THE SPONGE REXUS PROJECT: OVERVIEW OF A SOUNDING ROCKET EXPERIMENT FOR PMDs

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ABSTRACT

This paper describes the SPONGE experiment (Sounding rocket Propellant OrieNtation microGravity Experiment) developed at CISAS in collaboration with Thales Alenia Space Italy. The aim is to validate CFD codes created to study and design Propellant Management Devices in low-gravity.

SpongeCompressibleFoam is a code based on the OpenFOAM Platform, written at CISAS to simulate propellant management devices. These are passive static metal structures used in rocket tanks to control propellant behaviour; they work using surface tension to ensure gas free liquid delivery to the tank outlet.

SPONGE flew on board the REXUS9 ESA/SSC/DLR sounding rocket in February 2011 and it is designed to verify code predictions in low-gravity. It is based on two counter rotating plates: (i) the experimental plate on which the control equipment and a polycarbonate tank containing the sponge test-sample are placed, (ii) the balancing plate, rotating in the opposite direction with respect to the experimental plate and assuring a zero momentum transfer to the rocket.

The system rotates at four different angular velocities, allowing the study of the sponge behaviour and retention capability under different centrifugal forces. The design and results are presented.

ACRONYMS

SPONGE	Sounding *rocket Propellant OrieNtation microgravity Experiment*
PMD	*Propellant Management Device*
CFD	*Computational Fluid Dynamics*
ESA	*European Space Agency*
SSC	*Swedish Space Corporation*
DLR	*Deutsches Zentrum fur Luft- unt Raumfahrt*
UM	*User Manual*

1. INTRODUCTION

PMDs are passive metal devices used in rocket tanks, which work in low-gravity. They ensure gas-free propellant delivery to the outlet and guarantee a better propellant consumption, improving motor performance. For these reasons, it is important to study their behaviour and to test them.

In the past, many different experiments have been conducted to test PMDs and liquid behavior in low-gravity. There are different possible facilities, depending on the desired test duration and load factor (a/g_0):

Facility	a/g0	Duration [s]
Drop towers (free floating)	< 0.01	2-3
Drop towers (bracing wires)	0.01	5-10
Parabolic flights	< 0.02	30(each parable)
Sounding rockets	0.001	180
Buoyancy facilities	~Δρ	static

Thus, the main reasons to choose a sounding rocket instead of another facility are connected to the low gravity level that can be reached and to the possible

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longer duration of the experiment in the required conditions to test the PMD.

2. MAIN OBJECTIVES

The SPONGE experiment design has the following main goals:

- To validate a 3D CFD code developed at CISAS and able to simulate sponge PMDs;
- To verify the sponge retention capabilities during the flight;
- To extend the results found using the Bond number and the similarity principle.

Since a dynamic behaviour of the fluid in low-g cannot be reproduced on ground, data from a real flight and microgravity environment are needed.

The numerical code developed is based on the OpenFOAM platform [7]. It is a 3D transient VOF (Volume Of Fluid) code, which allows simulations of PMD screens without simulating all the pores characterising them. This accounts for an overall reduction of the computational costs and also simplifies the creation of the test case geometry, since it becomes useless to reproduce all the pores.

The results of the experiment are used, after the necessary elaborations, for a comparison with the behaviour predicted by the numerical code designed. In particular, the frames acquired during the flight and containing useful information about the liquid position and dynamics, need to be synchronised with the accelerations and velocities registered on board the experiment by the devoted sensors.

Figure 1.sponge PMD device mounted on its titanium base.

Then, the same acceleration profile of the flight phase will be reproduced by the numerical solver and the liquid surface positions will be compared with those that can be seen from the frames of the cameras.

3. EXPERIMENT DESCRIPTION

SPONGE consists of two different plates, housing different parts of the experiment. The upper platform rotates at four different velocities to impose the desired acceleration profile to the liquid wetting the sponge, which is inside a polycarbonate tank having a 2.5cm radius. It is placed 12.5cm far from the rocket spin axis, and it is therefore subjected to a centrifugal force. The profile is guaranteed by a DC motor coupled with encoder and gearbox. An RTD (Resistance Temperature Detector) monitors the liquid temperature, to verify the constancy of its properties (such as surface tension); a 3-axis MEMS accelerometer monitors the accelerations transmitted and a gyro measures the rotational velocities applied to the experimental module. These sensors need to be conditioned by appropriate electronic boards and to this extent, five conditioning boards are used, one for each sensor channel, all attached to the upper plate. A panel with 9 LEDs lights up the sponge area. Two cameras are connected to a frame grabber to acquire the frames of interest during the flight, from the rocket lift off until SPONGE is switched off.

The electric power is given to the system by the REXUS service module and a specific board has been foreseen to manage the power transmission to each of the electronic components.

A Helios PC/104 board controls the acquisition of all the signals and manages the control of the experiment timeline. This board is also connected to the acquisition board and to the frame grabber and houses a specific flash memory, where the flight data are recorded and stored.

The bottom plate is counter-rotating with respect to the main one and its motion is due to another motor of the same type. This design is meant to avoid the transfer of any produced angular momentum to the rocket.

The experiment is connected to the module case by means of the bulkhead, which we have been provided with. Picture n.2 shows the entire experiment module.

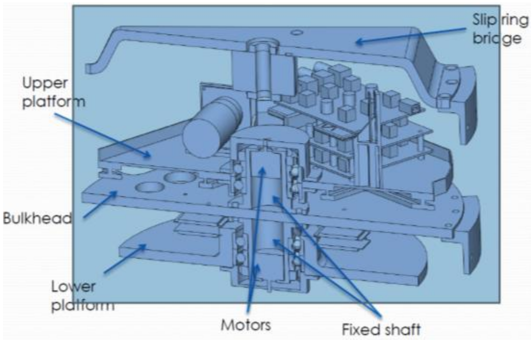

Figure 2. SPONGE experiment, CAD design.

The motor control board is attached below the bulkhead, it activates the drivers. These allow the two motors to impose the correct velocity profile to the plates and are placed below the bulkhead too.

The power transmission from the service module to the two plates is guaranteed by a slip ring. It is fixed to a bridge, which is in turn connected to the rocket case by means of two brackets. The slip ring is also used to transmit the signals from the upper to the counter rotating plate. This operation is particularly important, because both data recording on board and data downlink to the ground station (by means of the RS422 serial port to the service module) are performed.

It has been impossible to downlink the frames acquired, because of the reduced band width available. Thus, only the acceleration, temperature and rotational velocity signals have been down-linked, whereas the images have been stored on board.

In order to guarantee the experiment to be locked during the launch activities, a Cypres pyro cutter was used (the same used by paratroopers).

It was connected to a nylon wire provided by the same company, which had to be passed into some holes, one per each rotating plate, and then wrapped around a screw. With this technique, the wire was tight and the plates were locked well enough to overcome the launch phase without causing any damage to the experiment structure.

3.1. Mechanical Structure and Requirements

SPONGE mechanical structure has been designed in order to be housed in a module of the following dimensions:

- Height: 220mm;
- Diameter: 345mm.

The design process followed both analytical considerations (in the preliminary phase) and a FEM verification.

The design requirements and targets were:

- The structure had to withstand the vibrational environment during launch and re-entry;
- Electronic boards had to receive a heat input compatible with their operative range.

A FEM model has been developed, with a static acceleration as the structural load data, according to the UM (10g lateral, 20g axial). A minimum safety factor of 2 has been applied.

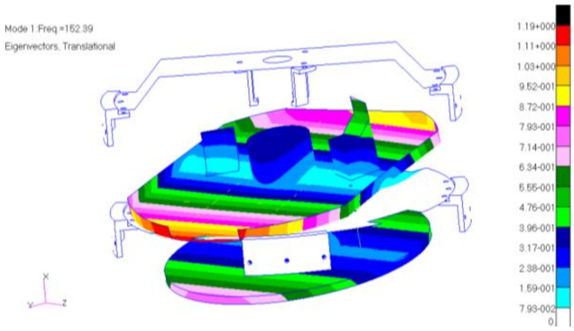

Figure 3. SPONGE experiment, FEM analysis.

Modal analysis has been used to avoid coupling rocket frequencies with the experiment ones. A minimum natural frequency of 300Hz for every single component has been set, while on the whole system 150Hz has been imposed as the lower limit.

Random vibration and sinusoidal (with fixed PSD) has been simulated, the observe the behaviour of the structure subjected to such loads (imposed by REXUS UM).

The material selection led to the adoption of aluminium, to reduce weight and maintain an acceptable cost of the experiment. To reach the objectives, ERGAL (Al7075 – T6) has been chosen.

Titanium was used for the sponge, and polycarbonate for the tank: usual material choices for transparent tanks are polycarbonate or plexiglass; while the second is stronger (higher yield stress), the first is more ductile, so it is easier to manufacture.

The thermal analysis performed showed that it was not necessary to use heaters to withstand thermal stresses; the lowest possible temperature was -30°C, dictated by the launch facility (Kiruna, Sweden) and the period for launch (February). The highest temperature can be reached in the ascent phase

In both cases, FEM transient analysis has been performed to determine the temperature reached by each component.

Electronic boards and cameras have been considered as a point mass both in the structural, vibration and thermal analysis.

3.2. Electronics

The electronics has been designed to:

- acquire two cameras;
- acquire the signals of a 3-axes accelerometer;
- acquire a gyroscope signal;
- read an RTD temperature sensor;
- control the two motors imposing the desired velocity profile;
- allow the communication between the experiment and the Service Module;
- require a power lower than 30W.

Since the motors are fixed on the bulk-head and all the sensors are on the rotating platform, the electronics has been split into two sub-systems:

- an acquisition system, fixed on the upper rotating platform where the PMD is located;
- a motor control system, fixed on the bulk-head.

The two systems are connected together through a slip-ring. The communication chosen is an RS422, the same used for the communication with the Service Module.

The Acquisition system is controlled by one PC104 SBC (Single Board Computer) acquiring the PAL signal from the cameras through a frame grabber, the analogue signals from accelerometers gyroscope and RTD.

The PC104 format has been chosen for the small sizes required for the whole experiment. The board chosen contains almost all the required functionalities.

Each analogue signal is filtered through a 5th order Bessel filter. This is possible thanks to five conditioning boards, one for each channel, with high-impedance differential inputs. The conditioning board for the RTD contains also a sink-type current source, thus allowing a 4-wire resistance measurement.

All the boards are powered by Power Regulators fixed on the rotating platform. In this way, the stabilized voltages do not pass through the slip-ring.

The Motors Control System is controlled by another PC104 allowing the communication between the PC104 located on the rotating platform and controlling two motor drivers though two RS232 ports.

Each driver is connected to a motor, receives the desired speed level from the SBC, and controls the speed reading its value from the quadrature encoder integrated in each motor.

Another power regulation board has been used, equal to the one previously described.

3.3. Software Design

SPONGE software structure has been designed to the maximum simplicity and highest possible reliability. The software tasks have been divided into different executables, so that they can be respawned by a software watchdog. The operating system is a standard Debian GNU/Linux, except for the kernel, which has been re-built to ensure operation on the 300 MHz PC104 hardware and to speed up the boot process.

Each board starts its own control software, managing the communication and taking care of starting the other tools and getting feedback from them.

The board 1 control software accomplishes the following tasks: (1) monitors the status of the board and of the signals (LIFTOFF, SOE); (2) communicates with board 2 through an RS422 link; (3) manages the ground downlink communication, which sends status packets from both boards to the GSE. It also receives the commands from ground segment. (4) When the SOE signal is received, starts the motor control software to execute the predefined rotational speed profile.

The board 2 control software: (1) controls data acquisition, acquiring the signals from the accelerometers, the gyro and the RTD sensor, using the ADC converter of the PC104 board (all data are saved to the flash memory disk); (2) communicates with the board 1 through the RS422 link, sending sub-sampled data from the sensors (to avoid bandwidth saturation), and receiving commands from the board 1; (3) starts the video acquisition application, which opens the two video channels and starts saving to disk frames at 25 fps in JPEG format. No image data is sent through the downlink, because this would require too much bandwidth.

4. QUALIFICATION TESTS

Various tests have been performed in order to assess SPONGE readiness for the flight and the satisfaction of the requirements. These tests can be broadly divided among:

- Tests conducted on the mock up, to verify concretely the elimination of the residual angular momentum transferred to the system.
- Thermal-vacuum tests performed on each of the experiment electronic components separately to verify them using a temperature range as close as possible to the flight profile.
- Vibration tests, at TUV (To, Italy) to determine the first mode of SPONGE structure and verify that it was different from the launcher frequency.
- Extensive software tests
- Functional tests, after each mechanical or thermal test, to verify the correct system operation.

4.1. Mock up Tests

A functional mock-up has been built to test the counter-rotating platforms and the angular momentum transferred to the bulk-head.

It is composed of two platforms simulating the two real rotating platforms and producing the same momentum of inertia, but with a simplified shape, in order to reduce the production costs. A third platform reproduces the bulk-head and is still, if no momentum is transferred.

These three platforms are connected to reproduce the flight configuration.

If one motor produces a different angular momentum with respect to the other, the central platform starts to spin. In this case, an angular momentum of a certain value is transferred to the rocket.

The two motors are connected each to a dedicated driver. Sending the speed profiles to the drivers is possible and also necessary to verify what will happen during the flight.

Using the mock up and its response to the different velocities, the PI control loop has been tuned.

4.2. Vacuum Tests

All the electronic boards have been tested as separated items, to check their behaviour in vacuum conditions and to verify if their temperature remains below the maximum allowed.

The maximum temperature measured is 50°C, on a processor (the maximum temperature for it is 85°C).

A test of the whole system has been performed to check all the boards in the final configuration. A complete flight test has been performed, and all the temperatures measured were in the range already observed during the previous tests.

The pressure in the chamber reaches 7 mbar. It is higher than the value expected during the flight, but from the calculations done, there is no relevant difference in terms of the convection coefficient in the two cases. In fact, convection is in any case less important than thermal radiation, as a heat exchange mechanism at these altitudes.

4.3. Vibration Tests

The vibration tests have been done at TUV, Italy and have been possible thanks to TAS-I.
All the three axes have been vibrated, following the indications given in the REXUS manual.
It is evident that a notching had to be applied to filter the frequencies used to vibrate the experiment, in order to avoid possible damages to the most loaded parts.
Picture n.4 shows the fixture connecting SPONGE to the vibrating basement. In case of x and y verification (the axes within the plane of the vibrating basement), the fixture did not have the central ring, whereas it was stiffened when vibrated along the vertical axis, as illustrated in picture n.4.

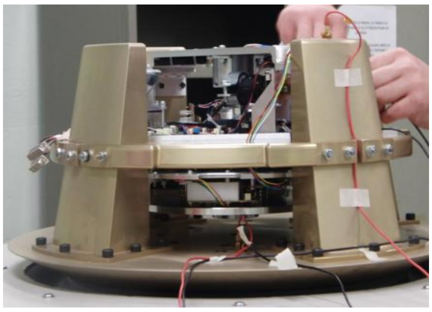

Figure 4. SPONGE experiment fixed to the fixture for the vertical vibration tests.

During the various tests, the procedure followed for each of the solicited axes, was:

- Sinusoidal frequency swap, to identify the first natural frequency;
- Very low level corresponding to 1.49 Grms;
- Notched low level corresponding to 1.98 Grms, to avoid resonance;
- First intermediate level corresponding to 2.8 Grms;
- Second intermediate level corresponding to 3.97 Grms;
- Full vibration level of 5.6 Grms.

The results of these tests have been successful on all the vibrated axes. The functional tests performed after each axis had been vibrated, showed that the experiment was working as expected and had not been damaged by the test.

4.4. Software Tests

The tests on the software have been conducted to verify each single block and task. This allows to find the eventual bugs more easily. Only after having tested the different functionalities separately, the whole software has been tested in terms of data acquisition, recording and transmission to the ground station altogether.
During the various tests, some minor adjustments have been done on the software, but in conclusion, there have been no critical problems.

4.5. Functional Tests

These tests have been performed to verify the general behaviour of the system, which has to fulfil some specific requirements.
Functional tests have been carried out: to verify the behaviour of each of the system components after they had been subjected to vacuum; to verify the electric connections after having soldered the cables, to check the cameras positions, distance and focus on the sponge device and the lighting quality; to ensure that the system had not been damaged during the vibration tests.
A series of functional tests was performed during the launch campaign at Esrange, to ensure that the experiment was working, before the bench tests and the final payload integration.

5. LAUNCH CAMPAIGN AND RESULTS

SPONGE experiment behaviour has been investigated starting from the signals acquired during the flight, after their synchronisation with the flight events timeline.
After the first 65 seconds of the flight, in which the rocket was spin-stabilised, it is possible to see three different peaks, which are particularly evident when looking at the red signal corresponding to the z axis in picture n.5.
The first acceleration peak on the left is the lowest in terms of acceleration amplitude and it corresponds to REXUS9 yo-yo de-spin; the second one, both in time and amplitude, corresponds to the nosecone ejection; the third one has been identified as the motor separation, due to which an impulse was given to the tank and consequently a certain amount of liquid was absorbed and withheld by the sponge (due to capillarity forces).
In particular, from picture n.5, it becomes clear that the platform did actually start to rotate, and it stopped only after few seconds.

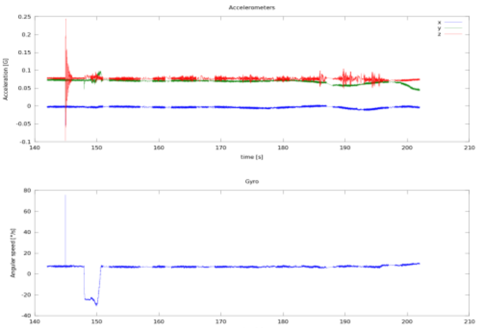

Figure 5. Signals acquired by the on board sensors. The box above shows the three accelerations, the one below the rotational velocity profile.

The number of the frames acquired by the two cameras is not always constant in equal time intervals, and this depends on the Helios board acquisition characteristics and in particular on the fact that it has a lower speed of data acquisition with respect to the frame grabber transmission velocity. The following list resumes the main aspects of the liquid motion inside the tank during the initial spinning phase and in the following phase, until the end of the experiment.

At the beginning, the liquid is attached to the tank wall due to the spin of the rocket.

The first more visible movement of the liquid is due to REXUS yo-yo despin. After this event, the fluid spreads remaining attached to the wall and occupies a more extended region.

When the nosecone detaches, a movement is slightly visible through the liquid bulk, but it does not cause its absorption in the sponge.

When the motor detaches, this causes an excitation acting on the liquid, which is pushed towards the sponge device and is partially absorbed.

With respect to the CFD simulations carried out before the flight, during the launch and the experiment phase, the liquid moved and rotated slower after the despin of the rocket. Thus, an investigation is being conducted to determine the reasons of the differences found.

The fact that not as much liquid as desired has been trapped by the sponge has not caused the total loss of the scientific data needed. In fact, even if it is impossible to determine the retention capability of the PMD device, an analysis will be carried out comparing the CFD and the flight experiment results. The complete liquid dynamics will be reproduced applying the same acceleration profile acquired during the flight, to the numerical simulation. This way, the 3D CFD developed at CISAS will be validated in terms of the global behaviour of the fluid inside the tank.

In order to have more detailed information about the retention capability of the sponge device or to verify the bubble point phenomenon, more data are needed and a new, upgraded version of SPONGE is required.

6. CONCLUSIONS

Concerning SPONGE behaviour during the flight and a possible upgrade, it is possible to say that:

- The platforms started to rotate, but they stopped due to a design problem (motors undersized) or to the cables that detached from their holders and prevented it from continuing the rotation.
- The liquid did not fill the sponge PMD, therefore the rotation of the platforms would have been helpless for the experiment in these conditions.
- The software and electronics worked very well and performed exactly the tasks expected.
- The design should be improved inserting a specific mechanism, to make sure that the liquid inside the tank goes into the sponge to be withheld due to capillarity forces.
- The scientific data are useful for the code validation, because the real liquid dynamics during the flight can be used to make comparisons with the results obtained from the OpenFOAM CFD code.

For the CFD code validation, it is possible to use, at least on a qualitative point of view, the data found from SPONGE flight. Anyway, also other information will be used, based on on-ground bubble point experiments.

In the meanwhile, an investigation is being conducted to identify the reasons of the failures found during the flight and to create a new upgraded experiment from SPONGE.

The scientific objectives will remain the same, but the causes of the previous failures will be eliminated.

7. AKNOWLEDGEMENTS

This experiment was possible thanks to the funding we got from Thales Alenia Space Italy. They provided us with the money and the facilities we needed to design and manufacture our experiment. Andrea Scapin was the company in charge of SPONGE manufacturing. The mock up was built by this company and Andrea personally supervised us during the assembly of the flight experiment.

Antonio Selmo is the electronic engineer and professor who designed and manufactured the conditioning boards and the two driver boards. He supervised us in various activities: soldering the MEMS sensors, creating and verifying all the SPONGE wiring. He allowed us to enter his laboratory and work with him, to test our electronics.

UNAVIA ATS produced the sponge device, together with the titanium plate supporting it.

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