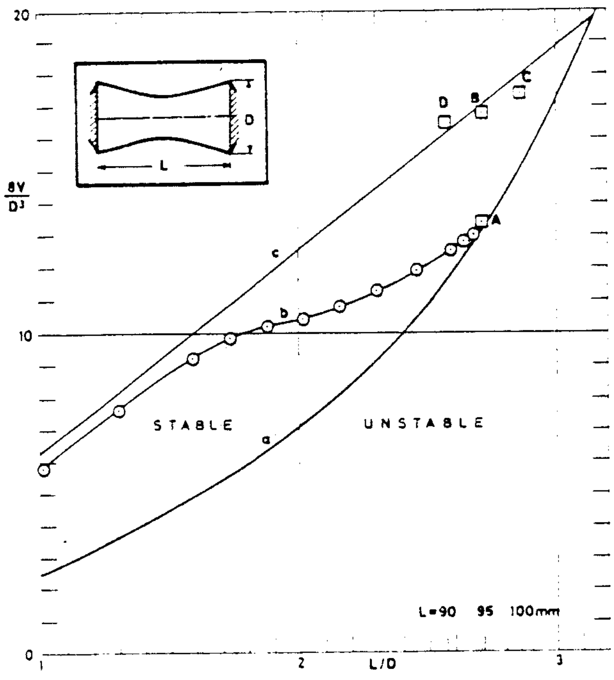
3. RESULTS AND ANALYSIS

Run 1

The liquid bridge disruption in Run 1 was not intentional. The idea was to establish a long cylindrical column by manual liquid injection (turning a syringe handle) while the disk separation was being automatically increased.

First, a short liquid bridge was obtained by slow injection of liquid through a 6mm filling hole in the FD (35mm in diameter) which remained anchored at the disk edge, growing until it came in contact with the rear disk (RD) that was 26mm apart. At that time, some major shuttle maneuvers happened to take place, widely deforming the bridge (which would have been broken certainly, when occurring at larger slendernesses).

Fig. 4: Actual path (b) in the stability diagram followed by liquid column in the first run. It is seen how it deviates from the cylindrical evolution (c) and gets unstable.



During the cylindrical stretching, the PS had no experience and did not manage to follow a cylindrical evolution, following instead the path shown in fig.4, 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 using neutral buoyancy simulation [7]).

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 disk to start a new trial was transmitted. This, in fact, was a good demonstration for the safety team, who had cast doubts (and established some hard rules) on the possibility of cleaning the FPM test chamber in flight.

Run 2

After cleaning, injecting liquid as above, and having reached a disk separation of 31 mm, the Payload Specialist started a long talk with the investigator on ground, concerning liquid visualization and ambient noise. The nominal illumination for this experiment was a meridian-cut light beam to visualize the tracers inside, combined with a background lighting (darkenend with a black mask with transparent square grid lines). As the mask got astray, the background illumination was dropped to avoid film overexposure. But the PS complained,

Fig. 5: Theoretical natural frequencies for axial vibration of a cylindrical column as a function of slenderness (no residual gravity and no rotation). The points correspond to the trials performed (see Fig.6).

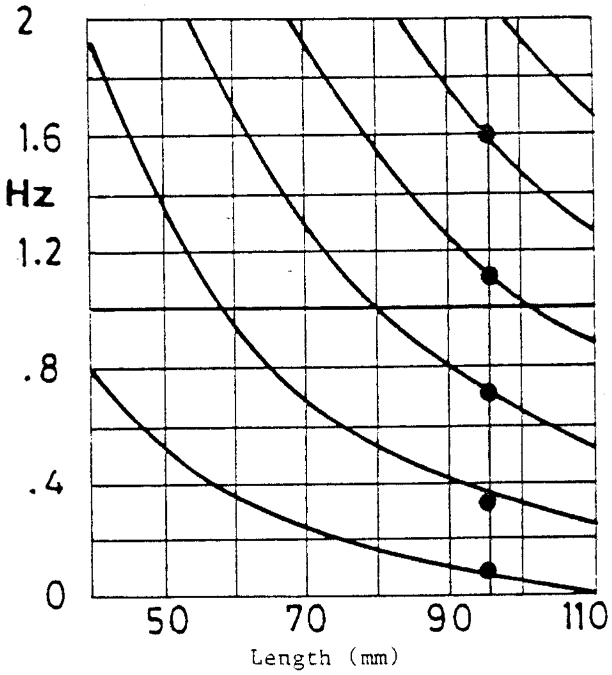
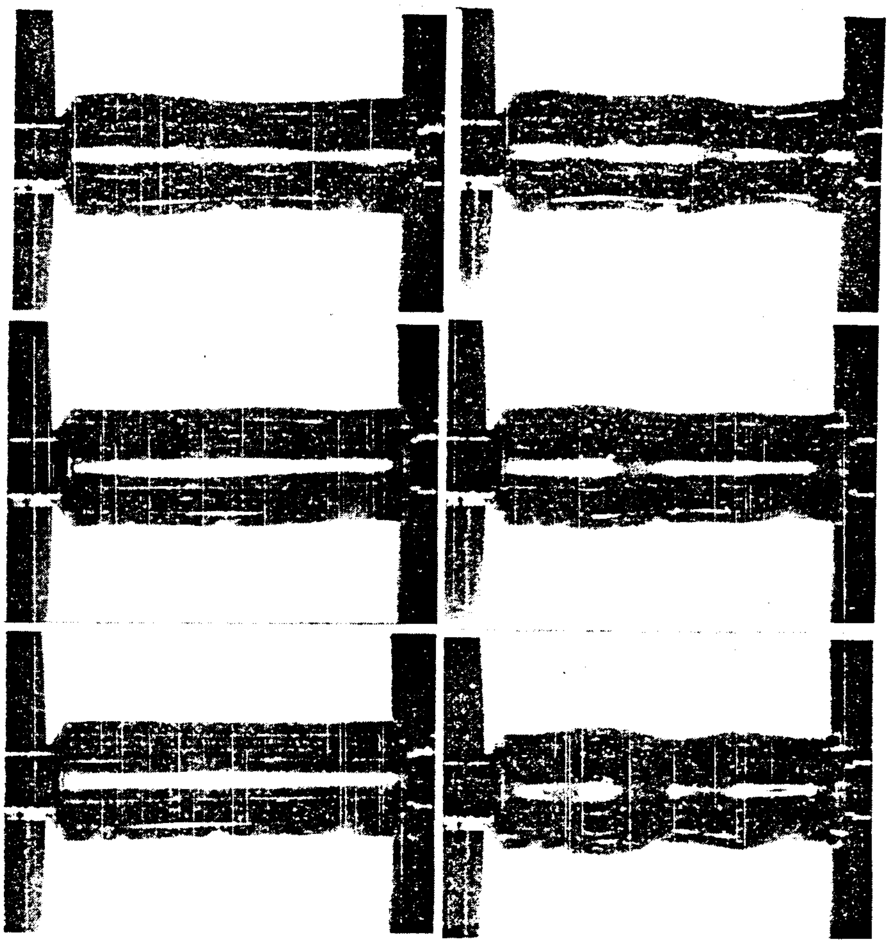


Fig. 6: Some consecutive film frames (at 2sec interval) showing oscillation of a 95mm long column at 0.3 Hz (0.93mm pick to pick amplitude).



and the investigator agreed when direct video link allowed to see the liquid bridge, that the background illumination would help a lot to clearly see the contour of the bridge, which was randomly oscillating and would be more difficuit to handle otherway. After some trials (in real time video) it was convened that the background light should be on and the film developed accordingly, after flight. Besides, to minimize perturbations the overall 3rpm rotation of the bridge (intended to see all around) was canceled.

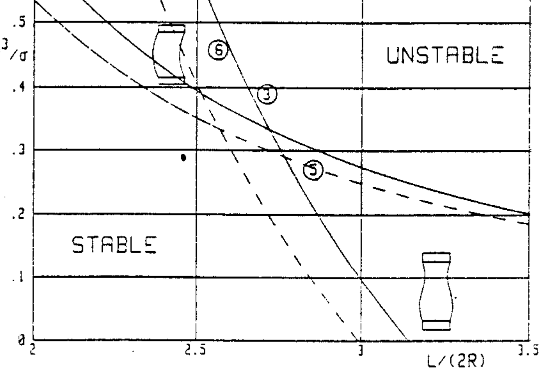
In this run, the oscillation trials were performed. The RD was set to a sinusoidal axial oscillation of 0.93mm pick to pick at selected frequencies of 0.1, 0.3, 0.7, 1.1, and 1.6 Hz, roughly corresponding to the first natural frequencies predicted by theory for a cylindrical liquid column of such a slenderness. During the 3min. 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 (Figs. 5-6).

Two or three minutes after the PS stopped the oscillation, the liquid column unexpectedly broke. The PS was not looking at it and no recording was on; it was attributed to shuttle maneuvers, but the g-level recording does not show any specific jump.

Run 3

The breaking in Run 2 left two drops well attached to the edges of the disks and thus the PS tried to approach the disk 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 disks (rotation of

Fig. 7: Points in the rotation-slenderness stability diagram for cylindrical liquid columns, exercised during Spacelab D1. Dashed line intends to show the effect of an axial residual gravity on the rotational stability limit (see also Fig.8).



the disks 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 (see Fig.7) 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.

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 100mm column at 10rpm with a ramp of 9 s/rpm (second rotation trial in the procedure), but, unexpectedly, as soon as the 10 rpm were reached, he started to recover, removing liquid while approaching the disks, stopping the camera, and going out of FPM duty for about one hour.

Fig. 8: Breaking sequence of a 100-mm-long cylindrical liquid column. Times, relative to the last picture, are -50, -10, -4, -2 and 0 seconds, respectively.

Run 5

The start is with a dry test chamber and the objective was to repeat Run 4 with success, what was finally achieved. The random oscillation in this column (100mm 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 5 min.). When subjected to 10 rpm of isorotation, the column broke in an amphora-shape mode, as expected (Fig.8).

Run 6

The goal of this run was to excite a C-mode deformation in a liquid column 90mm 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 more than 10^{-3} m.s^{-2}, 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.7.

By that time, experiment FLIZ had used resources (mostly crew-time) well 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 75mm which would have clearly shown a C-shape disruption mode.

4. LESSONS LEARNT

The details pointed out here concern marginal problems occurred during Spacelab flight and are irrelevant to the results of the investigations, but their inclusion here may be worth regarding future space experimentation (mainly from the users point of view).

A first logistic problem arose during the set-up: the background mask, intended to enhance visualization and ulterior data analysis from the images, was not found by the PS. The background mask was actually a plastic sheet of some 13x17cm^2, a commercial photosensitive film on which a square grid 1cm in side had been recorded. It was properly labeled, but, in order to avoid profusion of small containers, it 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 it had already cost several of 90 minutes initially allocated to the whole series of experiments and instruct 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 Spacelab 1 was awkward to control, but its settings were automatically recorded every second. The small manual syringe specially designed for D1 was much more handy, and helped the PS a lot to control the liquid supply and removal, but it was not connected to the data acquisition system. Training on ground was in excess optimistic: once up there, the PS was so busy coping with a highly sensitive liquid column that he had no time to keep 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 Spacelab 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 reliability of the data sources (problems with FPM cinecamera, malfunction of onboard video-tape recording, possible errors in data acquisition, etc.). For example, when the PS selected (according to the procedures) 12 rpm synchronously for both disks, the printout shows unrelated scatter from 11.2 to 12.7 in disk rotation rates (against an FPM accuracy 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 100 enlarged pictures have been manually digitized).

In contrary to the above drawbacks, the incorporation of a frame counter to the FPM housekeeping data for D1 Mission has represented a great improvement with regard to Spacelab 1 (the FPM camera does not record time on film).

5. CONCLUSIONS

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

Apart from 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:

- A large liquid mass was accurately positioned in the test chamber, well anchored to the sharp edges of coaxial disks.
- 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 axial vibrations showed a deformation with as many nodes (1,2,3,4 and 5) as predicted by theory.
- 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.
- Ambient noise in Spacelab seems to pose a bound on the maximum length of cylindrical columns of 35mm in diameter that can be handled in this laboratory: around the 100mm achieved during D1 Mission.

The detailed analysis of the 16mm film shot during FLIZ experiment is still in progress, and main results up to date are here presented. It can be anticipated that the overall result of FLIZ experiment has been excellent, and a follow-on proposal for Spacelab D2 (1990) has already been submitted to ESA for further work.

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