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Development of an enhanced fairing acoustic protection system to increase payload comfort

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Abstract

During the last years, there is an increasing demand from launch primes and space satellite suppliers to improve the payload comfort during flight and increase the payload volume. An improved Fairing Acoustic Protection (FAP) would address both needs. This research investigates a sound absorbing surface in the inner face sheet of the payload fairing sandwich structure.

The approach comprises the development of a prediction tool for acoustic impedance and absorption; validated by acoustic testing, such as impedance tube and alpha cabin measurements. Finally, the approach is applied to a real study case with a medium sized class Payload Faring (diameter 2.5 – 4.0 m).

1. Introduction

RUAG Space, the lead supplier of space products in the European market, develops, designs and builds payload fairings (PLFs) and other space structures. RUAG Space also designs and develops the acoustic protection technology used on the PLF to mitigate the effect of noise during the launcher flight and to increase the payload comfort. In this paper, a novel acoustic protection system with the corresponding acoustic prediction model is presented.

1.1 State of the art

Today, most PLFs are made of carbon fibre reinforced plastic (CFRP) sandwich panels. The advantage of these materials includes its high buckling strength and high stiffness to mass ratio. However, one of the main disadvantages of having a lightweight structure is the low noise reduction performance. In addition, the high relative stiffness of sandwich structures results in low structural damping. Both factors lead to potentially high acoustic levels inside of the PLF compartment, where most of the PLF structures on their own would have insufficient protection against acoustic loads occurring at lift-off and during flight. Furthermore, due to the continual increase of launch vehicle engine performance with a corresponding increase of acoustic noise generated by the more powerful engines, the acoustic protection of the payload becomes more challenging.

As a result, most of the PLFs today include a high performance acoustic noise control system to dampen the sound coming from the launcher engines and thus reduce the vibration transferred to the payload. This Fairing Acoustic Protection (FAP) is designed for the maximum acoustic load on the vehicle [1] to the structure, but also reduces the available volume for the payload.

The FAP can be in principle applied to the interior (i.e. internal FAP) or exterior (i.e. external FAP) of the PLF. Furthermore, the FAP can in general be a system applied on the PLF structure or it can be integrated within the PLF structure itself. The most common solution consists of internal FAP systems in the form of acoustic absorber mats applied to the PLF internal structure. One example of this solution is shown in Figure 1. This shows Ariane 5 PLFs, including the FAP mats used today to damp the noise at lift-off and during flight.

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Figure 1: Payload fairings at RUAG Space, where the FAP mats used today are shown [2].

Noise Reduction (NR) measures the acoustic shielding effect of the fairing which is the difference between the external and internal sound pressure level. This quantity is driven by the physics of the PLF system including any FAP measures.

1.2 Need for research

In recent years, launcher and satellite suppliers are demanding an improvement of the payload comfort and increase the payload volume. RUAG Space is working to fulfil this customer need with a research and development activity included in the Future Launcher Preparatory Program (FLPP) funded by the European Space Agency (ESA). This project started in September of 2017 and aims at developing new acoustic technologies to enhance the current FAP systems used in the Payload Fairing for different Launcher classes considering its impact on the payload volume.

1.3 Developed concept and verification approach

After an initial trade-off of existing technical solutions from various industrial sectors, the micro-perforation of the PLF inner face sheet has been selected for its potential in performance and the absence of added mass or volume. Micro Perforated Panels (MPP) are widely used as sound absorption devices in technical applications, from room acoustics to aerospace applications.

Compared to conventional FAP systems, MPPs also offer the advantage of its compact design. For instance, in small and medium launch vehicles, the reduced diameter of the payload compartment makes it difficult to integrate conventional FAP solutions, which needs to be compensated by a more sophisticated design of the payload in order to withstand the acoustic launch loads. In this case, having an acoustic solution as the MPPs that could be directly integrated in the face sheets without any impact in the available volume would be extremely beneficial.

The verification of the MPPs is carried out with a simulation tool that predicts the acoustic impedance/absorption of the presented system. The tool is empirically validated with acoustic testing, including the measurement of the acoustic impedance/absorption for normal and diffuse sound incidents. These results are correlated with predicted values from the tool thus ensuring its robustness. Finally, the acoustic performance enhancement of a PLF using the MPP technology is assessed by simulation.

In a last phase, the impact of the MPPs in the current manufacturing process of PLFs at RUAG Space is investigated; aiming to understand its impact on composite materials, processes and tooling used today and achieve repeatable acoustic properties.

2. Modelling approach of MPP

After an initial attempt of developing a prediction model based on the theory of Maa [3], the predicted values were not in agreement with the results from an impedance tube test used to validate the model. For this reason, the model was extended by considering as well the theory of Temiz [4]. This predicts the acoustic impedance of micro-perforated panels using as one of the input parameters the acoustic neck velocity (i.e. the acoustic velocity at the perforations cross-sectional area). As the acoustic velocity cannot be directly measured, the approach consists on determining the acoustic neck velocity in the holes from the exciting sound pressure.

In overview, the mathematical model developed within this project to predict the acoustic properties of the sandwich panels with micro-perforated internal face sheet consists of the combination of the three elements:

- the theory of Maa [3] for the linear part of the specific acoustic impedance
- the theory of Temiz [4] for the non-linear effect due to the excitation amplitude on the specific acoustic impedance
- Corrections empirically tested

The outputs from this engineering tool are acoustic parameters such as acoustic absorption or impedance. These can be used as an input for PLF models to assess the performance of the new acoustic protection systems at fairing level. The schematic representation of the overall model for the prediction of the acoustic impedance of a micro-perforated panel backed by a honeycomb core is presented in Figure 2.

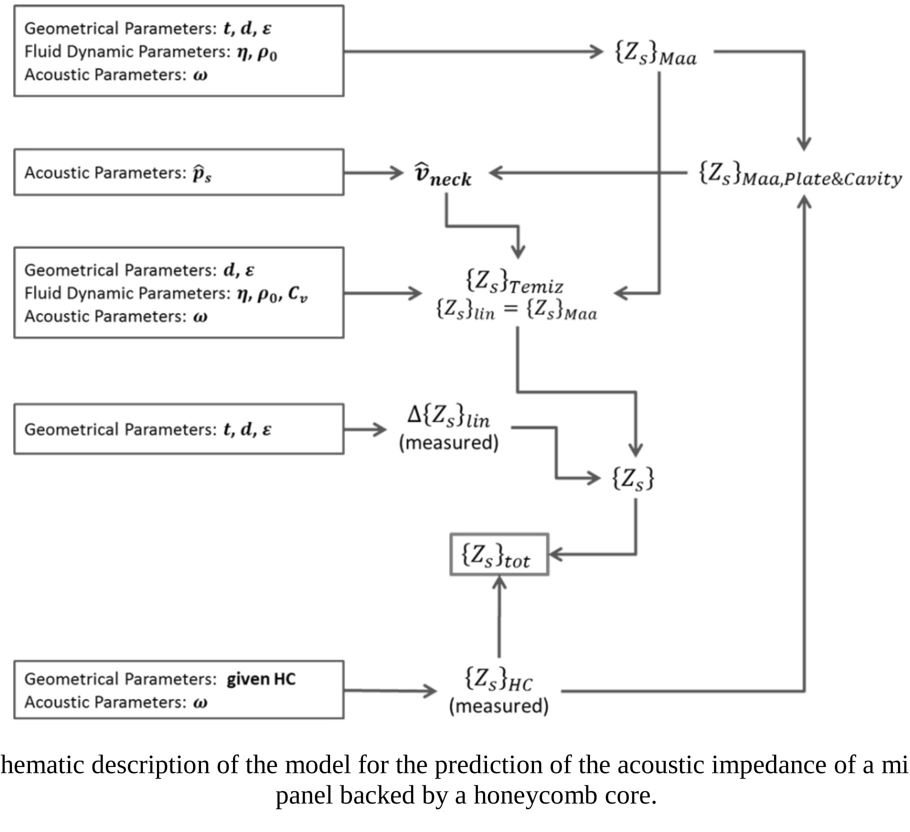

Figure 2: Schematic description of the model for the prediction of the acoustic impedance of a micro-perforated panel backed by a honeycomb core.

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2.1 Maa's model

Maa's model [3] predicts the resistance, which is the real part of the impedance $\mathrm{Re}(Z_s)$, and the reactance, which is the imaginary part of the impedance $\mathrm{Im}(Z_s)$, of a micro-perforated plate as:

$$\mathrm{Re}\{Z_s\}_{\mathrm{Maa}} = \frac{32\eta t}{d^2\varepsilon}\left(\sqrt{1+\frac{k_p^2}{32}}+\frac{\sqrt{2}k_p d}{32t}\right) \tag{1}$$

$$\mathrm{Im}\{Z_s\}_{\mathrm{Maa}} = \frac{\omega t\rho_0}{\varepsilon}\left(1+\frac{1}{\sqrt{9+0.5k_p^2}}+0.85\frac{d}{t}\right) \tag{2}$$

$$k_p = 0.5d\sqrt{\frac{\rho_0\omega}{\eta}} \tag{3}$$

where: η is the dynamic viscosity of air, t is the plate thickness, d is the hole diameter of the micro-perforations, ε is the perforation ratio, ρ_0 is the density of air, $\omega = 2\pi f$ is the angular frequency, and f is the frequency. The impedance of the (empty) cavity backing the micro-perforate plate is simply the reactance of the cavity space:

$$Z_{\mathrm{cavity}} = i\rho_0 c_0 \cot\left(\frac{\omega t_{\mathrm{gap}}}{c_0}\right) \tag{4}$$

where: c_0 is the speed of sound in air, and t_{gap} is the depth of the cavity behind the micro-perforated plate. The acoustic impedance of the sandwich panel is the summation of the impedance of the micro-perforated plate and the impedance of the cavity backing the plate.

2.2 Temiz's model

Temiz's model [4] predicts the resistance and reactance of a micro-perforated plate as:

$$\mathrm{Re}\{Z_s\}_{\mathrm{Temiz}} = \mathrm{Re}\{Z_s\}_{\mathrm{lin}} + \frac{F_c \hat{v}_{\mathrm{neck}}\rho_0}{2C_V^2\varepsilon} \tag{5}$$

$$\mathrm{Im}\{Z_s\}_{\mathrm{Temiz}} = \mathrm{Im}\{Z_s\}_{\mathrm{lin}} + \frac{G_c\omega\rho_0 d}{2\varepsilon} \tag{6}$$

where: ρ_0 is the density of air, $\omega = 2\pi f$ is the angular frequency, f is the frequency, d is the hole diameter of the micro-perforations, ε is the perforation ratio, C_V is the vena contractor factor (0.7 for sharp edges of the micro-perforation, as assumed in all further predictions), $\mathrm{Sh} = d\sqrt{\omega\rho_0/4\eta}$ is the Shear number, η is the dynamic viscosity of air, $\mathrm{Sr} = \omega d/\hat{v}_{\mathrm{neck}}$ is the Strouhal number, $\mathrm{Re}\{Z_s\}_{\mathrm{lin}}$ is the linear part of the resistance, $\mathrm{Im}\{Z_s\}_{\mathrm{lin}}$ is the linear part of the reactance, $\hat{v}_{\mathrm{neck}}$ is the neck acoustic velocity (acoustic velocity through the perforations), and G_c and F_c are functions given by:

$$F_c = \frac{1}{1+2\mathrm{Sr}[1+0.06\exp(3.74/\mathrm{Sh})]} \tag{7}$$

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$$
\begin{aligned}
G_c &= 0.20 - \frac{0.50}{\mathrm{Sr}}\left(1 - \frac{0.42}{\mathrm{Sh}^2}\right) + \frac{0.05}{\mathrm{Sr}^2}\left(1 - \frac{0.68}{\mathrm{Sh}^2}\right), \quad \text{if } \mathrm{Sr} \leq 1 \\
G_c &= -0.05\left[\frac{1}{\mathrm{Sr}}\left(1 - \frac{1}{\mathrm{Sh}}\right)\right] - 0.60\left[\frac{1}{\mathrm{Sr}}\left(1 - \frac{1}{\mathrm{Sh}}\right)\right]^2, \quad \text{if } \mathrm{Sr} > 1
\end{aligned}
\tag{8}
$$

2.3 Model with empirical corrections

In his work, Temiz [4] determines the linear resistance and reactance with impedance tube tests at low excitation amplitudes. In the work carried out at RUAG Space, the following considerations are done to adapt the models to the test setup considered:

- Empirical correction value of the linear impedance
- Impedance of the perforated honeycomb core
- Consideration of the acoustic velocity within the perforations, called acoustic neck velocity $\hat{v}_{\mathrm{neck}}$ as an input parameter.

The laboratory acoustic testing needed for the development of the prediction model of the MPP sandwich panel acoustic behaviour is carried out by Impedance Tube tests (i.e. Laboratory acoustic testing) performed on aluminium samples of (i) the Micro-Perforated Panels (MPPs) backed by an empty cavity and (ii) the MPPs backed by perforated honeycomb core.

All the tests performed with the MPP backed by the honeycomb core, have representative geometrical and fluid-dynamic configuration of the honeycomb core. The honeycomb core walls are thin enough that acoustic waves might propagate between neighbouring honeycomb core cells through vibro-acoustic coupling (i.e. wall vibrations). If acoustic waves would not propagate between neighbouring volumes (i.e. having honeycomb cells acoustically decoupled between each other) only the cells in fluid contact with the MPPs micro-perforations would be acoustically effective. Due to the relatively low porosity of the considered MPPs, this would drastically reduce the acoustic damping effectiveness of the panels.

The deviation of the linear resistance between the model of Maa and the measurements at low excitation amplitudes are considered by an empirical correction value that is determined experimentally. The reactance calculated with Maa's model has been found in good agreement with the reactance measured at low excitation level (linear part of the reactance). The model equations for the prediction of the acoustic impedance of the micro-perorated panel are as follows:

$$
\mathrm{Re}\{Z_s\} = \mathrm{Re}\{Z_s\}_{\mathrm{Temiz}} + \Delta\mathrm{Re}\{Z_s\}_{\mathrm{lin}} = \mathrm{Re}\{Z_s\}_{\mathrm{lin}} + \Delta\mathrm{Re}\{Z_s\}_{\mathrm{lin}} + \frac{F_c \hat{v}_{\mathrm{neck}} \rho_0}{2 C_v^2 \varepsilon} \tag{9}
$$

$$
\mathrm{Im}\{Z_s\} = \mathrm{Im}\{Z_s\}_{\mathrm{Temiz}} = \mathrm{Im}\{Z_s\}_{\mathrm{lin}} + \frac{G_c \omega \rho_0 d}{2\varepsilon} \tag{10}
$$

The effect of the honeycomb core on the prediction model of the acoustic impedance is considered in addition.

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2.4 Model correlation after introducing the correction factors

Once the correction factors are introduced in the model, the sound absorption coefficient predicted is compared to a sample tested at the impedance tube. This is used to define the final hole pattern. Figure 3 shows the correlation between the model and an aluminium sample with the final hole pattern selected for this investigation.

As shown in Figure 3, the predictions of the sound absorption coefficient at different neck velocities have a good correlation to the empirical values.

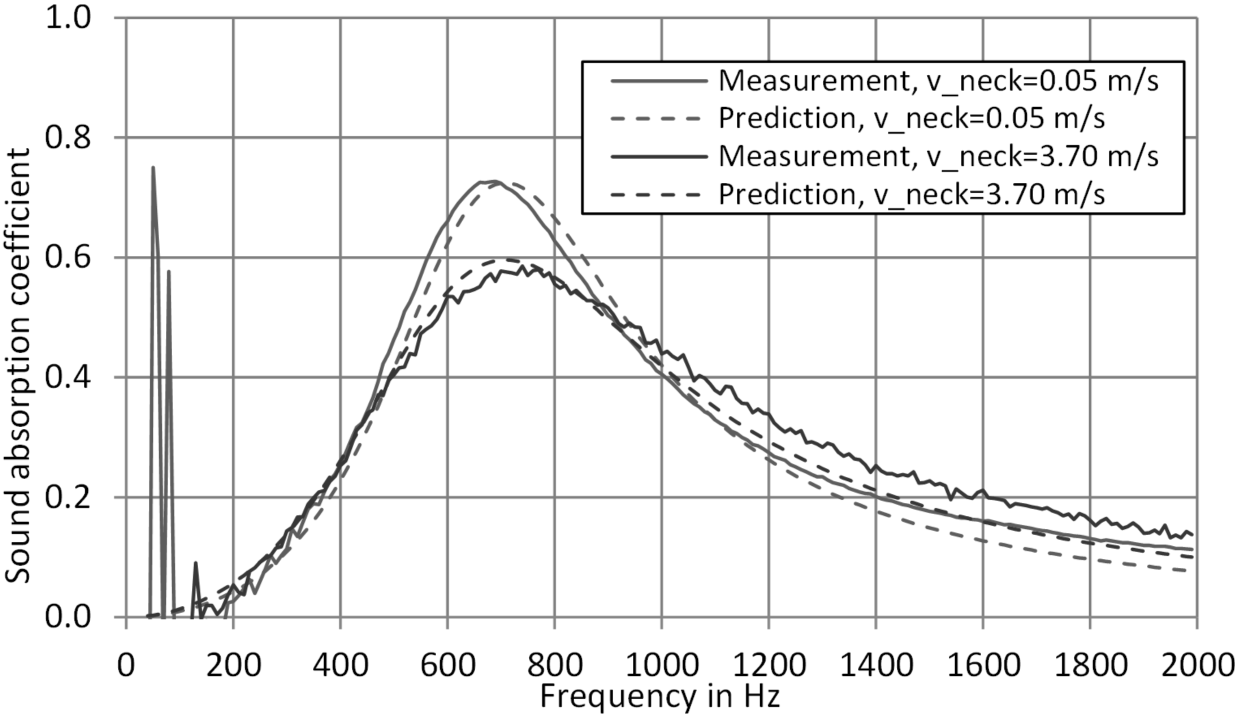

Figure 3: Correlation between model and measurement after empirical correlation with aluminium samples.

3. Empirical validation of the tool

For validation of the model, several MPP samples have been tested in an impedance tube. The sound absorption and the acoustic impedance of 6 samples made of CFRP discs of 100 mm diameter are measured. The frequency-averaged maximum deviation between the 6 samples and their average, in terms of absorption is about 20%. These impedance tube test results are used to derive the model correction parameters that are:

- Honeycomb core cavity impedance
- Empirical correction value of the linear impedance

The correction coefficients evaluated through impedance tube testing of the CFRP samples lead to an impedance model which takes into account all the details, including holes and surface roughness of the final design panels. The correction parameters evaluated with the CFRP panel are in good agreement with those evaluated for the Aluminium samples. This is an indication of the reliability of the proposed methodology.

4. Case study of MPPs in a PLF for medium sized launch vehicles

Due to the fact that the sound incidence inside the PLF is rather diffuse than normal, diffuse sound field measurements (alpha cabin test) have been used for 400 – 10’000 Hz,. In order to cover the frequency range below 400 Hz, impedance tube measurements have been used between 120 – 400 Hz.

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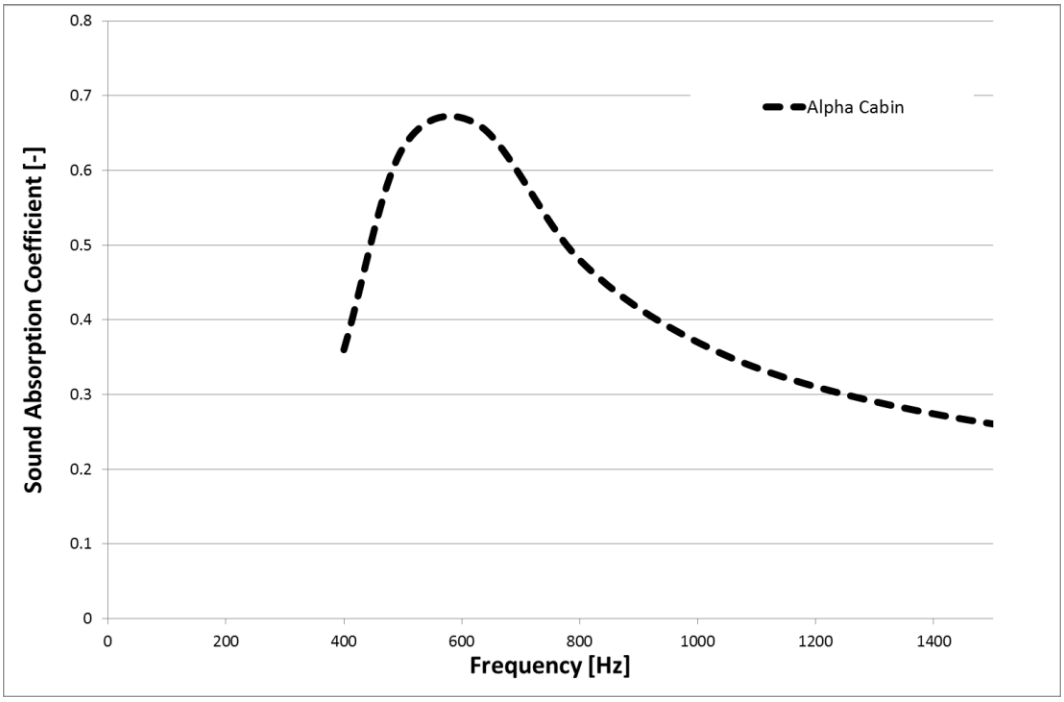

Figure 4: Sound absorption coefficient from alpha cabin measurements.

In order to assess the acoustic performance of the micro-perforated sandwich structure when applied in a PLF for medium sized launch vehicles, the measured absorption coefficient has been implemented in a statistical energy analysis (SEA) model, typically used in these applications. Two different coverage areas (surface treated with MPP) have been defined for the assessment:

- 96% coverage
- 65% coverage

Figure 5: shows the differential noise reduction between the baseline, untreated PLF and the MPP treated PLF with 96% coverage. The maximum noise reduction improvement is 12.32 dB at 2000 Hz.

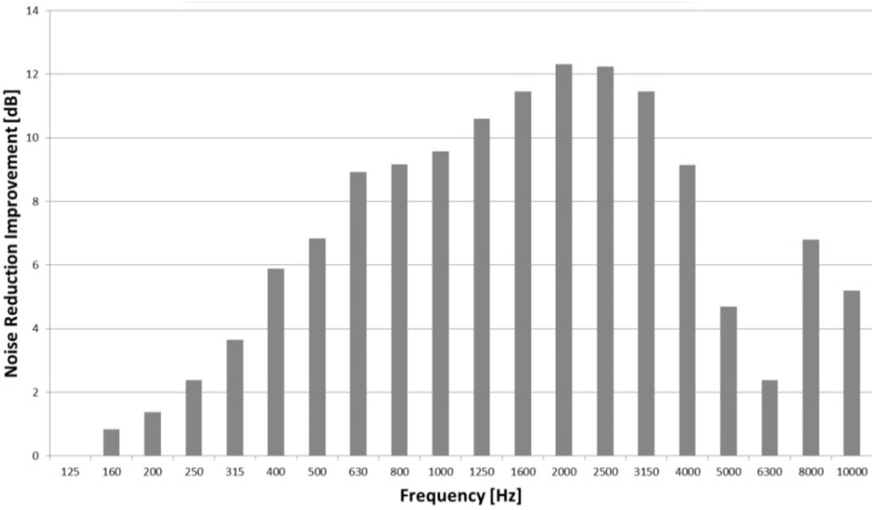

Figure 5: Differential noise reduction of baseline and MPP treated PLF (96% coverage)

Figure 6: shows the differential noise reduction for the scenario with 65% MPP coverage. The maximum noise reduction improvement is 10.62 dB at 2000 Hz.

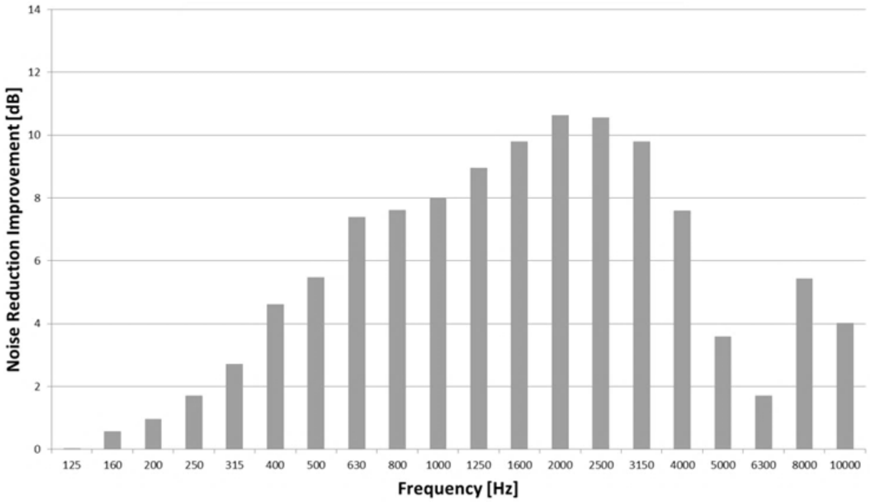

Figure 6: Differential noise reduction of baseline and MPP treated PLF (65% coverage)

5. Preliminary assessment of impact on structural mechanical properties

Various methods for the introduction of micro perforations have been assessed [5]. A common approach is the use of abrasive methods. However, a drawback of abrasive methods is the potential impact on the mechanical performance of the structures. For a preliminary assessment of this impact, samples perforated by drilling are mechanically tested in 4 point bending and compared to reference samples without perforation. An image of the test setup is shown in Figure 7. 5 samples of each type are tested at room temperature dry condition, having the same layup and core thickness.

Figure 7:4 point bending test setup

The performance of the panels in bending strength is compared for both types of panels in Table 1.

Table 1: 4 point bending

	Non perforated	**Perforated (drilled)**
Bending strength [%]	100.00	100.34
St dev. [% of bending strength]	5.1	2.8

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These preliminary results give a first indication that the micro perforation does not affect the structural performance of the composite panels. Further testing will have to follow based on the selection of the final manufacturing method for introduction of micro-perforations.

6. Conclusions

This paper summarizes the modelling approach to predict the noise attenuation by use of micro perforated panels in Payload Fairings. The modelling approach in this investigation is based on Maa [3] theory and is extended with the theory of Temiz [4]. In addition, experimental correction factors are introduced and validated empirically to enhance the fidelity of the simulation tool. The simulation tool shows good correlation between predicted and measured data by impedance tube test, thus validating the modelling methodology considered in this work.

The acoustic performance of a medium sized PLF using the micro-perforated sandwich technology has been assessed by implementing the measured absorption coefficient from alpha cabin measurements into an acoustic model. It has been shown by analysis that the potential benefit for acoustic noise reduction can be significant in terms of noise reduction improvement.

In a last project phase the impact of mechanical performance of drilled holes is measured experimentally, indicating that for the pattern and hole size of MPPs considered in this investigation, there is no impact on the structural performance of the composite panels.

This research confirms that the use of MPPs could improve the noise attenuation in space products, improving the noise comfort of payloads.

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