A HYBRID FEM-SEA APPROACH FOR THE VIBRO-ACOUSTIC ANALYSIS OF VEGA-C LAUNCHER AT LIFT OFF

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In the framework of the European Space Agency funded program VECEP, aimed at further increasing the performance of the VEGA launcher, a vibro-acoustic analysis, driven by the acoustic field generated at lift-off, is performed on the VEGA Inter-stages. The Inter-stages are examined to derive the acceleration level at the equipment locations and the average vibration response of the connecting interfaces. Due to high modal density of the structure, a random noise and vibration analysis through deterministic methods, e.g. based on Finite Element/Boundary Element techniques, turns out to be unfeasible in a medium to high frequency range. Conversely, the employment of a fully energy based approach in such frequency range is restricted by the need to simulate the equipment as lumped masses, connected to the main structure throughout rigid links. A Hybrid method is thus adopted to combine the equipment local deterministic responses with the mean value of the dynamic response of the launcher mayor sections. The implemented analysis resorts to a FEM solver to extract the modal parameters associated to the deterministic subsystems of the VEGA Inter-stages. The development of the statistical subsystems and the set-up of the global hybrid models are realised within a numerical environment, formerly devoted to SEA methodology only, in which the required dynamic analysis is also performed. The structural and acoustic models of the Inter-stages are validated through comparison with theoretical and numerical estimates. As required for the assessment of the equipment qualification status, the activity is finalized with the delivery of the dynamic response database, numerically generated by applying a stochastic diffuse field to the Inter-stages validated models.
Keywords: Vibro-acoustics, SEA, FEM, Hybrid, VEGA

1. Introduction

The evolution of VEGA (Vettore Europeo di Generazione Avanzata - European launcher of advanced generation) within the ESA (European Space Agency) funded program VECEP (VEga Consolidation and Evolution Program) includes a new design of the rocket Inter-stages, for which a preliminary numerical investigation is necessary to verify the compliance with the acceleration level imposed as limit for the equipment and payload protection. To this purpose, the Inter-stages IS_01, IS_12 and IS_23 are analysed in terms of their vibro-acoustic response to the diffuse acoustic field generated at lift off by the P120 engine [1]. In particular, the objective is to predict the acceleration response level at the equipment locations, for subsequent verification of their qualification status, and the dynamic average response of the Inter-stage interfaces. Despite the relatively high skin thickness and the opportunity to perform the required dynamic analysis on each Inter-stage separately, their dimensions still require the involvement of a large number of structural modes, not to mention the even higher modal density of the coupled interior acoustic cavities. Above 200/300 Hz Finite Element

Method (FEM) and Boundary Element Method (BEM) techniques [2-3] turn out to be computationally unfeasible, even recurring to modal superposition procedures, so that Statistical Energy Analysis (SEA) approach becomes more appropriate to assess the response of both the structure and the acoustic cavity [1,4-5]. On the other hand, the development of structural models entirely based on a SEA approach is restricted by the need to simulate the equipment as lumped masses, connected to the main structure throughout rigid links. These components are not suitable for SEA modelling because they have no modal behaviour by definition, whereas a large modal density is required for a SEA model to be accurate.

Regardless of their intrinsic limitations, either a FEM or a SEA approach had to be adopted in the past for a fluid-structure dynamic analysis, with the choice based on the identification of a frequency limit to select the appropriate frequency range for each method. The recent development of a Hybrid technique [6-7] allows the two basic approaches to be combined within a unique model to take full advantage of both methods specific strengths.

Due to the premises, Hybrid approach is judged as strictly necessary for the examined systems to improve the accuracy in the assessment of the equipment local acceleration levels. In principle, hybrid modelling requires an iterative process, aiming at the optimization of the subsystems geometry, dimension, number and typology (using either SEA or FEM) to assure the same accuracy level in each examined frequency range. Consequently, for predictions in a large frequency band, more than one hybrid model might be necessary, where the number of subsystems modelled according to one methodology or the other could accordingly change. In the present work, the solution at lower frequency is not specifically requested because already available from a separate analysis performed by Avio via a fully deterministic approach; it derives that in the foreseen frequency range, [200-1600 Hz], a single hybrid model is adequate to perform the analysis.

For all Inter-stages, the numerical predictions are obtained through the development of the Hybrid FEM-SEA models and the execution of the frequency domain dynamic analyses in the prescribed frequency range. The acoustic loading is applied as a diffuse field, acting on the external surface of each investigated Inter-stage; the Power Spectral Density (PSD) of the pressure autocorrelation function is assumed as constant all over the surface area. The activity was supported and financed by Avio, who provided the Inter-stages FEM models and all necessary data and information.

2. Hybrid Model Description and Validation

The models are developed in a commercial code, VAOne [8], starting from either a CAD geometry or a FEM mesh of the examined Inter-Stages. The format of the FEM input data file is the same as used for NASTRAN FEM analysis. The SEA and FEM subsystems are defined and generated in VAOne environment to set up the overall Hybrid model. The actual frequency dynamic analysis resorts to a preliminary FEM solver to extract the modal parameters associated to the deterministic subsystems of the VEGA Inter-stages. Since no experimental data are available, the validation process of the hybrid structural models is carried out relying on:

- theoretical assessments of SEA subsystems against simplified formulations to verify the consistency with some global distinguishing parameters, like the structural and acoustic modal densities, and the structural ring and coincidence frequencies:

$$n_s(f)=\frac{A}{2}\sqrt{\frac{12\rho_s\left(1-\nu^2\right)}{Eh^2}}\,;n_a(f)=\frac{4\pi V}{c_a^3}\,f^2;\ f_r=\frac{1}{2\pi R}\sqrt{\frac{E}{\rho_s\left(1-\nu^2\right)}}\,;\ f_c=\frac{c_a^2}{2\pi}\sqrt{\frac{12\rho_s\left(1-\nu^2\right)}{Eh^2}} \quad (1)$$

  in which: E, ρ_s and ν are the structure Young's modulus, density and Poisson's ratio; h, A and R are the shell thickness, area and curvature radius; c_a and V are the acoustic cavity sound speed and volume;
- numerical mutual double checks against equivalent FEM models, performed in the frequency region where the two approaches are both reasonably applicable.

2.1 The Inter-stages models

The Inter-stages IS_01 and IS_12 are made of aluminium. The former is cylindrical and presents a non-uniform lateral surface thickness, 4 mm thicker in the area where the openings are located (Fig.1); the latter is constituted by two sections, having the form of a cone frustum connected through an internal interface (Fig. 2). The third Inter-stage, IS_23, has different characteristics; it is realized in composite material and it is reinforced over the lateral surface by axial and circumferential stiffeners. The shape is still conical, split in two sections connected by an internal frame (Fig. 3). Frames, reinforcing elements and skins are all constituted of composite material.

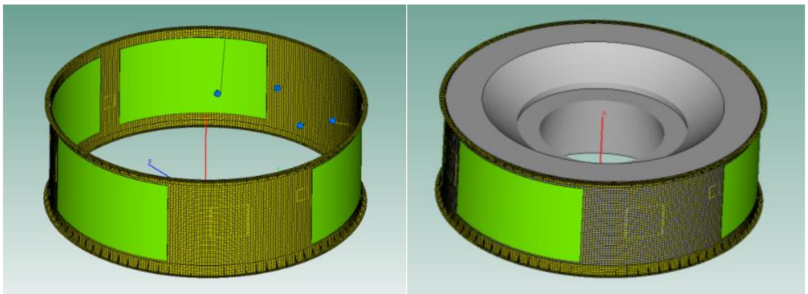

Figure 1: IS_01 Structural Hybrid model - Alone (left) - Coupled with acoustic subsystem (right).

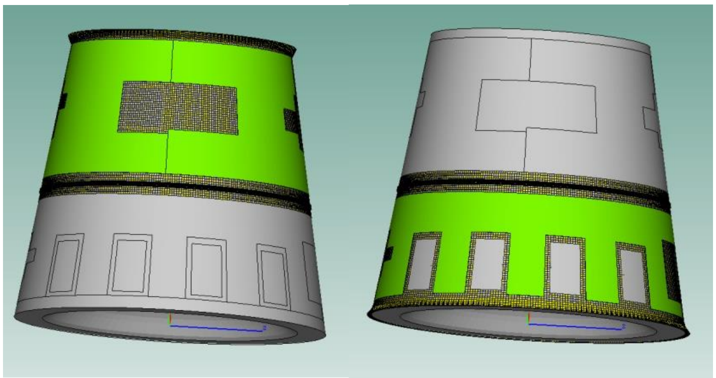

Figure 2: IS_12 Hybrid model coupled to acoustic subsystem – Upper section (left) – Lower section (right).

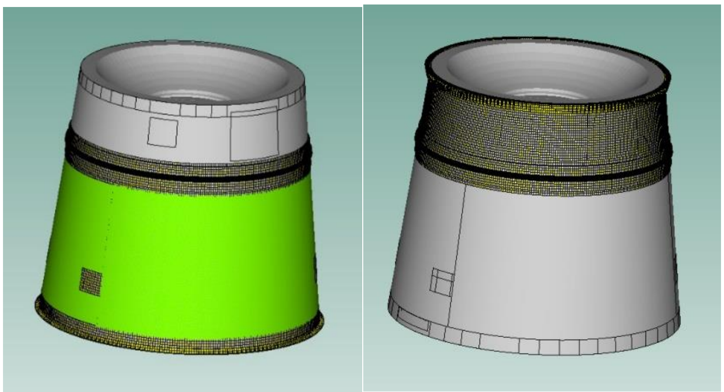

Figure 3: IS_23 Hybrid model coupled to acoustic subsystem - Lower section (left) – Upper section (right).

The main geometrical and dynamic characteristics of the three Inter-stages are reported in Table 1, in which the theoretical estimates of the ring and coincidence frequencies, Eq. (1), are recalled. For each section the mean radius and/or thickness are considered for the theoretical evaluations.

The theoretical ring and coincidence frequencies are not reported for IS_23 because no simple formulations are available for this kind of structures. The various subsystems of the Inter-stage models are recognizable in Figs. 1-3: SEA structural in green, FEM structural in gold-brown and SEA acoustic in grey.

Table 1: Inter-stages main parameters

Inter_Stage	Property	Lower Section	Higher Section
IS_01	Length (m)	1.18	NA
	Diameter (m)	3.4	NA
	Ring Frequency (Hz)	500	NA
	Average Coincidence Freq (Hz)	1100	NA
IS_12	Length (m)	1.182	1.444
	Mean Diameter (m)	3.15	2.62
	Ring Frequency (Hz)	540	650
	Coincidence Frequency (Hz)	1400	1500
IS_23	Length (m)	1.446	0.533
	Mean Diameter (m)	2.4	1.9

The three hybrid FEM-SEA models are built up by assembling the following subsystems:

- IS_01: 6 FEM structural subsystems (2 large subsystems for the upper and lower rings, 2 large subsystems for the areas where several equipment are located, and 2 small subsystems connected to a single equipment each); 4 large SEA structural subsystems (modelling the areas with lower thickness); 1 SEA acoustic subsystem;
- IS_12: 17 FEM structural subsystems (3 large subsystems for the external and internal interfaces, 8 subsystems for the retro rockets frames and masses and 6 large subsystems for the main areas where the equipment are located); 4 large SEA structural subsystems (2 for each of the main sections); 1 SEA acoustic subsystem;
- IS_23: 6 FEM structural subsystems (1 very large subsystem for the upper section, 1 very large subsystem for the external lower ring and 4 very small subsystems for the equipment located on the lower section lateral surface); 4 SEA structural subsystems (for the lower section); 1 SEA acoustic subsystem.

The choice of the best configuration of SEA and FEM components for the IS_23 model was quite demanding due to the complexity of the structure and the high stiffness generated by the internal reinforcements. In particular, the presence of the equipment in the upper section enforced the design of SEA subsystems whose size turned out to be too small to comply with SEA accuracy criteria in the investigated frequency range. For this reason, the final choice was to model the entire upper section as a unique FEM subsystem, leaving the SEA subsystems for the Inter-stage lower section. These specific components are modelled as “Ribbed” subsystems, in which the dynamic contribution of the reinforcing elements, whose geometries are reported in Fig. 4, are directly accounted for. Ribbed subsystems are known to be quite difficult to simulate because intrinsically non homogeneous structures, which is exactly opposite to what SEA is based on. The reinforced panel dynamic properties are derived by using a modal approach in which heuristic rules are used to account for all the parameters involved (skin characteristics, stiffeners spacing and properties) [8].

2.2 Models Validation

A preliminary check is performed by analyzing the modal density and radiation efficiency of the Inter-Stages: all SEA subsystems in the IS_01 and IS_12 hybrid models present a good agreement with the characteristic theoretical parameters reported in Table 1 and their asymptotic values described in Eq. (1). As an example, in Fig. 5 the modal density and radiation efficiency are reported for all SEA subsystems present in the IS_12 hybrid model.

For each SEA subsystem, the modal density displays how the ring frequency is close to the theoretical value (curves with ring frequency around 500 Hz refer to the lower section components, the others curves are related to the upper section elements); asymptotic values also confirms theoretical modal density estimates, evaluated for the curved subsystems through the equivalent flat panel relation in Eq. (1), valid above ring frequency. The radiation efficiency curves confirm the theoretical values for both the characteristic frequencies (ring and coincidence), thus assuring for the congruency of the SEA subsystems. Similar checks performed for IS_01 SEA subsystems provide the same level of reliability.

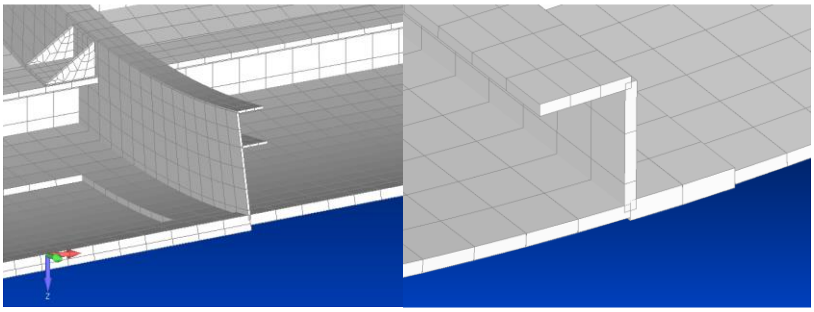

Figure 4: Inter-stage IS_23 – Stiffener Geometry: Circumferential (left), Axial (right).

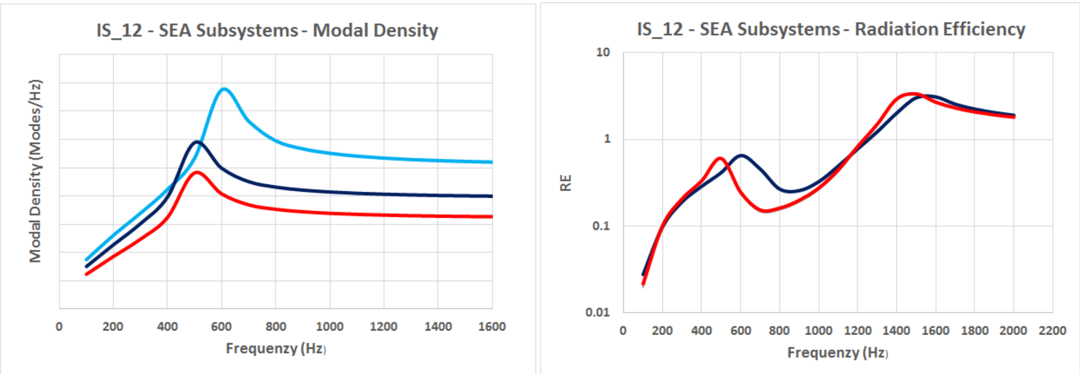

Figure 5: Inter-stage IS_12 – SEA subsystems - Modal density (left) – Radiation efficiency (right).

As already stated, the IS_23 SEA subsystems congruency with simplified theoretical estimates is more difficult to attain, and only a direct comparison with equivalent full deterministic models is available to check their reliability.

As inferred from Fig. 6, above 2 kHz the SEA predicted modal densities show the typical up and down behaviour of reinforced shells, which does not permit a clearly identification of the systems ring frequency. The same modal density pattern is observed for an equivalent flat reinforced panel, suggesting how the dynamic response of this type of structure is overruled by the reinforcing scheme properties and a clear identification of the ring frequencies turns out to be unreliable. The high radiation efficiency of the panels, even at low frequency, derives from the enhancing acoustic effects associated to both the reinforcement scheme and the constitutive composite material. A cross check is achieved through an equivalent full deterministic analysis.

A validation process also based on comparison with an equivalent full deterministic analysis is applied, either to limited portions of the Inter-stages hybrid models to verify the accuracy of the coupling loss factors among specific SEA and FEM subsystems, or to the entire Inter-stages models for an overall check of the Hybrid approach accuracy. For each examined system, the results are compared in the frequency range where the two models (hybrid and full FEM) are expected to be accurate. As an example, in Fig. 7 the result for two equipment located on IS_23 are reported. It is visible how the two curves overlap, implying that the Hybrid method provides a consistent prediction of the system dynamic response. The same procedures applied to IS_01 and IS_12 models provide analogous agreements for the located equipment.

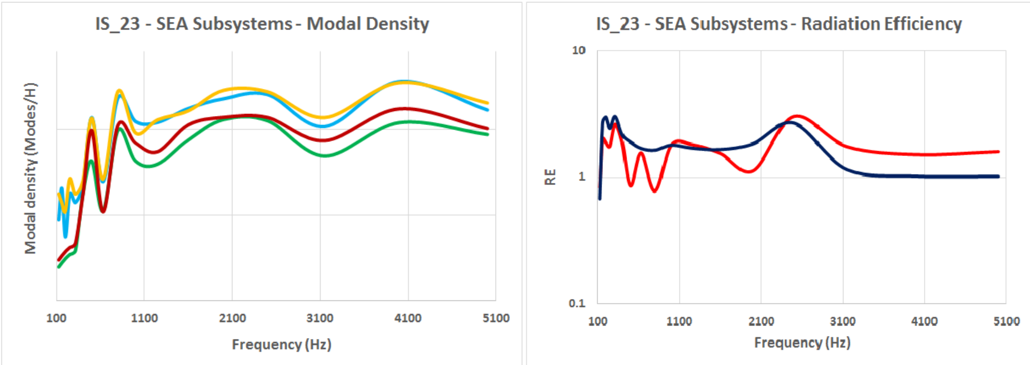

Figure 6: Inter-stage IS_23 – SEA subsystems - Modal density (left) – Radiation efficiency (right).

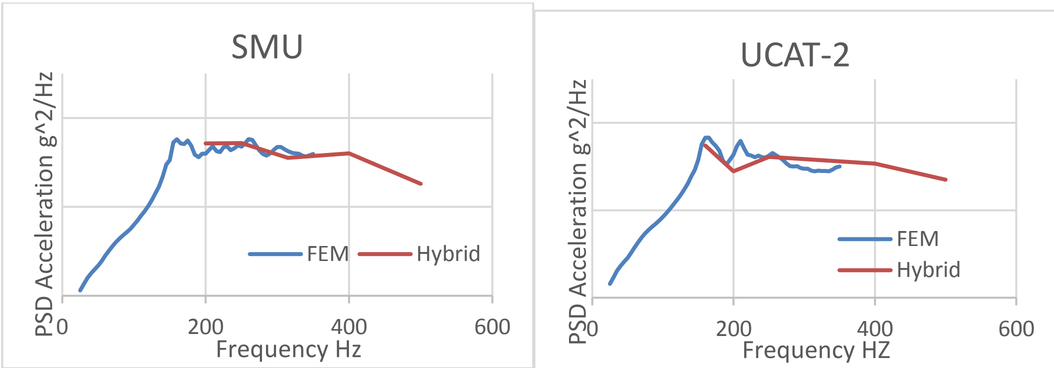

Figure 7: PSD Acceleration for two equipment of IS_23.

3. Inter-stages Vibration Analysis

The description of hybrid models response to the acoustic field generated at lift-off by the P120 Engine is reported in terms of an average acceleration for the SEA and FEM subsystems, together with local acceleration for the points where the equipment masses are positioned. In particular, all the external and internal interfaces have been modelled as FEM subsystems to retain all their dynamic contributions, otherwise ignored by using a SEA “beam” type subsystem for their simulation. The data are reported as Band-limited RMS spectrum response, and for this reason are strictly associated to the frequency band selected for the analysis. In the analysis the damping is assumed as constant on frequency and similar for all the structural (values set to 0.04) and the acoustic (values set to 0.001) subsystems. As an example, some of the equipment response are reported in Fig. 8.

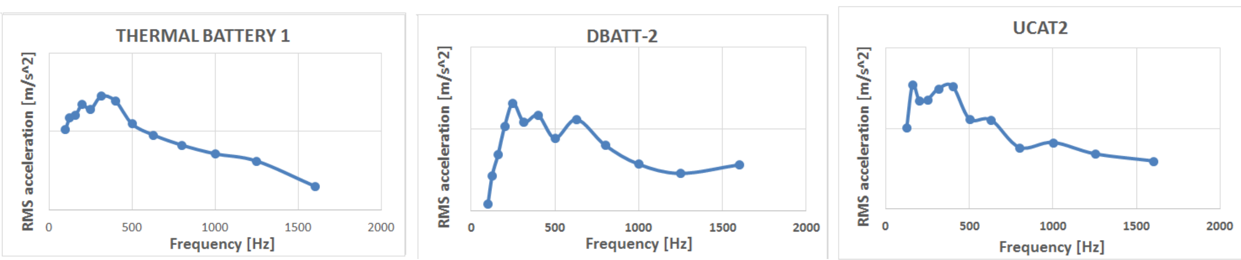

Figure 8: Inter-stage Equipment Acceleration - IS_01 TH.BATTERY 1; IS_12 DBATT-2; IS_23 UCAT2.

For IS_01 and IS_12 Inter-stages the acceleration levels are very high in the low frequency range. In particular, the main contribution to the vibration energy is clearly associated to the structures ring frequency, along with global modes impact occurring at lower frequency; above ring frequencies the

acceleration levels attenuate significantly for almost all equipment, with some high frequency contributions deriving from the coincidence frequencies effect. In general the dynamic of the lumped masses simulating the equipment appears as confined to the low-mid frequency.
While the first 2 Inter-stages are characterized by a clear dependence on the principal frequencies, with a ring frequency lower than the coincidence frequency, IS_23 exhibits a completely different dynamic behavior, totally dominated by the reinforced scheme effect on both the radiation efficiency and the modal density. An apparent lower coincidence frequency, deriving from the combined effect of composite material and reinforcing scheme acoustic properties, causes a high energy transfer from the external excitation field to occur in a larger frequency range. The ring frequency effect is difficult to identify, since masked by the ribbed nature of the structure. By assuming the IS_23 lateral surface as constituted by the skin properties alone, the ring frequency and the coincidence can be clearly identified at, respectively, 650 Hz and 2.4 kHz; no evidence at all of such details can be inferred from the real structure response, thus confirming the overruling effect of the reinforcing scheme on the dynamic response. Also for IS_23 the acceleration level attenuates above 400 Hz frequency for almost all equipment, but few of them present relevant energy also at higher frequency.

Up to the ring frequencies, the dynamics of the IS_01 and IS_12 interfaces present the same energy distribution pattern observed for the equipment, while a much higher energy contribution is also evident when approaching the coincidence frequencies, as visible in Fig. 9, in which the response for some of the interfaces associated to the examined Inter-stages are reported.

The IS_23 interface acceleration level is again difficult to correlate to the characteristic frequencies because of the disguising effect introduced by the reinforcing scheme, but the presence of a large contribution at 1 kHz is, nonetheless, clearly deduced from all responses. This behavior is difficult to explain and to attribute to a single specific cause and is possibly the result of many different and combining factors.

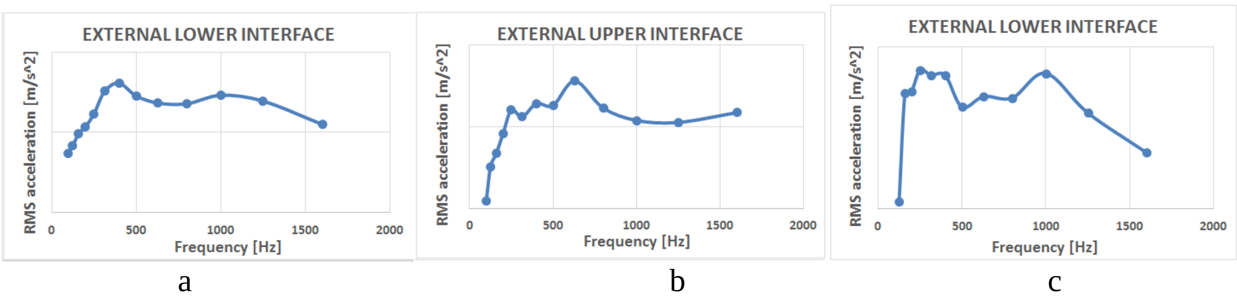

Figure 9: Acceleration of Inter-stage External Interface – IS_01 (a); IS_12 (b); IS_23 (c).

4. Inter-stages Acoustic Analysis

The hybrid model response to the acoustic field generated at lift-off is reported in terms of “average pressure” for the SEA acoustic subsystems. The pressure data are described as dB value referred to the Band-limited RMS spectrum response, in which the reference pressure is the standard pressure value 2.e-5 Pa.

The average pressure levels associated to all Inter-stage cavities are reported in Fig. 10. The responses reflect the same frequency energy distribution of the structural Inter-stages, with the higher energy concentrated at the characteristic frequencies already identified for the structures.

As for the vibration response, a specific coincidence frequency cannot be identified for IS_23, due to the radiation efficiency being almost constant in the examined frequency range. As expected, the Transmission Loss property of IS_23 Inter-stage is slightly lower compared to the other Inter-stages, due to the combination of the low coincidence frequency, associated to the employment of composite material, and the high radiation efficiency of the reinforced shell. The pressure levels related to the examined frequency range confirm a slightly higher overall value for IS_23, which appears to be the most critical inter-stage in terms of payload protection.

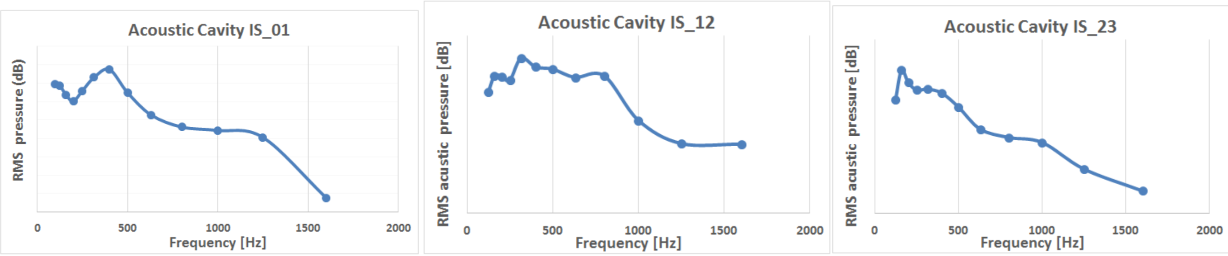

Fig. 10: Acoustic cavity response RMS Pressure (dB) - IS_01; IS_12; IS_23.

5 Conclusions

The Hybrid FEM-SEA approach, employed in the present document, allows predicting the mid to high frequency response of complex vibro-acoustic systems, where many degrees of freedom are required to capture the dynamic behavior of some of their components, while others are stiff enough to be adequately simulated through a deterministic approach since their responses are not sensitive to manufacturing tolerances. Each "statistical" subsystem introduces a single energy variable, thus leading to a large reduction of the computational burden.

When applied to the Inter-stages of VEGA launcher, the validation of this approach is carried out through a series of numerical tests, executed to verify the accuracy of the SEA and FEM subsystems selected in the hybrid model, as well as of the coupling loss factors between mixed subsystems. After completing the validation process, the diffuse field vibro-acoustic analyses reproducing VEGA extreme conditions at lift-off is performed on each Inter-stage separately, providing the required equipment acceleration levels. For all Inter-stages the highest values are detected around the ring frequency and in the low to mid frequency range.

The Hybrid approach is verified to be very effective and accurate in modelling the complex structures under examination, allowing the extension and integration of SEA methodology to frequency ranges where large sections of the structure are characterized by a "diffused" vibration or acoustic response behavior, while others smaller parts, like the areas with the attached equipment, are better described by few contributing modes.

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