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NLR-TP-99570

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This report is based on a presentation held at the 42nd Space Science and Technology Conference, Tokyo, Japan, October 28 - 30, 1998.

Division: Space
Issued: February 2000
Classification of title: unclassified

Abstract

Modern spacecraft tend to contain increasingly large volumes of liquids. Adequate understanding of the interaction between spacecraft dynamics and liquid dynamics is necessary for the realization of the required mission performance. This paper discusses the necessity of in-orbit experiments and sketches the Sloshsat mini-spacecraft testbed that is currently under development.

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1 Introduction

Spacecraft may carry a variety of liquids, such as liquid propellants for attitude and orbit control, cryogenic liquids for cooling of experiments to extremely low temperatures, liquids in heat pipes or nutation dampers, and liquids for transfer to other spacecraft and space stations.

Liquids behave as a deformable medium with mass density. As a result, the motion of the liquid in a container results in forces exerted by the liquid on the walls of the container. These forces modify the motion of the spacecaft, which in turns influences the motion of the liquid. That is, interaction between the dynamics of the spacecraft and the liquid occurs.

Mathematical analyses of the dynamic interaction distinguish between the case of completely filled containers and the case of partially filled containers. The latter case is more general and more complicated. One will find free surface wave motion and even more complicated forms of surface motion, and these motions are generally referred to as “sloshing”.

The forces exerted by the liquid on the spacecraft container wall influence the stability of spacecraft maneuvers, and they influence the performance displayed during maneuvering as well as in quiescent state. The nature and intensity of these influences depend on the ratio of liquid mass to spacecraft dry mass, on the fill ratio, on the geometry and location of the container, and on the physical properties of the liquid. They also depend on interaction with the dynamics of structurally flexible components and on the dynamics of the estimation and control algorithms implemented.

In the case of three-axis stabilized spacecraft, interaction dynamics is more complicated than in the case of spin-stabilized spacecraft, as in the latter case the effective inertial force field has a more simple structure - which simplifies the computations. Nevertheless, one must consider that some spacecraft operate in control modes involving spin-stabilization as well as three-axis stabilization. The general case of spacecraft translational and rotational motion is the focus of the present study.

Interaction dynamics has been of concern in several European spacecraft projects. Of these we mention only the IRAS, the Symphonie, the DFS Kopernikus series, the OLYMPUS, the SOHO, and the ISO. Amongst interaction dynamics studies in the USA we mention specifically those concerning the GALILEO and CASSINI interplanetary probes.

Looking forward to the operation of the International Space Station, one foresees operations of robotic manipulators that are to position new containers with liquid propellant onboard. Here, too, the interaction of dynamics between manipulator and container requires careful analysis.

2 Equivalent mechanical models for liquid motion

The motion of the liquids of interest satisfies the Navier-Stokes equations together with time-varying boundary conditions. The liquid motion is usually considered in a coordinate system that moves with the spacecraft, which makes that the spacecraft motions appear as a body-force field in the Navier-Stokes equations. The boundary conditions at the tank wall become stationary and only the free surface remains transient (Ref.10).

The motion of the spacecraft depends in turn partly on the motion of the liquid. The presence of baffles and similar devices to increase damping, requires modelling in order to reduce the complexity of the geometry. The practical model for the prediction of interaction force is different from the model for liquid distribution, although both models could be derived from a same, detailed simulation model.

The liquid motion is influenced by four classes of forces: gravity (a body force, here created by the motion of the spacecraft), inertia, viscous, and capillary forces. Their ratios are described by the nondimensional Froude, Bond, and Weber numbers. The Froude number represents the ratio of inertial over gravity forces, and is typically large. The Bond number represents the ratio of gravity forces to capillary forces, and is typically smaller than one. The Weber number represents the ratio of inertial over capillary forces, and is often of the order of one. The order of magnitude of these numbers gives an indication of the simplifications that may be introduced in the equations of motion.

It is to be noted that the modelling of energy dissipation requires much attention. Viscous forces do cause damping of the liquid motion, but in experiments more damping has been observed than can be explained by viscous interaction (Ref.9). Moreover, capillary waves show higher damping than gravity waves of the same frequency (Ref.12). Although the discrepancy might be resolved by closer control of experimental conditions (contamination), one cannot yet exclude the influence of physical mechanisms that have been neglected in the model. A possible cause, identified during the development of SMS (see below) is impact damping of the liquid with its container. If one considers the motion of the center-of-mass (“com”) of a sloshing liquid, the reversal of the com velocity at its point of closest approach to the wall involves the exchange of a nonzero amount of linear momentum (Refs.3,8). If the liquid and the wall are taken mathematically incompressible (Ref.7), the collision of the liquid com with the wall is completely elastic. However, in reality some kinetic energy will be lost and that will appear as damping.

For accurate analyses, the liquid flow should be modelled with full consideration of the Navier-Stokes hydrodynamics equations. Commercial codes such as FLOW-3D have been developed to carry out such analyses. The FLOW-3D code is based on finite differences, but other methods exist, such as combinations of finite-element programs and boundary element programs (e.g. Ref.13). These general purpose programs are computation-intensive, and have not yet been developed/simplified to a degree sufficient for spacecraft attitude and orbit controller design and performance evaluation. Moreover, validation of the software remains a challenging objective.

To simplify the modelling and subsequent analysis, engineers have long ago taken recourse to simplified mechanical systems that can be made to duplicate the dynamics of the liquid in one particular state. Dynamics near that state are predictable with fair accuracy. In the case of small spacecraft motions (linear dynamics) one aims at reproducing the resonance frequencies of the sloshing modes. The archetype model involves a point mass m_1 that accounts for the liquid that remains solidly attached to the container, plus a point mass m_2 attached with linear springs to the wall of the container. The momentum of m_2 is to account for the free surface wave motion. The influence of this motion on the spacecraft is represented by the force exerted by the spring on the wall (Ref.5). Several such mass-spring systems may be introduced, to represent sloshing in several modes. Linear dampers may be introduced to represent liquid viscous damping. A related equivalent model is the one displaying a pendulum with a linear torsion spring. Liquid swirl can be represented through the introduction of one or more reaction wheels with torsion springs. See also Refs.1,2,4,11. When large linear and angular motions occur, these mechanical models become deficient in their power to represent liquid dynamics.

In view of this state of modelling, it was decided to advance in an organized manner: develop an improved equivalent mechanical model for interaction dynamics prediction for arbitrary motions and suitable for controller design, develop a reliable CFD code for highly accurate dynamics predictions, and develop a small spacecraft for in-flight experimentation and interaction dynamics software validation. The next sections of the paper elaborate these activities.

3 Sloshsat mini-spacecraft project

A small (115 kg) spacecraft named Sloshsat FLEVO (Facility for Liquid Experimentation and Verification in Orbit) has been defined at NLR for the experimental study of the dynamic effects of onboard liquid. The users of the spacecraft measurements are assembled in an Investigators Working Group (IWG). An objective has been to pair complementary investigations such that an experimental control scenario generates a liquid flow that is amenable to verification by CFD.

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 Fig.1. With respect to the center of the box, the spacecraft com is near the Z-axis, at location -0.20 m. The principal moments-of-inertia (“moi”) 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 about 80 kg.

The payload is a cylindrical tank with height equal to radius and with hemispherical ends. The cavity of the tank is smooth and has no inserts. Its radius is 0.228 m, so the capacity is about 87 litres. Contained is 33.5 litres of water. The tank center line is parallel to the X-axis ; its center is on the Z-axis, 0.07 m above the midpoint of the box. The material of the tankwall is polyethylene, for its resistance to leaching and to allow capacitive sensing of liquid height.

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 (Ref.6), and the tank instrumentation.

The principal instrument 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. In addition there are embedded sensors for velocity and thermodynamic measurements.
Fig.1 shows the locations of the 12 nozzles of 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 midplanes.

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, the preliminary launch date is set for December 1999. After ejection from the Space Shuttle, Sloshsat stays near and communicates with the ground operations center via a transceiver on the Hitchhiker bridge.

Altogether 24 hours of free-flying experiment operations are planned, distributed over the Shuttle time in orbit.

4 Sloshsat Motion Simulator

NLR will be responsible for the operation of the spacecraft and for the establishment of initial conditions of the spacecraft state, prior to the experimental investigations. For this reason a simulator has been developed about a core denoted by SMS (Sloshsat Motion Simulator). Some validation of SMS has been achieved with the accurate prediction of the PAM-D anomaly (Ref.15). Further validation proceeds by using CFD predictions of experimental investigations by IWG members.

SMS predicts the dynamic behaviour of two interacting bodies : the tank with a contained slug. For convenience, both the tank cavity and the slug are taken to be spherical, a limitation that can be removed if necessary. However, the spherical approximation is expected, on the basis of integral theorems, to be suitable for the Sloshsat geometry. The slug radius is variable in a range such that the slug moi spans the range of moi's of liquid in the Sloshsat tank. The slug has uniform density and always contacts the cavity wall. At the point of contact a force F_L and torque T_L, act. A sketch of the geometry, with the important variables, is given in Fig. 2.

The constitutive equation for the slug radius has been derived as (Ref.14):

$$\ddot{y} + Ay - By^{-3} = N \qquad (1)$$

where A is a constant that contains the surface tension of the liquid, B contains (the square of) the angular momentum of the liquid, and N represents the radial force on the slug. The surface tension should be specified negative if the wetting conditions in the tank are such that the liquid is spreading, i.e. tries to achieve its maximum moi. A term with $\dot{y}$ can be added to represent damping. Comparison with analytical results showed the slug to have dynamic properties similar to liquid drops or bubbles of the same size. The appropriate dynamics equations for the slug can be derived in the form (Ref.14):

$$\mathrm{m}\left[\frac{\mathrm{d}\underline{\mathrm{V}}}{\mathrm{dt}} + \underline{\dot{\mathrm{v}}} + 2\underline{\Omega}\times\underline{\mathrm{v}} + \underline{\dot{\Omega}}\times\underline{\mathrm{r}} + \underline{\Omega}\times\left(\underline{\Omega}\times\underline{\mathrm{r}}\right)\right] = -\underline{\mathrm{F}}_{\mathrm{L}} \qquad (2)$$

$$\frac{2}{5}m(R-r)\left[-2\dot{r}\left(\underline{\Omega}+\underline{\omega}\right)+(R-r)\left(\underline{\dot{\Omega}}+\underline{\dot{\omega}}+\underline{\Omega}\times\underline{\omega}\right)\right] = -\underline{\mathrm{T}}_L - (R-r)\underline{e}\times\underline{F}_L \qquad (3)$$

where $\underline{V}$ denotes the linear velocity of the spacecraft com, r the relative position of the slug, $\underline{v}$ the relative linear velocity of the slug, $\underline{\Omega}$ the spacecraft angular velocity, and $\underline{\omega}$ the relative angular velocity of the slug. Additional equations must be introduced in order to make the SMS model determinate. These equations relate the force F_L and torque T_L to the dynamic variables, except for the normal force which is made determinate by Eq.(1). It is noted that other relations could be used to complete the formulation of the model. An extra relation had to be incorporated also in SMS: at its minimum it is necessary to fix the size of the slug. In consequence the slug acts as if frozen, i.e. as a solid. Then the value of the normal force is obtained by the solution of the equations, but required is the specification of the process that makes the transfer of momentum between tank and slug determinate. For this purpose the outcomes of SMS were compared with the prediction by a CFD package of the interaction force between liquid and tank; see next.

5 Remarks on CFD activities

In support of the Sloshsat project the University of Groningen (RUG) has further developed its CFD package COMFLO to predict the behavior of liquid in the Sloshsat tank (see http://www.math.rug.nl/~veldman/cfd-gallery.html). With this package the trajectory of the liquid com and 'normal force' values for a Sloshsat motion have been calculated for comparison with SMS data. The 'normal force' is calculated as the inner product between the total liquid force on the tank, and the direction vector from the tank center to the point on the wall where the force acts, as determined from the total torque by the liquid on the tank.

We show some results from a simulation of a maneuver designed to transfer liquid from one end of the tank to the other end, and to keep it there. The desired motion is therefore a linear translation of the tank along its centerline. However the com of Sloshsat changes during the liquid transfer, and the thruster action does not pass through the com, so that a torque must be generated on Sloshsat in order to keep the centerline parallel to its initial direction in inertial space. The results (Fig.3) are quite comparable to the SMS predictions (Fig.4). (In Fig.4 the horizontal line gives the force due to surface tension at minimum slug size.). Notice the effect of thrust pulses (3 Hz) and of liquid and slug oscillations. Fig.4 also shows the temporal average of the normal force; this plot passes through the center of the black area of high frequency numerical noise generated by impacts on the tank. A plot of the liquid com in the tank (not shown here) indicates that the liquid moves nearly symmetrically to the other end of the tank, as desired.

6 Remarks on control design efforts

The two principal control objectives are: pure spin-up and spin-down of the spacecraft around each body axis consecutively, to achieve Weber numbers from zero to fifty; and pure acceleration along the tank centerline, holding angular rates to zero, to achieve a Bond number of twelve.

The most straightforward method would be to carry out pure open-loop control, starting from a perfectly quiescent initial state. However, some amount of feedback control would be required to help reach the principal control objectives. Moreover, it would be desirable to introduce a control concept such that the desired quiescent initial state will be attained in short time. Several control concepts have been developed for this purpose. To align the angular velocity vector with one of the tank principal axes, a control concept has been proposed which uses information about actual angular velocity and location of system com. The latter data are obtained by processing the MSS output. To damp to motion of the liquid, the control concept employs in addition information about the swirl of the liquid. Both control concepts are derived from the SMS model. To improve robustness, a further control concept has been proposed based on the use of thrusters with local linear acceleration measurements and on Lyapunov theory. This leads to a set of six independent second order controllers, one for each degree-of-freedom. Further research is to be conducted, taking into account thruster output levels and state estimation errors.

7 Concluding remarks

The interaction between dynamics of spacecraft and dynamics of contained liquids is of great importance. It impacts on spacecraft stability as well as on mission performance. The absence of an effective gravitational field renders current mathematical dynamics models complex and computationally intensive, and renders their validity somewhat questionable in the general case due the absence of adequate controlled zero-g experimental results. An in-orbit test program has been conceived that aims at increasing one’s grasp on this difficult subject. The Sloshsat mini-spacecraft is to be play a key role as free-flying test bed.

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Acknowledgements

Sloshsat FLEVO is a harmonized program between ESA and the Netherlands Agency for Aerospace Programs (NIVR). Main contractor is the National Aerospace Laboratory NLR, with participation of Fokker Space, Verhaert, Newtec, Rafael, and NASA. The Sloshsat FLEVO development is carried out within the framework of the ESA Technology Development Programme (TDP) Phase 2 and the NIVR Research and Technology (NRT) program.

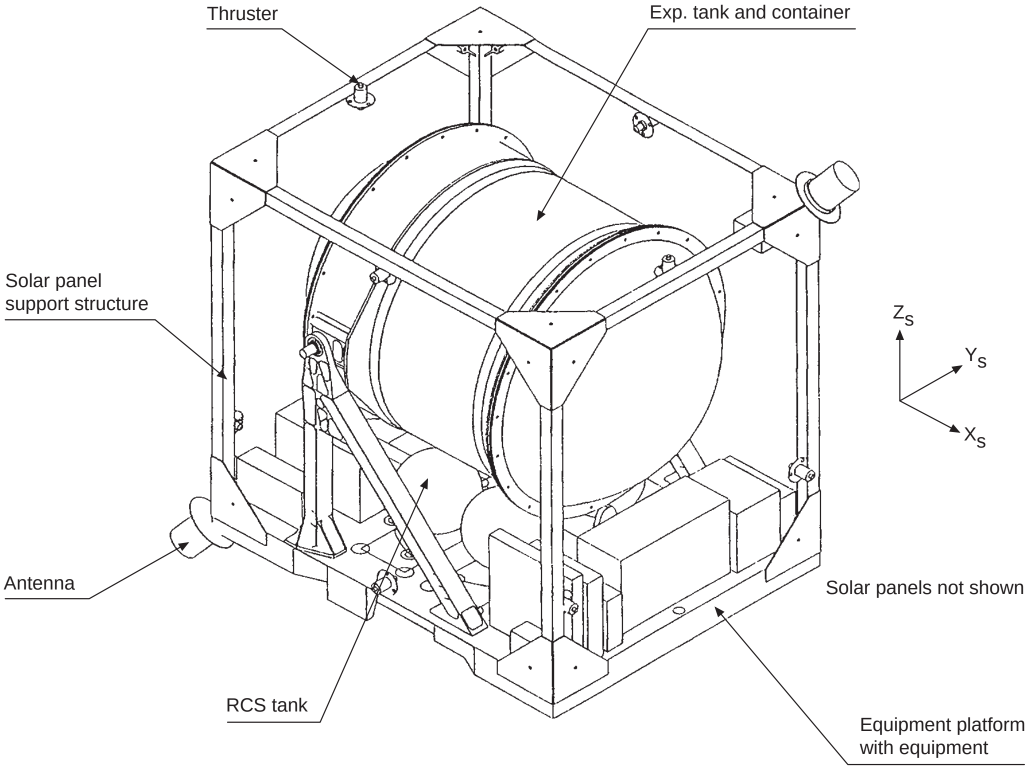

Fig.1 View of the Sloshsat main components

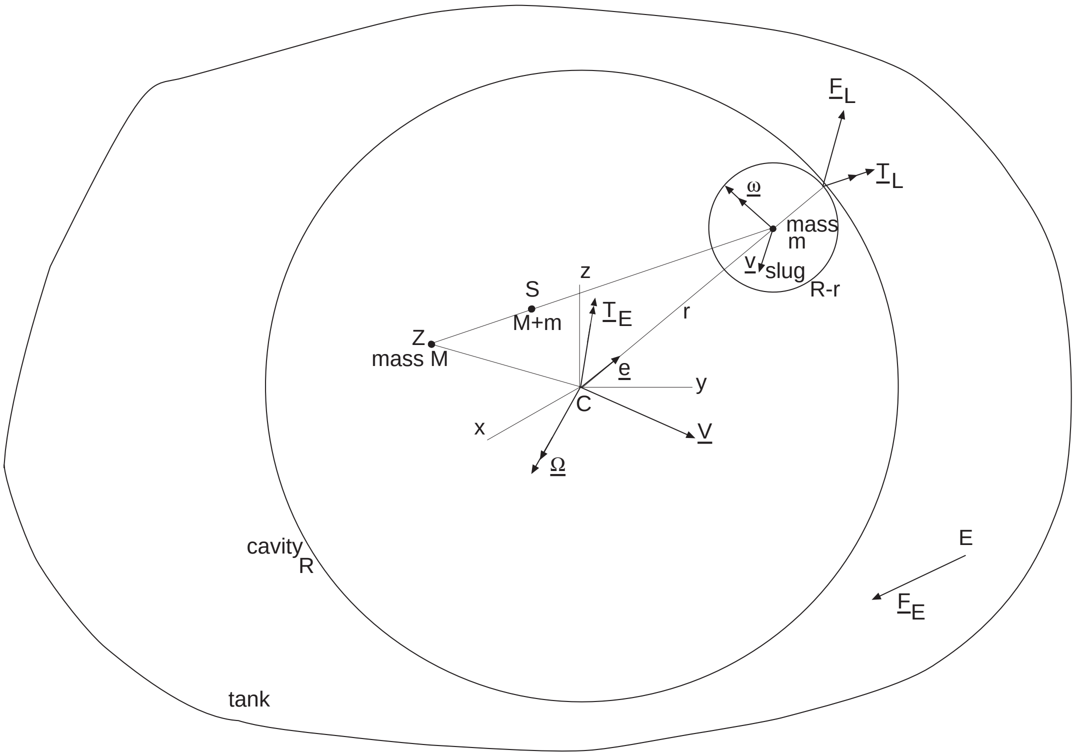

Fig.2 The spacecraft and slug dynamic two-body system

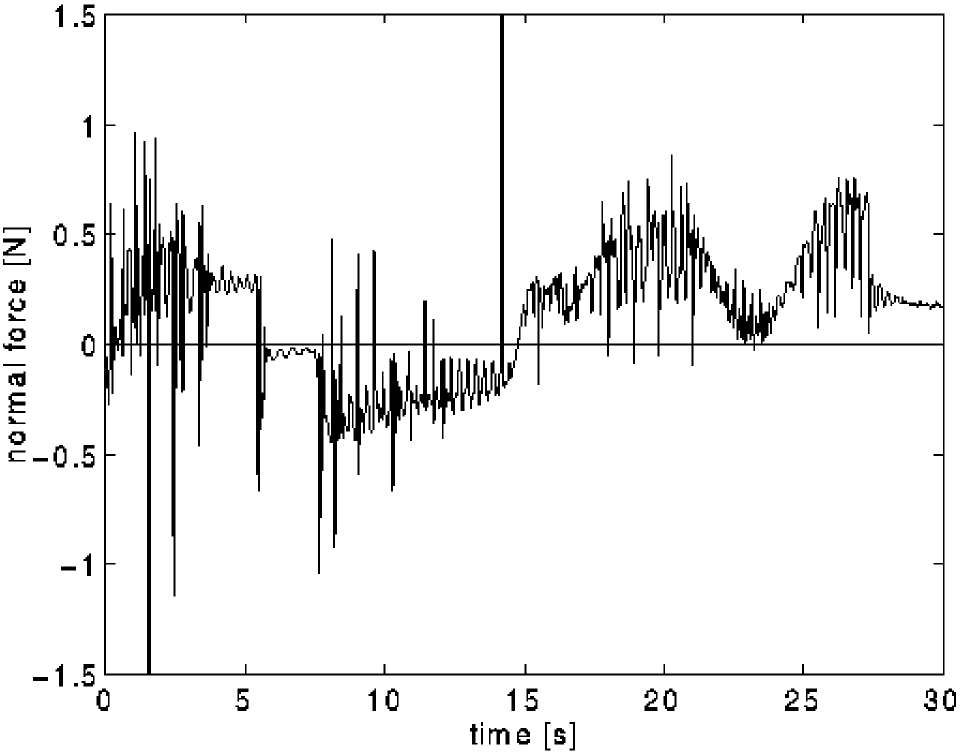

Fig.3 Net normal force (Newton) between fluid and spacecraft versus time (seconds), as computed with the CFD package COMFLO

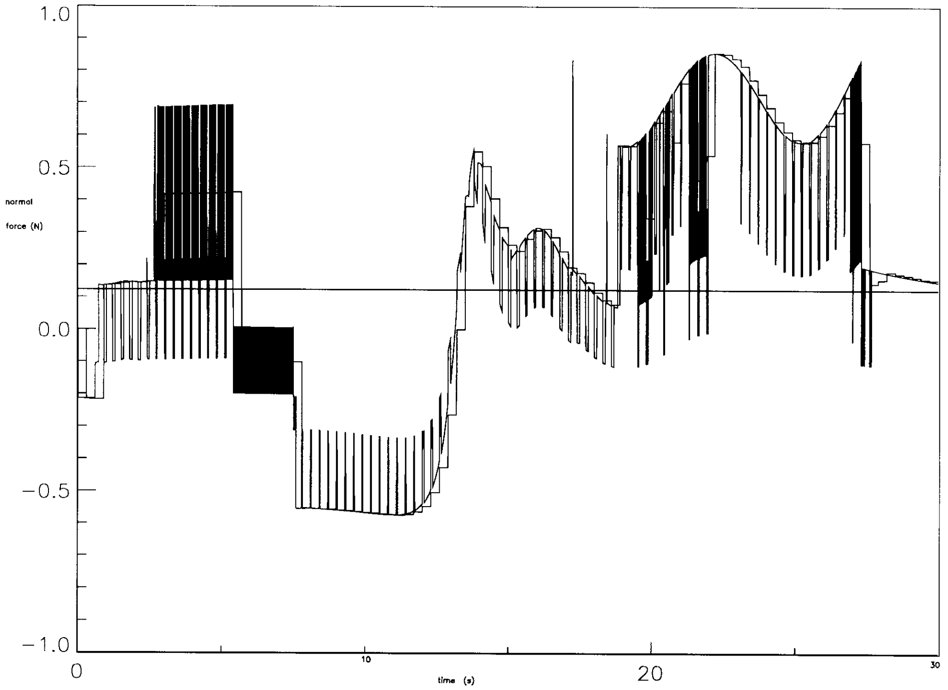

Fig.4 Normal force (Newton) between slug and spacecraft versus time (seconds), as computed with the SMS two-body simulator