DYNAMIC BEHAVIOUR OF A RAILGUN-LAUNCHED NANOSATELLITE

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Abstract. ***ηSat*** *is the name of a data-collecting nanosatellite, conceived to be launched by means of an electromagnetic railgun; the project is being executed by the Aeronautics Department of the National University of Córdoba (DA-FCEFyN-UNC) and the Applied Research Center of the Aeronautical Universitary Institute (CIA-IUA), both of Córdoba, Argentina. The whole program is managed by the DLR-AS (Deutschen Zentrum für Luft und Raumfahrt - Institut für Aerodynamik und Strömungstechnik - Braunschweig, Germany), joining several R&D European groups.*
Its primary mission will be the collection of data from remote hydro-meteorological autonomous stations, which are developed under a parallel project by IUA; as a secondary mission, ηSat will serve as test bench for the technological development of miniaturized components and systems able to withstand extreme accelerations.
The electromagnetic railgun launching implies very interesting economic and operative characteristics, mainly for low-cost space projects, although the challenges implied by the extreme acceleration and shock levels (up to 10000 g), along with the reduced mass and dimensions allowed (respectively 5kg and 120 mm diameter) impose serious engineering problems to assure component's integrity. The approach used, which is described in this paper, consists in two detail levels: the first was the development of a lumped-parameter model, used for the study of different structure concepts, both with linear and non-linear stiffness and damping. The results obtained with this simple model were used to clarify some design issues, such as structure materials, load distribution and dynamic solicitations to specify the electronic equipments, as well as dampers and structural joints. Moreover, this model allowed us to define shock and vibration tests requirements for the Development and Qualification phases of the project.
Once obtained the main loads, two Finite Elements Models were elaborated: one for the solar panels assembly (in order to analyze stress and strain levels mainly in solar cells and elastomers) and the other for one of the electronic modules (to assess the structural behaviour of the electronic components).
The combined use of these two approaches allowed us to define several guidelines for the structural design of ηSat, such as fixing structure and stiffness and damping levels for the solar cells and electronic equipment support structures.

Keywords: *nanosatellite, extreme accelerations, structural dynamics*

1. INTRODUCTION

ηSat-IE is the name of a space project, which consists in designing and building of a 5 kg nanosatellite, intended to be launched by an electromagnetic railgun. The whole program is managed by DLR-AS (Deutschen Zentrum für Luft und Raumfahrt - Institut für Aerodynamik und Strömungstechnik), including several european firms and R&D groups.

Its main mission will be data collection; it is intended to be the space component of a hydrometeorological network, being developed under an independent program backed by the government of Córdoba. (see PICTOR, 2002). A secondary mission is to serve as a development bench for miniaturized space components and systems resistant to extreme acceleration and shock levels.

Although satellite dynamic environment is a well established topic for conventional launching (i.e. Griffin &French, 1991 and Brown, 2002), this is not the case for high-g launching; historically, R&D in this area has been reserved for military groups, being public bibliography limited and badly outdated (Waye, Peterson, Botner, 1986). Regardless these shortcomings, some modern concepts have appeared about the design of high shock resistant structures (i.e. Johnson &Wilke, 2003), immersed in an experimental frame. Lack of established design criteria makes necessary detailed analysis about structural response to these solicitations, while careful test plans are a must for concept validation.

Several models were developed for different project phases: first at all, a simple lumped parameters, three-masses model, which served as a quick tool to obtain an insight of satellite structural behaviour, as well as to make a preliminary assessment of the shock damper main characteristics. Finally, Finite Elements Models (FEM) were developed to estimate the structural behaviour of critical components, such as solar cells and electronic equipments.

2. GENERAL DESIGN CONSIDERATIONS

ηSat-IE general design is shown at Fig. 1; the nanosatellite, which overall dimensions are 120 mm diameter and 240 mm length, consists in an external shroud structure, which support solar panels, as well as external systems, such as sensors and antennae. This shroud, moreover, serve as a resistant structure, transferring and distributing launch loads. Electronic systems are contained in seven separate modules, which must assure its integrity. In turn, structural modules-shroud joints must transfer dynamic loads.

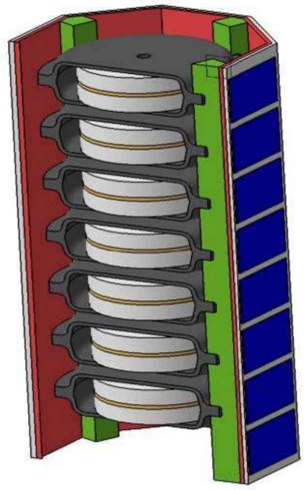

Figure 1. ηSat layout

This layout allows us to obtain an adequate independence between different structural components, diminishing mechanical loads on electronics, even taking into account integration issues. The whole spacecraft will be mounted in a damping support (not presented here), which will serve as an interface with the launcher.

3. MATHEMATICAL MODELS

In this section the different mathematical models used for the structural analysis will be presented, going from the simplest (3DOF lumped parameters) to the more complex FEM ones.

3.1. 3DOF Lumped Parameters Model

The 3DOF Lumped Parameters model used, which comes from Zapico, *et al* (2005) and can be seen in Fig. 2, consists in three main submodels: the shroud, the internal systems and the damper or support; each one will be described in the following, together with the loads model.

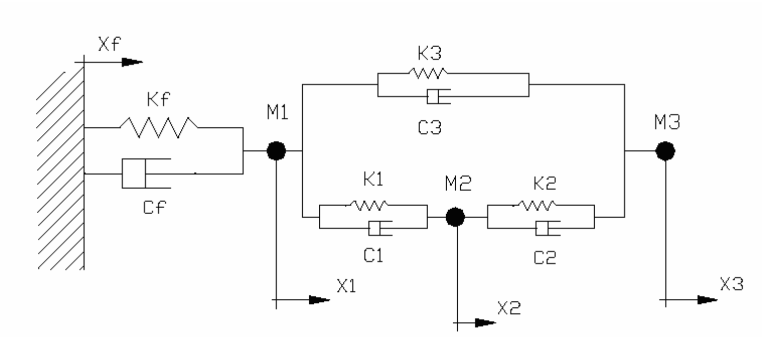

Figure 2. 3 DOF Lumped Parameters model

3.1.1. Shroud

Due to its geometry and to the fact that it is a monolithic structure in Carbon Fiber Reinforced Composite (CFRC), this substructure presents a very high specific stiffness, so it was modeled by mean of two masses (denoted as *m1* and *m3*), representing possible mass distributions, joined by an elastic rod (*k3*); also a viscous damper (*c3*) was modeled.

This modeling allows us to take into account different mass distributions, as well as stiffness and damping coefficients coming from different constructive parameters, such as shroud and substrate thickness; also, the values of *m1* and *m3* may be varied according to different equipments mounted on them.

3.1.2. Internal components

Since the internal arrangement forms a very compact structure, it was modeled as a unique mass (*m2*), joined to the shroud by means of two rigid rods, in turn *k1* and *k2*; in similar manner that used for the shroud, damping coefficients *c1* and *c2* were introduced to allow later design adjusting of this joint.

3.1.3. Support/Damper

An external damper, modeled as a classical elastic foundation which parameters were denoted as *kf* and *cf*, was added to study its influence in the overall dynamic characteristics of the system.

3.1.4. Loads Model

Due to the great masses difference between the satellite and the launcher, structural excitation was treated as a foundation movement, corresponding to the integration of railgun acceleration; Figure 3 shows corresponding diagrams. As can be seen (and was treated in Zapico, *et al* (2005), the impulse given by the railgun was modeled by means of a 10000 g magnitude step function with a duration of 60 msec; its integration provides the velocity and displacement of the foundation.

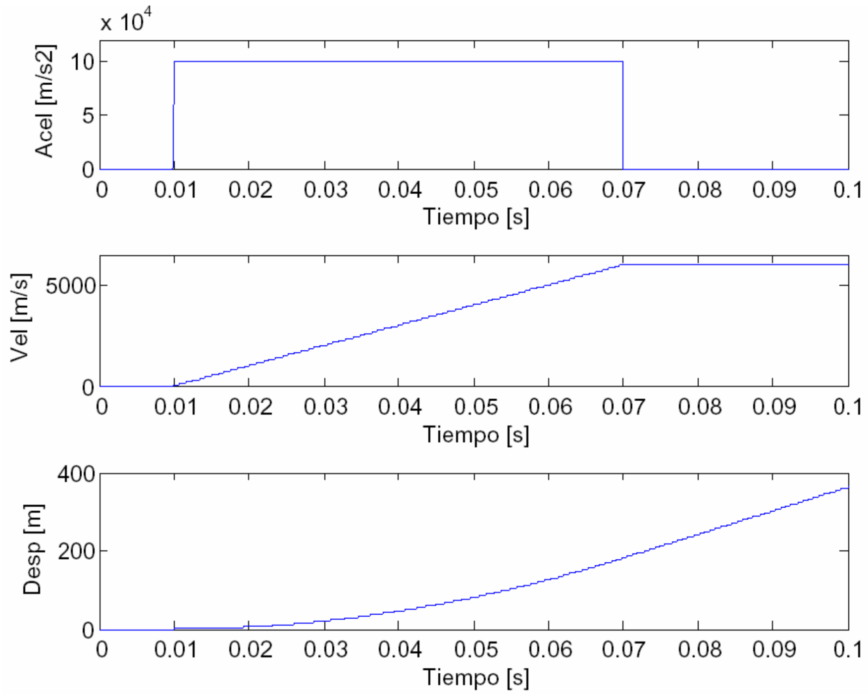

Figure 3. Dynamic load condition

3.2. Finite Elements Model

The structure was modeled in two submodels: The shroud, including the solar panels, and a module (representative of the seven systems modules). The damper was not modeled here beyond the representation of the forces it imposes to the structure, because its design is subject of a different effort.

In the following, they will be described:

3.2.1. Shroud

The shroud, which is shown in Fig. 4, consists in four main arrangements; an octagonal CFC shell, being 2 mm thickness, four Al 7075 rods, which support the system modules, and eight solar panels, bonded to the shell by means of 2 mm-thickness silicone substrate.

The mesh was modeled with 4-node tetrahedrons, being in all cases the materials considered to have lineal, isotropic behaviour; moreover, the substrate is considered to be nearly incompressible

Figure 4. Shroud modeling

The properties for each one of the components are shown in Table 1

Table 1. Shroud materials and FE modeling properties

Component	Material	Density [kg/m^3]	E Module [Pa]	Poisson Module	Max. Element dimension [mm]	Ultimate Tensile Strength [Pa]
Rod	7075 T6	14700	7.355 e10	0.33	7	4.90 E8
Shroud	CFC	1800	1.1 e11	0.3	3	1.18 E9
Solar Cells	Silicon	4100	7.3 e10	0.33	2	6.80 E6
Substrate	Silicone adhesive	1100	4.6 e6	0.499	3	3.79 E6

All material properties were obtained from usual databases, except those for the solar cells, which were experimentally obtained by Paz (1999). Moreover, density of the rod was altered to simulate the loads imposed to it by the internal masses.

3.2.2. Systems Module

This module, which represents a generic electronic systems container and is shown in Fig. 5, is formed by two hemi-shells (which, in turn, are bonded together), which surround the floating electronic board; this board is supported and damped by two silicone elastomeric cushions, bonded both to the board itself and to the shell.

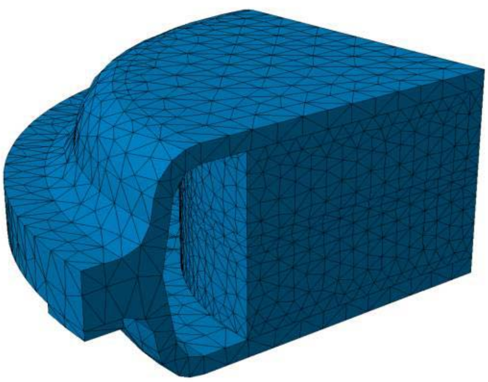

Figure 5. Electronic module modeling

As before, the mesh was modeled with 4-node tetrahedrons, being in all cases the materials considered to have lineal, isotropic behaviour; also, the silicone cushions are treated as nearly incompressible. Table 2 shows the parameters used for this model:

Table 2. Module materials and FE modeling properties

Component	Material	Density [kg/m]	E Module [Pa]	Poisson Module	Max. Element dimension [mm]	Ultimate Tensile Strength [Pa]
Shell	CFC	1800	1.1 E11	0.3	3	1.18 E9
Elec. Board	GFC	20000	4.5 E9	0.3	1.8	8.5 E7
Cushions	Silicone adhesive	1100	4.6 e6	0.499	1.8	3.79 E6

It must be noted that the density of the electronic board is modified to simulate the mass of the electronic components on it (estimated in 0.1 kg for the whole board).

3.2.3. Loads Model

As in the Lumped Parameters Model, the load was supposed to be a foundation movement; a classical sinusoidal shock, which will be justified in paragraph 4.1., was imposed, being its amplitude and period respectively 18000 g and 3 msec. Such a shock represents the energy given to the components in the first half cycle of the transient imposed during launch.

4. RESULTS

In this section we will discuss the different results obtained for each one of the models presented before.

4.1. Results - 3DOF Lumped Parameters Model

The results of the 3DOF Lumped Parameters model were presented in Zapico *et al.* (2005), and will be only repeated here to serve as a basis for the discussion of the load states for the FEM of the components.

Figures 6 and 7 show, respectively, the acceleration time history for the mass point m2 (in fact, the internal system arrangement) and the PSD for each of the masses considered.

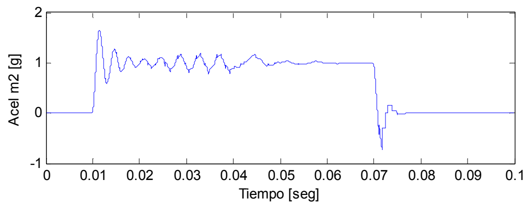

Figure 6. Dynamic behaviour of the internal systems

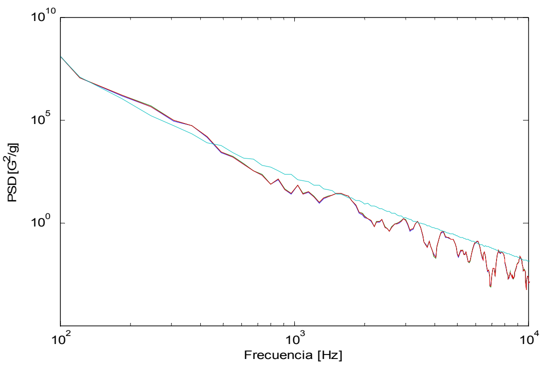

Figure 7. 3DoF Model Spectral Response

It may be seen that the dynamic response of the internal mass is one typical of a step function response, in this specific case a 3 msec period damped sinusoid with an amplitude of 18000 g. This behaviour justifies the load assumption for the Finite Elements Model described at paragraph 3.2.3.

The spectral response, in turn, shows the amplification factor in the vicinity of 300 Hz (frequency corresponding to that of the shock damper) and several moderate natural resonances, but at frequencies higher than 1500 Hz and several orders of magnitude smaller than that of the foundation. This great difference between both peaks allows us to presume a rigid behaviour of the satellite structure.

4.2. Results – Finite Elements Model

The objective of this model was to assess the stress level in each one of the main components of the nanosatellite, in order to validate the design concepts utilized. In the following we will show the most significant of them:

4.2.1. Shroud

The stress states for three elements of the shroud are presented: the cell substrate in Fig. 8, the cells themselves in Fig. 9 and the shell-rod joint in Fig. 10. All of them correspond to the maximum stress observed.

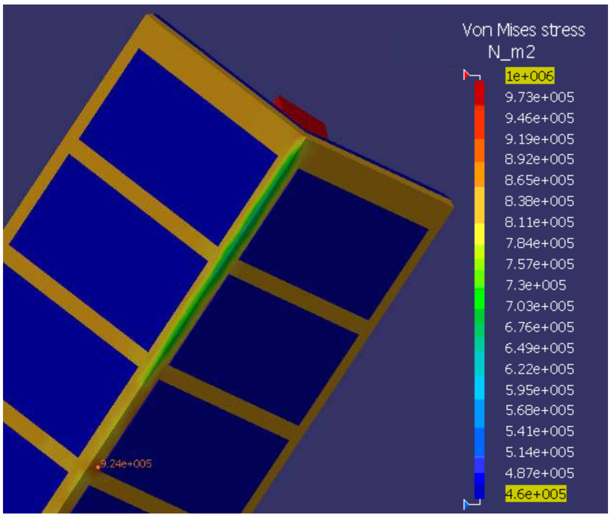

Figure 8. Von Mises stress for elastomeric substrate

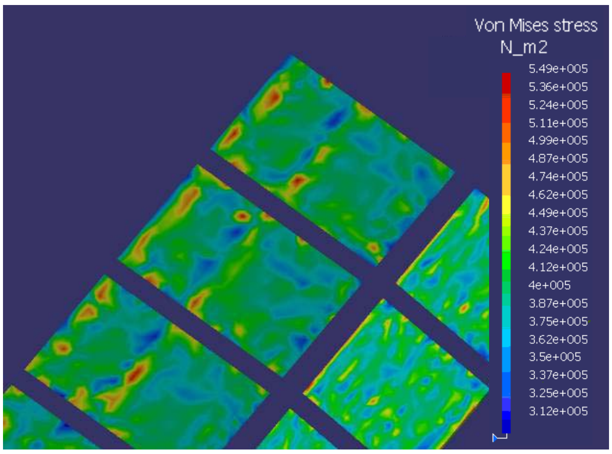

Figure 9. Von Mises stress for solar cells

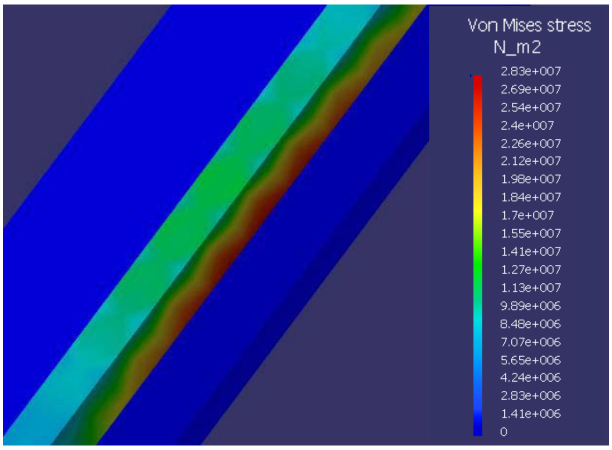

Figure 10. Von Mises stress for shell and rod

It may be seen that in every case, the maximum stress observed is much less than the UTS for each material, giving safety factors greater than 4; this specific safety factor is that of the elastomer, which is the *a priori* most compromised element. Other critical part, such as the solar cells, show a safety factor of 12.3; the shroud and the rod, despite their load transfer role, show even greater safety margins.

4.2.1. Electronic Module

The stress states the constitutive elements of the electronic module presented in the same way as before: the resistant shell in Fig. 11, the electronic printed circuit board (PCB) in Fig. 12 and the elastomeric cushions in Fig. 13. As before, all the results correspond to the maximum observed Von Mises stress.

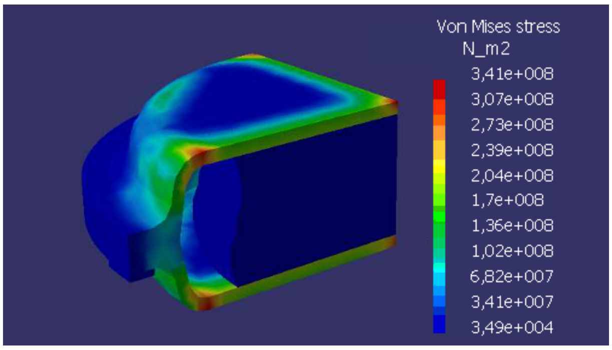

Figure 11. Von Mises stress for shell

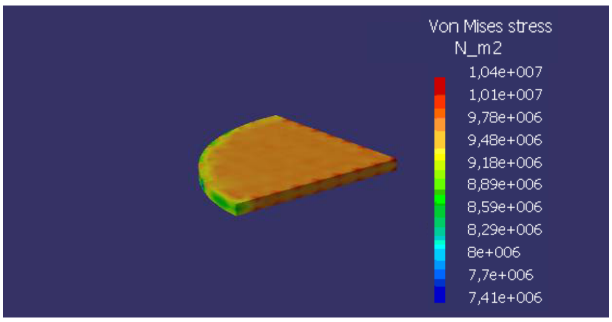

Figure 12. Von Mises stress for electronic PCB

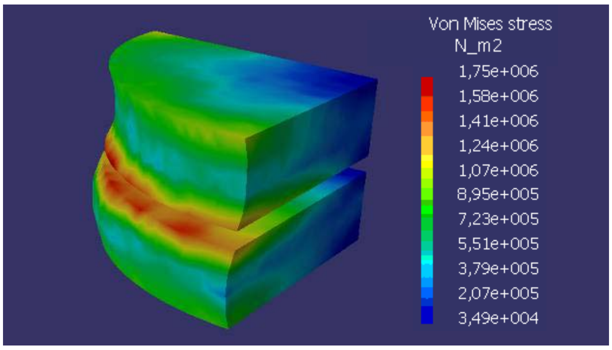

Figure 13. Von Mises stress for elastomer

Also as for the shroud case, it may be seen that the maximum stresses observed is less than the UTS for the respective material. However, in this case, the safety factors are smaller than those encountered for the shroud, being noticeable the value of 2.15 obtained for the elastomeric cushions; this fact suggest us to take care of these components in the detailed design phase in order to avoid to compromise their damping function.

The shell and the PCB board, in the other hand, show safety factors of 3.4 and 8.2, respectively, which are adequate due to the greater confidence in material characteristics.

5. CONCLUSSIONS

Two dynamic structural models of ηSat were presented; both were used in conjunction to predict the load levels at which the different systems and components of it will be subjected during the raigun launch.

The lumped parameters model was used to estimate the overall dynamic behaviour of the structure, showing that the natural frequencies induced by the launch were several times lower than the structural ones (300 Hz vs. 1500 Hz).

In view of this result, a sinusoidal shock was imposed as the load case for the Finite Elements Model, were individual components up to level of solar cells and electronic PCB were modeled in detail. The results obtained from the analysis showed a good stress state, with adequate safety margins and a healthy structural behaviour, with no critical points at this design level.

In addition, the analysis suggests that the most compromised part of the structure (the internal elastomeric cushions), although presenting an adequate safety factor, merit special care in the determination of its mechanical properties with the dispersion of the technological parameters (i.e. application mode, curing conditions). Also, these results will be invaluable in the planning and analysis of results of the shock tests of the components, which should be performed as next stage of this project.

6. ACKNOWLEDGEMENTS

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- Applied Research Center of the Aeronautical Universitary Institute (CIA-IUA).

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