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LOW GRAVITY LIQUID MOTIONS IN SPACECRAFT

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What is "low gravity" fluid motion?

- o effective linear acceleration is small
- o liquid has a free surface or interface

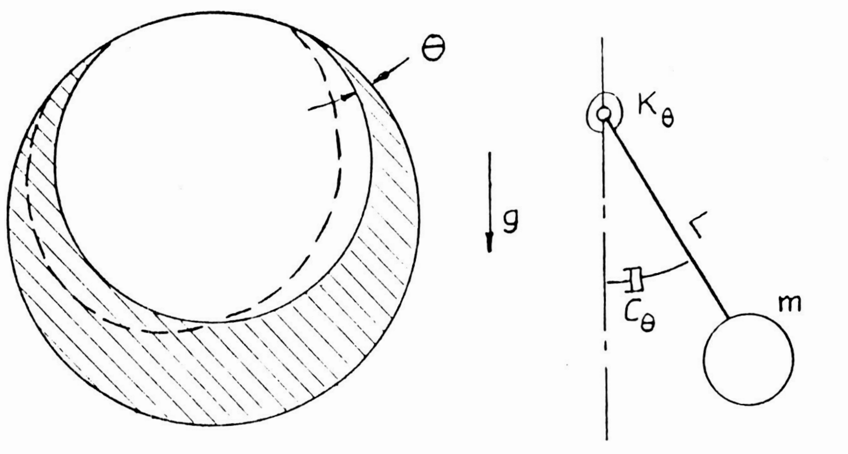
This definition includes more than just small "Bond number" cases because forces other than surface tension may be important.

Note: $Bo = \rho g d^2/\sigma$

Examples include

- o free–surface sloshing
- o liquid reorientation
- o liquid draining
- o tanks with bladders
- o spinning tanks
- o thermal motions (not discussed)

Free–Surface Sloshing



$$f = [K_\theta/mL + g/L]^{1/2}$$

"Spring" term in equations of motion:

$[\ \rho g - \sigma\nabla^2\ ][\dots\ ]$

Some Still Unresolved Questions:

- o Does contact angle change with motion? How? (liquid and tank characteristics, velocity?)
- o What configurations have a zero–frequency mode in 0–g?
- o How does damping vary as Bo $\rightarrow$ 0?

$$\gamma = A(\nu^2/gd^3)^{\frac{1}{2}}[1 + B(\sigma/\rho g d^2)^{0.6}]$$

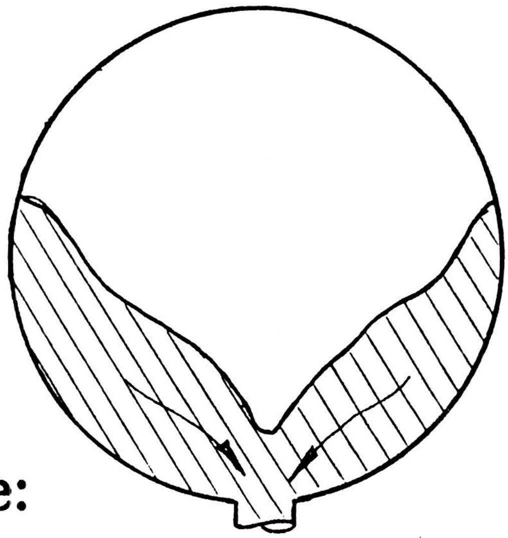
for Bo > 1

- o In–space vehicle motions are slow but of large amplitude
  - – low–g slosh will be nonlinear
  - – does this imply breaking waves and splashing (important for cryogens)

Low–G Sloshing R & D

- o Frequency, forces, damping
  - – tank shape
  - – liquid volume
  - – Bond number
  - – contact angle
  - – viscosity
- o Requires extended periods of low–g availability
  (Slosh period = 10 sec. for 30 cm tank, $\rho/\sigma = 30\ sec^2/cm^3$ and $g = 10^{-5}\ g_0$
- o Complimentary analyses and/or CFD codes with reliable surface tension representation
- o Ground testing is of little value for Bo < 1 – but drop towers can guide for in–space tests

Liquid Draining



Primary issue:

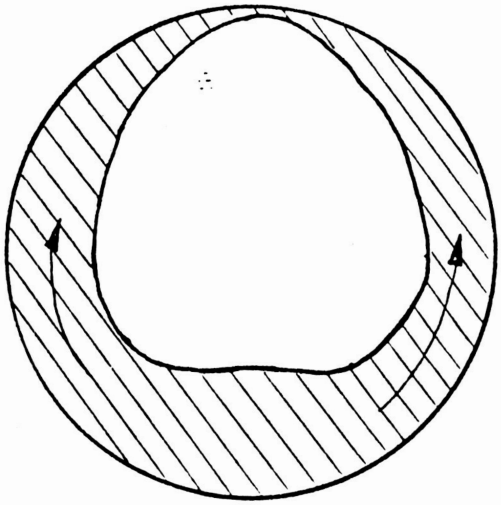
- o What liquid volume remains when gas first enters the outlet?

- o This "residual" depends on:
  - tank shape
  - outflow rate
  - contact angle
  - Bond number
  - viscosity

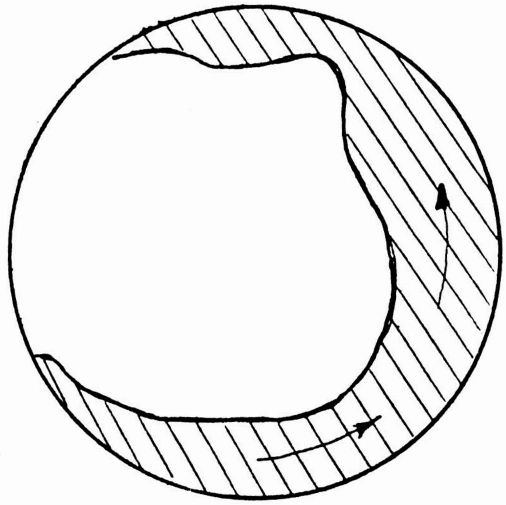
- o Perhaps not a critical problem (most tanks have capillary control)

  (But may become important again for spinning tanks)

Liquid Reorientation



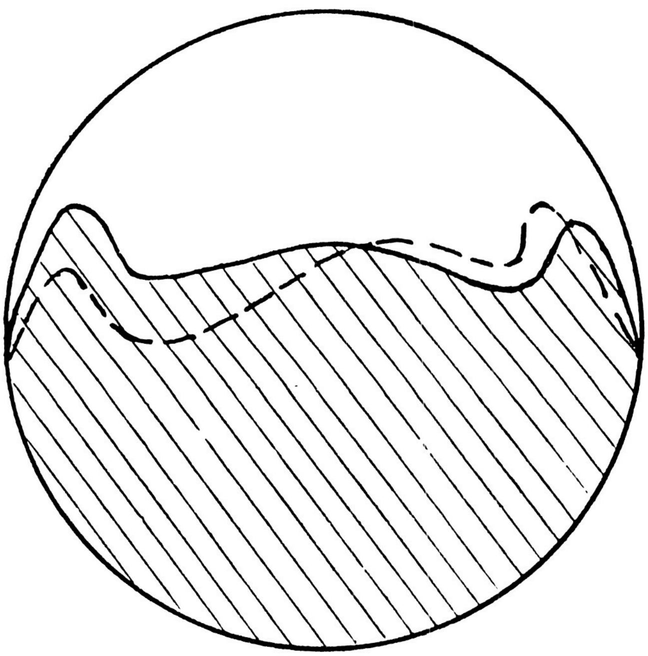
Symmetrical

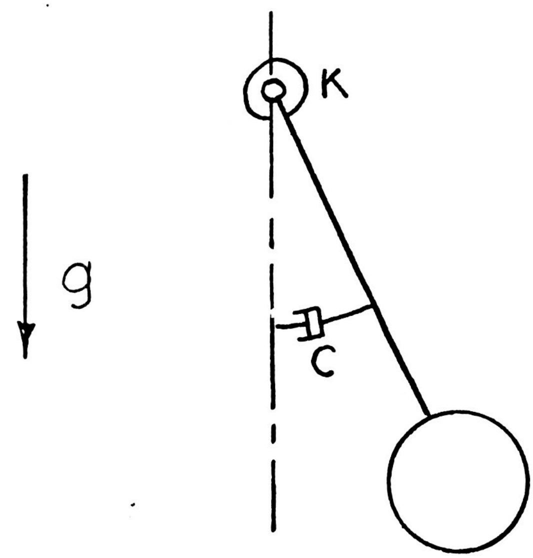


Anti–symmetrical

- o Anti–symmetrical case is more common – similar to large amplitude sloshing
- o R & D Requirements
  - – reorientation time
  - – forces and moments
- o Testing requires extended period of low–g availability and method of producing small linear accelerations
- o Complimentary analyses and/or CFD codes are needed

Sloshing in a Bladdered Tank





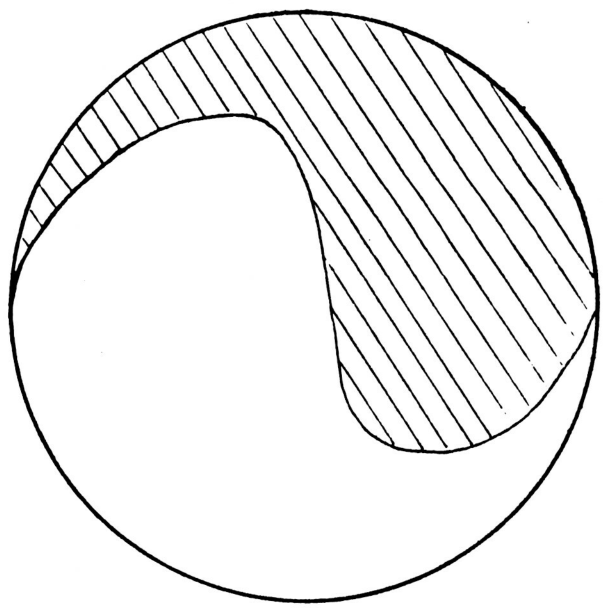
$$f = [\ K/mL \ + g/L\ ]^{1/2}$$

"Spring" term in equation of motion:

$$[\ \rho g \ - \ D\nabla^4\ ][\ldots\ ]$$

where D = structural rigidity of the bladder – similar to surface tension

- Some 1–g tests have been conducted with liquids of different densities, to vary "spring" and thus determine K for $g > 0$
- No theory available yet for slosh dynamics
- Some peculiar configurations are possible



Liquid on "top"
(TDRSS)

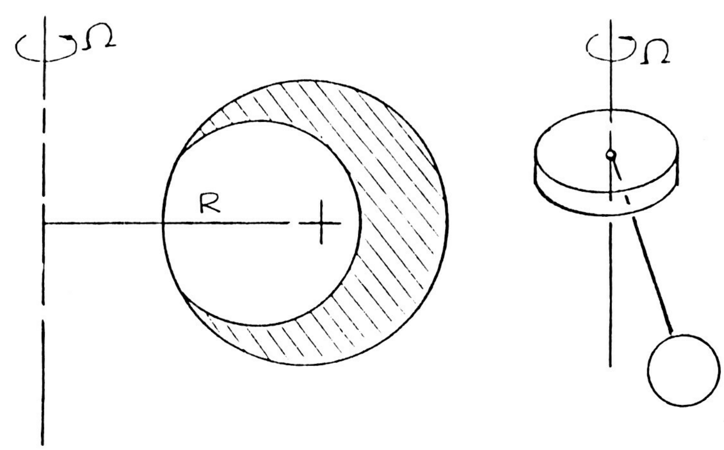
R & D Requirements for Slosh in Bladdered Tanks

- o Dynamics are similar to low–g sloshing but heavily damped

- o Low–g static configurations and slosh dynamics are not yet predicted theoretically (fluid–structure interaction problem)
  - bladder stiffness
  - tank shape
  - liquid volume and position
  - g level

- o Possible to do some ground testing for $g > 0.1–0.2\ g_o$

Liquid Oscillations in a Spinning Tank



Typical $R\Omega^2 = 1 - 10 \times 10^{-5}\ g_o$
(near low–g conditions)

Two kinds of oscillations occur:

- o Free surface modes

  "slosh" – $f > 2\Omega$

- o Internal modes

  "inertial waves" – $f < 2\Omega$

Some important issues:

- o what are the resonant frequencies of internal modes (easy to couple with nutation of spacecraft)

- o what is the energy dissipated by liquid motions (can destabilize a "prolate" spacecraft even if there are no resonances)

- o Little theoretical or experimental guidance is available (so spacecraft are designed too conservatively)

- o Fundamental information from ground testing is difficult if not impossible to obtain
  - $R\Omega^2 >> g_o$ (very rapid spinning)
  - wrong Reynolds number regime
  - instrumentation & visualization problems

- o Ground testing can only reliably establish energy–dissipation rates that can be scaled–up

R & D Requirements

Basic information and design guidance is needed on internal mode dynamics:

- o resonances
- o moments and forces
- o damping

Extensive period of low–g availability is required to establish resonances and damping

- o spin facility in space

Analysis and testing must proceed together to resolve fundamental questions

CONCLUSIONS AND RECOMMENDATIONS

1. Sustained low–g availability is needed to investigate:
   a: free–surface sloshing
   b: reorientation and draining
   c: slosh in bladdered tanks
   d: liquid motions in spinning tanks

2. Technical need and high scientific value for reliable low–g test data, analyses, models, and design guidance

3. Ground tests for $Bo < 1$ are of little use