11th International Conference on Vibration Problems
Z. Dimitrovová *et al.* (eds.)
Lisbon, Portugal, 9-12 September 2013

VIBRATION LOADS IN THE PROCESS OF DESIGNING SCIENTIFIC SPACECRAFT PAYLOADS

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Keywords: Spacecraft, Random, Acoustic, Sine, FEM, SEA

Abstract. *Scientific missions constitute fundamental cornerstones of space agencies such as ESA and NASA. Modern astronomy could not be understood without the data provided by these missions. Scientists need to design very carefully onboard instruments. Payloads have to survive the crucial launch moment and later perform well in the really harsh space environment. It is very important that the instrument conceptual idea can be engineered to sustain all those loads.*

IDR/UPM (Instituto de Microgravedad "Ignacio Da Riva", Universidad Politécnica de Madrid) is a Research Institute whose R&D activities are focused on space science and technology. In particular IDR/UPM is specialized in the thermal control and structural design and analysis of spacecraft and scientific instruments. Currently IDR/UPM participates in instruments of the ESA Solar Orbiter mission and of the ESA/NASA ExoMars mission.

Based on this experience a research work has been performed at IDR/UPM on the role of the different types of dynamic loads (sine, random, acoustic) in the design process of scientific missions' instruments. These loads, always important, become even more critical when the mission thermal requirements are also very restraining. In this case the structural design parameters, like the materials selection, the geometrical lay-out, the sizing of the different elements and the presence of dedicated thermal control structural elements (relatively large radiators, for instance), need to take into account also the thermal requirements. At the same time scientific payloads usually have stringent pointing requirements that have to be maintained when the large temperature variations between illumination and eclipse periods cause thermoelastic distortions in the instrument structure.

In this paper the main findings of this work are presented.

1 INTRODUCTION

In the present century and the former, space exploration has opened the doors for new areas of human knowledge. One of the main points of interest lies in scientific missions. Thanks to them, year by year a better understanding of the universe is achieved, including critical areas like Earth and space weather, astronomy and Solar System planet exploration, just to cite a handful. Each of these missions supposes a new and distinct technological challenge, as all will imply invariably developing a specific research activity in an environment where it has never been performed before (as Mars Curiosity) or, for some missions, the new access to some environments will give the chance to develop new scientific activities (like the first space telescopes). This fact, and the necessity that the success probability should be almost one, due to the exorbitant costs and the impossibility (in most of the cases) of repair, makes comprehensive analyses during the design phase indispensable. Among these, the structural vibration load analyses are of the maximum importance. Being the loads on the payload characterized by the launcher system and its interaction with the spacecraft [1, 2], the specific features of each scientific payload will combine with them, driving the design to its final state.

Two of the most promising missions for the next years are ESA's Solar Orbiter and ESA/NASA's ExoMars. Solar Orbiter will radically improve our understanding of the heliosphere using a combination of remote sensing and in-situ instruments in an orbit around the Sun which combines closeness and high solar latitude in a new way that has never been done before. ExoMars is a set of two missions, with launches scheduled for 2016 and 2018 respectively. The 2016 mission will take to the Martian orbit the Trace Gas Orbiter, which will characterize and map the Mars atmosphere, and will search for methane, which could constitute almost a proof of life on the red planet.

IDR/UPM is in charge of performing the structural analyses, assessing through them changes in the process of design, and of designing the thermal control system for one of the main instruments on board each of these missions. As we will see in the following pages these two disciplines are closely interweaved. Specific thermal requirements will generate mechanical designs (geometries, materials) which will have to be ensured compatibility with the vibrational load launch environment through dynamical structural analysis.

2 SOLAR ORBITER/PHI

2.1 Instrument description and FE model

Solar Orbiter, with launch windows from end of 2017 to mid of 2018 will go as close to the Sun as 0.28 AU. Until NASA Solar Probe Plus arrives, it will be the first man made satellite to orbit so close to the Sun and it will allow Sun-synchronous observation over a fixed point for intervals of several days around the perihelion. Additionally, a series of gravity assisted manoeuvres with Venus will result in a high inclination orbit (up to 34 degrees) allowing the satellite to observe the polar regions of the star.

PHI (Polarimetric and Helioseismic Imager) is one of the main instruments of the mission. PHI will provide high-resolution and full-disk measurements of the photospheric vector magnetic field and line-of-sight (LOS) velocity. The LOS velocity maps will have the accuracy and stability to allow detailed helioseismic investigations of the solar interior, in particular of the solar convection zone [3].

An international consortium headed by the Max Planck Institute für Sonnensystemforschung is in charge of the design of the PHI instrument. IDR is in charge of structural analysis and structural design assessment and thermal control system design and analysis.

PHI is composed by two aluminium blocks joined by carbon fibre struts. The blocks are mounted to the satellite sandwich panel via three titanium feet. The mounting is isostatic. In this way the thermo-elastic deformations will not affect its optical performance. The setup can be appreciated in Figure 1. All the remaining elements are the optical subassemblies, which do not contribute to the structural behaviour of the instrument.

The finite element model employed for the analyses, built following ESA's standards [4] can be seen in Figure 1 on the right side of the image. For the blocks 2D shell elements were used of type CTRIA3 (3279) and CQUAD4 (20423). The struts were modelled using 1D CBAR (120) elements and three dimensional CTETRA (767407) elements for the feet. The different subassemblies which do not contribute to the structural behaviour of the instrument were modelled as lumped masses using CONM2 (13) cards with the moments of inertia.

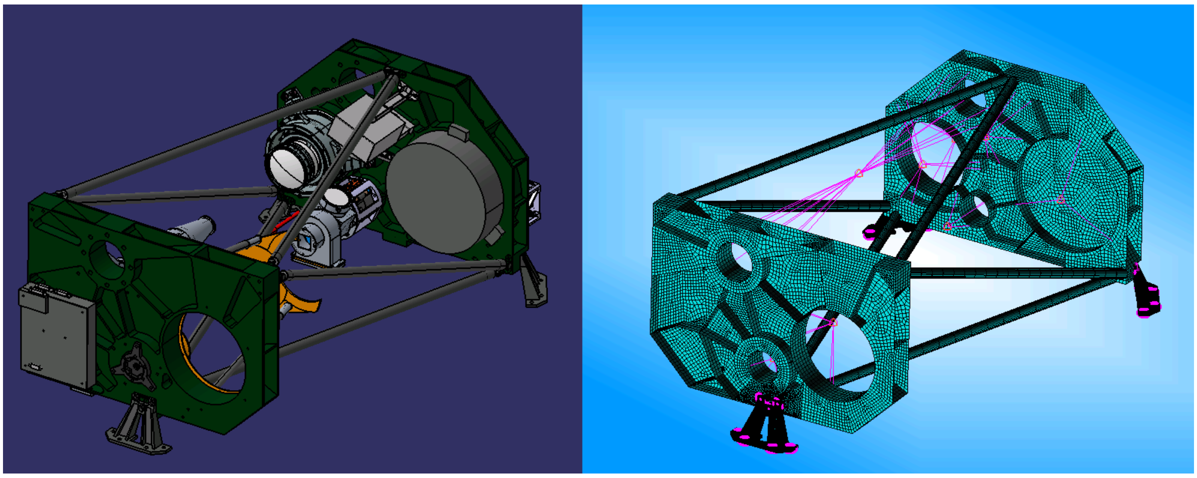

Figure 1: PHI OU, CAD and FEM models.

2.2 Dynamic analyses

The vibrational environment imposed by the launcher (ATLAS V) can be seen in Figure 2. Additionally, the first global normal mode of the structure must be above 140 Hz.

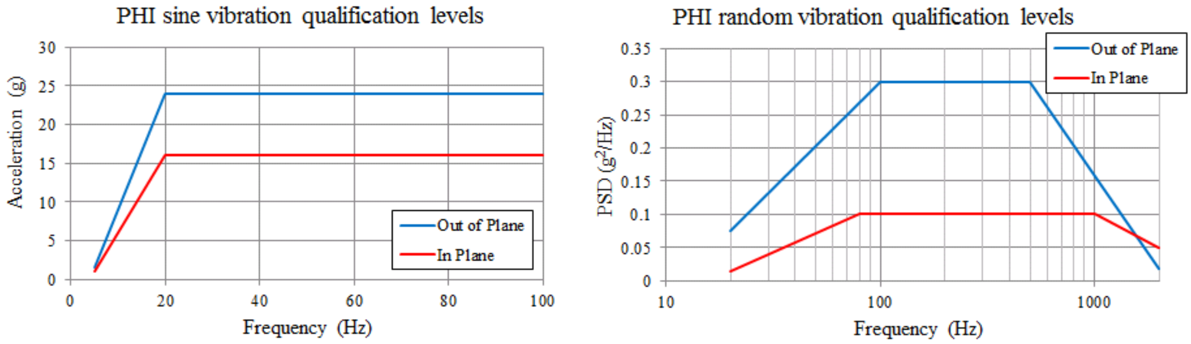

Figure 2: PHI sine and random vibration qualification levels.

The first dynamic analysis performed to the PHI Optic Unit (as it is performed to every space instrument) was a normal mode analysis, which would serve as a base for all the remaining. In a first stage of modelling the first frequency was found to be 139.5 Hz. In that stage, the feet were modelled using shell elements in a slightly conservative approach. The three dimensional mesh feet raised the frequency to 140.15 Hz. An image of the first mode is depicted in Figure 3. It can be seen that the front block pivots around the central mounting foot. In Table 1, the first ten normal modes eigenfrequencies can be seen.

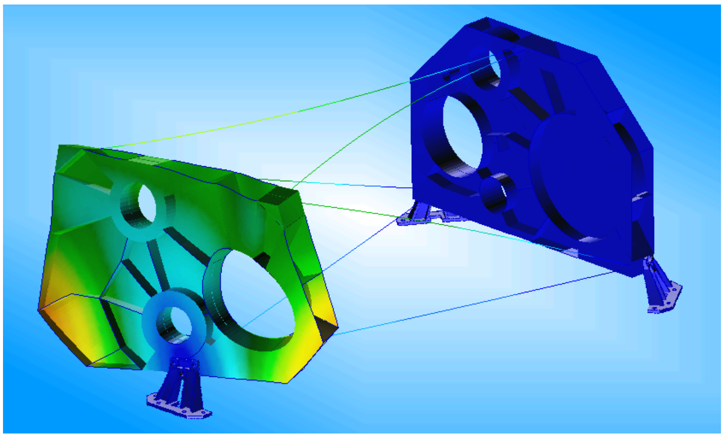

Figure 3: PHI first normal mode at 140.2 Hz.

Using the normal modes analysis as a base, three more dynamic analyses were performed: two sine vibration (sine from 5 Hz to 100 Hz with the specified levels derived by the satellite prime constructor, and micro-vibration, 1g from 5 to 500 Hz in all axes, to find out the amplification in the mounting points of all the subassemblies) and one random vibration analysis.

Mode nº	Frequency (Hz)	Mode nº	Frequency (Hz)
1	140.2	6	235.6
2	150.5	7	240.4
3	180.8	8	242.9
4	185.4	9	256.1
5	208.8	10	256.5

Table 1: PHI OU first ten eigenfrequencies.

The sine analysis does not show potentially harmful issues for the instrument or the satellite. As the first frequency is above 140 Hz, up to 100 Hz the acceleration and stress levels gradually increase, reaching their highest values at the maximum frequency, but far from being close to the admissible values for the selected materials.

The micro-vibration analysis, on the other hand reveals a potential problem. As it can be seen in Figure 4, which shows the amplification levels found in the centre of gravity of the Filtergraph (one of the most crucial subassemblies of PHI OU), there is a potential high amplification in the 400 Hz to 500 Hz frequency range. In it, the mentioned subassembly has a normal mode, so coupling is expected. In this and all the remaining PHI figures the X direction is orthogonal to the medium plane of the structural blocks.

The random vibration load analysis confirms this. In Figure 5, a plot of the PSD of the acceleration in one of the mounting bolts of the Filtergraph can be seen. The different curves show the response in the three main directions (X, Y, Z) due to the three different random analyses in all three directions. The same effect can be appreciated in it. Peaks around 140 HZ, 180 Hz, and around 200-300 Hz and 400-500 Hz frequency ranges. Regarding the PSD amplitude levels, it is to be said that the analyses were performed prior to the environmental testing of the instrument, so these should be confirmed once the damping levels are measured and the model is correlated.

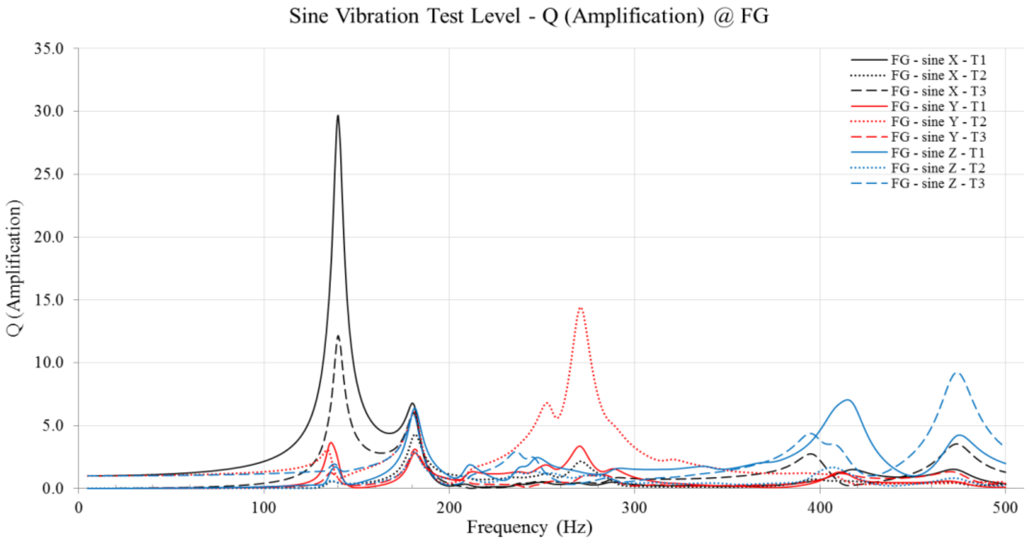

Figure 4: Microvibration analysis - 1 g sine sweep from 0 Hz to 500 Hz for Filtergraph in PHI OU.

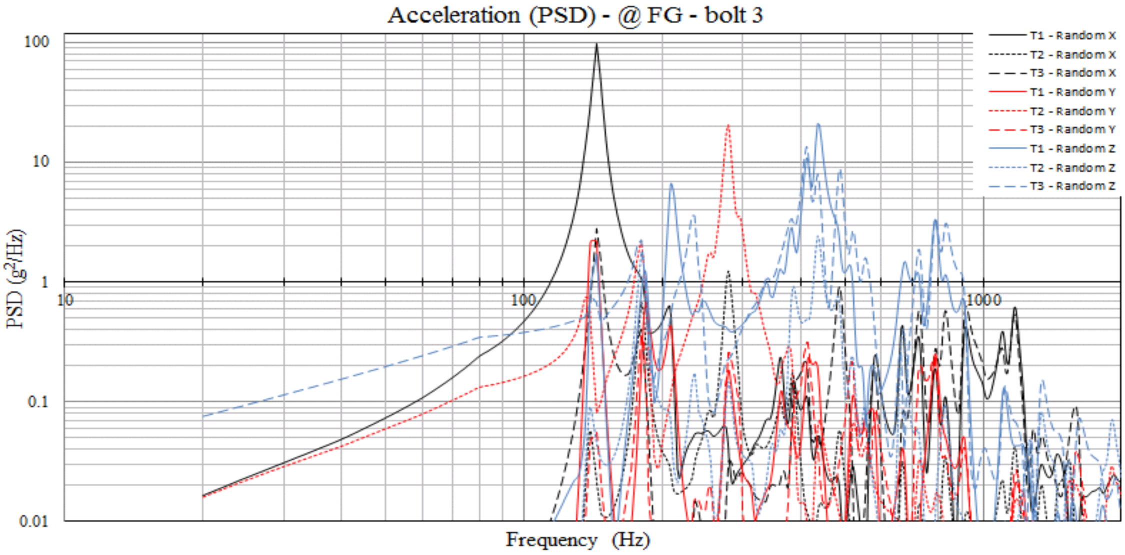

Figure 5: Random vibration analysis: PSD acceleration response for one of the Filtergraph interfaces.

2.3 Modifications in the design of the PHI-OU

Hence, due to the sine and random analyses and the depiction of the first mode some conclusions arise that will help in the improvement of the design. In first place, the first mode could be fixed increasing specifically the stiffness of the lower section of the front block. With that objective, a sandwich panel will be included between the inferior sides of both blocks. In second place the coupling between the structure and the Filtergraph is worrying. Adding this to the fact that the overall levels for the frequency should be raised, as there are more modes close to the limit of 140 Hz, a change in the material was agreed, in order to change its stiffness/density ratio. The new material in which the structural blocks will be manufactured is a beryllium and aluminium alloy, with commercial name AlBeMet 162 (62% beryllium and 38% aluminium). AlBeMet 162 has a density of 2100 kg/m3 and a Young modulus of 193 GPa. The new eigenfrequency distribution and the associated modal effective masses using AlBeMet 162 blocks, can be seen in Figure 6.

PHI successfully passed ESA Preliminary Design Review and is heading towards Critical Design Review with good prospect.

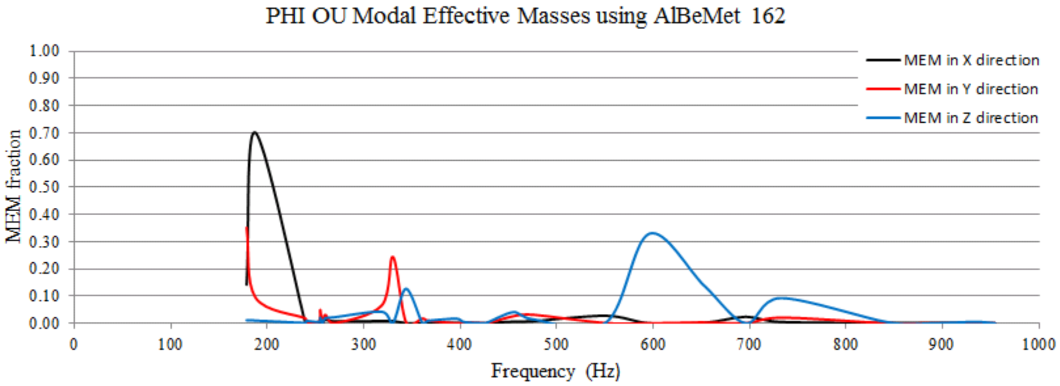

Figure 6: PHI Optics Unit modal effective mass for the normal modes, 0 – 1000 Hz.

3 EXOMARS/ NOMAD

3.1 Instrument description and FE model

ExoMars Orbiter Spacecraft named ExoMars Trace Gas Orbiter (EMTGO) is an ESA/NASA mission. The objectives of the ExoMars program will be pursued as part of a broad cooperation with NASA that will build towards a Mars sample return mission in the following decades. Two missions are foreseen within the ExoMars program for the 2016 and 2018 launch opportunities to Mars. NOMAD will go on board the 2016 mission.

The 2016 mission is an ESA led mission that was going to be launched by a NASA supplied Atlas V Series 4 rocket. Finally, due to budget cuts, the launch vehicle will be a Russian Proton, and the Russian space agency, Roscosmos, will be in charge of some of the remaining instruments. ESA will supply a Mars Orbiter (Trace Gas Orbiter) that will carry a 600 kg Entry, Descent, and Landing (EDL) Demonstrator also supplied by ESA. The scientific instruments will be accommodated on the ExoMars TGO. The TGO will have three missions: to carry the EDL demonstrator to Mars, to serve as communication link to the ExoMars 2018 mission rover and, as its name indicates, to characterize the Martian atmosphere.

NOMAD will conduct a spectroscopic survey of Mars' atmosphere in the UV, visible and IR spectral ranges. NOMAD consists of three channels: a solar occultation channel (SO) operating in the infrared wavelength domain, a second infrared channel capable of doing nadir, but also solar occultation and limb observations (LNO), and an ultraviolet/visible channel (UVIS) that can work in all observation modes. SO and LNO operate in the IR domain.

An international consortium headed by the OIP sensor systems and BIRA (Belgisch Instituut voor Ruimte-Aeronomie) is in charge of the design of the NOMAD instrument. IDR is in charge of structural analysis and structural design assessment and thermal control system design and analysis.

The main challenge of this instrument is the nadir observation mode. The energy associated to the IR radiation coming from the Mars surface is of the same order of magnitude that the IR thermal radiation at ambient temperature. Therefore, inside the LNO box, a temperature of -100 ºC is to be obtained in order to have a signal to noise ratio that allows science in this wavelength. Unlike other low temperature requirements, which are usually bounded to a small detector, cooling to this temperature a medium size box which is surrounded by an ambient temperature environment poses a considerable challenge. As an answer to this thermal requirement, a multistage thermal radiator was conceived at IDR. It has to be large to reject the necessary amount of heat, and due to the radiative geometric constraints it can be only stiffened in certain areas and directions. The assembly of the instrument can be seen in Figure 7. The lowermost box is the SO, and the top box is the LNO with the cryo-radiator on top.

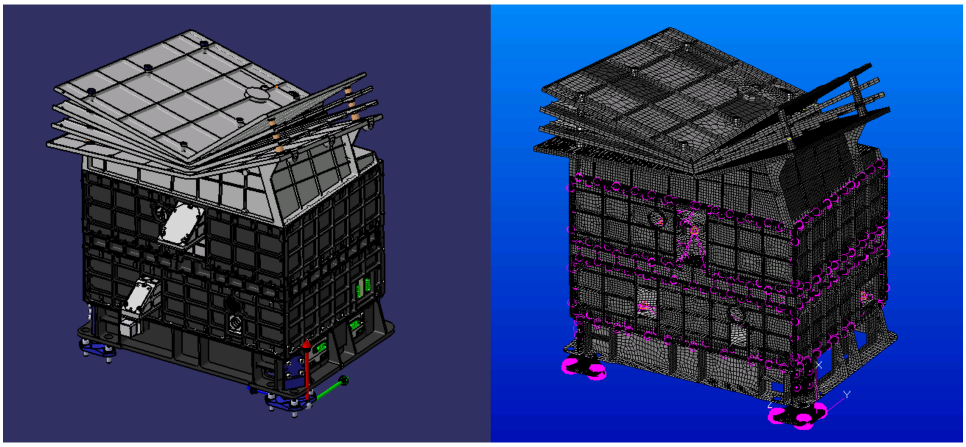

Figure 7: NOMAD, CAD and FEM models.

The multistage radiator is composed by a baseplate that includes the first stage of the radiator, two intermediate stages that shield the radiation to the top stage, and a fourth top stage, which takes the most important role in heat rejection. From the first (base) to the last stage, titanium bolts give the mounting pressure to the ULTEM standoffs used to separate and insulate conductively between each pair of stages. The SO, LNO and cryo-radiator are all made in an aluminum alloy (7075 except the top plate, which is made of 6082 to ensure high thermal conductivity). The instrument is mounted isostatically on three titanium feet that absorb thermoelastic deformations. This mounting is due to optical reasons (considerable difference of temperatures between hot and cold conditions) and to the restrictive satellite interface conditions imposed by the prime constructor, THALES-ALENIA.

On the same Figure 7, the finite element model employed for the different analyses can be seen. All the thin parts are modeled as shell like elements, CQUAD4 (88375) and CTRIA3 (32545), the linear elements (bolts, ULTEM standoffs) like CBAR (1590), and the feet are modeled in 3D using a fine mesh of CTETRA (280141) elements in order to accurately search for high stress areas. The subassemblies that did not contribute to the structural behaviour were introduced as concentrated masses using CONM2 (21) cards with their moments of inertia.

3.2 Dynamic analyses

The frequency of the first global normal mode should be above 140 Hz. The vibrational environment on the deck of the satellite can be seen in Figure 8. In this case, as NOMAD is on the external surface of the satellite exposed to acoustic vibration as well, and due to the particularities of the cryo-radiator (large and thin surfaces with not too high stiffness) a preliminary and conservative acoustic analysis was performed to one of the intermediate plates. The acoustic levels can be seen in Figure 9.

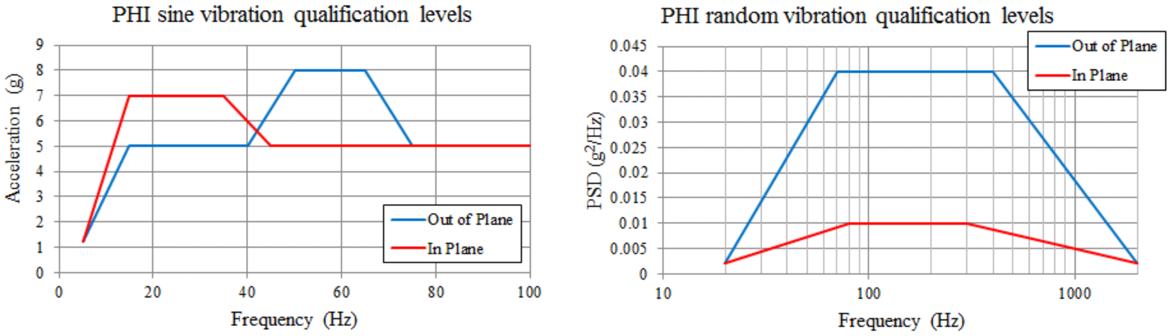

Figure 8 NOMAD sine and random vibration qualification levels.

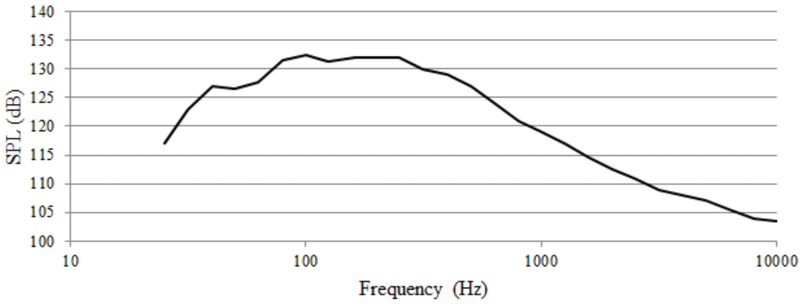

Figure 9: Acoustic sound pressure levels for NOMAD.

The normal mode analysis revealed a number of interesting facts. In first place, it brought out the presence of a local mode at 90 Hz in an area of the LNO baseplate under one of the subassemblies, the AOTF. Conversations with our OIP-BIRA colleagues brought out that in a previous instrument with the same mission sent to Venus (SOIR), one of the AOTF broke during the environmental tests. This issue should be studied more in detail in the sine and random vibration analysis. In second place, there are several normal modes in the cryo-radiator mid stages below 100 Hz but they are all local, so it was considered acceptable. The first and fourth stages could be stiffened as usual (ribs in orthogonal directions), but the sides of the different stages that faced each other should act as mirrors for the radiation, so they could only be stiffened in one direction in order not to block the infrared radiation being rejected to space. As a result of this, all these local modes appear. Most worrying revealed to be a global mode that, in the first modelling approximation (with 2D shell feet), had an eigenfrequency of 108 Hz. The current 3D mesh of the feet revealed to be less conservative and more realistic than the previous. It gave an eigenfrequency of 116 Hz, which was agreed as valid with ESA and THALES-ALENIA as long as the sine vibration analysis up to 100 Hz did not show that the interfaces with the satellite would be overloaded. Figure 10 shows the normal modes of NOMAD up to 140 Hz, and Figure 11 illustrates some of the modes: on the left the mode at 90 Hz with the detail of the AOTF area, in the middle a local mode of the intermediate plates, and on the right side the global mode at 116 Hz.

Sine vibration analysis revealed what was expected: the acceleration on the AOTF interface was too high and local reinforcement would be needed in that area. It also revealed that the local modes in the cryo-radiator would not be harmful and that the instrument would not damage the spacecraft deck.

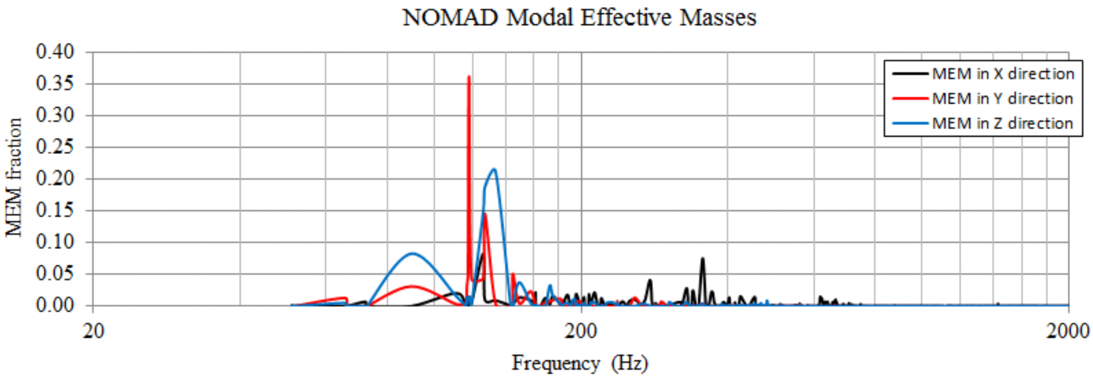

Figure 10 NOMAD modal effective mass for the normal modes, 0 – 2000 Hz.

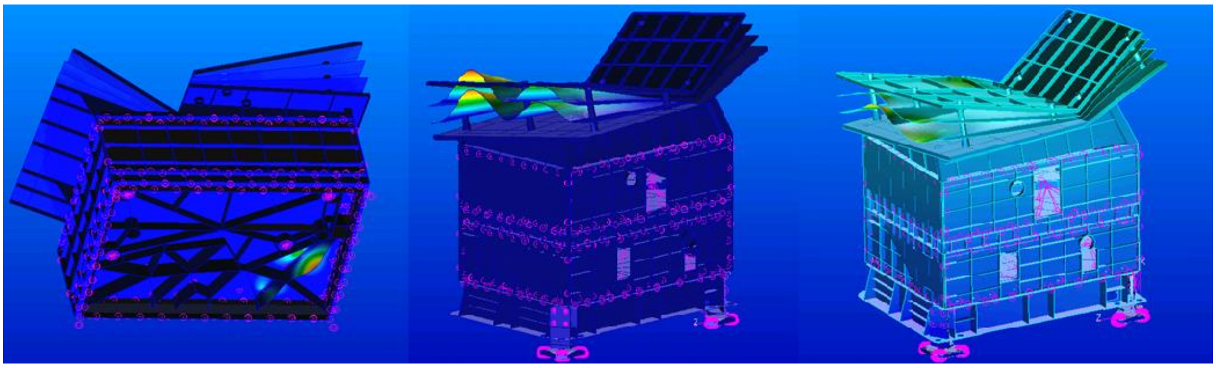

Figure 11: NOMAD normal modes at 90 Hz, 72.3 Hz and 116 Hz.

An additional acoustic analysis was performed to one of the mid plates, to check if it would be affected by the launch acoustic environment. For this analysis, the software was VA One. Two models were used for this analysis. For the low frequency range, a FEM-BEM model directly derived from the detailed FE model [5] presented in Figure 7 was used. For the high frequency, a SEA model was derived from the FEM. In this case, due to the nature of the analysed components, the high frequency zone starts at in the 315 Hz central frequency band in thirds of octave. From the third of octave centred on 315 Hz there are more than 3 modes per band, so the Statistical Energy Analysis (SEA) could be used from that point on [6]. The solutions of both models were coupled in the 315-500 Hz zone. The Von Mises stress values can be seen in Figure 12. The absolute maximum stress is around 20 MPa, which gives a margin of safety of more than 4, hence no further vibroacoustic analysis will be needed.

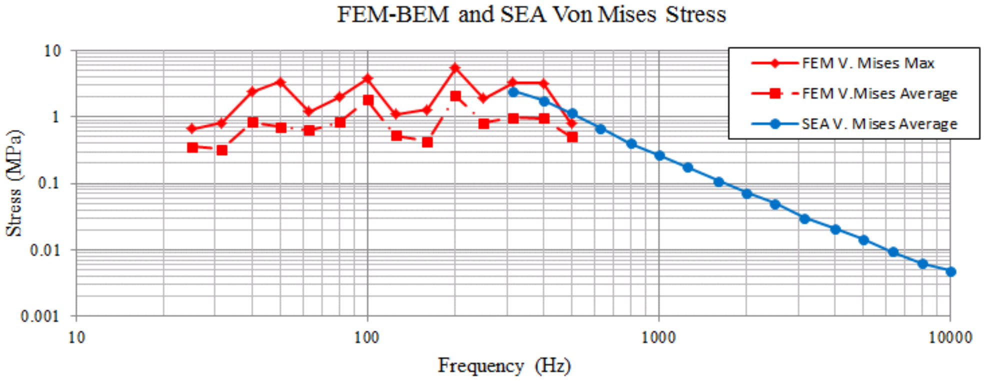

Figure 12: NOMAD plate Von Mises stress due to vibroacoustic environment.

3.3 Modifications in the design of NOMAD

The main points that have evolved during the NOMAD design have been the feet, the cryo-radiator and the area under the AOTF.

The feet shown in Figure 7 are the last of many attempts, in which a compromise between being stiff enough to fulfil the frequency requirement, providing an isostatic mount and respecting the maximum allowable loads in the inserts (very low, around 2000 N per each bolt) was finally reached.

The cryo-radiator was stiffened in order to eliminate the maximum local normal modes that was possible. In order to do this, the top stage was stiffened towards the space side in both directions, the first stage was stiffened towards the inside of the instrument, and the intermediate stages along the direction of the expected radiation, so it would not be blocked.

And last, the detailed analysis around the area of the AOTF indicated the need of reinforcing that area, to avoid failure during the test. Detailed analysis in the case of NOMAD is crucial, because no structural-thermal model will be developed for environmental testing.

4 CONCLUSIONS

As it is shown in this article, vibration load analysis plays an important role in the design of spacecraft payloads. We have seen this for two scientific instruments that will be on board of two of the most promising missions for the next years.

PHI has seen important (fundamental) changes in the design due to this fact. The material, the layout and the inclusion of a sandwich panel all have originated from the results of these analyses.

NOMAD has taught even more lessons during a long and frantic design process with budget cuts and atypically short time schedules.

There is, however, one more lesson that needs to be learned. This is timing. All these changes in the design are the result of common design flow, were vibration load analyses are performed at a time were many features have been already defined. Some are logical, like the stiffening of the area under the AOTF in NOMAD (detailed design), but some others, like the change of material and layout in PHI could have been avoided if these analysis techniques would have been introduced earlier in the design. IDR is working towards this objective and it is developing a concurrent design facility in which the purpose is to be able to make all the current analysis software communicate through a database, including NASTRAN and VAOne. This will allow preliminary vibration loads analysis during initial stages of the design.

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