Sound transmission characterisation: application to a sandwich composite space structure

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Abstract
Acoustic insulation represents a very important issue in many fields of acoustic engineering. This issue is generally assessed through one characteristic named sound insulation parameter or noise reduction level (NR). Research for materials with high mechanical-resistance-to-weight ratio promotes sandwich composite structures, but these ones present lower acoustic insulation performances than metallic homogeneous structures. Thus, the correct identification and assessment of the main transmission loss factor drivers for sandwich composite structures are essential to improve their acoustic isolation efficiency.
In space industry, acoustic characterization of sandwich composite structures, such as launcher fairing, is a key point for payload and equipment acoustic comfort assessment, when facing severe broadband environment during lift-off phase.
In this paper, the overall approach of acoustic specification to payload is detailed with a particular attention given to the noise reduction level estimation of the fairing structure. The first part will present the Vibroacoustic logic used for acoustic specification. Then, the method employed for fairing exterior acoustic field prediction will briefly be described. Next, the modelling of the composite structure depending on the frequency domain is studied. Finally, the methods used for Vibroacoustic computations as well as comparison with measurements are exposed.

KEY WORDS: Vibroacoustic LF/HF, Composite structure, Noise Reduction.

1. Introduction.

In the spatial industries, the launch vehicles are subjected at lift-off and during flight ascent to severe acoustic and aero acoustic environment. This environment is broadband and random and covers a large band of frequency, in the low and high frequency regimes (15-2800 Hz). Electronic equipment and satellites are consequently excited and the induced vibrations must be predicted before flights, in order to be sure that they can endure the induced loads without any damage.

This is why, it is essential to have methods that compute the equipment Vibroacoustic response over all frequency ranges of concern. The fairing noise reduction level is an important parameter for payload comfort.

The first part is dedicated to present the logic used to cover the two frequency domains.

2. Vibroacoustic logic

Acoustics covers several dynamic environment of the launcher's life:

- Engine generated acoustic loads during lift-off,
- Aerodynamic loads during ascent,
- Specific acoustic noise excitations (like venting).

The spectra of acoustic environments cover a wide frequency range. Predicted environments are generally limited to frequencies below 10 kHz for manned structures and below 2800 Hz for general structures.
For the fairing, payload acoustic environment is defined up to 2800 Hz.
This wide frequency range load can damage structures in low frequency regime, large area structures directly impacted by acoustics and equipment items that generally have their first modes in Mid/High Frequency. Thus it is necessary to compute the System response all along the frequency range.
Vibroacoustic analyses are divided into two domains along the frequency spectrum:

- Low Frequency [15-200Hz], where the modal density of a given component (number of mode per octave band) is quite low (less than 7 modes per octave band). FEM method can be performed while the number of Eigen modes is quite low,
- High Frequency [50-2800Hz], where the modal density of a given component is too important to look at each Eigen mode in particular. In this frequency range, a statistic method must be used. This method is based on transfer of energy between the components (Statistical Energy Analysis, see [2]).

Vibroacoustic overall logic for computation of response of sub-components is defined according these two approaches with an overlap between the two domains on the frequency range [50-200Hz], when possible. It is possible in the case of big launchers Fairing of sandwich construction, as many modes are present in the 125 Hz octave bands. This overlap is used to cross-check the two methodologies in order to validate the modelling.
With the Maximum Expected Environment computed with these two approaches and a Qualification Margin policy applied, a standard Random Qualification level is chosen to envelope those levels.

Acoustic logic can be summarized with the following diagram:

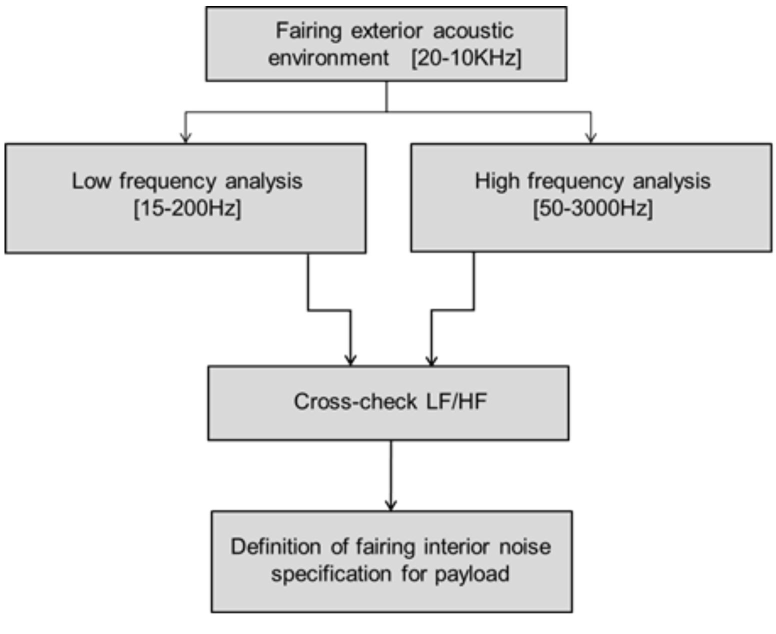

Figure 1. Vibroacoustic logic for payload interior noise specification

3. Prediction of fairing exterior acoustic environment

The acoustic loads predictions on space vehicle generated by the interaction of jet thrusters with the launch pad require models base on experimental data, as numerical methods are not available for predicting supersonic jet noise in the presence of waterfall. Simulations are generally validated using reduce scale tests.
In that frame, Airbus Defence and Space homemade software "BRUITJET" based on tests realised in Russia at TSNIIMASH enables to predict wide range acoustic environment during lift-off phase, see [3].

3.1 Method

To represent this interaction, different noise regions are identified. Each of these regions is represented by a system of independent acoustic sources with their own acoustic power and spectrum. The launcher is not modelled, only the free field is computed.
The acoustic field is computed in the symmetrical plan of the duct and the jet. The overall level as well as the spectrum features of the field is obtained by summation of contributions of the different sources.
Hiding and reflections conditions of sources due to the geometry of the duct are established by geometrical conditions. Their power, radiation and directivity come from many experimental data and literature, [3].
Finally, the entrance data for the computation are geometrical data of the studied launch pad configuration and the thermodynamic properties of the jet at exit nozzle.
The Ariane 5 launch pad is presented in the following figure. It is composed of two closed duct to evacuate boosters' jet as well as on closed duct for the Vulcain engine.
Closed duct enable to put away jet sources to reduce acoustic environment on the launcher. Water injection systems on the launch pad table and inside ducts are also present ignition phase.

Figure 2. Ariane 5 launch pad

3.2 Theoretical aspects

To solve the acoustical problem, the jet is decomposed in different regions as shown in the figure here below, ref [3].

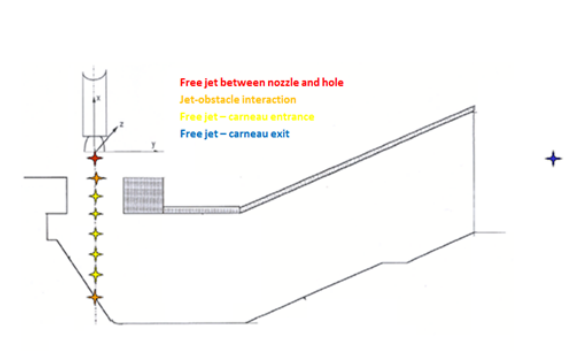

Figure 3. Sketch principal [closed duct]

The regions for the acoustic field computation are detailed here below:

- Free jet region (between exit nozzle and hole) : the acoustic field is modelled as punctual sources,
- Region of strong interaction with the hole,
- Region of the duct entrance (between hole and deflector) : the acoustic field is modelled by a distribution of decorrelated sources,
- Region of the duct exit,
- Reflected acoustic field modelled through the images sources method (inside duct, deflector, for open duct).

There are different types of noise through the frequency ranges:

- Low frequency noise generated in the region of the duct exit,
- Mid frequency noise mainly coming from the jet/ground interaction,
- High frequency noise coming from free jet and acoustic waves reflections on the launch pad.

4. Prediction of fairing exterior acoustic environment

The vibroacoustic characterisation of the fairing is done by two computations. One performed for the low frequency domain using modal basis and one for the high frequency domain using SEA (Statistical Energy Analysis).
The low frequency study is mainly used here to understand the PSD of acoustic pressure dispersion inside the cavity. Otherwise, for internal noise specification inside the fairing at the beginning of a new launcher definition, SEA method is used, ref [4].

4.1 Low frequency domain

The analysis is performed in two steps. First, the modal basis is computed with MSC-NASTRAN FEM software and then Airbus D&S Low Frequency Vibroacoustic software LASCAR BF is used.
The FEM model used for Vibroacoustic study is the same as the one used for static analysis with mass data added. Fairing sandwich composite structure is then modelled in detailed with NASTRAN PCOMP card that defines the properties of an n-ply composite material laminate. The sandwich of the fairing is composed of carbon and aluminium mainly due to weight constraints.
A picture of the FEM model is shown in the following picture. Payloads volumes are included under the fairing. Tetrahedral elements are used for fluid meshing.

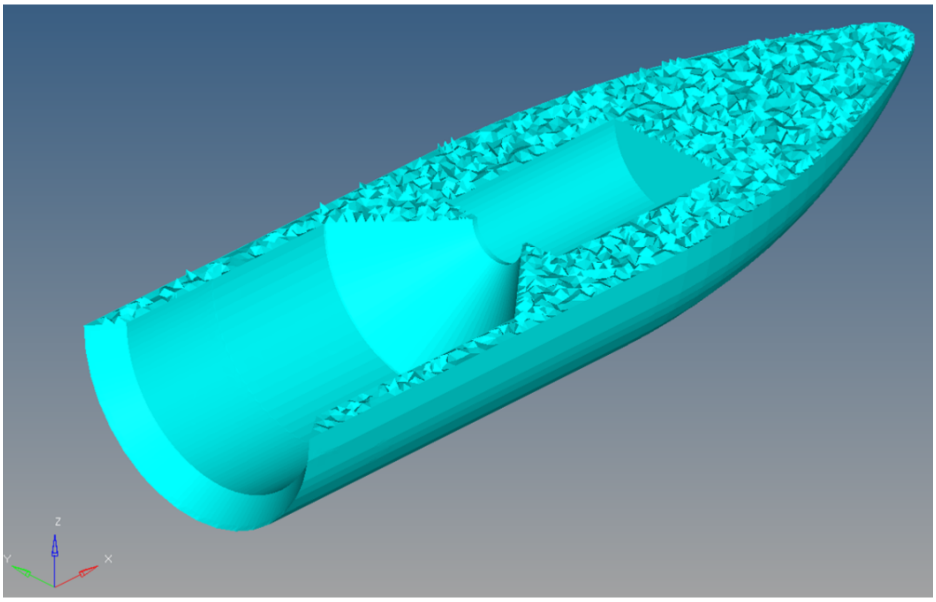

Figure 4. Fairing FEM model

The fairing low Vibroacoustic analysis was done with the Airbus D&S software LASCAR BF up to 200Hz using a critical damping loss factor of 2% for the structure and experimental data using reverberation time so as to infer an equivalent modal damping factor for the fluid to take into account the acoustic protection. The acoustic excitation is supposed to be defined as a diffuse field excitation.
LASCAR BF computes the response of a structure under a random excitation using a modal basis coming from NASTRAN (sol 103) and an acoustic excitation matrix in Pa^2/Hz, [4].
The PSD excitation is assumed to be homogeneous on the wetted area so as the excitation matrix can be decomposed as a product of an auto spectrum function simply depending of the noise entrance level and a correlation function depending of the type of excitation applied to the structure.

The excitation can be written as followed,

$$S_{PP'}(|P-P'|;\omega) = C(|P-P'|;\omega)\sqrt{S_{pp}(P,\omega).S_{pp}(P',\omega)} \quad \textbf{(1)}$$

Since the excitation is assumed to be homogeneous, it can be simplified in,

$$S_{PP'}(|P-P'|;\omega) = C(|P-P'|;\omega).S_{pp}(\omega) , \quad \textbf{(2)}$$

where the correlation function C in the case of a diffuse field is analytically known as,

$$C(|P-P'|;\omega) = \frac{\sin\left(\frac{|P-P'|\omega}{c}\right)}{\frac{|P-P'|\omega}{c}} . \quad \textbf{(3)}$$

At the highest frequency of study, 200Hz, the distance of the diffuse field correlation is two meters supposing that two points are correlated if the correlation function is at least equal to 0.1. This hypothesis enables to increase the size of the acoustic excitation meshing compared to the structural meshing, hence reduce times computations.

Joint-acceptance function that assessed acoustic field efficiency on fairing structural modes is calculated following,

$$j_{rs}^2(\omega) = \frac{1}{A^2}\sum_i\sum_j S_{p_i p'_j}(\omega)\cdot\Phi_{ir}\Phi_{js}\cdot\Delta S_i\Delta S_j , \quad \textbf{(4)}$$

with:

A : the total wetted area,

Φ_{ir} : the modal shape of the mode r at node i,

ΔS_i : the equivalent area associated with node i, $\Delta S_i = \frac{A}{N}$,

N : number of excitation nodes,

$S_{p_i p'_j}(\omega)$: the pressure power spectral density between nodes i and j at frequency ω.

This function simply described the efficiency of the acoustic field on the structural modes.

Finally, the response of the fairing is computed. For root mean square acceleration, the equation can be written as followed,

$$\overline{\gamma_i}^2 = \int\sum_r\sum_s \Phi_{ir}\Phi_{is}\cdot\omega^4 H_r(\omega)H_s^*(\omega)\cdot A^2 j_{rs}^2(\omega)d\omega, \quad \textbf{(5)}$$

with:

Φ_{ir} the modal displacement of the mode r at node i,

$H_r(\omega) = \frac{1}{\omega_r^2} \cdot \frac{1}{1 - \frac{\omega^2}{\omega_r^2} - i\eta_r \frac{\omega}{\omega_r}}$, the transfer function of the mode r supposing that modes are normalised by the generalised mass.

Once the fairing structural response is computed, using Neumann boundary condition and green function considering rigid interface, the fairing inner pressure is assessed.

The synoptic of LASCAR BF software for fairing structural response is summed up in the following sketch.

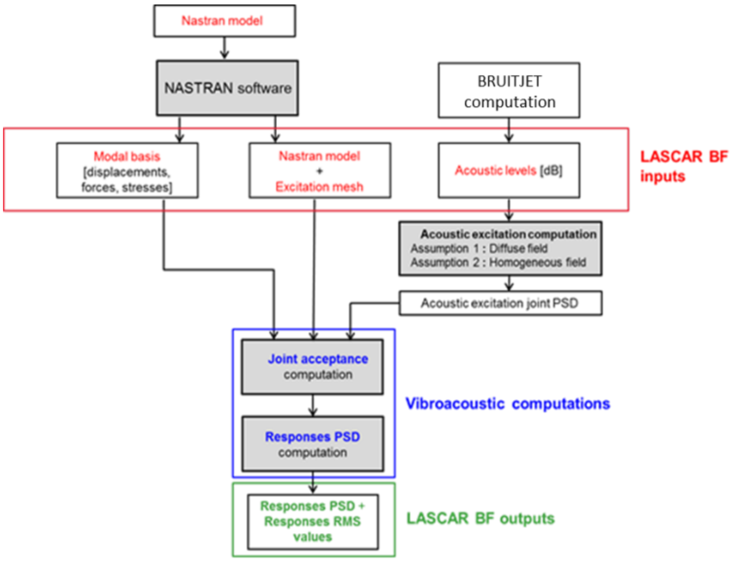

Figure 5. Synoptic of LASCAR BF

4.1 High frequency domain

In the High Frequency domain, the acoustic level is estimated by the SEA (Statistical Energy Analysis) with the in-house Airbus DS software SEALASCAR, ref [4].
SEA is a statistical method based on the exchange of energy between sub-components. A sub-component is a sub-division of the structure and the geometry of each sub-component is approximated by a simplified geometric shape (plate, cylinder, cavity etc...).
This method can be applied when the modal density of the structures and cavities is high (7 modes per octave band at least).
SEA method is not used to provide absolute acoustic levels, but in order to characterize the impact of a design change in the launcher.
The SEA method is based on a statistical analysis on transferred energy between sub-systems. There is no dumping like in FEM method but energy dissipation by the sub-systems, called dumping loss factor.
For structures, the dumping loss factor can be expressed either by a fixed value (for instance 1%) or by the following empirical relation. It yields, ref [4]:

$$\frac{A_0}{f^{B_0}}, \qquad \textbf{(6)}$$

where f is the central frequency of the considered octave band. A_0 and B_0 are coefficients different in the case of equipped or non-equipped structures and coming from flights and acoustic tests experience.
In SEALASCAR, the calculation of the modal density of sandwich structures is based on the theory of Erickson, where the shear of the core is taken into account, [5].

For cavities, the damping loss factor is :

$$\eta_c = \frac{C_0 S\alpha}{4\omega V}, \quad \textbf{(7)}$$

where C_0, S and V are respectively the sound speed, the surfaces and the volume. α is the Sabine absorption coefficient, given by test. In the computations, experimental data using reverberation time so as to infer an equivalent modal damping factor for the fluid is used. After having described the different approaches Airbus D&S used to compute the noise inside the fairing, NR levels are compared with ground test and flight measurements.

5. Comparison of simulations with flight and ground test measurements

5.1 Comparison of simulations with ground test measurement – Empty fairing

This section is dedicated to the comparison of results coming from low/high frequency simulations with results of ground test performed at the reverberant chamber of ESTEC regarding the "Noise Reduction" NR in dB per octave band.
The NR is computed as the difference between the external noise and the internal noise inside the fairing.
The internal noise reduction level is calculated as the average of acoustic power inside the overall fairing volume.

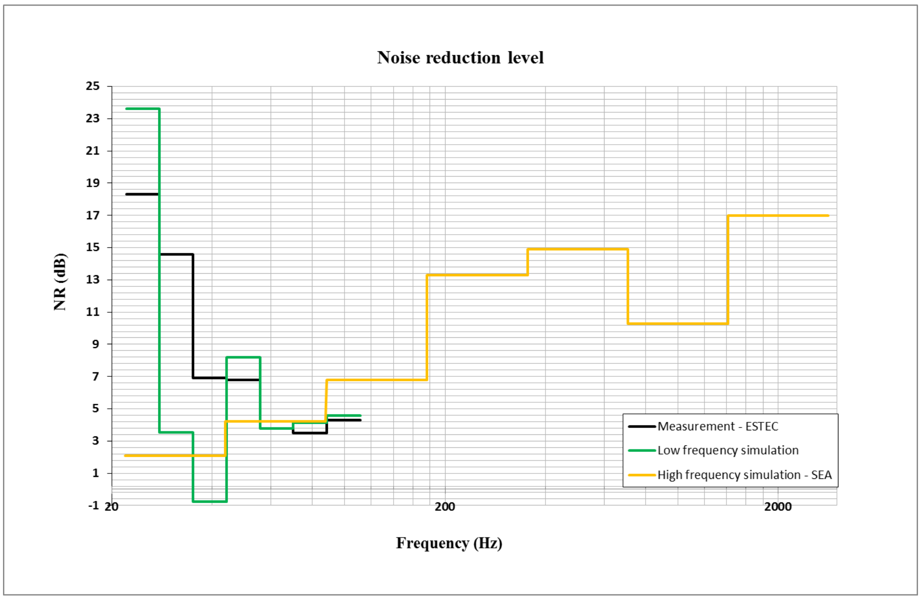

Figure 6. Comparison between simulation and ground test

Measurements and simulations are well correlated after 40Hz. Low frequency estimation and high frequency one have an overlap in the frequency range [40-100Hz] with maximum differences of 2dB.
Added to this, differences observed before 40Hz are mainly due to the assumption of diffuse field which is not respected in measurements due to cutting frequency of the reverberant room (modal behaviour).
After having compared simulation with reverberant room measurements for empty fairing, flight configuration is studied.

5.2 Comparison of simulations with flight measurement – Fairing with payloads volumes

The objective of this section is to compare noise reduction levels computed by simulations with measurements coming from flight 215 L570 [fairing with payloads] and ground test presented before [empty fairing].
The following figure presents the upper part configuration for the flight 215 (570) composed of a long fairing and a SYLDA family D. The fairing is covered by an acoustic protection. The payloads inside were manufactured by Space Systems / LORAL and I.S.R.O.
The fairing internal pressure during flight is measured by two sensors. For the external noise a sensor located on a tour on the launch pad one for each Ariane 5 flight is used.
However, to better represent the external noise that load the fairing; acoustic filed has been measured during the experimental Ariane 5 flight 164 L521 using sensors outside the fairing.
To take into account exterior noise dispersion between flight 570 and 521 a correction computed as the ratio between sensors located on the tour is applied.

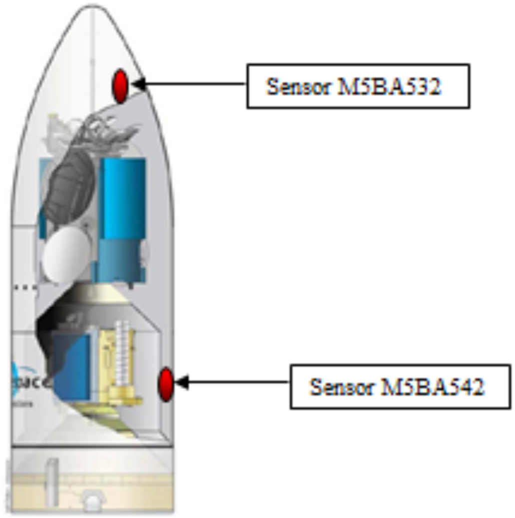

Figure 7. Fairing configuration for flight 215 L570

The next plot present the noise reduction level estimated during with flight measurements to see the influence of the payload volume inside the fairing.

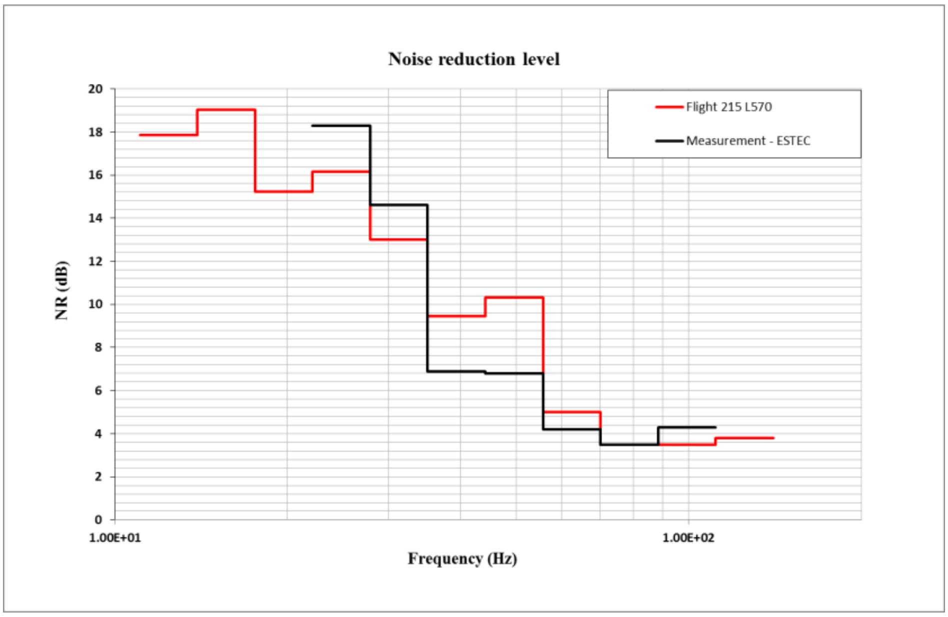

Figure 8. Comparison between flight and ground test measurements

The two measurements fit quiet well. Differences are not only due to the payload volume that modify modal behaviour of the fluid but also due to fairing excitation that is not composed by a diffuse field during lift-off.
The next plot shows that using two types of correlation, simulations can covered the noise reduction measured in flight.
The blue curve represents the noise reduction level coming from low frequency simulation using a rocket engine noise correlation instead of a diffuse field one. This correlation is coming from [1] and can be seen as a progressive wave coming from jet engine noise in longitudinal and radial direction.

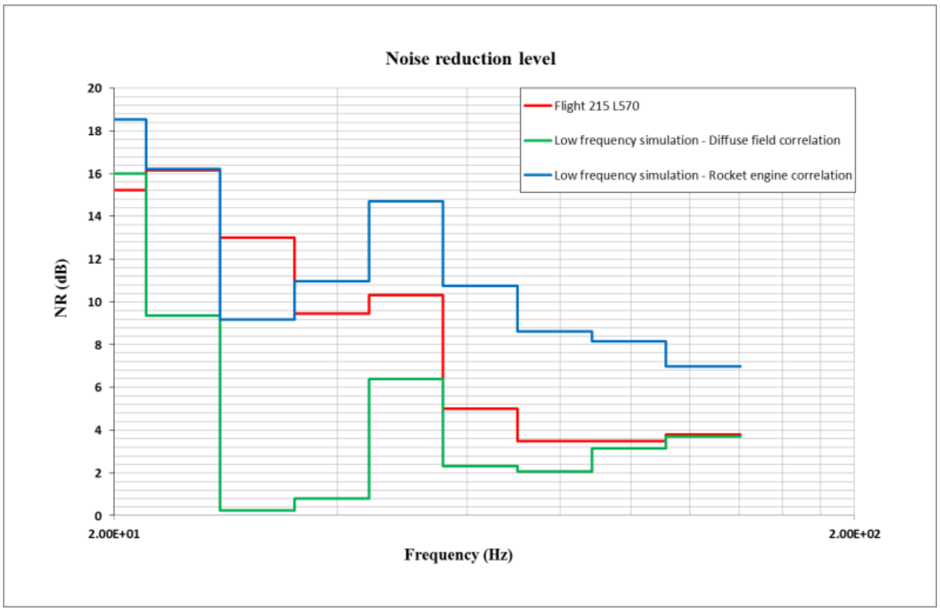

Figure 9. Comparison between flight and simulations (for two type of correlation)

Engine rocket noise correlation match well with flight in low frequency (f<30Hz) and for frequency superior to 30Hz, diffuse field correlation fit well with flight. Diffuse field dis mainly due to the impingements of acoustic waves on the launch pad. The flight noise reduction level is framed with simulations.

6. Conclusion

This paper is focus on our capability to predict noise reduction level for a space sandwich structure of major importance for payload comfort.
It has been firstly shown that low frequency method using finite elements and high frequency ones are able to well represent the sandwich structure and fit with reverberant room measurements for an empty fairing.
Then, noise reduction level measured in flight has been compared to low frequency simulations for configuration flight fairing. It has been shown that two types of correlation, the rocket engine noise for frequencies less than 30Hz and diffuse field for frequencies above are able to frame the flight. Indeed, rocket noise correlation during lift-of phase can be seen as a mix between progressive waves added with a diffuse field.
Work is still in progress on that topic to understand what is the part of those two correlations model is in order to improve low frequency simulations and payloads acoustic environment for new launcher.

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