NUMERICAL ANALYSIS AND VIBRATION TESTS OF THE *TRANSITION RADIATION DETECTOR BOX S* FOR THE AMS-02 EXPERIMENT

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ABSTRACT

The paper deals with the numerical and experimental characterization of the *"Transition Radiation Detector Box S"* structure, a subsystem of the AMS-02 experiment on particle physics, developed by the "Servizio Progettazione Meccanica INFN Roma 1". This analysis had the final aim to qualify the structure following the requirements given by NASA in order to flight on board the Space Shuttle and to be assembled on the International Space Station. The models, described with finite elements, were used to obtain dynamical data useful both for the design of the interface main structure–shacker and for the experimental tests. These last ones have been carried out by an electrodynamic shacker at the research center ENEA Casaccia. As said before, a flange – interface between the *"Box S"* and the shacker vibrating structures – simulating the in flight actual constraints, had to be designed and tested. The finite element model was also used to achieve the better positions for the accelerometers. The structure was able to support the dynamic stresses imposed, and the data gathered during the experimental texts permitted to verify the validity both of the structure design and of its finite element models, being the experimental natural frequencies in good agreement with the numerical ones.

INTRODUCTION

The Alpha Magnetic Spectrometer AMS is a space experiment on physics of particles in a cooperation program among Agenzia Spaziale Italiana (ASI), Istituto Nazionale di Fisica Nucleare ($INFN$), National Aeronautic and Space Administration ($NASA$) and U.S. Department of Energy (DOE). The final purpose of the project is to measure, for a long time and with high precision, the composition of the cosmic rays in order to check the current theories on the Dark Matter and in turn on the Anti–Matter.

The structures outlined in the paper have been described in details in the following References: [1], [2] and [3]. Besides, the finite element models, with the numerical tests, along with the experimental tests have been presented in [3] and [4].

TRD Box S structure, integrated with the $AMS02$ Unique Support Structure (USS), supports the main components of the $AMS02$ Gas Supply System. There are two great spherical tanks, for Xenon and CO_2, a smaller cylindrical, for the gas mixing, and all the elements forming the gas circuit: valves, filters, and sensors for monitoring of temperatures and pressures. The Xenon and CO_2 tanks are made of composite wound metal shells, whose diameters are of about 15 and 12 inches respectively, while the empty weight is approximately 16 and 9 pounds. They were designed so as to contain 109 pounds of Xenon and 18 pounds of CO_2
Polar bosses fix the tanks to the Box S through supports at both ends: one of them with a ball joint, whereas the other one can slide axially, so as to absorb the thermal expansions and avoid radial loads.

The requirements on the reliability of the mission, along with the structural tests necessary to flight inside the cargo bay of the Space Shuttle and, in orbit, to be assembled with the International Space Station (ISS), are reported in the NASA document JSC-28792 Rev.B [5]. In particular, for the static structural tests, an acceleration of 13 g has to be applied along the most critical direction, whereas 3.25 g must be the accelerations on the two other perpendicular axes.
From the dynamical point of view, the first natural frequency of the Transition Radiation Detector (TRD) Box S is required to be higher than $50Hz$, and that due to interference problems with the frequencies of the vehicle. In addition, the payload must support the vibrations induced both by the assembling procedures and by the structure of the launcher during the flight, for these reasons dynamical tests have to be carried out with random signals whose Power Spectral Density (PSD) versus frequency is supplied by the launcher people.

The paper presents the tests, carried out in a first step numerically by the finite element (FE) models of the TRD Box S and of the interface (Test Fixture), necessary to bolt the TRD Box S on the shacker, and after experimentally on the actual structures.

DESCRIPTION OF THE BOX S STRUCTURE

The system under test was assembled at C.R. ENEA Casaccia. The main structure – made of the aluminum alloy 7050 T7451 – was manufactured by milling a single Al alloy block. The mounting side is flat (plate) with two large holes in order to house the Xe and CO_2 tanks (Fig.1). Ribs, in the rear part, stiffened the structure; they started with 149 mm in depth at the top and tapered down to 45 mm at the bottom. All the system was designed symmetrical with respect to the centreline from the Xe to the CO_2 tank axes. Additional stiffeners were present to support local loads. The front plate was $6mm$ thick, whereas rib thickness varied from 3 mm to 5 mm. The design provided a rigid bolted connection at the top and a flexible connector, consisting in a helicoidal spring (stainless steal: $POWERFLEXH631$ type) at the bottom of the plate. This last element was necessary because of the large relative displacements between the beams supporting the system. Therefore, the structure is practically supported only by the upper beam, which practically has to satisfy all the structural requirements (static and dynamic), since the additional flexible support at the bottom is only a fail-safe structure.

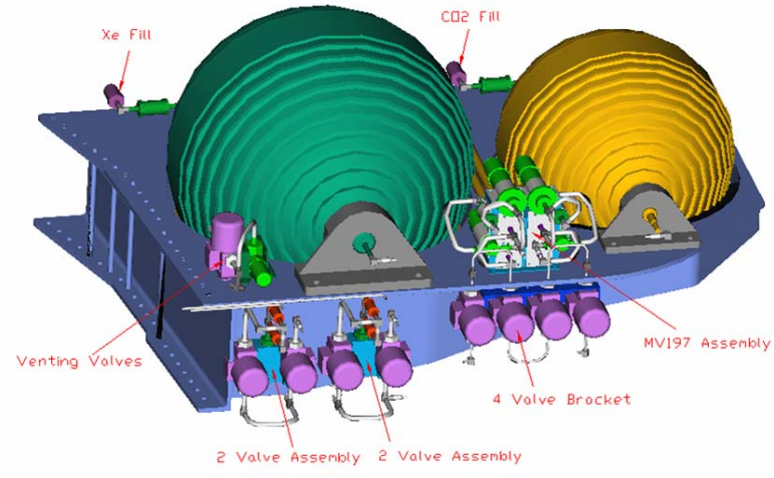

Figure 1: Transition Radiation Detector Gas Supply Box S

The upper interface with the USS has a U-shape structure, such as to be inserted and bolted in the USS standard hole pattern, positioned on the lower side of the USS upper trunnion bridge. The plates forming the U-channel consist of an extension of the frontal main plate. The USS hole pattern has been copied, both at the front and at the back of the Box S, so as to connect the two structures with 21 ($\frac{1}{4}$ $inch$) screws. The spring is instead linked to the Box S and to the USS lower beam by a triangular bracket. For safety reasons, even if the predicted reactions induced by the spring are low, the number of bolts necessary to fix the spring to the structures was increased from 2 to 3 per side.

The tanks, designed and built by Arde Inc., have been sized to hold 109 pounds of Xenon and 18 pounds of CO_2 respectively. They are fixed to the Box S through a polar mounting at one end, whereas the other axis is allowed to slide axially, so as to avoid stresses on the thanks when they expand for thermal problems or they moves due to vibrations. Arde also manufactured the small stainless steel Mixing tank, positioned at the back of the support plate, close to the USS upper trunnion bridge. Brackets, supporting this last tank, have a proper design optimizing the tank position with respect to the Box S.

NUMERICAL MODELS AND EXPERIMENTAL TESTS

The dynamic analysis has been carried out on two models corresponding to the different Box S configurations, the flight configuration and the one adopted for the vibration tests (Test Article Model: TAM). The first ten natural frequencies and normal modes were derived by MSC.NASTRAN, applying the Lanczos method in order to solve the real eigen–problem.

The constraints of the structure have been reproduced modelling the bolts as perfectly fixed, so the degrees of freedom of the nodes, relevant to the holes, were blocked. The same procedure was adopted for the last part of the spring, which was positioned – as said before – at the other extremity of the Box S structure in order to allow the movement of the two beams in the middle of which the Box S is positioned [6]. The results of this analysis are shown in Tab.1.

Mode	Frequency (Hz)	Frequency (Hz)
1	69.00	69.78
2	80.57	80.57
3	114.12	116.14
4	154.83	149.06
5	183.48	159.67
6	196.42	193.68
7	259.94	248.94
8	265.13	277.07
9	364.20	328.67
10	371.91	360.03

Table 1: Natural frequencies for the Flight and for the TAM configurations

The mode shapes of the first 3 modes – in the TAM Configuration – are presented in Figs. 2, 3, and 4. As known, it is possible to have an idea of the contribution due to a single mode to the whole dynamic behavior by the evaluation of the effective modal masses [7]. The effective modal mass, relative to the elastic $k-th$ mode, is given by the following relationship:

$$M_j^{(k)} = \frac{\left(\Phi_R^{j\,T}\,\mathbf{M}\,\Phi^{(k)}\right)\left(\Phi^{(k)\,T}\,\mathbf{M}\,\Phi_R^{j}\right)}{\left(\Phi^{(k)\,T}\,\mathbf{M}\,\Phi^{(k)}\right)} \tag{1}$$

where Φ_R^j is the considered $j-th$ rigid mode shape, and $\Phi^{(k)}$ is the elastic $k-th$ eigenvector. The results obtained by the MSC.NASTRAN code are reported in Tab. 2.

$k-th$ mode	Frequency (Hz)	$M_x^{(k)}$	$M_y^{(k)}$	$M_z^{(k)}$
1	69.78	28.83	36.20	1.54
2	80.57	17.50	37.34	1.79
3	116.14	3.81	1.85	0
4	149.06	8.90	0.86	0.07
5	159.67	17.51	0.07	0.19
6	193.68	1.35	0.07	51.4
7	248.94	0.02	0.38	8.50
8	277.07	0.7	1.07	0.61
9	328.67	0.27	0.25	0.02
10	360.03	0	0.19	0.05

Table 2: Effective modal masses (TAM configuration)

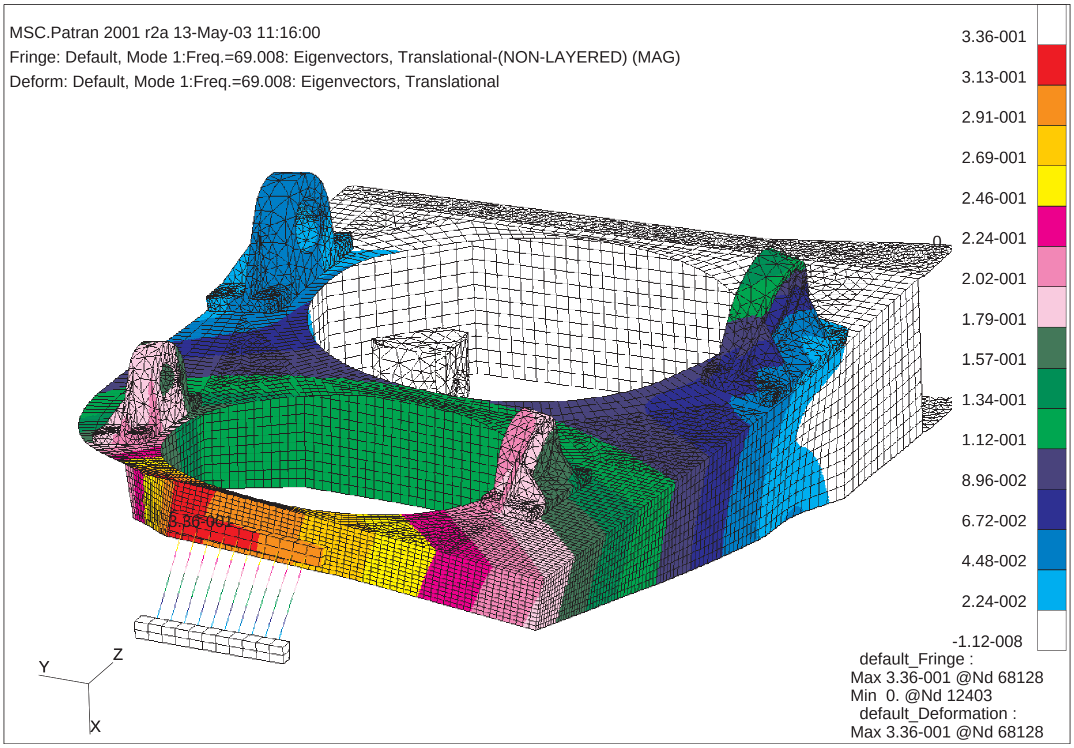

Figure 2: Configuration Test Article Model (TAM): 1^{st} mode

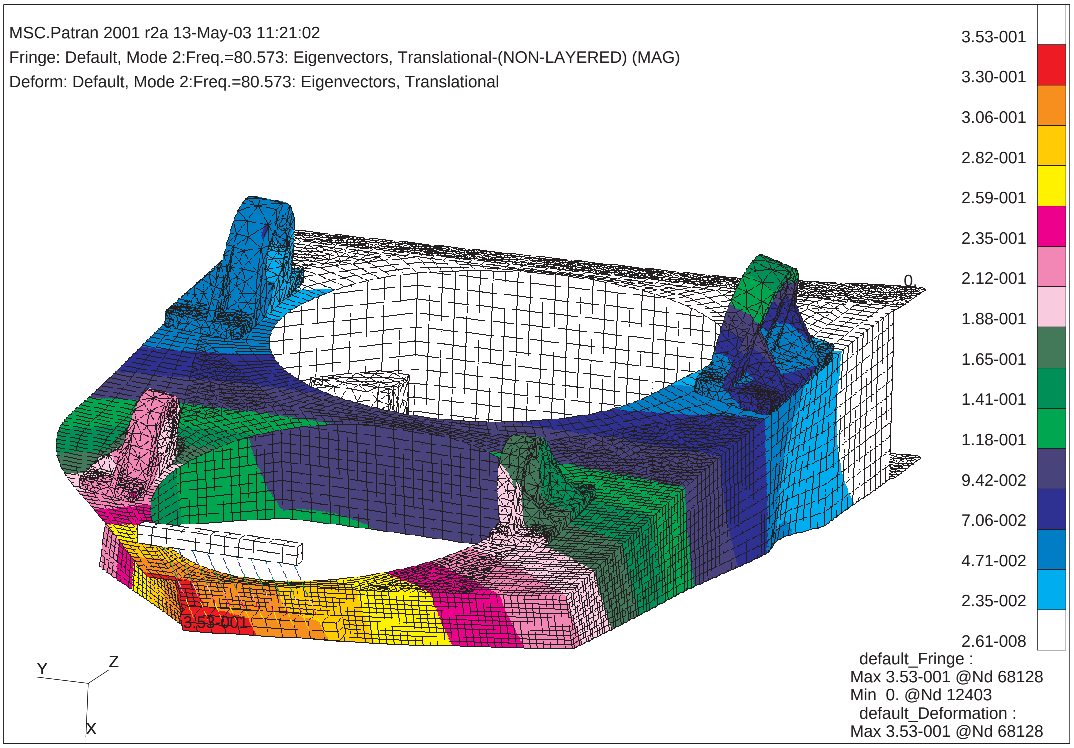

Figure 3: Configuration Test Article Model (TAM): 2^{nd} mode

Vibration tests were carried out at the Research Center ENEA Casaccia. Preliminary tests were necessary in order to characterize the test fixture, following the requirements, contained in the JSC-28792 Rev.B [5], which had to be used for the BOX S structure too. Firstly, a Sine Sweep from 10 Hz up to 300 Hz, with the acceleration amplitude equal to 0.25 g and with 2 octave per minute of sweep rate, had to be carried out. A second Sine Sweep equal to the first one was necessary after a random test at the Minimum Workmanship

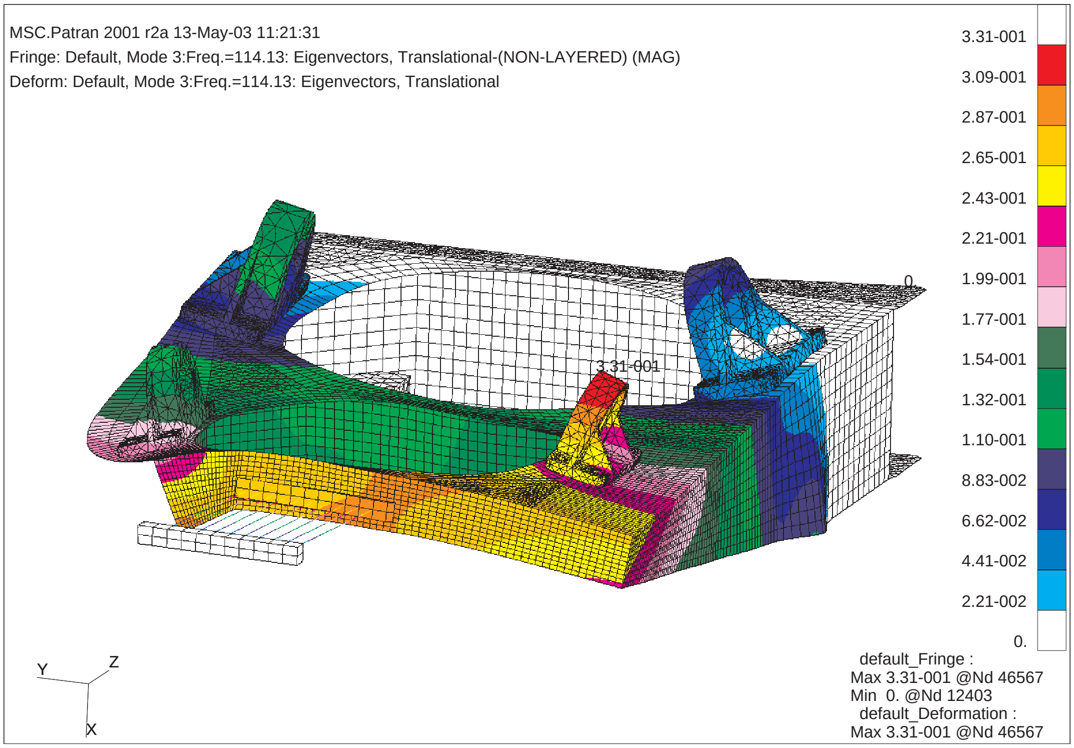

Figure 4: Configuration Test Article Model (TAM): 3^{rd} mode

Level (MWL), whose data are given in Tab.3, while its behavior is shown in Fig. 5. As mentioned before, after the random vibration, another sweep test, equal to the first one, has been required to check the possible variations both of the natural frequencies and of the response magnitude, signs of changes in the structure. In order to avoid possible misunderstandings of the complete vibration tests, the torque of the bolts used to fix the interface on the shacker and the one of the bolts and nuts used to locate the BOX S on the flange were checked after each test. Following the document JSC-28792 Rev.B, the structure can be considered qualified for the launch if no significant changes are present in the frequency responses obtained from the two sweep tests.

20 Hz	$0.01\, g^2/Hz$
20 - 80 Hz	$+3\, dB/Octave$
80 - 500 Hz	$0.04\, g^2/Hz$
500 - 2000 Hz	$-3\, dB/Octave$
2000 Hz	$0.01\, g^2/Hz$

Table 3: Power Spectral Density (MWL)

The experimental means disposable at the Centro Ricerche Casaccia (ENEA) were composed as follows: an electrodynamic Shaker *Unholtz-Dickie Corp.* Model T4000, piezoelectric accelerometers *Endevco* Models 2224C and 2228C, charge amplifiers *Carlo Gavazzi Space* and a signal analyzer *LMS Roadrunner*. The shacker was equipped with a slipping table of magnesium alloy so as to permit to test the structure along its three orthogonal axes. The input level of the acceleration was controlled by a *Gen Rad* Vibration Control System (VCS), which used – in our case – a control accelerometer placed in the central position of the upper beam of the Test Fixture.

The tanks had not to be tested, because they have been previously qualified, in fact the Xenon tank has been already used on the ISS, while the CO_2 tank was designed and used on the X-33 vehicle. Therefore, for the Box S vibration tests, dummy elements were used: a metal cylinder, whose weight was 57.4 kg, with axes similar to the actual tank, simulated the Xenon container. On the contrary, the CO_2 tank was simulated with a hollow sphere of 1.85 kg and filled with 4.5 kg of alcohol (IsoPropilyc Alcohol: IPA). Finally a dummy element (weight 0.95 kg) simulated the mixing tank (Fig.6).

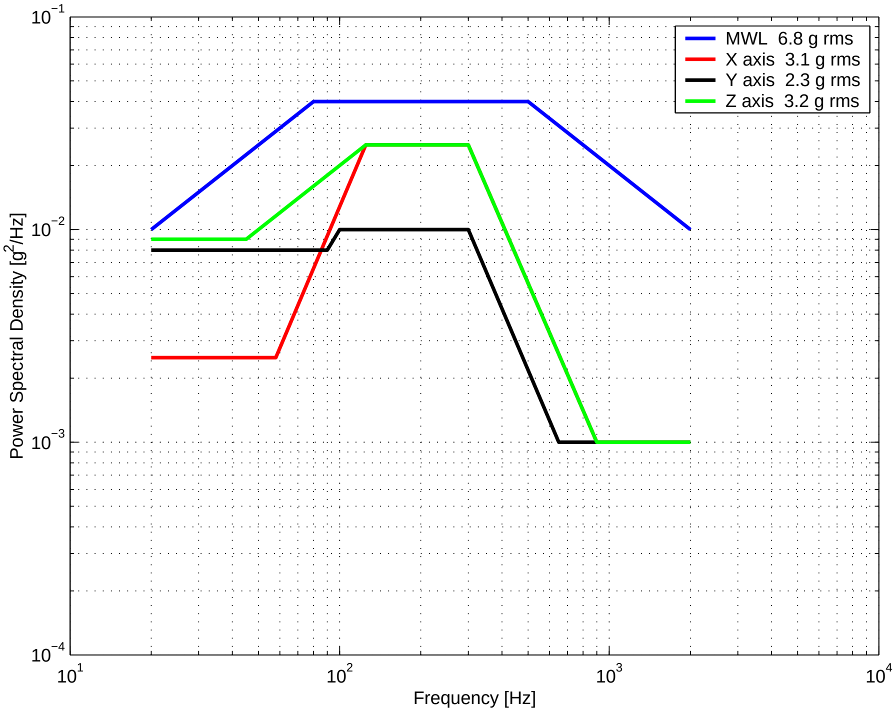

Figure 5: Flight Random Vibration and MWL levels (log–log plane)

The gas distribution system, mounted at CERN (Geneva), was filled under pressure of 100 *bar* in order to check, after every test, the seal both of the pipes and of the electro-valves.

In a first step, vibration tests – in the same sequence of the qualification tests: Sweep/Random/Sweep on the three axes – have been carried out on the Test Fixture, so as to check the natural frequencies and the mode shapes obtained during the design procedure through finite element models. For the mentioned tests, 9 accelerometers have been used, one of them, positioned either on the vibrating table or on the slipping table, controlled the input acceleration. All the tests, carried out on the Test Fixture structure, showed a good agreement with the data obtained by the numerical test. In particular, a peak at 519.5 Hz was found out for the principal beam, and that is very similar to the natural frequency of the numerical mode: 523.9 Hz. Two lower frequencies (at 279.3 Hz and at 317.2 Hz) were present due to the bending and to the bending and torsion of the transverse beam of the flange. As one can see, these natural frequencies are very different from the ones of the Box S, therefore no interferences between the two structures were expected.

After the integration of the Box S on the Test Fixture, three position (A,B and C) were chosen for monitoring the output accelerations, Fig.7. In addition, a set of three accelerometers (for three orthogonal axes), were positioned on the rear part of the cross main beam simulating the one of the Unique Support Structure (USS), on which the Box S must be assembled. These last accelerometers have been considered as control for the acceleration input. A rough identification of the natural frequencies has been obtained by using the *"peak picking"* approach. As one can see from Figs.8 and 9, where the frequency responses of the structure, with respect to the input acceleration, are shown, peaks of resonances are present. In particular for the Sine Sweep in the x direction (Fig. 8) the first natural frequency is at 70.0 Hz, while the second one, with a much smaller amplitude, was at 81.8 Hz. For the y direction (Fig. 9) the first significant peak was at $80,8$ Hz and the second one at 105.4 Hz. The resulting natural frequencies, achieved by the Sine Sweep, permitted to validate the finite element numerical model. As shown in Tab.4, there is a good agreement between the first three natural frequencies (along the x axis), in fact the maximum relative error (in percentage) is relevant to the 3^{rd} mode and is of the order of 10%. In any case, it is worth noting that all the 1^{st} natural frequencies are greater than the imposed limit of 50 Hz. Therefore, the structure is accepted to fly on the Space Shuttle cargo bay. As prescribed from NASA, for each axis, a comparison between the sine sweep outputs, before and after the random test, had to be carried out, in order to control the integrity of the structure after the flight (random) test. All the controls were positive, as it is possible to see, for example, from Figs.10, 11. The most significative difference has been find out in the x direction at a frequency higher than 150 Hz, but that was a local mode relative to the valves.

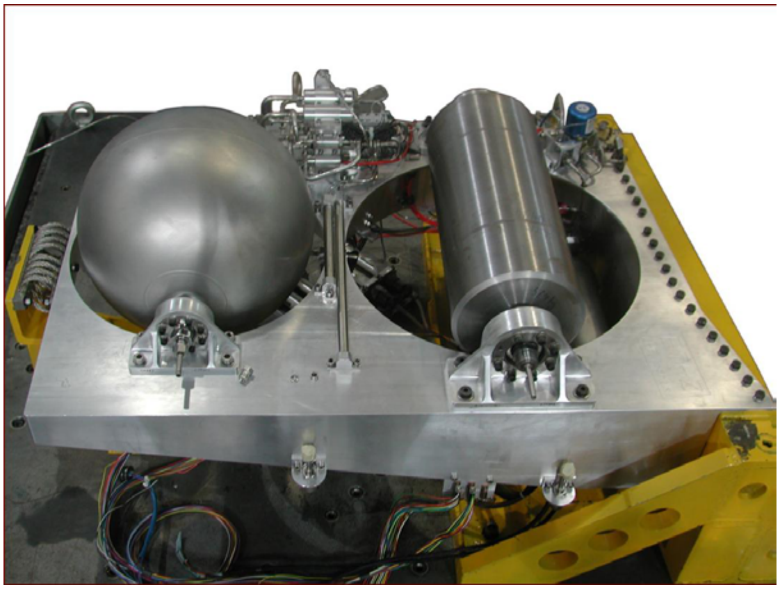

Figure 6: Dummy elements simulating the tanks of Xenon and CO_2

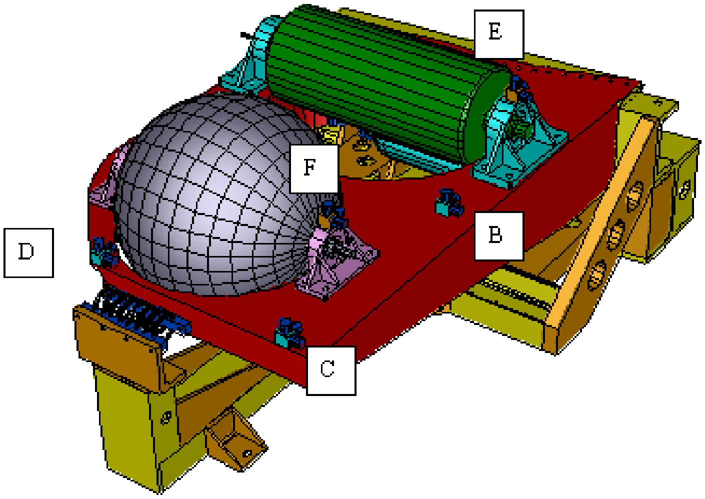

Figure 7: Accelerometer positions on the Box S and on the Test Fixture

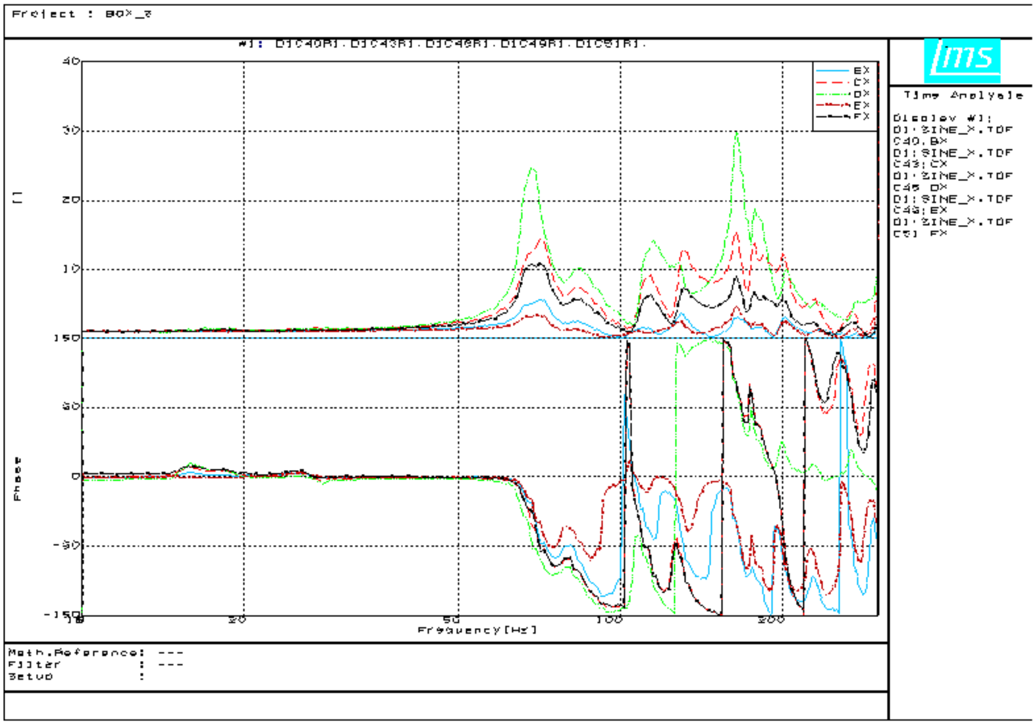

Figure 8: Test Box S: Sine sweep responses (accelerometers in the x axis)

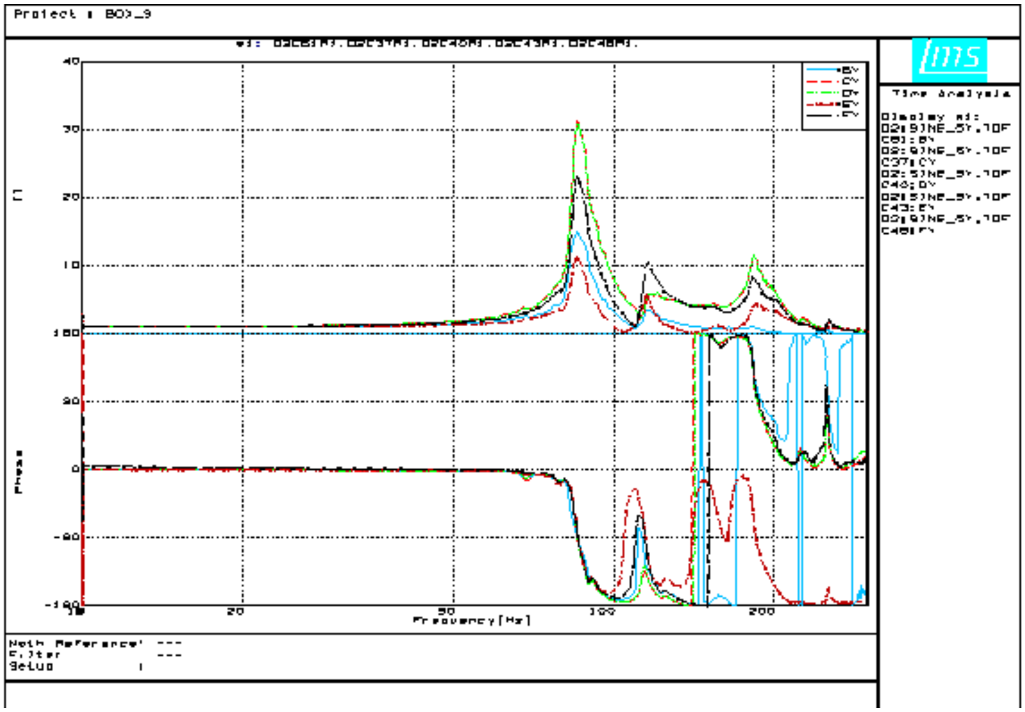

Figure 9: Test Box S: Sine sweep responses (accelerometers in the y axis)

From the static point of view, the Box S predicted behavior (obtained numerically) satisfied the safety requirements described with details in [2]. Only few results, out of the one presented in [4], are reported in the following. For the case when the static loads were in the sequence 3.25 g (x axis), 13 g (y axis) and 3.25 g (z axis), the numerical displacement were equal to 9.301 mm, 2.350 mm and 2.746 mm respectively. In particular, when the maximum acceleration is in the tank axial direction, i.e. ± y, the main bracket of the Xe tank is the

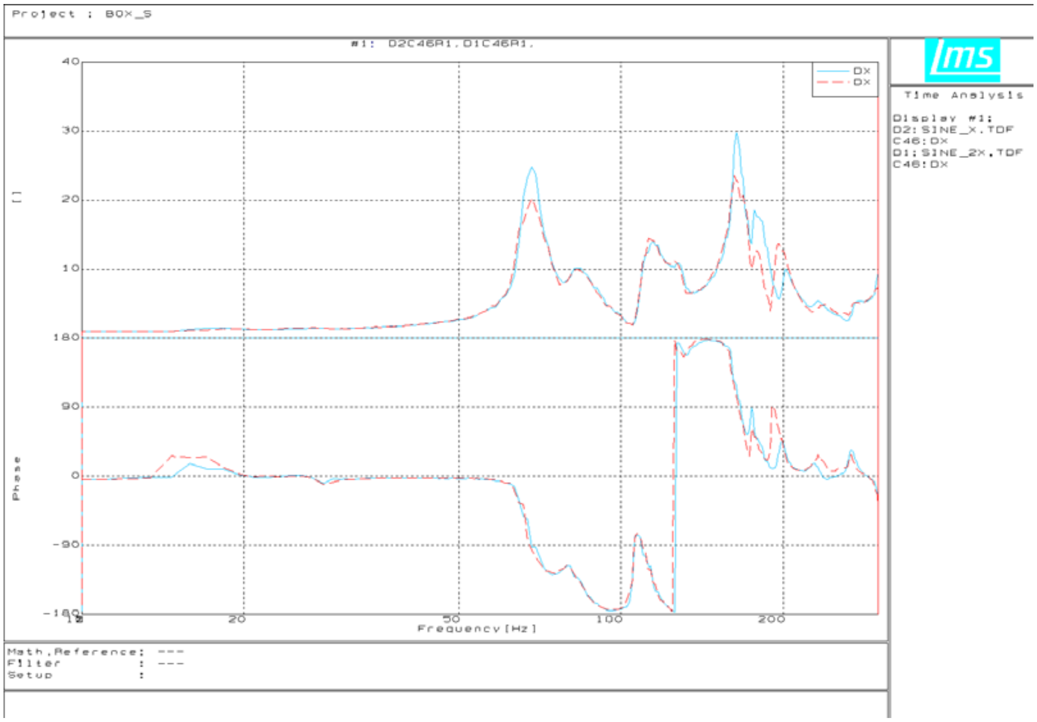

Figure 10: Test Box S: Comparison between the two sine sweep outputs (x axis) for the accelerometer labelled D_x

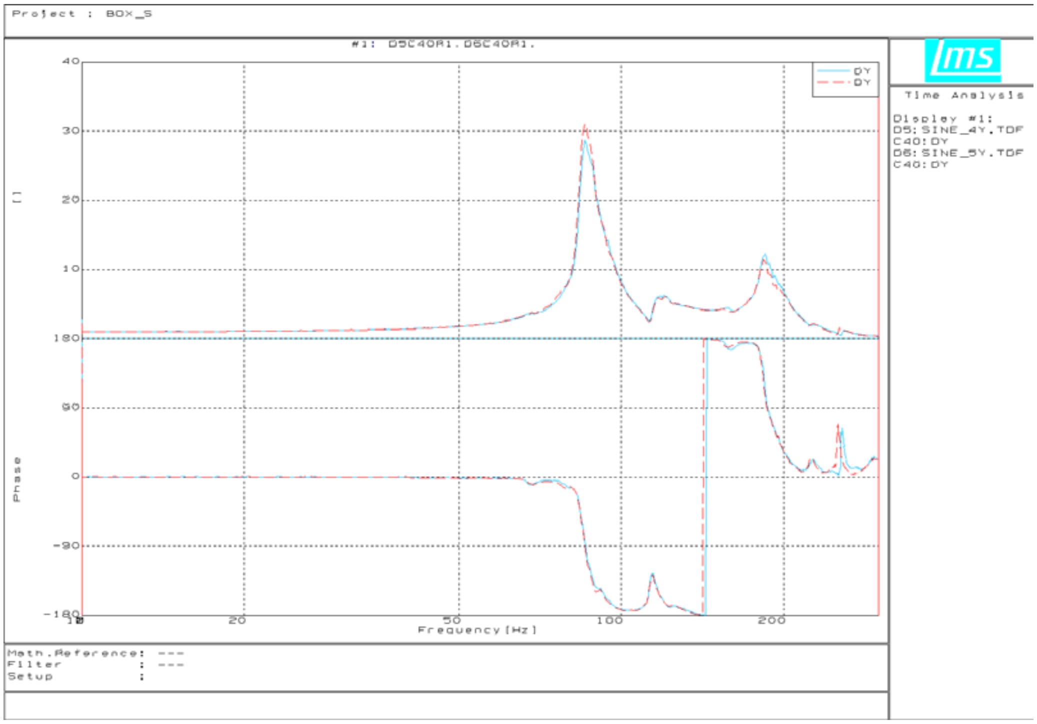

Figure 11: Test Box S: Comparison between the two sine sweep outputs (y axis) for the accelerometer labelled D_y

	f_{exp} (Hz)	f_{Num} (Hz)	$\varepsilon_f\%$
1	70.0	69.8	0.29
2	81.8	80.6	1.71
3	105.4	116.14	-10.19

Table 4: Comparison between the first three experimental and numerical natural frequencies

most loaded. The maximum predicted displacements were: 0.774 mm for 13 g. The largest reactions arose both at bolt fixing the main support for the Xe tank to the plate and at the upper interface of the plate with USS. For the load case 13 g along the positive direction of the x axis, and 3.25 g along the positive directions of the two other axes, the displacements were equal to 9.301 mm, 2.350 mm, and 2.746 mm respectively. When the maximum acceleration (13 g) was normal to the plate (± x), the inertial action of the tank masses (Xe and CO_2) produced a plate bending with maximum sag at the bottom of the plate, where the spring is positioned. A positive effect of the spring for the bending moment has been observed because of its opposition: it lowered the intensity of the reactions at the upper screw location.

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