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Simulation of liquid dynamics onboard Sloshsat FLEVO

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Abstract

The Sloshsat FLEVO project has an Investigators Working Group which prepared orbital experiments on the behaviour of liquid in spacecraft. These are to be performed with a dedicated small satellite, of about 90 kg empty weight and about 34 kg of water in a 87 litre tank. The spacecraft dynamics are simulated by SMS, the Sloshsat Motion Simulator. SMS predictions and those generated by a CFD simulation are compared for an example.

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Introduction

The dynamics of a spacecraft with a partially filled tank is often more unpredictable than the dynamics of terrestrial vehicles with liquid. One cause is the additional regime wherein liquid distribution and flow is governed by capillary properties, another the absence of support structure and its force on the spacecraft. The requirements on predictability are high: damage to the spacecraft may cause loss of life, and always results in exceptional expenses as compared to terrestrial repair jobs.

Although computational tools exist that allow to integrate the equations that describe the development of the spacecraft and liquid motions, an experimental investigation is necessary. This is not because validation of the results is required, but primarily because some physical phenomena are not well understood. One example is the unexplained high level of damping that investigators report after execution of a low-gravity liquid dynamics experiment. Note that unexplained damping is a more general phenomenon (Miles, 1998). An experiment will generate documented data for model assessment.

There are practical causes also for the execution of experiments. Liquid management strategies are concerned about the liquid state following a manoeuvre and not about the intermediate stages. The simulation of the detailed behaviour of the liquid, for a range of conditions to assure robustness, would constitute an enormous amount of work. A series of in-orbit tests appears to be a much better option.

The operational difficulties that stem from the presence of a large amount of onboard liquid can and have been countered successfully by various engineering schemes. The increase in requirements on performance and costs in hardware, consumables and time, make a more fundamental approach timely in the era of the space station.

Experiment definition

The shape of the tank on Sloshsat is a straight cylinder with hemispherical ends. The length of the cylindrical section is equal to the radius of the cylinder, hence the specification of this size completely determines the tank. The tank cavity is smooth except for some minor intrusions by sensor hardware. The tank radius is 0.228 m, which gives it a volume of 87 litres. The liquid fill ratio is 27/70 which makes that the ullage cannot form a sphere that fits in the tank and so a contact line will bound the liquid free surface. The liquid is pure water and liquid mass is about 33.5 kg. The tank shape is similar to that of actual spacecraft tankage. It is made from aramide fibre re-inforced epoxy, with a polyethylene liner.

The Weber number: $We = \rho U^2 L/\sigma$ of the liquid motion in the tank is the ratio of inertial over capillary forces, since ρ = liquid density, U = characteristic liquid velocity, L = tank radius and σ = surface tension.
If $We < 50$, one may estimate that a CFD simulation of the liquid motion will require less than about 5000 grid points, a manageable number. Also, for this Weber number constraint, the liquid is likely to stay coherent, in one 'blob', unless a direct impact of the liquid with the tank wall occurs (Mironov,1992). A typical Weber number for the experiments is 10. Similarly, the Bond number : $Bo = \rho\, aL^2/\sigma$ for the liquid configuration in the tank, where a = ambient body force field, is typically less than 10 which means that the liquid free surface is shaped (strongly) by capillary forces.

The experiments are categorized in 3 types: I. Hydrostatics and Stability, II. Settling Manoeuvres, and III. Spacecraft Dynamics. The main activities in each category are:

I. execution of a graduated spin-up about a spacecraft principal axis, and back, in order to realize hydrostatic liquid configurations and small oscillations about the hydrostatic equilibrium.

II. translation of the tank along its centreline, at different accelerations, in order to move the liquid from one (hemispherical) end of the tank to the other, and keep it there.

III. various spacecraft manoeuvres, e.g. thrusting along the spacecraft axis of maximum moment of inertia while the spacecraft is spinning about that axis.

The data for the evaluation of the experiments should consist of the motion of the spacecraft, the liquid distribution, especially near the contact line, and liquid velocity data.

Sloshsat FLEVO spacecraft

The shape of Sloshsat is a rectangular box with dimensions 0.78, 0.50, and 0.74 m respectively, along an XYZ coordinate system. A sketch of the spacecraft, with the XYZ directions, is given in figure 1. With respect to the centre of the box, the spacecraft centre of mass (com) is near the Z-axis, at location -0.20 m. The principal moments of inertia are 7.8, 6.5 and 5.8 kg.m^2 about the X,Y and Z axes resp. The Sloshsat mass, without liquid, is 73 kg. These inertial parameters have been used in calculations; in the meantime Sloshsat dry mass increased to about 90 kg so actual data are different from the quoted values.

Figure 1 shows the locations of the 12 nozzles of 1.1 Newton thrusters that constitute the reaction control system of Sloshsat. The X-thrusters are in the plane Z = - 0.07 m, the other thrusters are in the box mid-planes.

Sloshsat is to be launched from the Hitchhiker bridge on the US Space Shuttle. A Memorandum Of Understanding to this effect has been signed by ESA and NASA; a preliminary launch date has been December 1999.
After ejection from the Space Shuttle, Sloshsat stays near and communicates with the ground operations centre via a transceiver on the Hitchhiker bridge. Altogether 24 hours of free-flying experiment operations are planned, distributed over the Shuttle time in orbit.

The sensors of interest for the slosh investigations can be grouped in two systems: the Motion Sensing Subsystem (MSS), with 6 accelerometers and 3 gyroscopes, and the tank instrumentation for mapping of the liquid.
The components of the MSS are the Allied Signal QA-3000-010 accelerometer and the LITEF micro-FORS fibre optic gyroscope. The accelerometers are in 3 orthogonal pairs. Two pairs are on the bottom plane of the box, at the ends of a diagonal in that plane, the remaining one is at the top plane, in a corner not above one of the other pairs.
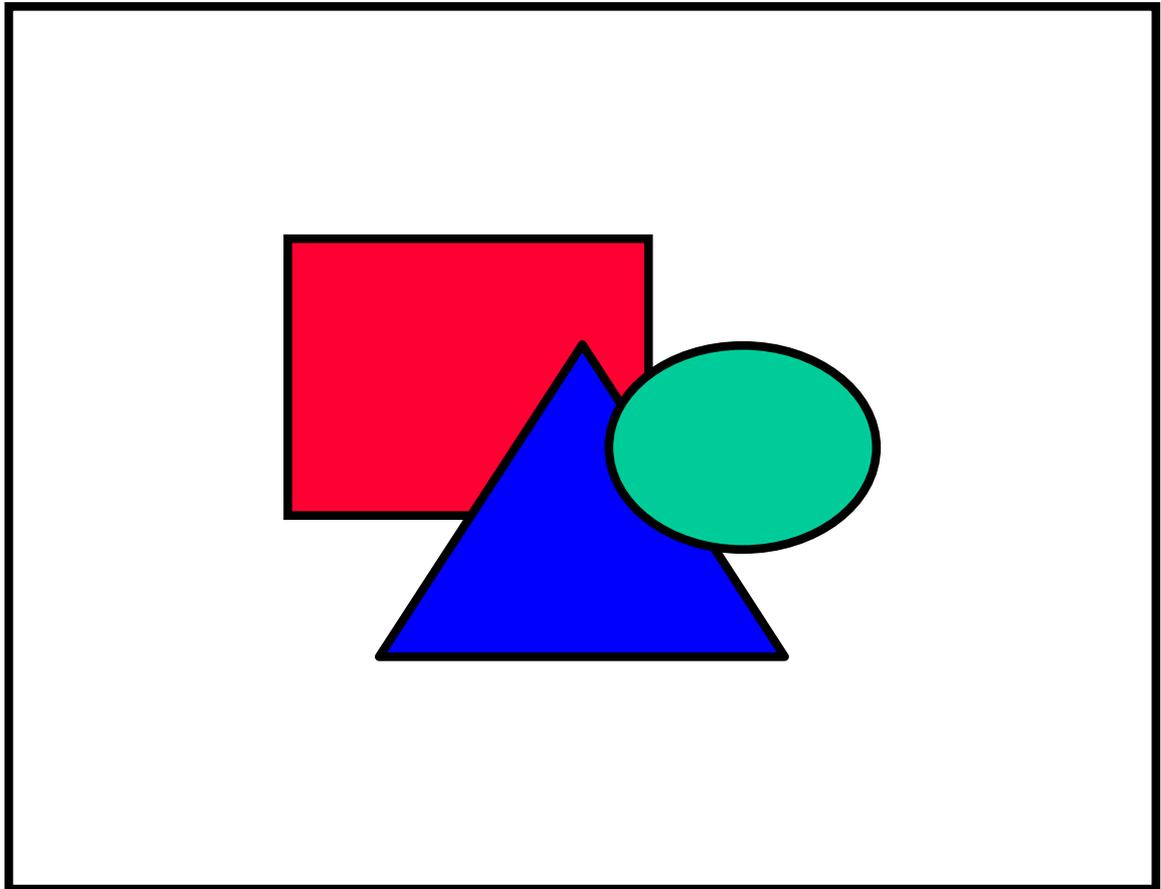
The sensing axes of the accelerometers are aligned with the Sloshsat XYZ directions; the two that sense along the Z-axis are in the bottom plane. The gyroscopes also sense components along the spacecraft axes. Readout of the MSS sensors occurs with 30 Hz.

The principal instrumentation in the tank is the so-called Coarse Sensor Array (CSA). It consists of 137 rings of fine platinum wire that are embedded in the tank wall. Between them the electrical capacitance is measured at 270 evenly distributed locations on the tank wall. These data show the thickness of the water layer until their saturation when the layer is thicker than about 0.03 m. Thus, the contact line region can be identified. Sensors of coated Pt wire (3) are to measure the liquid height near predicted contact line locations. At 10 locations on the tank wall liquid velocity magnitude is measured with ntc thermal sensors by a transient method. A sensor is heated by a current pulse and its exponential temperature decay is determined. The value of the exponent is calibrated against liquid velocity in a laboratory set-up.
The CSA is sampled with 3 Hz. The tank sensor data are transmitted to the ground and are not used onboard Sloshsat.

The gyroscopes provide angular rates, which serve as input data for the control of spacecraft motion. The control cycle is 3 Hz, so every 333 ms a set of 10 commands are determined. Each command contains 12 thruster on/off settings, to allow the 30 Hz thruster activation rate.

Models of liquid dynamics

For the liquids of interest, the liquid behaviour is described by the Navier-Stokes equations. The generic configuration has the liquid in a fixed boundary (container) that is closed by a free surface, constrained by contact line conditions and a fixed liquid volume. The motion generally is calculated with respect to the container, whence the container motion appears as a body force field in the Navier-Stokes equations.

If the container motion is a uniform spin, special simplifications are feasible (Greenspan, 1969). If the motion is a uniform acceleration, like gravity, the free surface can often be approximated by a plane and analytical solutions for simple container shapes can be found (Abramson, 1966). If the configuration is somewhat more complicated, the method of solution still proceeds via the identification of series of special functions, but the coefficients are found numerically (Bauer, 1988; McIver, 1989). The same holds true for liquid configurations with a closed free surface (drops, bubbles). An analytical solution provides expressions for all properties of the liquid system, such as boundary pressure and total force on the container, to any desired accuracy.

Computational Fluid Dynamics, or CFD, models provide data for specific cases, and therefore become expensive when parameters need to be optimized during many runs. However, if the algorithm can be shown to be stable, accurate prediction of liquid behaviour is feasible (Chen, 1994; Navickas, 1986; see also http://www.math.rug.nl/~veldman/cfd-gallery.html).

For application to slosh dynamics in spacecraft two difficulties exist, one physical, one numerical. The physical problem comes from uncertainty about liquid behaviour at the contact line; the stiction effects cannot be predicted accurately and so, in the capillary regime, lead to wrong conditions at the edge of the free surface. The numerical problem occurs when it is required to predict the motion of a spacecraft that has more than half of its inertia in sloshing liquid. Then a special formulation of the governing equations is required or the numerical solution process diverges (Vogels, 1987).

Since ages engineers have relied on mass-spring-damper models to represent dynamic systems. For spacecraft slosh problems extensive use of such models have been made (Abramson, 1966; Peterson, 1989; Dodge, 1991). The liquid is replaced by an oscillator whose mass, spring constant, and other parameters are determined from comparison with a liquid slosh problem that has known (analytical) expressions for the force on the tank and other dynamic quantities of interest. The oscillator parameters depend, in general, on the gravity level assumed for the liquid slosh.

In a manoeuvering spacecraft the ambient body forces that act on the liquid are generated by the spacecraft motion and so are highly variable. Consequently the oscillator parameters must be introduced as unknowns in the state vector of the spacecraft and solved along with the spacecraft motion. The solution then provides the trajectory of the liquid centre of mass (com), the

interaction force and torque with the tank and other quantities such as the kinetic energy of the liquid. For Sloshsat a particularly simple model has been derived (Vreeburg, 1995) that relates the normal force, N, between liquid and tank to the distance, y, along the normal to the liquid com by the formula:

$$\frac{3}{5}m\ddot{y} + 8\pi\sigma y - \frac{5}{2}\frac{h^2}{my^3} = N \tag{1}$$

for liquid mass m, surface tension σ and angular momentum h. It would be of interest to investigate how this equation might be obtainable from a very general formulation of the interaction condition (Lee, 1995).

The Sloshsat motion simulator

The Sloshsat Motion Simulator (SMS) is a tool for the development of spacecraft control, and a framework for the interpretation of results.

SMS is constructed as a two-body system, an invariable solid and a slug to model the liquid. The slug has uniform density and a constant mass, equal to that of the liquid in Sloshsat, and its com has variable distance to the wall. The normal force at the wall is expressed by equation (1). In SMS the interaction between the bodies is actually calculated as exchanges of momentum. The minimum distance between the liquid com and the wall is determined; when this distance is reached with normal liquid velocity an impact results. The conditions on the impact phenomenon need to be specified (Brach, 1991). No limitations on the amplitudes of the motions exist, however Sloshsat is to be operated such that the liquid remains one coherent mass.
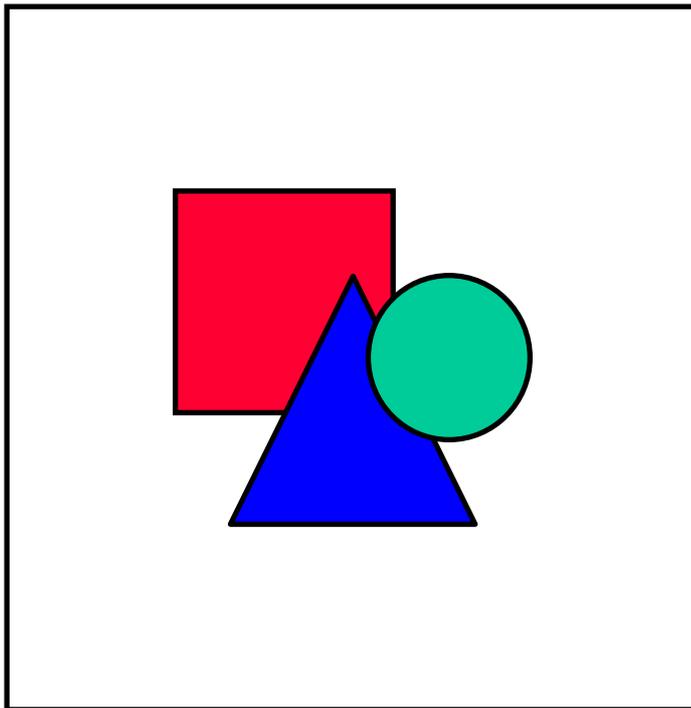

Figure 2 shows the cross-section of the Sloshsat tank with the approximate location of the dry Sloshsat com. The extreme locations of the liquid com in the tank have been calculated and are seen to be about halfway between the tank geometric centre and the wall. In SMS the liquid model is a spherical slug, and its extreme locations are plotted also; it is the quarter circle near the origin. The Sloshsat tank is modelled as a spherical cavity with a radius that allows the slug to get a moment of inertia (moi) comparable to the maximum of the liquid moi in Sloshsat. It is not

complicated to make the slug have direction-dependent properties, or to place the slug com away from the surface normal at the pressure point. However this will be done only when such proves to be necessary.
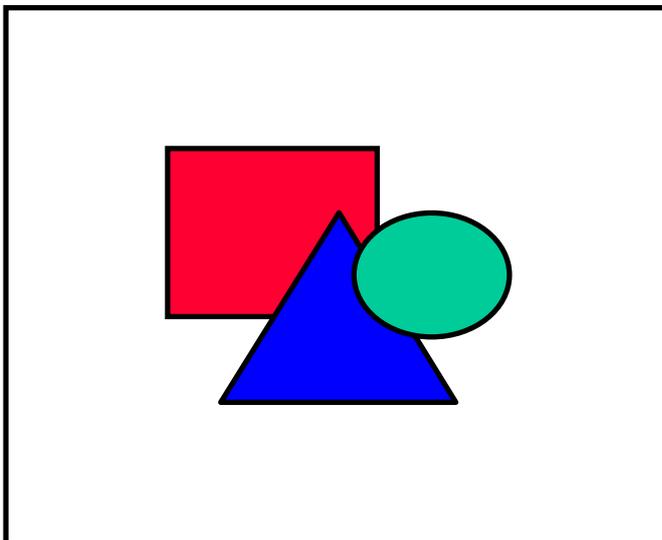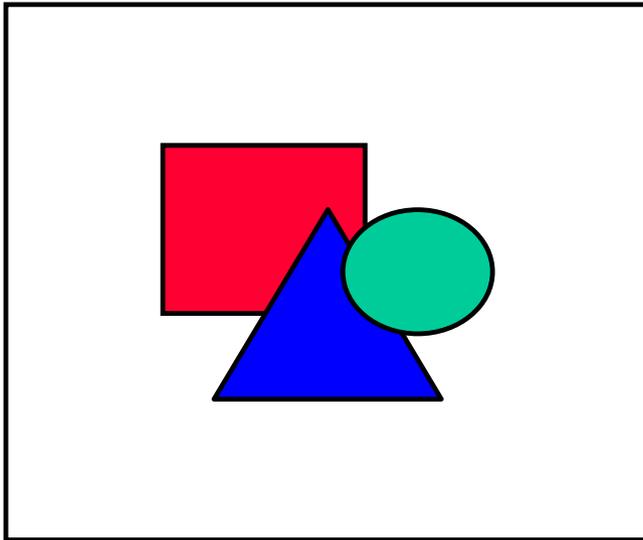
The force between liquid and tank is mainly due to the liquid pressure. Since each pressure contribution is normal to the wall, the total force will pass between the tank geometric centre and an origin of a hemispherical end cap. The consequent torque on the dry Sloshsat results by multiplication with the distance from the com to the force, and some additional lines are drawn in figure 2 in order to show that this distance is of the same magnitude in the simplified geometry of SMS.

Validation of SMS predictions (Vreeburg, 1997) has been started with the simulation of actual spacecraft behaviour as reported in the literature. A comparison between predictions, from a CFD calculation and from SMS, of a Sloshsat manoeuvre has been made also. The manoeuvre takes liquid at rest from one end of the tank to the other end and keeps it there.

The trajectory predicted by Jeroen Gerrits with CFD package COMFLO, operated at the University of Groningen, is shown in figure 3. The SMS prediction is in figure 4; it compares well with the CFD result.

Acknowledgment

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