ANALYSIS OF GOCE'S DISTURBANCES INDUCED BY HYPERVELOCITY IMPACT

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ABSTRACT

In this paper it is presented a general overview of the study "Spacecraft Disturbances from Hypervelocity Impact", performed by CISAS and Alenia Spazio under an ESA contract. The project aims at analyzing the propagation of shocks due to hypervelocity impacts from the external shell of a spacecraft to its internal components. Object of the study is the GOCE satellite, which has been recognized to be very sensitive to small disturbances because of its payload, that is very sensitive to acceleration.

In the following, the current development of the study will be also presented. Up to date, it has been focused on the review of GOCE configuration to design representative targets, on the experimental design and on the investigation of the background noise inside the CISAS Impact Facility.

1. INTRODUCTION

Space debris and meteoroids are a well known source of possible damage for satellites. Nevertheless, among the potential effects induced by hypervelocity impacts on a spacecraft, mainly direct structural damage has been investigated so far. However, some experiments have recognized that the shock environment induced by hypervelocity impact could be close to what is generate by Pyroshock devices [CNES, 2001; Pavarin et al., 2002], being therefore a real threat for equipment and instrumentation. The induced vibration environment have studied by means of acoustic emission by Prosser et al. [1996-1999] but its full characterization as suggested for example by NASA [1999] have not been jet performed.

The characteristics of the vibration environment induced by a hypervelocity impact are under investigation in the frame of the ESA contract "Spacecraft Disturbances from Hypervelocity Impact". Object of this study is the GOCE satellite, because of its very accurate and sensitive gradiometer, that is very sensitive to even very small external disturbances [Faraud, 2002, 2003]

Object of this investigation is to study the structural propagation of transient disturbances on typical satellite jointed panels, particularly closer to the GOCE ones. Beyond assessing the potential risk to the GOCE mission, this study aims also at the identification of a general numerical and experimental verification criterion allowing reliable prediction/characterization of the vibration environment induced by hypervelocity impacts to generic spacecrafts. The review of the structural configuration of GOCE has led to both identify the load paths and select the most representative targets configurations, to be reproduced within the experimental set-up. Preliminary tests have been performed at the CISAS Impact Facility to investigate its back ground noise. In this paper, a general overview of the study is presented together with the preliminary results obtained.

2. GENERAL OVERVIEW OF THE STUDY

The study develops through four main groups of activities:

- Review of Spacecraft configuration
- Target and instrumentation
- Impact testing
- Evaluation of the impact tests results
- Extrapolation

2.1 Review of Spacecraft configuration

This group of work packages is focused on the analysis of the configuration of a spacecraft (GOCE), particularly regarding the load paths inside the structure to identify the reference configuration to be tested in the framework of the study. These work packages aim also to identify impact conditions to be considered experimentally, through a detailed analysis of the MMOD environment relevant to GOCE.

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2.2 Target and instrumentation

These work packages are focused on the design and manufacturing of the target and on the procurement of the instrumentation. After preliminary SPH (Smooth Particle Hydrodynamics) analyses and the preparatory test campaign that identified the expected acceleration conditions, targets and experimental set-up have been designed and the instrumentation has been defined and procured. Finally the test matrix has been defined.

2.3 Impact testing

This group of work packages is related to the experimental activity and to the validation of the raw signals recorded during the experiments.

2.4 Evaluation of impact tests results

These work packages have to analyze the data provided by the experimental campaign. Considering the high challenging level of the activity, two parallel approaches have been introduced: a full experimental one and a numerical-experimental based one. In the first, data are analyzed to identify wave dispersion, attenuation and reflection and correlation between impact conditions and acceleration field are performed. In the second, experimental data are used to validate numerical analysis based on SPH, FEA (Finite Element Analysis) and SEA (Statistical Energy Analysis) to asses the possibility of using numerical techniques to propagate acceleration data inside complex structures.

2.5 Extrapolation

These work packages have been introduced to identify extrapolation options (with SPH numerical models) to extend experimental data to impact conditions (projectile mass and velocity) not achievable in laboratory. Moreover, other options are studied to propagate experimental (or numerical) data through complex assembly structures that have not been tested in laboratory.

3. REVIEW OF SPACECRAFT CONFIGURATION GOCE

The reference spacecraft selected for the *Spacecraft disturbances from HVI* study is the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite. This satellite is sensitive to very low acceleration and has to satisfy severe micro-vibration system requirements. Accelerations due to micro-vibration perturbations caused by various natural events, like atmospheric drag, Sun flux, MMOD impacts etc. have not to hamper the achievement of the required acceleration measures.

GOCE aims at providing global and regional models of the Earth's gravity field and of the geoid with high spatial resolution and accuracy.

The GOCE orbit is sun-synchronous (96.5 degrees of inclination), circular, at very low altitude (between 240 and 250 km). Launch occurs nominally in a well-defined time window (daily and seasonal) allowing optimal sequencing of the mission phases. The mission should start between 2006 and 2008.

The presence of eclipses affects the system operation and degrades the gradiometer measurement performance proportionally to eclipse duration. The system satellite cannot support battery recharging at full payload operation in presence of eclipses lasting as long as 30 minutes; moreover the gradiometer measurements are severally affected by thermal perturbations induced by long eclipses. For these reasons a particular mission profile has been selected. The optimal mission sequence assumes that launch occurs in an epoch when the nominal orbit is affected by long (up to 30') eclipses. Therefore, the *Commissioning* operations take place in presence of eclipses of diminishing duration and the first Instruments *Calibration* may start as soon as the Long Eclipse season is over. At the end of the Gradiometer set-up and calibration, the first *Measurements Phase* starts. The total duration of this phase is six months. Then, in presence of a second long-eclipse, a hibernation phase begins, which lasts as long as the duration of the long eclipse season (about 4 months). As soon as the eclipse duration has dropped below 10', the sequence of phases is repeated: new Gradiometer calibration (fifteen days) and new measurement phase (six months).

The GOCE configuration has been selected to satisfy both normal satellites rules like:

- Accommodation of spacecraft units
- Optimization of thermal dissipations
- Compatibility with Launcher's induced requirements.

and specific satellite necessities like

- Minimization of the disturbance torque and forces induced by the atmospheric drag with an optimized cross-section in the flight direction
- Maximization of the spacecraft passive aerodynamic
- Symmetrical configuration around the flight direction
- Provision to minimize clank and micro-disturbances effects

These requirements have been managed to obtain the present GOCE configuration design solution (see figure 1).

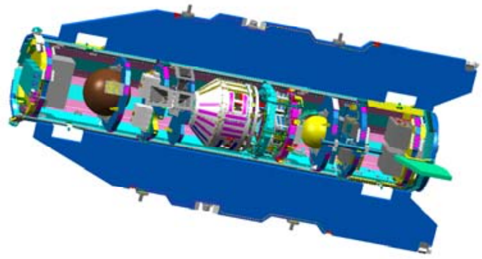

Figure 1 GOCE Satellite: Drawing of the present GOCE configuration.

The satellite consists of an octagon prismatic shell, about 5 m long and with a transversal cross section of about 1.1 m². The octagon is composed of a single half shell of 180° and of eight additional panels that are part of the backside shell for integration reasons. Once in orbit, the half shell is pointing towards the sun, while the remaining panels are in shade. All electronics units are placed on seven internal platforms labelled floors. The octagonal shell is a sandwich structure with CFRP face-sheets 2 mm thick and Al H/C core 11 mm high. Five floors are both with face-sheets and H/C in aluminium, while two floors are with CFRP face-sheets and H/C in aluminium

The Octagonal cylinder detachable panels are connected together by CFRP lashings, through hole inserts and screws.

Figure 2 Picture of the GOCE Engineering Model EM.

The floors are attached to the Octagonal cylinder by embedded metallic brackets. Each embedded bracket provides typically four threaded holes to fix the floors to the side panels of the octagonal cylinder (see Figure 3)

Figure 3. Picture of the connection between floor and side panels.

High structural stability is a crucial requirement in order to fulfil alignment, gravity gradient and micro-vibrations requirements under relevant perturbations.

The mechanical stability is to be guaranteed during the calibration and the measurement phases of the mission. The micro-vibration environment shall not interfere with the GOCE measurements. Therefore, limited residual accelerations and vibration constituents shall turn up at the Gravity Gradiometer Accelerometer Sensor Head (ASH) locations.

There are basically two main micro-vibration requirements: the first in the time domain, as maximum expected micro-vibration acceleration amplitude; the second in the frequency domain, as linear micro-vibration acceleration spectral density. If the micro-vibration time requirement is violated, the output of the scientific channel can be saturated, while if the micro-vibration frequency requirement is violated, the quality of the scientific measurements can be not sufficient to achieve the mission objective.

The micro-vibration disturbances produced by all possible satellite's internal sources are to be limited in order to not generate any linear acceleration at the location of each ASH accelerometer with amplitude higher than 2.0E-05 m/s^2. Events producing accelerations violating the micro-vibration requirements but not exceeding the level of 2E-05 m/s^2 can be tolerated, provided that they do not occur more frequently than 1 per day and their duration is less than 10 s.

The micro-vibration requirements are defined at the ASH locations. The application of the structural transfer functions allows redefining the acceleration spectral density micro-vibration requirements specified at the receiver locations in terms of force spectral density micro-vibration requirements specified at the disturbance source locations. The GOCE general acceleration-to-force transfer function is derived by dedicated GOCE mathematical model (FEM), simulating the structural transmission between any disturber and receiver location.

4. PRELIMINARY ASSESSMENT OF MMOD IMPACT DISTURBANCES IN GOCE

The effect of MMOD impacts on the GOCE satellite has been preliminarily evaluated by Faraud [2002, 2003]. A MMOD impact is a complex phenomenon, which produces a wide range of compressed/shocked states and dependent expansion states. Purely elastic behavior, plastic flow, melting, vaporization and changes in chemical or electronic structure can occur during a single impact event. In thin plates, the shock propagates parallel to the face of the plate in a quasi-planar way, then it expands in the plane of the plate. The developed quasi-planar shock degrades during the time as consequence of shock divergence effects, overtaking release waves and shock energy dissipation. However, due to lack of information, the preliminary disturbance estimate conducted at Alenia assumes GOCE as rigid body, i.e., with infinite impedance.

With the support of ESABASE analyses, Rankine-Hugoniot jump conditions (one-dimensional impact theory) and relationship between shock velocity and collision velocity, it is possible to evaluate the shock velocity into impacting MMOD. Then, assuming that the time of contact between MMOD and GOCE is equal to the time necessary to stress wave to propagate into MMOD and to return back to the point of interface between the impacting MMOD and satellite, it is possible to evaluate the acceleration induced to the satellite.

The MMOD impact distribution (in terms of MMOD mass/diameter and velocity) on the GOCE external surface is evaluated using the NASA ORDEM 96 and Grün model for the description of the orbital debris and meteoroid environment, respectively.

Taking into account the whole spectrum of mass considered by the MMOD environment models, the analysis estimates about 12 MMOD impacts a second, with a large predominance of meteoroid impacts with respect to debris impacts due to the different mass spectrum on which the two environment models are developed. The impact velocity distribution shows that micrometeoroids and orbital debris impact the octagonal cylinder at about 18 km/s (20 km/s on the external floor most exposed to the meteoroid environment) and 11 km/s (15 km/s on the external floor most exposed to the debris environment), respectively.

Figure 4 reports an example of cumulative impact frequency as function of the acceleration induced by MMOD impacts onto the GOCE external floor 7 (area $< 1m^2$).

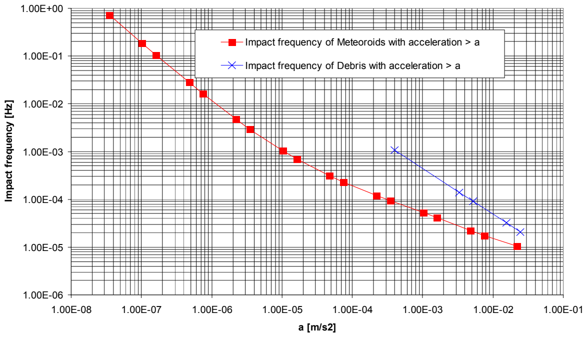

Figure 4: MMOD flux distribution in the GOCE external floor 7, Faraud [2003, Alenia].

The curves represent the impact frequency with acceleration higher than that reported in the acceleration-axis. It is necessary to consider that the meteoroid and debris impacts occur at the same time. This is important because the severity of the level of acceleration for GOCE depends both on the acceleration amplitude and disturbance frequency. Various curves have been obtained for the various parts of the satellite and one single cumulative curve has been plotted for the whole external structure of GOCE. The same curves have been also plotted as function of the MMOD induced instantaneous velocities. These graphs show that any MMOD impact causes very low delta-velocity to the satellite (between 1.0E-20 to 1.0E-11 m/s)

A high level of uncertainties due to the made assumptions affects the above results.

The purpose of the on-going study is to allow better knowledge on the real effects induced by MMOD impacts on satellite.

5. DEFINITION OF LABORATORY IMPACT CONDITIONS

The range of impacting particles to be considered for the study of *Spacecraft disturbances from HVI* has been selected with reference to both GOCE and other satellites, in order to have useful results not only for a particular satellite. Therefore, it is convenient to consider MMOD with masses capable to induce significant disturbance or damage onto a generic satellite.

The typical starting particle selected for the present study and representative of the MMOD impacts is debris with diameter **around 0.1 cm**. The main reasons of this selection are:

- Projectiles with diameters around 1 mm can be easily fired with the CISAS test facility
- The Mean Time Between Impacts of particles with diameter between 0.01 cm and 0.1 cm is acceptable (not too high and around 160 days according to the results obtained by Faraud [2002])
- The ballistic limits of the GOCE (and a few other satellites) structures are estimated to be reached with aluminium projectiles with diameters roughly about 1 mm. In this way, it is possible to investigate disturbance propagation in presence and absence of perforations (different modes – extensional and/or flexural) firing projectiles over and under the ballistic limits.

The laboratory impact velocities are determined by the CISAS LGG performance and are around 2-5 km/s.

4. TARGET AND INSTRUMENTATION

In this frame, in the preparation of the former part of the study the following activities have been accomplished:

- Evaluation of test condition by means of SPH models
- Assessment of the back ground environment of the facility
- Identification of the strategy to evaluate the measurements uncertainty.

The preliminary assessment of the expected test conditions was accomplished by SPH and was useful to identify the expected characteristics of the phenomena to be measured. Particularly, these investigations highlighted the characteristics of the vibration field, in

terms of acceleration levels and frequency content. Finally, even the signal dependency from the projectile velocity and mass could be estimated.
The analysis of the background environment has highlighted three main components that could affect the ongoing experiment:

- Electromagnetic noise source: it is mainly due to the external environment and the induced plasmas environment,
- Acoustic noise source, due to the propellant expansion inside the vacuum chamber and the debris cloud expansion inside the impact chamber.
- Mechanical noise source due to (i) the structural coupling between the gun and the vacuum chamber through the ground, the gun support systems or through the gun barrel; (ii) the shock generated by sabot fingers striking onto their stopper device; (iii) the secondary impact of the debris cloud onto complex targets; (iv) secondary impact of the debris cloud onto the target support system.

Finally, this preliminary phase has been focused on the analysis of the sources of uncertainty that will need to be identified in the foregoing experiment to provide reliable data. Particularly the source of uncertainty to be considered in the development of the experiment are:

- Background environment
- Load effects
- Measurement chain
- Mounting set-up

4.1 Experimental design

The experiment has been designed based on the following main guide lines:
Control and minimization of the back-ground environment as electromagnetic external environment, electromagnetic internal environment, acoustic internal environment, external vibration environment, internal vibration environment, and to obtain high experimental flexibility
For this experiment a completely new target chamber has been designed and built up (fig.5). The chamber is 980mm diameter, 1000 mm length. It is fully equipped with electrical connection to fit through instrumentation connections.
A special care have been given to the electrical feed through connections to avoid electromagnetic/electrostatic interference. The flight chamber has been designed to reduce the acoustic disturbances due to propellant expansion on the target and to shield the electromagnetic disturbances due to sabot impact on the stopping device. Even differential pumping between flight chamber and impact chamber may be applied if strictly necessary.
The data acquisition system has channels with 100kS/s sampling frequency, 1MS/s sampling frequency, 10MS/s sampling frequency. Data are acquired by a software internally developed at CISAS which provides, after each test, a report checking the signal for validity for:

- Saturation
- Electrical spiked
- zero-shift
- signal to noise ratio
- Positive versus negative SRS
- Velocity validation
- Displacement validation

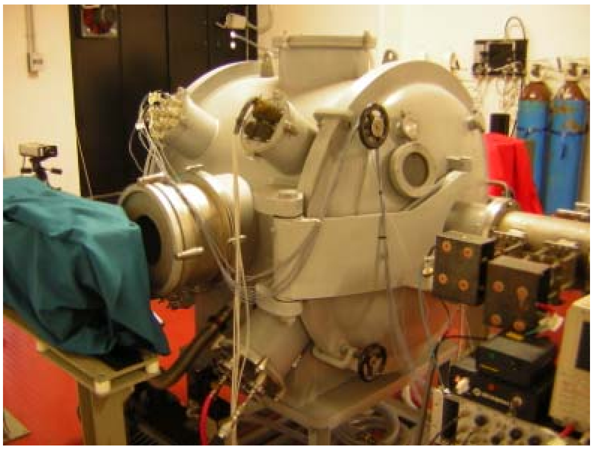

Figure 5: Picture of the impact chamber set-up for the experiment.

5. TEST MATRIX

Tests have been divided into four main categories:

1. Preparatory tests , to tune the facility set-up, to identify the back ground noise and to define the expected acceleration range on different zones of the target. They are a total of 42 shots
2. Tests on simplified target. The aim of this group of tests is to acquire knowledge in shock propagation, to identify the type of waves propagating on different zones of the target, to identify the relationship between vibration fields and impact conditions, to tune numerical models. The total number of tests in this frame is 56
3. Tests on complex target aiming to provide information on wave propagation through S/C structure joints, to identify transfer function of elementary structural components, to tune numerical model on complex assemblies. The total number of tests on this group is 52
4. Momentum transfer, aiming to measure on different panels the momentum transferred by HVI. The total number of tests in this frame is 6

6. EXPERIMENTAL CAMPAIGN

Since the execution of any impact test is always associated with significant undesired vibrations, it was recognised, as a fundamental step, that it is necessary to assess and possibly reduce the interfering inputs that build up the background noise environment of the Impact Facility. This is helpful to increase the signal to noise ratio and simplify the following analysis of data,

The main sources of the background noise were theoretically individuated and analysed separately, through dedicated experiments designed to isolate each of the previously identified sources of disturbance. The test set-up was the same used during real impact tests but operation sequences and conditions were changed in order to separate the different effects.

The following issues were analyzed.

- Mechanical vibrations associated to the extremely high mechanical impulsive loads that propagate through the facility structure and through the ground during the projectile acceleration phase;
- Acoustic vibrations produced inside the facility's flight chamber as a consequence of propellant sudden expansion outside the muzzle of the gun;
- Mechanical vibrations produced by the impact of sabot fingers onto the sabot stopper plate. This operation is necessary to separate the real impactor, that is typically an aluminium sphere, from its plastic carrier, named sabot.
- Mechanical vibrations produced by impingement of the debris cloud, generated by the primary impact, on complex targets or surrounding structures;
- Acoustic vibrations coupled with the debris cloud expansion in the low-vacuum environment of the impact chamber;
- Electromagnetic noise related to the redistribution of electrical charges around the debris cloud and production of impact plasmas.

It has been found that the main source of undesired acceleration inputs is related to the acoustic coupling between the expanding propellant and the target. All the sources of disturbances have been combined together and the effect on the parameter of interest, SRS, has been evaluated (see figure 6-7).

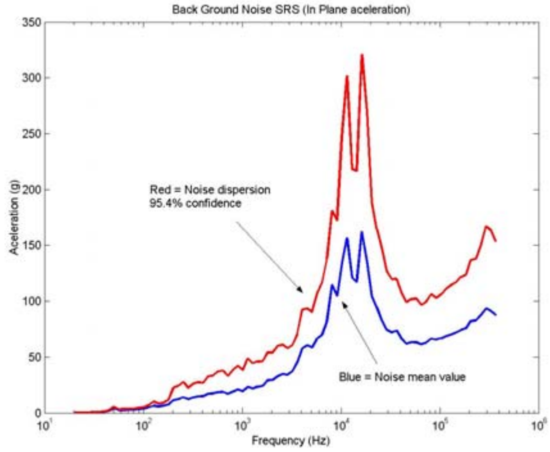

Fig.6. SRS of the background noise. In plane disturbances

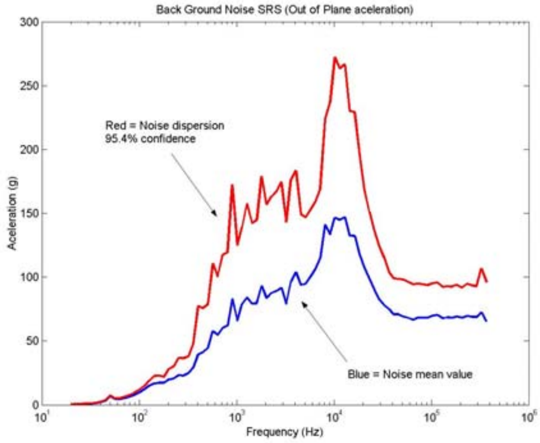

Fig.7. SRS of the background noise of the out plane disturbances

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