SIMULATION OF A SPACECRAFT ACOUSTIC TEST BY HYBRID FE-SEA METHOD: APPLICATION TO THE CALIPSO SPACECRAFT AND COMPARISON WITH EXPERIMENTAL DATA.

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OVERVIEW

The prediction of the random response of the structure and units of a spacecraft submitted to an acoustic test is performed using an Hybrid FE-SEA method. The Hybrid method allows to rigorously couple BEM, FEM and SEA descriptions of different subsystems of a system in a fully coupled analysis. It is implemented in the VA One software developed by ESI group and was applied to the prediction of the random levels on the CALIPSO spacecraft. For some targeted components of the spacecraft, a comparison was made between various modelling strategies (pure SEA, FE description with SEA excitation, standard BEM/FEM approach). Based on these local analyses, a complete hybrid model of the spacecraft was built and used for vibro-acoustic predictions. Results are compared with the levels measured during the acoustic qualification test of the spacecraft.

1. INTRODUCTION

CALIPSO is the product of a cooperation between CNES and NASA. It is made of the CALIPSO payload provided by NASA and built by Ball Aerospace & Technologies Corporation, mounted on a PROTEUS platform provided by CNES and built by Thales Alenia Space. CALIPSO is on orbit since the 28th of April 2006. The main parts of the spacecraft are described in figure 1.

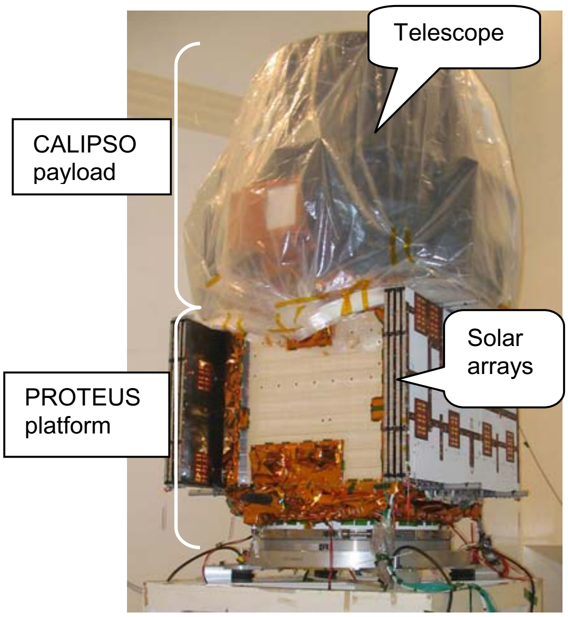


FIG 1. View of the CALIPSO spacecraft in the acoustic chamber

The aim of the work described in this paper was to define a modelling strategy for the prediction of the random response of CALIPSO subjected to a diffuse acoustic field. Standard FE, BEM and SEA methods are available to the analyst, and the recently developed Hybrid FE-SEA technique allows the coupling of those methods. The choice depends on the dynamic properties of the components, the loads, and the frequency range of interest. Starting from the FE model used for the dynamic analyses, several modelling options were systematically investigated for a number of spacecraft subsystems, and an Hybrid model of the system was eventually built.

The Hybrid method developed by ESI group allows to:
- transform the parts of the structure having a high modal density into SEA subsystems,
- keep for the rest of the structure the dynamic behaviour described by the FE method,
- couple the FE description of a structure to a BEM description of an acoustic field where required by the complexity of the acoustic field or structure,
- couple the structure to an SEA diffuse acoustic field excitation on the other parts of the structure (described with either SEA or FE).

The Hybrid model of CALIPSO is described in figure 2 where the following elements are shown:
1) BEM fluid for the computation of the acoustic field around the telescope.
2) SEA diffuse acoustic field exciting some SEA or FE subsystems.
3) FEM subsystem (yellow).
4) SEA subsystem (green).

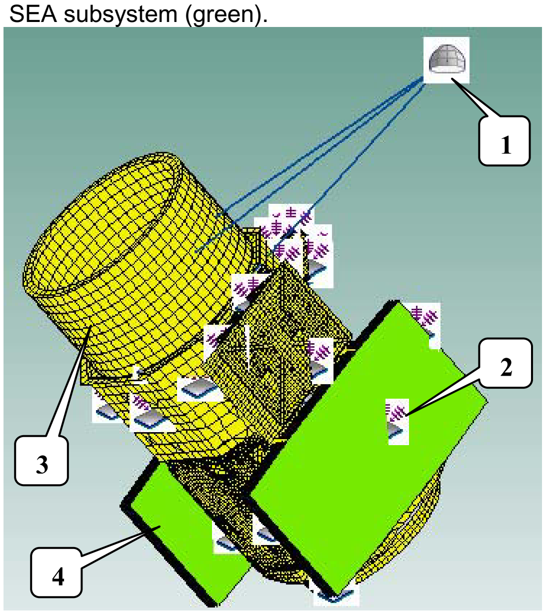


FIG 2. Hybrid model of the CALIPSO spacecraft

The hybrid method allows to limit the computation of the acoustic field by BEM method to some parts of the spacecraft only. The other parts are excited by an SEA diffuse acoustic field, allowing to reduce the total computation time. Moreover, the possibility to replace some FE components of the spacecraft by SEA subsystems provides additional computation time and memory savings.

The following section describes the Hybrid method and its implementation in the VA One software. Then, the process to build a Hybrid model of CALIPSO is presented and discussed. First, local analyses have been made on some parts of the spacecraft in order to check the various modelling strategies available in VA One. The comparison between the various prediction results were used to decide on the most appropriate method for each subcomponent of the spacecraft. Finally, a complete Hybrid model of CALIPSO was built and the results of the analyses are compared with the measurements obtained during the acoustic qualification test on the spacecraft.

2. DESCRIPTION OF THE HYBRID METHOD

The Hybrid FE-SEA method can be used to rigorously couple FE and SEA descriptions of different subsystems of a system in a fully coupled analysis. The method and its application are described in references [1-7]. Hybrid coupling between an FE structural subsystem and an SEA subsystem occurs via a combination of point, line and area type junctions. These junctions are referred to as “Hybrid junctions”. For the CALIPSO structure, interest primarily lies in coupling :

- the FE body structure to the SEA solar panels using a series of “Hybrid Point Junctions”,
- Some FE panels to the SEA description of the diffuse acoustic fields in the surrounding fluids using a series of “Hybrid Area Junctions”.

2.1. Hybrid FE-SEA equations

In order to improve efficiency, the Hybrid FE-SEA method in VA One is implemented to work in modal coordinate of the FE subsystems (rather than nodal degrees of freedom). Consider an FE subsystem connected to a set of SEA subsystems across hybrid junctions. The total dynamic stiffness matrix D_{tot} of the coupled system (FE and SEA parts) includes the standard FE contribution D_d (composed of the modal mass and stiffness matrices - complex if the FE subsystem has damping), augmented by the dynamic stiffness contribution of the SEA subsystems:

(1) $$D_{tot} = D_d + \sum_k D_{dir}^{(k)}$$

The summation is over the number of SEA subsystems in the model. It is shown in ref [1] that the contribution of SEA subsystem is the direct field dynamic stiffness matrix $D_{dir}^{(k)}$ associated with each subsystem k. $D_{dir}^{(k)}$ is the dynamic stiffness at the junction of the SEA subsystem as if the SEA subsystem was of infinite extend (details are given below for hybrid point and area junctions)

The equation of motion for the modal contribution is written:

(2) $$D_{tot} q = f_d + \sum_k f_{rev}^k$$

where f_d is the deterministic generalized forces directly applied to the FE subsystem and f_{rev} are the reverberant forces due to the diffuse field in the connected SEA subsystems. The cross-spectral matrix of the force exerted by the reverberant field is proportional to the resistive part of the direct field dynamic stiffness matrix, which is a form of diffuse field reciprocity statement (see reference [2]):

(3) $$S_{f\_rev,f\_rev}^{(k)} = E[f_{rev}^{(k)} f_{rev}^{(k)^*}] = \alpha_k \operatorname{Im}(D_{dir}^k)$$

where α_k is proportional to the energy level of the connected SEA subsystem.

Equation (3) is a form of diffuse-field reciprocity statement, and is the core of the hybrid coupling as it relates the statistics of the dynamic forces exerted on an FE subsystem to the energetics of the connected SEA subsystem.

Equations (1-3) can be used to yield the input power to the SEA subsystems due to the direct excitation of the FE subsystem:

(4) $$P_{inj}^{(k)} = \omega/_2 \, D_{dir}^{(k)} \otimes S_{qq}$$

where $\otimes$ is the dot product, S_{qq} is the modal cross-spectral response of the FE subsystem to the external loading resulting from solving equation (2). It involves contribution from both FE-deterministic and SEA-random partitions.

Applying the power balance equation to each SEA subsystem, the power input to each connected SEA subsystem can be found in terms of the energy in any other SEA subsystem: this is the definition of the coupling loss factors between SEA subsystems, and they are thus seamlessly and rigorously obtained in terms of the FE dynamic properties and the direct field dynamic stiffness matrices. This allows building an SEA-like power balance equation which rigorously account for the coupling of SEA subsystem across FE subsystems.

Detailed formulation is presented in ref [1]. Several academic validation cases are presented in reference [3] and industrial cases are presented in reference [5, 6 and 7].

2.2. Hybrid point and area junctions

As discussed hereunder, in order to describe the coupling at a given Hybrid junction it is necessary to compute the “direct field radiation impedance matrix” that an SEA subsystem presents to the modes of an FE structural subsystem. Typically, this matrix is full and complex and accounts for the mass, stiffness and damping that each SEA subsystem presents to the FE structure.

For an area junction, a detailed BEM or IEM model could be used to compute this impedance. However, significant savings in computational expense can be obtained by adopting an approximate description of the impedance. A numerically efficient algorithm has been implemented for automatically computing the impedance that an (optionally trimmed) fluid half space presents to the modes of an FE structural subsystem. The algorithm uses a wave number transform to compute the Green’s function of the fluid half space and adopts an efficient method for computing the (full and complex) nodal dynamic stiffness matrix of a given area junction. The nodal dynamic stiffness is then projected onto the structural mode shapes. The algorithm is described in more detail in reference [8]. Since the approach is based on the impedance of a fluid half space, the approach is approximate for highly non-planar junctions. However, in practice this approximation is often adequate when the main concern is with the net energy flow across a given junction. The advantage of the approach is that it is typically several orders of magnitude faster than a traditional BEM or IEM analysis.

For point junctions, some analytical results can be used to find the "direct field impedance matrix". Consider for example a thin plate (described with SEA) bolted to a FE structural component at a point. The direct field impedance of the plate is the point impedance of the infinite plate (where only waves propagating away from the bolt are present). The impedance can be obtained for any value of the bolt diameter by using recently developed analytical formulas [9]. These formulas are obtained by describing the displacement and stress fields at the bolt-plate interface in terms of a series of outgoing cylindrical waves (composed of Bessel functions), and by solving for the wave amplitudes using displacement compatibility and force equilibrium. In physical coordinates, the impedance matrix is a 6×6 matrix relating the three displacements and three rotations at the connecting point to the three forces and three moments. If N bolts connect the plate with the structural component, then in principle the analysis should account for the coherence of the waves emanating from each bolt. The $6N\times6N$ impedance matrix would then be widely populated. However, if the wavelength of a free wave in the plate is short compared to the spacing between the bolts, then the phase of a wave arriving at a bolt is extremely sensitive to perturbation, and the resulting coherence can be neglected. In this case, the impedance matrix can be derived from the analysis of each connection in isolation.

2.3. Diffuse acoustic field loading

Central to the development of the Hybrid method is a "diffuse field reciprocity relation" [2] regarding the forces exerted by a reverberant field on its surrounding boundaries. The relation implies that the cross-spectral matrix of force is proportional to the real part of the direct field impedance matrix of the boundary, and to the energy of the reverberant field (eq. 3). This was shown to be valid when the response of a subsystem constitutes a diffuse random wave field. It makes a connection between the energetic of the field and the elastic forces at the boundary, and as such it forms the key to coupling SEA to FE. For an area junction, the reciprocity relation yields the forces that a diffuse acoustic field exerts on a FE structural subsystem in terms of the radiation impedance matrix. The assumptions underlying the fast computation of the radiation impedance thus apply to the calculation of the forces (the result is approximate for highly non-planar junctions or unbaffled junctions).

3. COMPARISON BETWEEN BEM/FEM, HYBRID AND SEA MODELS OF COMPONENT RESPONSE TO ACOUSTIC EXCITATION

For a number of components of the spacecraft, comparisons have been made between the various methods available in VA One. These methods are:

- the standard BEM/FEM approach where the acoustic fluid and loading are described by the BEM, and are coupled to FEM description of the dynamic behaviour of the structure,
- the Hybrid approach where a structure can be described by FEM, and excited by an SEA diffuse acoustic field (DAF),
- the pure SEA approach with a structure modelled by SEA subsystems, and excited by an SEA DAF.

The aim was to select the most appropriate method for each part of the spacecraft before carrying out the computation on the whole spacecraft. The criterion is the accuracy of the prediction when compared to the BEM/FEM solution (considered as the reference result) and the gain obtained by using the Hybrid or SEA method.

3.1. Acoustic excitation on the baffle

Some local vibro-acoustic analyses were performed on the baffle alone (see figure 3):

- a BEM/FEM analysis,
- an hybrid analysis with the acoustic excitation described with an SEA diffuse acoustic field,
- an SEA analysis with the baffle modelled as an SEA cylinder subsystem.

In the first two models, the baffle FE model was extracted from the complete model and simply supported boundary conditions were applied at the interface with the spacecraft. Modes were extracted up to 1200 Hz. The analyses were performed with a 5Hz bandwidth and a constant acoustic pressure equal to 120 dB.

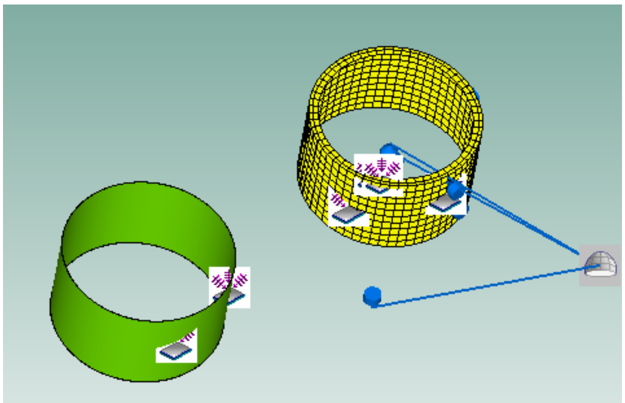


FIG 3. FEM/BEM and SEA model of the baffle

The random response levels at several points of the baffle computed by BEM/FEM method and the mean level computed by the SEA method are plotted in figure 4.

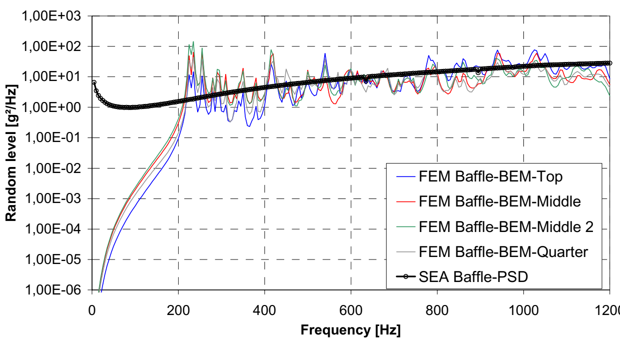


FIG 4. Random level on the baffle : SEA and BEM/FEM results

The spatial and frequency dispersions of the response obtained from the FEM/BEM model is fairly small (less than 10 dB), and the SEA model is shown to yield an accurate prediction of the mean random level.
In figure 5 the random level computed at one point located in the middle of the baffle with the BEM/FEM and the Hybrid model is shown. In the Hybrid model, the baffle is modelled with FEM, and the excitation is described by an SEA DAF.

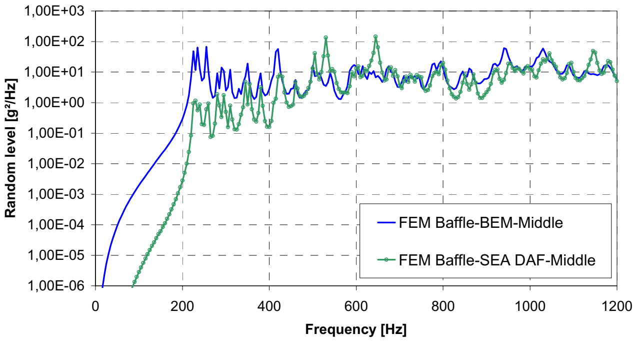


FIG 5. PSD in the middle of the baffle – comparison between BEM/FEM and hybrid SEA/FEM models

The predictions are very similar above 400 Hz. Discrepancies at low frequencies are due to the assumptions underlying the Hybrid area junction (baffled structure, small curvature when compared with free wavelength). Similar conclusions were obtained with other locations on the baffle.

These results show that the various methods yield similar predictions of the random levels on the baffle alone. When the baffle is mounted on the spacecraft, it is important to check the results obtained on the spacecraft structure in order to validate the coupling with the rest of the structure. This is particularly critical for the configuration where the baffle is described with SEA as an Hybrid junction is then used at the coupling with the payload module. In figure 6, the random levels predicted on the +Z panel of the payload module by the various methods and for an acoustic excitation on the baffle only are shown.

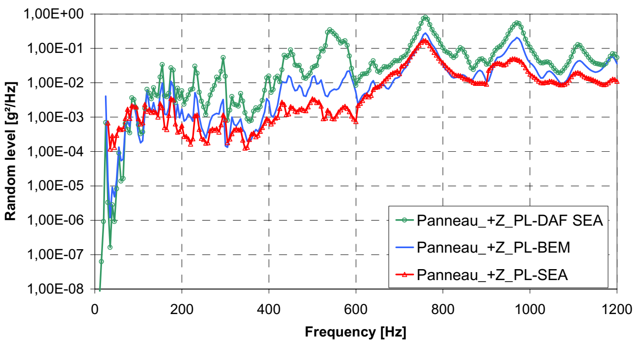


FIG 6. Random level on the PL +Z panel for an excitation on the baffle only

The results are slightly different but the Hybrid model with the baffle described with an SEA subsystem and coupled to the FE model of the spacecraft is shown to yield realistic results. Similar trends are obtained at other observation points of the payload module.

One advantage of the BEM/FEM approach is the possibility to evaluate the spatial distribution of the acoustic pressure around the structure. The baffle forms a kind of open cavity, and it is interesting to check the internal pressure. In figure 7 the pressure at two points within the baffle is shown as computed by the BEM/FEM model. It is shown that the acoustic pressure varies significantly inside the baffle.

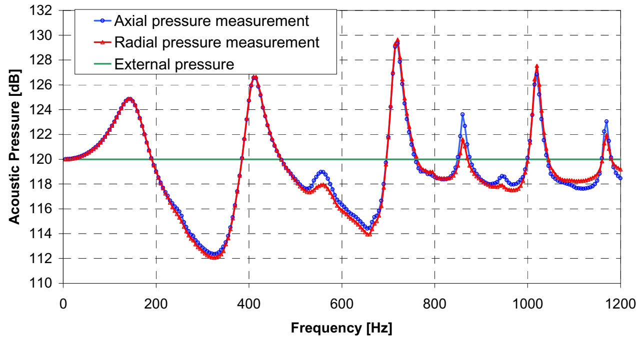


FIG 7. Acoustic pressure inside and outside the baffle

The following statements may be deduced from the analyses:
- the SEA model of the baffle is sufficient in order to get the mean random level on this part of the structure.
- the computations made with the BEM/FEM method or the hybrid SEA/FEM method give similar results.
- the hybrid method gives realistic results when the SEA baffle is mounted on the spacecraft.
- one advantage of the BEM/FEM method is the possibility to predict the variations of the acoustic pressure within the baffle.

Considering that the variations of the acoustic pressure within the baffle may have an influence on the random levels on the primary and secondary mirrors of the telescope, the BEM/FEM method was retained for this part of the structure for the computations at spacecraft level.

3.2. Acoustic excitation on the solar arrays

The same approach as the one used for the baffle was applied to the solar arrays. Local analyses were performed on one panel using FEM/BEM, Hybrid FE-SEA and SEA models (see figure 8).

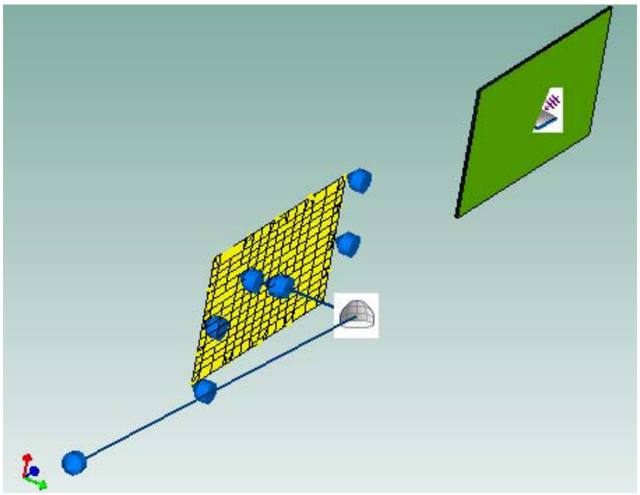


FIG 8. FEM and SEA model of one panel of the solar arrays

The random levels computed at various points of the panel with the BEM/FEM method and the mean level from the SEA model are shown in figure 9.

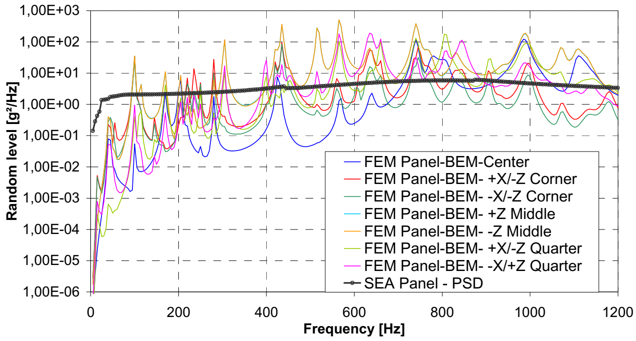


FIG 9. Random levels on the solar array panel : comparison between BEM/FEM and SEA results

As for the baffle, the SEA model gives a decent estimation of the mean random level on the panel (although the variations around the mean are more significant).

The random level at the centre of the solar panel computed by the BEM/FEM and the hybrid FE-SEA (FE model of the panel excited by an SEA DAF) models is shown in figure 10.

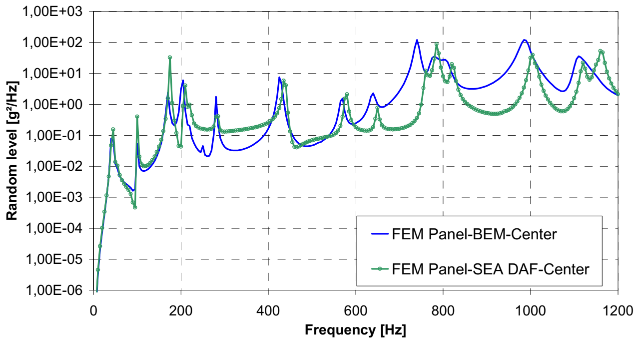


FIG 10. Random level in the centre of the panel : comparison between BEM/FEM and hybrid methods

The agreement between the two predictions is seen to be good.

The three modelling approaches seem to be valid for the solar array panels. Considering that the distribution of the random levels on the solar array is not a critical information, a modelling of this element by an SEA subsystem is adopted.

If the panels of the solar arrays are replaced by SEA panels, their connection with the hold-on and release mechanisms, described with NASTRAN CBAR finite elements, is made with Hybrid point junctions.

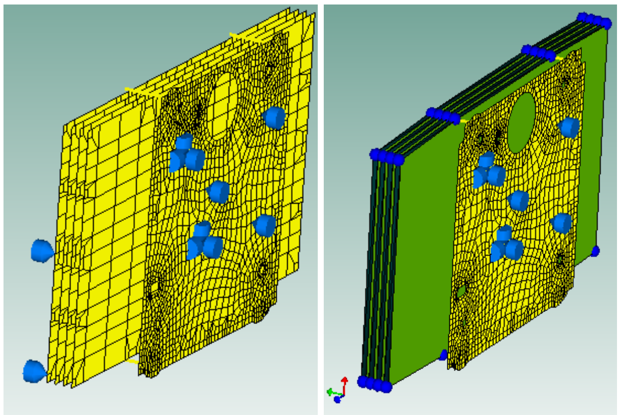


FIG 11. +Y solar array and platform +Y panel: FE model (left) and hybrid model (right).

Here again, it is important to check that the transfer of energy between the solar array and the platform is correctly captured by these Hybrid junctions. The random level close to the centre of the platform +Y panel (located behind the solar array) for an acoustic excitation on the external panel of the solar array is shown in figure 12. The prediction of the 3 models are shown (FEM of the solar array + BEM fluid and excitation, FEM + SEA DAF, SEA panel + SEA DAF).

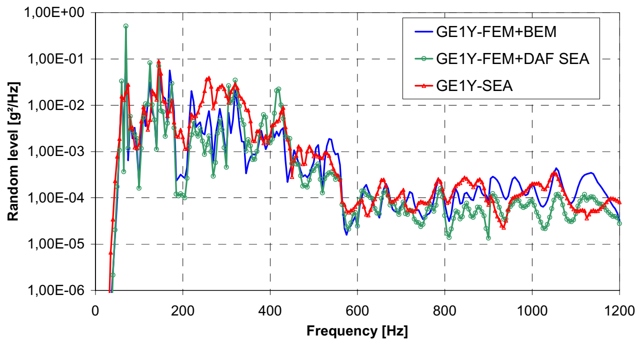


FIG 12. Random level on the platform +Y panel for an acoustic excitation on the solar array external panel: comparison between the three methods

The results obtained with the FE model of the solar array or with the SEA model are very similar. This suggests that the transfer of energy across the Hybrid junctions is correctly captured. The results obtained at other points of the platform are also very close to each other. This confirms that the solar panels can be replaced by SEA subsystems without loss of accuracy.

3.3. Acoustic excitation on the platform +Y panel

The panels of the platform and the bottom part of the payload are small flat rectangular surfaces bearing internal or external units. The various modelling strategies available in VA One have been tested on the platform +Y panel. First, this panel was separated from the spacecraft and simply supported at its interface point with the rest of the structure.

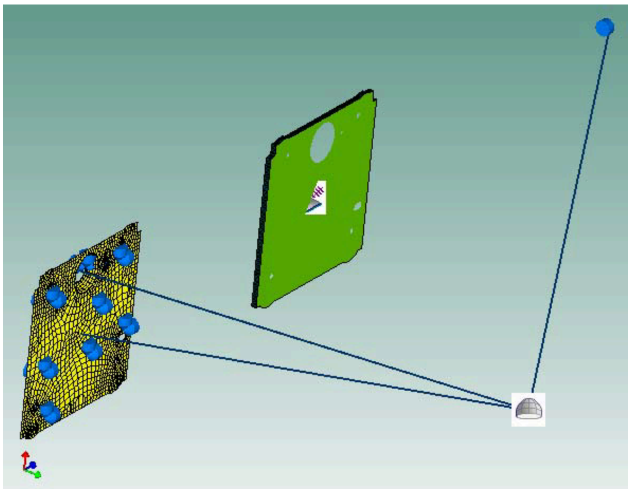


FIG 13. Platform +Y panel : FEM and SEA model

The platform +Y panel bears several units: they are included in the FE model as rigid body and point mass elements. The total mass on the panel is around 20 kg. In the SEA model of the panel, the additional mass was included by increasing the mass density of the material used to describe the skins of the sandwich panel. The models prediction of the panel response to a diffuse acoustic field excitation is shown in figure 14.

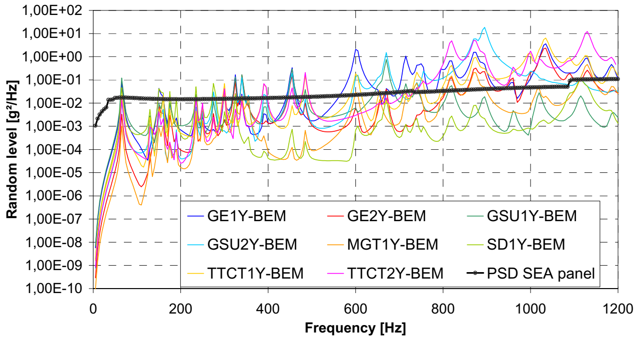


FIG 14. Random level on the platform +Y panel : BEM/FEM results and SEA mean level

The SEA model correctly predicts the mean random level on the panel. However, if the variations of the random level on the panel is requested (so that the mounted equipment environment can be evaluated accurately in order to obtain a dedicated specification for each unit), the FE modelling is necessary.

The random level close to the centre of the panel computed with the BEM/FEM and hybrid FE-SEA models is shown in figure 15.

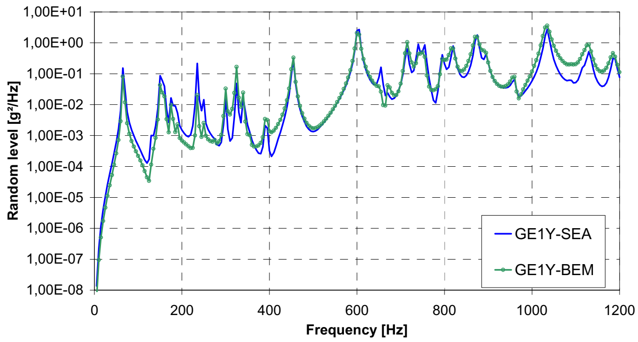


FIG 15. Random level on the platform +Y panel : comparison between BEM/FEM and hybrid SEA FEM results

It can be seen that the response of the platform and payload panels can be accurately captured with the Hybrid model where the panel is described with FE and the fluid loading with an SEA diffuse acoustic field. That way, the resolution of the acoustic problem by BEM can be avoided but information concerning the distribution of the random levels on the panels is still available.

4. SIMULATION OF THE CALIPSO SPACECRAFT ACOUSTIC TEST

A simulation of the acoustic test on the whole spacecraft was performed and the predictions compared with the tests. The finite element model used for these analyses is the one used for the sine test predictions during phase C of the program. This model has been updated after the sine tests and gives reliable results in the 0-100 Hz frequency range. No modification was made for the vibro-acoustic simulations.

The diffuse acoustic field pressure spectrum used in the simulation was the value measured in the acoustic chamber during the CALIPSO spacecraft acoustic qualification test (see figure 16).

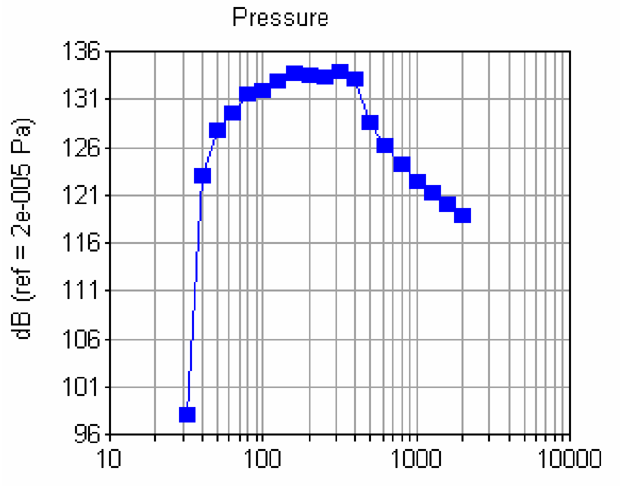


FIG 16. CALIPSO qualification acoustic spectrum

Without knowledge of the damping, mainly at high frequencies, the damping loss factor of the structure was set to 1% for the whole structure (modal critical damping ratio).

The model of the spacecraft used for the simulation is the one shown in figure 1. The modelling strategies for each component were decided based on the local analyses described earlier:

- the panels of the solar arrays are described by SEA subsystems,
- most of the external surfaces of the satellite are excited with SEA DAFs,
- the baffle, the primary and secondary mirrors are excited by an acoustic field described with a BEM fluid.

Modes of the FE parts of the spacecraft were extracted up to 1200 Hz. The predictions of the FE model might be unreliable at high frequency, but overall the results proved to be satisfactory.

Results are provided at various locations of the platform and the payload described in the figure 17. The measured and predicted random levels at these observation points are shown in figures 18 to 21.

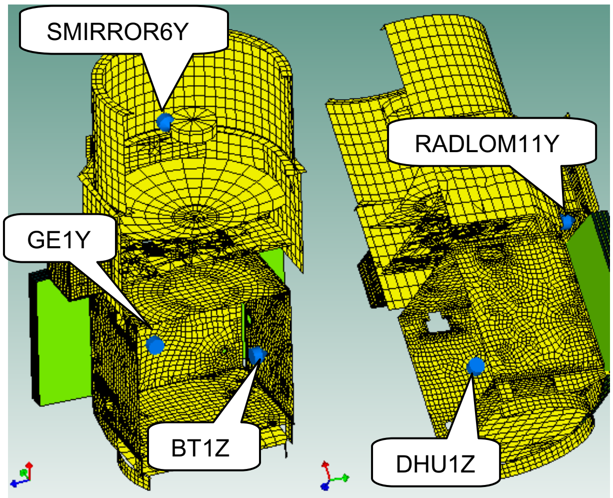


FIG 17. Platform and payload restitution points

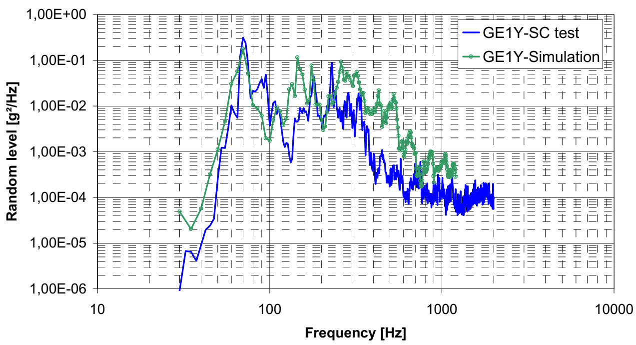
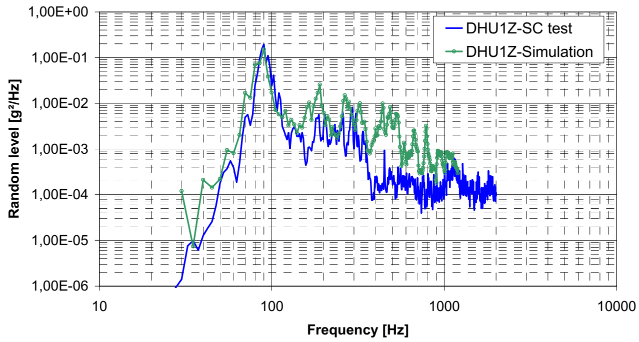


FIG 18. Random level on the GE1Y accelerometer (platform +Y panel)

The out of plane random level on the platform +Y panel, close to one electronic unit, is correctly predicted over the whole frequency range (less than 10 dB difference).



Random level on the DHU1Z accelerometer (platform +Z panel).

The DHU is a large and heavy electronic unit mounted on the platform +Z panel. The random level obtained on the panel close to the unit is also correctly predicted by the Hybrid model. The predictions are only really pessimistic in the 400-600 Hz frequency range.

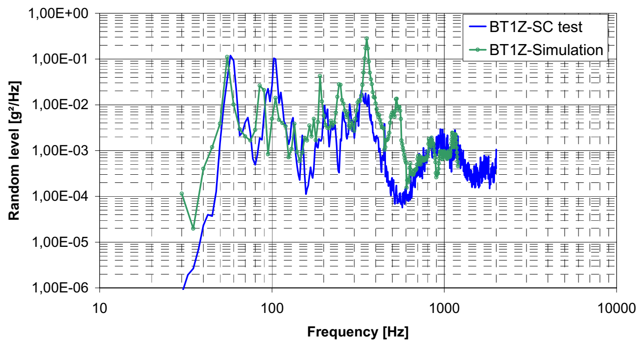


FIG 19. Random level on the BT1Z accelerometer (platform –Z panel)

The out of plane random level close to the battery is also correctly predicted. Some peaks are higher than the level measured during the test above 300 Hz. This may be due to the behaviour of the battery itself and to the constant value chosen for the damping coefficient. The battery having its own, quite complicated, dynamic behaviour, this simple assumption about damping may not be valid.

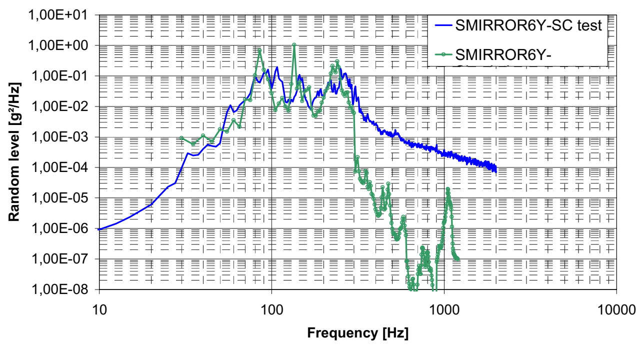


FIG 20. Random level on the secondary mirror of the telescope

The random level on the secondary mirror of the telescope is correctly predicted up to 300 Hz. After 300 Hz, the level predicted by the software drops rapidly while the random level measured during the test decreased more slowly (test data might be polluted by noise). The maximum random levels in the 80-300 Hz frequency range are well reproduced.

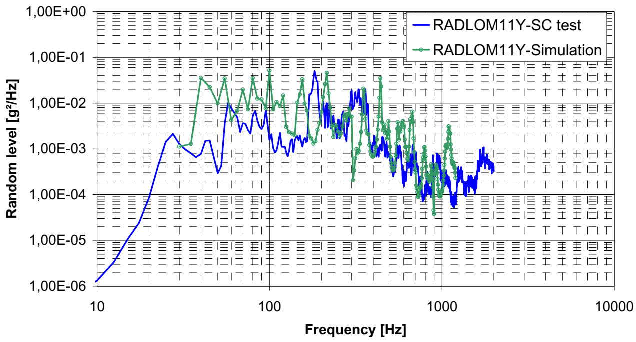


FIG 21. Random level on the RADLOM11Y accelerometer (unit mounted on the payload +Y side)

The random level on the radiator of the LOM (Laser Orientation Mechanism) is also correctly predicted over the whole frequency range.

5. CONCLUSIONS AND PERSPECTIVES

The analyses made on CALIPSO show that the Hybrid method implemented in the VA One software provides a flexible and computationally efficient tool to predict the spacecraft random response to a diffuse acoustic field environment. The results show that it is possible to replace some parts of the structure (the ones having the highest modal density) by SEA subsystems while the rest of the structure is kept as FE. The acoustic excitation can very often be described with an SEA diffuse acoustic field rather than a BEM fluid. BEM is however still necessary for structures with complex geometry or when information is needed on the spatial variations of the acoustic pressure.
A systematic approach was adopted to define the modelling strategy: starting with local component analysis, an optimized model was created which allows to reduce the computation time and conserve accuracy.

6. ACKNOWLEDGEMENTS

The CALIPSO payload has been built by Ball Aerospace & Technologies Corporation which has provided the finite element model of the payload used for the analyses made during the CALIPSO program.
The authors would like to thank Ball Aerospace & Technologies Corporation and NASA for the authorisation to use this model for the studies described in the present paper.

7. REFERENCES

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