ISIDORO MARTÍNEZ'S RESEARCH ON LIQUID COLUMNS UNDER MICROGRAVITY

The Liquid Bridges project (or Liquid Columns, from the original Spanish title "Columnas líquidas en ingravidez"), refers to a main line of research initiated by the late Prof. Da Riva in 1974 at IDR-UPM (at that time Lamf-ETSIA) and coordinated by ESA, on the behaviour of liquid bridges in microgravity, where Prof. Martinez has been contributing since his graduation in 1975, and on which he made "a precursor film" (150 MB file), and his PhD Thesis in 1978, all at Universidad Politécnica de Madrid (UPM).

Liquid bridges form when a finite volume of liquid is established between two or more non-contacting solids. The simplest liquid bridge is a cylindrical liquid mass spanning between two solid discs in weightlessness. It is assumed that the solid supports are planar, circular and coaxial, that the liquid gets anchored to the edges of the discs, that the liquid is surrounded by another fluid (either a gas or an immiscible liquid), and that its volume is kept constant (other constraints could be imposed, as liquid filling from a reservoir at a prescribed pressure instead of at a prescribed volume, solid supports free to float in a force field instead of being mechanically fixed, etc.).

You can easily make a small liquid bridge by just putting some water or saliva in between your thumb and index. Large liquid bridges as the long liquid columns 10 cm long used for research can only be established under weightlessness. Besides its own scientific interest, research on liquid bridges aimed at understanding the floating-zone technique of single crystal growth, so important in the semiconductor industry, and other containerless high-temperature materials processing applications.

For experimentation, once in a microgravity environment (where gravity forces are closely balanced by centripetal acceleration of the space carrier), the liquid bridge must first be established, usually by feeding liquid from a syringe-like device through a centre-hole in one of the concentric support-discs while separating the discs proportionally, to avoid spillage by overflow or rupture (similar procedures are followed for simulation experiments on ground with immiscible liquids). Provided that other loads are smaller, be they mechanical (gravity, vibration, rotation), electrical, magnetic, thermal, etc., the liquid bridge is held together by surface tension forces (i.e. capillary forces) at the interfaces (liquid/fluid, liquid/solid and fluid/solid), and usually adopts an axisymmetric shape like in Fig. 1, where a typical liquid bridge under microgravity is shown, corresponding to experiment STACO on the Advanced Fluid Physics Module (FPM) aboard Spacelab-D2 in 1993 (Greenwich-Meridian-Time tagged: 118 day, 11 hr, 29 min, 05 s). The liquid (centred quasi-cylindrical column) is of silicone-oil 10 times more viscous than water, surrounded by ambient air. A background raster with two rows of squares 10 mm in side, and other vertical lines, was used to enhance the image analysis. Because of the liquid transparency and refractive index effect, the liquid edge appears as a thick black stripe, and the marked background axis can be seen through the liquid with uneven spacing ticks (marks were at every 10 mm). The two solid supports are made of aluminium, of 30 mm in diameter, with a sharp cut-back (30? edge) to prevent liquid spreading over the edges, and they are 85 mm apart. Notice that more than 9 background-centimetres correspond to the 85 mm -long column, because of parallax.

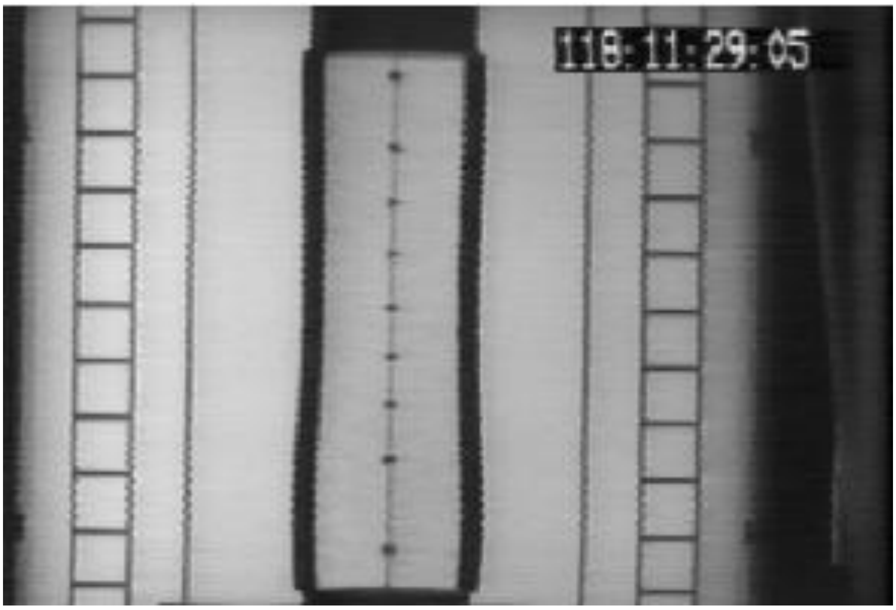

Fig. 1. A typical quasi-cylindrical liquid bridge, 30 mm in diameter and 85 mm long, under microgravity aboard Spacelab-D2 (1993).

Liquid bridges, like that in Fig. 1, are only stable under some parametric bounds for their geometry, as shown in Fig. 2.

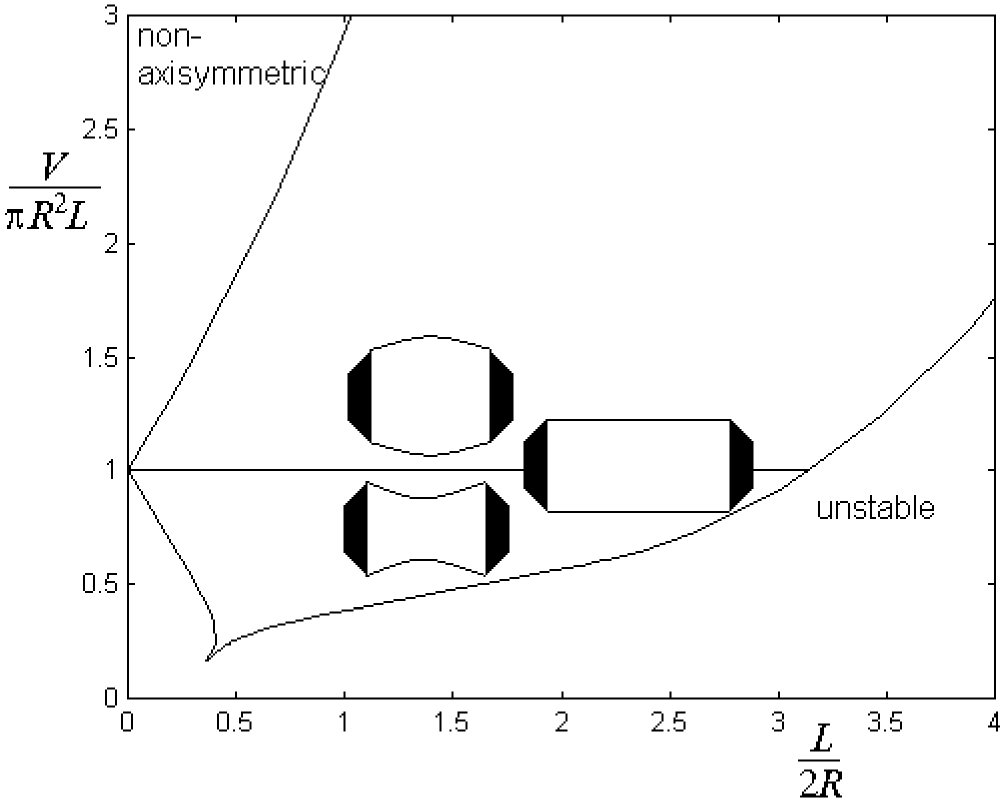

Fig. 2. Stability diagram for liquid bridges of volume V, in perfect weightlessness, between equal coaxial discs of radius R (cut-back as a dove tail to help the liquid pinning at the edge), separated a distance L. If the volume is $V=\pi R^2 L$, the shape is cylindrical (horizontal line, with stable slenderness up to $L=2\pi R$, the Plateau-Rayleigh limit); larger volumes are barrel-shape, and smaller volumes are spindle-shape.

You may find in Table 1 a summary of the project, and in Table 2 some selected images and videoclips of the experiments.

Table 1. Summary of the project.

Subject	Behaviour of liquid columns under microgravity.
Field	Capillarity, Fluid Mechanics, Physics.
Objective	Analysis of liquid bridge shape and their stability, shape deformation and inner motion due to several mechanical stimulation.
Achievements	Theory developed and experimentally confirmed. Experimental program developed (in international multi-user space facilities). Telescience (tele-operation) developed. Unexpected g-jitter effects detected and quantified. Last experimental results fully explained, with accurate prediction capability.
Configuration	Liquid column anchored to solid discs and held by interfacial forces.
Theory developed	Equilibrium shapes and stability limits for a parametric set (*L*,*V*,*B*,*W*,*H*): *L*, length; *V*, volume; *B*, Bond number (gravity); *W*, Weber number (rotation); *H*, disc size difference. Linear dynamics of oscillation and breaking. Non-linear dynamics of oscillation and breaking.
Experimental setup (basic)	Liquid filling under microgravity through a centre hole (6 mm in diameter) in a disc (30 mm in diameter).
Experimental procedure	Establishing the column (small drop or small bridge, followed by cylindrical stretching). Oscillating one disc. Rotating both discs in iso-rotation (preferably eccentric). Stretching (at constant volume or cylindrically). Removing liquid at constant disc separation.
Experimental execution (telescience)	Shared scenario (1 voice channel for several crew-persons. Multi-task operation for payload-specialist crew (PS). Disperse information links (computer data, video image, switched voice link, ambient TV). Drop-outs in communications (incomplete orbit coverage, and malfunctions). Non-transparent voice loop (PI-FPM-WL-APS-CIC-PS). Field work for investigators (PI).
Experimental results	Solved problems in establishing the liquid column (two methods available). Solved problems in recovering broken bridges. However, uncontrolled breakages occurred in later experiments. Found that zero-g stability limits can only be approached up to 90% due to g-jitter. Unexplained shape deformation in SL-D1 (one order of magnitude larger than expected). Unexplained breakage in SL-D2. Good agreement between vibrational behaviour of columns with theory. High-precision automated image analysis developed (a tenth of a pixel).
Open problems (theory)	G-jitter characterisation and response. Coupling of axisymmetric perturbations (e.g. vibration and isorotation). New axisymmetric perturbations (thermal or solutal deformations). Non-axisymmetric perturbations.

Open problems (experiment)	Better bubble control during column formation. Better anchorage control during column formation and after rupture. Video-recording was of poor quality (new digital video will solve it). FOV clipping, zooming, tilting and slant by software, to simplify optical path. Parallax and depth of field should be avoided (go to parallel viewing). Lack of redundancy in past experiments (go to two sides viewing). Automatic synchronous merging of all data sources (video as the master data). Better uniformity of illumination and background contrast with liquid column. Quantification of diffraction effects on edges. Effects of experimental simulation in immiscible baths (Plateau tank), and with microzones (e.g. cleanliness control, measurement uncertainties).
Publications	References to this work can be found in ESA microgravity data base: http://eea.spaceflight.esa.int/ and in Da Riva's team research.
Presentations	Liquid bridge experiments in Spacelab

Table 2. Selected videoclips of our experiments with liquid columns under microgravity (Xvid® codec needed).

Year/Platf.	**Experiment**	**Videoclips**	**Size**
1983 Spacelab-1	Floating Zone Stability (1-ES-331)	FPM operations and first live liquid column (ad hoc video transmission)	47 MB
		Filling, vibration, and rotation of a conical bridge (16 mm cine-film at ½ fps)	4 MB
		Filling, vibration, rotation and breakage of a near cylindrical column (16 mm cine-film at ½ fps)	3 MB
1985 Texus-12	Maximum Injection Rate	Injection-retrieval at increasing speeds until breaking (6 minutes 16 mm cine-film at 20 fps)	28 MB
1985 Spacelab-D1	Floating Zone Hydrodynamics (FLIZ)	FPM operations preparation	4 MB
		FPM operations preparation and first inside view	14 MB
		Drop contact and spreading (meridian light cut, tracers)	12 MB
		Complete cine-film record at 2 fps	9 MB
1988 Texus-18	Freezing of a Long Liquid Column	Freezing a water column from a right-hand disc at −50 ºC (6 minutes video transmission). Notice edge pinning.	37 MB
1989 Texus-23	Eccentric Rotation of a long liquid column	Eccentric rotation of a liquid column, with 90º mirror (6 minutes video transmission).	33 MB
1991 Texus-29	Dopant Striations in a Floating Zone of Silicon	Silicon crystal growth inside a mirror furnace (6 minutes video transmission).	33 MB
1993 Spacelab-D2	Stability of liquid columns (STACO) Run 1. Axial vibration	Liquid column formation by drop contact	2 MB
		Upper disc forced oscillation (full)	4 MB
		Liquid recovery	19 MB
		Upper disc forced oscillation	46 MB
	Stability of liquid columns (STACO) Run 2. Stretching	Long liquid column at rest (to sense background noise)	8 MB
		Column stretching at constant volume (controlled breaking)	8 MB
		Liquid recovery after breakage	1 MB

	Stability of liquid columns (STACO) Run 3. Unequal discs	Wobbling of unequal discs column (unexpected breaking)	20 MB
1994 Texus-33	Controlled Acceleration of a Long Liquid Column	After liquid injection, the whole test cell is moved up and down sinusoidally, to see its deformation (6 minutes video transmission).	38 MB