Application of metamaterials to control noise scattering during space vehicle lift-off

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Abstract

Metamaterials made of resonant building blocks based on Helmholtz resonators have been developed as perfect acoustic absorbers. The performance of these metamaterials is analyzed when used to control the scattering of noise during a space vehicle lift-off. In this event, two main contributions of sound should be controlled: i) the reflected from the launch pad and ii) the transmitted through the faring wall. Numerical models are developed to predict the vibro-acoustic response of two metamaterials designed for these two problems. The approach is to simplify the numerical model by obtaining a simplified panel with equivalent acoustic and mechanical behavior on the frequency range of interest. The first solution is based on a rainbow trapping structure that will be applied as an exhaust channel cover. Later, an ultra-thin perfect absorber is designed to be added to the fairing composite sandwich. Results show a significant noise reduction while small effects of the vibro-acoustic coupling are theoretically and numerically observed. The developed methodology enables a simplification in the noise control analysis and opens the way for its use in other applications.

Keywords: metamaterials, scattering, vibro-acoustic coupling, launch vehicle, rocket.

1 Introduction

The acoustic loading environment is one of the most restrictive specifications for spacecraft design and manufacturing. The predominant acoustic loads occur at the lift-off and atmospheric flight phases. During the lift-off, an intense pressure wave is generated by the rocket engine exhaust gases, and it is reflected on the launch pad towards the launch vehicle. During the atmospheric flight, the acoustic loads are due to the unsteady aerodynamic phenomena. The acoustic pressure fluctuations at the fairing are transmitted through the composite structure and generate a diffuse acoustic environment inside the fairing cavity [1]. Vibro-acoustic effects are induced in the payload, which can lead to structural fatigue or damage. Components with a large surface and small weight, for example solar panels or antenna reflectors are very sensitive to the acoustic field [2]. Since future missions of Earth Observation and Space Telecommunications require larger reflector antennas to increase their resolution and sensitivity, acoustic excitation is becoming a more important aspect in satellite survival during launch [3]. Therefore, an effective mitigation method of acoustic noise is needed to ensure the reliability of the launch. Several strategies have been used as water injection at the launch pad level or insulation systems at the fairing as microperforated panels. However, even using these techniques, the Overall Sound Pressure Level that a satellite must be able to withstand is around 140 dB [4]. Thus, there is a need for a sound mitigation technique that scatters the noise emitted by the rocket to alleviate the acoustic loads on the payload.

In recent years, interest in metamaterials has increased due to the possibilities they offer for controlling acoustic and vibration waves. In the acoustic field, metamaterials have been used to design sub-wavelength absorbers as metaporous materials, metamaterials composed of membrane-type resonators, quarter wavelength resonators, and Helmholtz resonators (HR). The latter metamaterials have been extensively analyzed during the last years to develop perfect acoustic absorbers in the low frequency range [5, 6]. These absorbers are based on a waveguide loaded with HRs. The geometry of the inner structure and the resonator defines the resonance frequency, at which the energy absorption will occur. It is possible to include a single HR to absorb, mainly, acoustic energy at a single frequency or a set of tuned HRs, to mitigate broadband noise by overlapping several resonances. These structures present extraordinary values of absorption: for a single HR, an absorption peak of 0.97 was experimentally observed for normal incidence [6] while for the rainbow trapping absorber a broadband absorption of 0.98 was measured [5]. These metamaterials present three advantages: high absorption performance, quasi-omnidirectional behavior, and the possibility to act on a broadband frequency range. The quasi-omnidirectional feature is of great interest because inside the fairing cavity the acoustic field is considered diffuse [2] and at the launch pad level each sound source radiates energy in a different direction [7].

In this work, two different structures have been designed as shown in Figure 1. A single resonator absorber (SRA), which will be placed inside the fairing cavity to increase the transmission loss; and a rainbow-trapping absorber (RTA), which would be placed as a cover of the jet deflector to absorb acoustic energy and prevent direct reflections from the launch pad. The two structures have been designed, from an acoustic point of view, in the relevant frequency range between 100 and 500 Hz. The objective is to assess the noise attenuation that

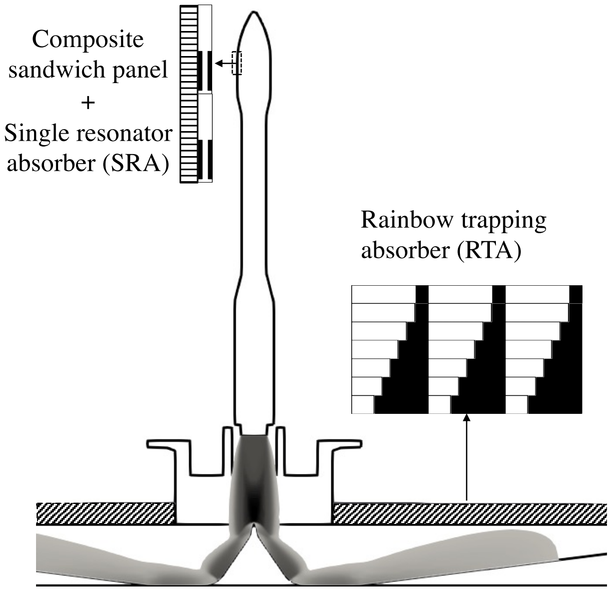

Figure 1. Sketch of the implementation of the metamaterials.

these metamaterials can achieve in the spacecraft launch problem. Using an optimization method, the geometry of each system has been tuned to provide perfect absorption and sub-wavelength dimensions following the method explained in Refs [6, 5]. This approach results in a geometry composed of cavities and necks made of thin walls. Given the structural requirements that the structure may be subjected in real working conditions of the problem it is necessary to study the influence of the vibro-acoustic response on the acoustic performance. The direct simulation of this cannot be resolved through a direct simulation because the size of the real sample results in an extreme computational cost. Therefore, an equivalent medium approach, which is more efficient from a computational point of view has been used. A methodology has been developed to obtain a plate with equivalent mechanical and acoustic behavior to those of metamaterials. This methodology is summarized in section 2. In section 3 the results of the equivalent system and the vibro-acoustic analysis are presented. Finally, section 4 summarizes the conclusions of the work.

2 Methodology

The vibro-acoustic simulation will be conducted in VA One software (ESI Group) where the Finite Element Method (FEM) will be used to model the structure domain and the Boundary Element Method (BEM) will be used for the fluid domain. The direct approach would be to study the vibro-acoustic response of a metamaterial panel with the maximum detail in its geometry. However, this entails different problems. First, a refined finite element mesh is needed to capture all the geometry components, which exponentially increases the computational cost with the number of elements. In addition, the detailed structure, composed by cavities and walls, has consequently a high modal density due to local modes that will not be relevant for this study. Only the global modes of the meta-structure might have a significant effect. It is known that a high modal density also increases the computational cost due to modal superposition, so it is not necessary to consider all the deformation mode shapes. Furthermore, to properly tune the resonance frequencies of each resonator is vital to model the visco-thermal losses in the fluid domain [5] which implies an additional difficulty. Hence, our approach is to model the problem by a simplified system with equivalent acoustic and mechanical response on the frequency range of interest.

2.1 Equivalent system characterization

The vibro-acoustic problem is influenced by the acoustic and structural properties of the system. Therefore, for each domain it is necessary to have equivalent properties. The equivalent properties are obtained for a reference panel of 1x1 m^2.

The acoustic behavior of the structure is based on the sound transmission through the metamaterial. The main characteristic is the scattering of the system, which is composed of the reflection and transmission coefficients and the absorption coefficient as the system has intrinsic losses. Therefore, the goal is to model the absorption of the system by means of an equivalent impedance boundary condition. The acoustic impedance matrix of the system has been obtained directly from the acoustic design, which notation is:

$$\begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, \qquad (2\text{-}1)$$

where P is the acoustic pressure, v is the particle velocity and the suffix 1 or 2 refers to the side, front and back, respectively, of the metamaterial.

The mechanical behavior is modelled by FEM simulations using anisotropic elastic parameters. The panel of study is composed of a periodic repetition of a unit cell in two directions. Their arrangement defines the structural response, so the repetition directions are the main components of interest. The equivalent structural parameters are: E_i as the Young's modulus along i-direction, ν_{ij} as the Poisson coefficient due to a strain in the j-direction when stress is applied in i-direction and G_{ij} is the shear modulus in j-direction on the plane whose normal is in i-direction. These constants are used to define the mechanical properties of a flat plate whose most relevant eigenfrequencies are tuned to match the relevant eigenfrequencies of the detailed model. The FEM software used for the mechanical analysis is MSC Nastran (The MacNeal-Schwendler Corporation MSC, Irvine, CA, USA).

2.2 SRA vibro-acoustic model

The SRA structure has been designed to be implemented inside the fairing adhered to the existing sandwich honeycomb. In the vibro-acoustic analysis we want to analyze the transmission loss effect that the metamaterial adds in reference to the sandwich structure. The external structure of the fairing is assumed to be composed of 2 mm thick carbon fiber skins and an aluminum honeycomb core. To study the transmission loss, reverberation and semi-anechoic rooms have been simulated by means of two BEM fluids with an infinite rigid plane connected to the first one as shown in Figure 2. The acoustic source is a diffuse acoustic field. It is included through a set of 100 acoustic plane waves evenly distributed. A normalized acoustic field of 1 Pa has been considered.

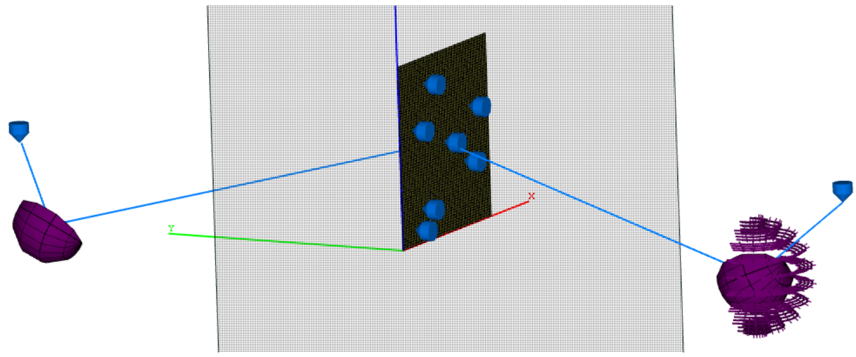

Figure 2. Overview of the VAOne vibro-acoustic model depicting the two BEM fluids (semi-anechoic room on the left, reverberation room on the right), the reference panel and the rigid plane.

The reference panel structure is modelled by means of an FE model based on CQUAD4 elements with structural properties defined by a PCOMP property. The structural behavior of the SRA panel is modelled by means of an FE flat panel (CQUAD4 elements) with structural properties defined by a PSHELL. Both the reference panel and the assembly are assumed to be simply supported on the four edges. In order to include the acoustic response of the SRA panel, an additional FE acoustic cavity is required so that a FE area junction between the acoustic cavity and the structure can be used to include an impedance matrix by means of an area isolator.

2.3 RTA vibro-acoustic model

The RTA structure has been designed to be used as a cover of the launch pad exhaust channels. Therefore, the sound source is the jet from the rocket engine and its impact against the deflector. The vibro-acoustic model is composed of a metamaterial panel exposed to the acoustic sources on one side in an unbounded domain as shown in Figure 3.

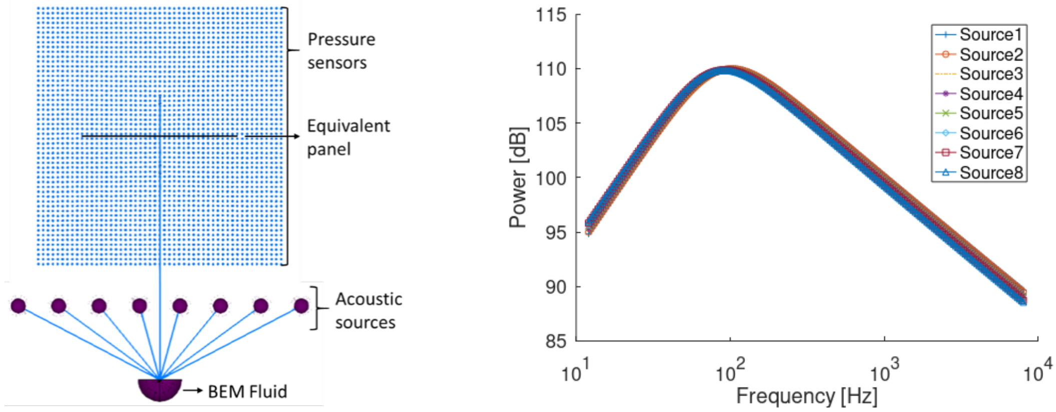

Figure 3. On the right, overview of the Va One vibro-acoustic model. On the left, monopoles power spectrum.

The structural behavior of the Helmholtz resonator panel is modelled by means of an FE flat panel (CQUAD4 elements) with structural properties defined by a PSHELL. The mechanical properties have been tuned so that the FE flat panel first eigenfrequencies match the first eigenfrequencies of a detailed model of the HR panel. A panel of 1.5x2 meters has been considered. The boundary conditions applied are the restriction of the 6 degrees of freedom of all the nodes located at the edges of the plate to represent a frame. The acoustic excitation is a distribution of 8 sources designed by the Distributed Source Method (DSM) to replace the jet as presented in [8]. Each source is represented by a monopole. The spectrum associated with each monopole defines the pressure that would be obtained in the free field by the following equation:

$$p(r) = \frac{Ae^{-ikr}}{-4\pi r} \; ; \; |A| = (4\pi\rho c W)^{1/2} \tag{2-2}$$

where r is the distance from the monopole, k is the acoustic wavenumber, A is the pressure amplitude, ρ is the fluid density, and c is the speed of sound on the fluid. The pressure amplitude is computed in terms of the sound power of the source, W, which is presented in Figure 3. On the right, overview of the Va One vibro-acoustic model. On the left, monopoles power spectrum.. The acoustic domain is represented by an exterior BEM fluid only connected to the structure and the acoustic sources. Finally, a set of pressure sensors has been used to cover a 3x3 m measurement plane.

3 Results

3.1 Structural results

Through mechanical characterization, each metamaterial has been modelled as a flat plate. As a reference, a 1x1 m^2 panel has been used for each case.

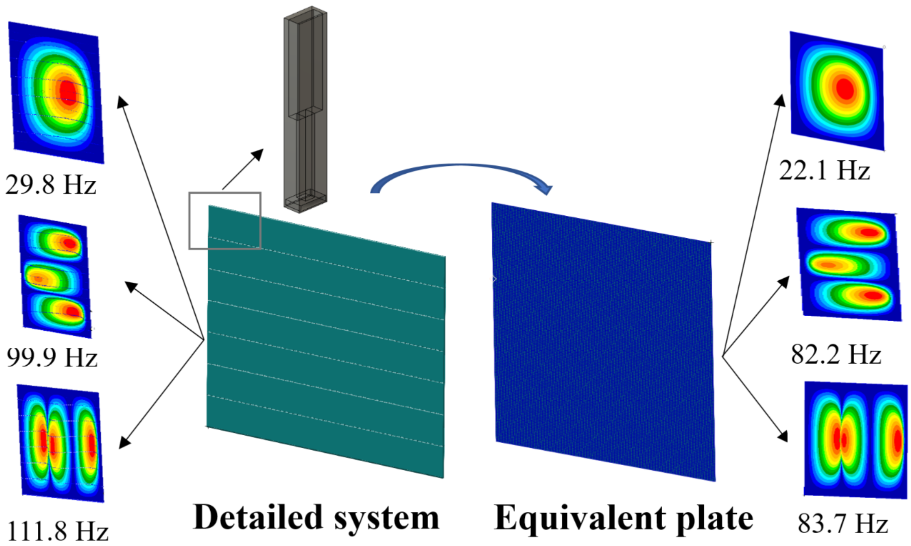

Figure 4. Comparison between most relevant eigenfrequency of SRA system and equivalent panel.

Regarding the SRA, which is intended to be implemented on the fairing, Figure 4 shows the FEM model of the metamaterial with all the details and the flat plate with an equivalent response. In addition, the first three eigenfrequencies of each system are presented. In Figure 5 the same information is presented for the RTA system. As it can be seen, the mode deformation shapes of the equivalent systems are the same as the original ones. The criterion to define the relevant eigenfrequencies is the mass fraction that a displacement mode can move. The threshold has been set to 5% of mass fraction resulting in three key eigenfrequencies. The most relevant eigenfrequencies are those that have asymmetric mode shapes.

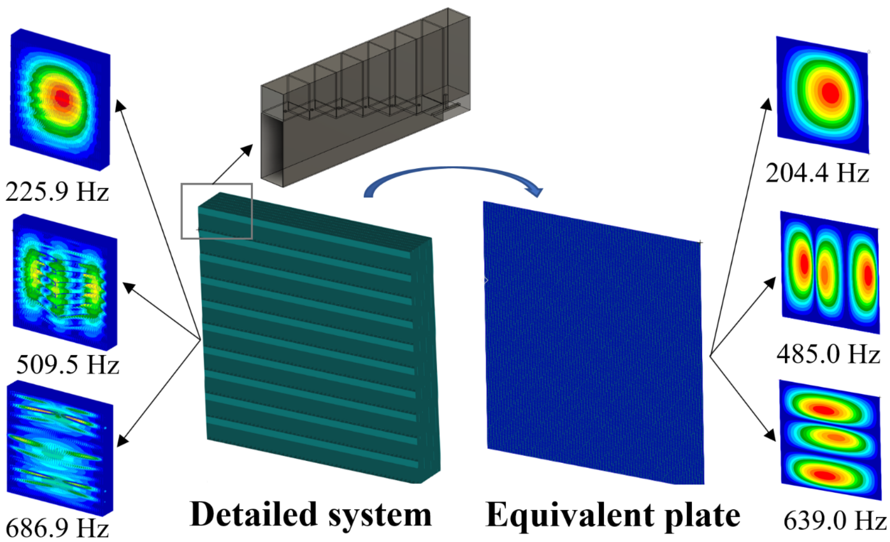

Figure 5. Comparison between most relevant eigenfrequency of RTA system and equivalent panel.

Table 1. SRA and RTA most relevant eigenfrequencies summary.

	Detailed system			Equivalent system			
	Mode	Frequency (Hz)	Mass fraction	Mode	Frequency (Hz)	Mass fraction	**Absolute frequency error (Hz)**
SRA	1	29.8	50%	1	22.1	50%	**7.7**
	5	99.9	9%	5	82.2	8%	**17.7**
	6	111.8	10%	6	83.7	12%	**28.1**
RTA	1	225.9	55.4%	1	204.4	56.4%	**21.5**
	515	509.5	8.7%	5	485.0	9%	**24.5**
	1028	686.9	9.8%	10	639.0	11.4%	**47.9**

As presented in Table 1, for both metamaterials, the first eigenfrequency is the most relevant as it can move 50% of mass. The two following eigenfrequencies can move approximately 10% of mass, which is 5 times less. Regarding the frequency error between the eigenfrequencies, they are between 7.7 Hz and 28.1 Hz for the SRA system while for the RTA system are between 21.5 Hz and 47.8 Hz. Hence, the SRA equivalent system provides a better approximation. Although the absolute errors are not small, the behavior of both systems is characterized.

3.2 Acoustic results

By means of a simple waveguide simulation, it has been shown that the impedance boundary condition on a flat plate generates absorption results equivalent to those of the acoustic design. The 4-microphone method has been used as explained in [9]. Figure 6 shows the comparison between the absorption coefficient calculated by acoustic optimization and VA One for each system under analysis. The results using the impedance boundary condition reproduce the absorption of the system very accurately. Thus, the absorption of the metamaterials will be modelled accurately in the vibro-acoustic analysis.

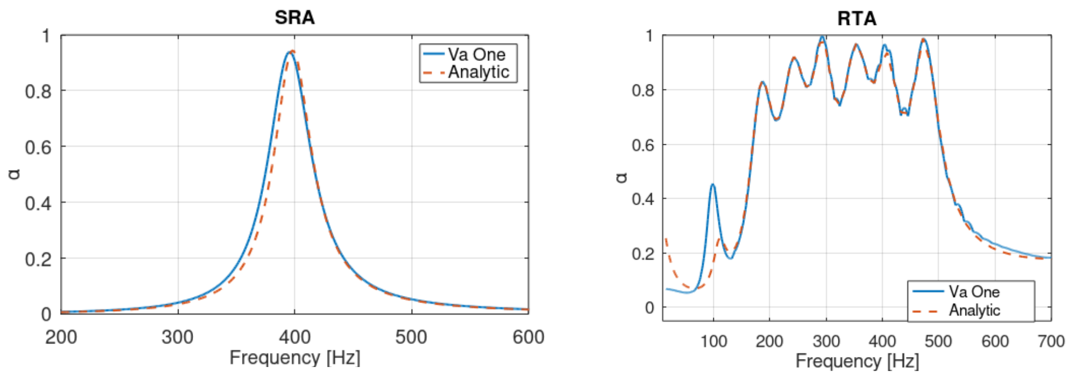

Figure 6. Comparison between the absorption obtained using the analytical model (dashed orange line) and the modelling in VA One (solid blue line). SRA results on the left and RTA results on the right.

3.3 Vibro-acoustic prediction results

The tuning of the structural modes has been carried out based on a reference panel. In the vibro-acoustic analysis panels of a different size have been considered and therefore the structural frequencies are different. Figure 7 shows the relevant modes for each metamaterial panel in contrast to the mass fraction that the modes move.

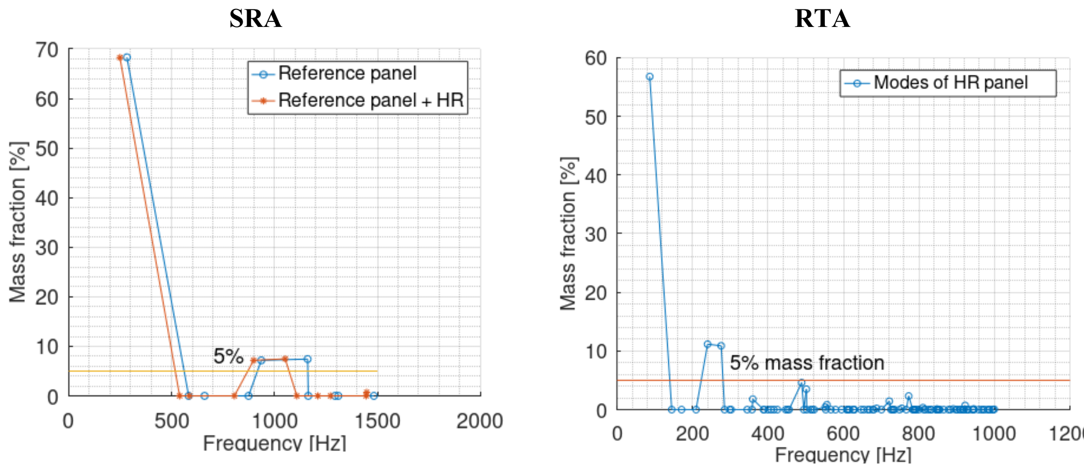

Figure 7. Relevant modes definition. Eigenfrequencies in contrast to the fraction of mass that each move. On the left, modes for the reference sandwich structure and for the sandwich structure + SRA. On the right, modes of the RTA panel. The horizontal line is at 5% of mass to distinguish the relevant modes.

Figure 7 shows, as well, the comparison between the modes of the sandwich reference panel considered for the fairing wall before and after adding the SRA panel. There are three main frequencies: 248.3 Hz, 898.1 Hz and 1051 Hz for the reference panel and 282.4 Hz, 935.3 Hz and 1160.5 Hz when the SRA is added. There is a shift to lower frequencies due to the Helmholtz resonator (HR) panel.

To distinguish between the noise reduction that is generated by the acoustic component or by the dynamic component added by the RAS, three different results are presented in Figure 8. The results of the sandwich panel (blue), the results of the sandwich panel and only the structural contribution of the SRA (orange) and the results of the panel together with the structural and acoustic contribution of the SRA panel (yellow).

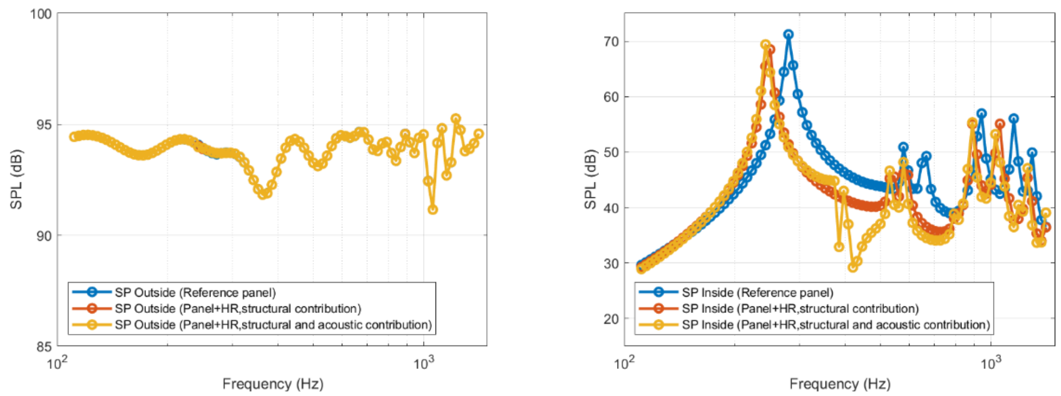

Figure 8. SPL on the emitter room (left) and receiver room (right) for the SRA vibro-acoustic analysis in 1/24-octave bands.

Figure 8 left presents the SPL in the source room (the reverberation room), which shows almost negligible differences between the structures analyzed. On the right, the SPLs in the receiver room shows pressure peaks at frequencies matching the resonant frequencies of each structure. As previously shown in Figure 7, the structural contribution shifts the eigenfrequencies of the panel. The acoustic contribution is clearly identified in the decrease of SPL around the 420 Hz band. In total, at the design frequency band of the SRA there is a reduction of approximately 15 dB.

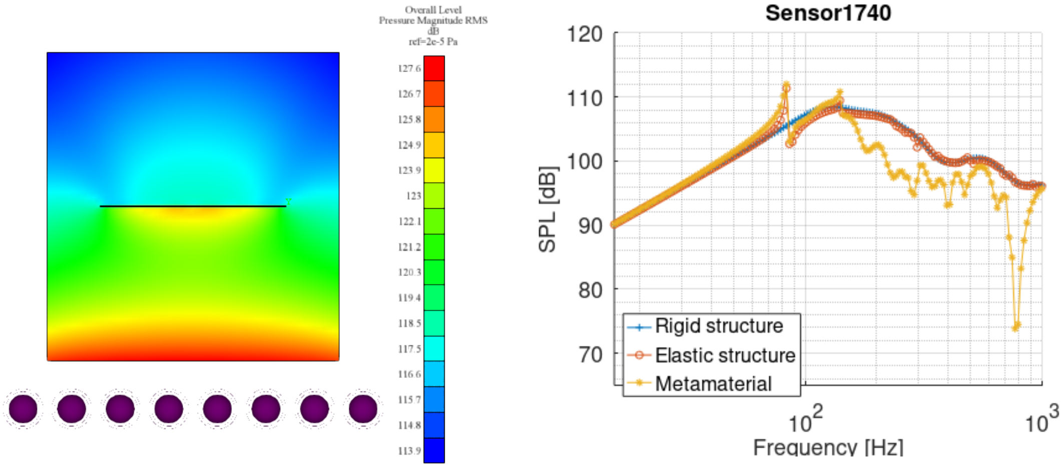

Figure 9. Results of the RTA vibro-acoustic analysis. On the left, contour of Overall Level Pressure Magnitude RMS (dB) with the. On the right, SPL results of a sensor located close to the structure.

Concerning the vibro-acoustic analysis of the RTA panel, which is intended to be implemented as a cover of the exhaust ducts of the launch pad, the results are presented on Figure 9. In this configuration, the interesting effect is the one with reference to a rigid plate as it is a noise mitigation technique that is already used as a cover in the launch facilities. As shown in the contour map presented, in the semi-space behind the structure, there is a noticeable decrease of SPL as the structure gets in the noise propagation path, which was one of the expected results. Moreover, between the sources and the metamaterial, as reflections due to the structure appear, the SPL increases. However, if we measure the SPL by a sensor located close to the panel, in the case of metamaterial there is a significant reduction in SPL between 100 Hz and 500 Hz compared to the rigid plate. This implies a reduction of the acoustic energy inside the channels and therefore of the energy that will be radiated from the output of the channels to the launch vehicle. It is worth noting the effect of structural modes. As shown in Figure 7, the most relevant structural modes are located at 86.7 Hz, 239.93 Hz and 275.92 Hz. As it was stated before, the first eigenfrequency can move more than 50% of the mass. The effect of the 86.7 Hz mode is clearly present on the SPL results in Figure 9. Results of the RTA vibro-acoustic analysis. On the left, contour of Overall Level Pressure Magnitude RMS (dB) with the. On the right, SPL results of a sensor located close to the structure.
. This effect is due to the structural behavior because it is also present in the red line where only the structural contribution of the RTA is modeled.

4 Conclusions

In this work the performance of two different metamaterials intended to reduce the launch noise during the lift-off are studied. One metamaterial has been designed to be placed inside the fairing cavity to increase the transmission loss, called single resonator absorber (SRA). The other is called rainbow-trapping absorber (RTA), and it is designed to be placed as a cover of the exhaust ducts to absorb acoustic energy and prevent direct reflections from the launch pad to propagate upwards. The structures have been optimized in extensive detail for the acoustic problem. However, it is necessary to evaluate the influence of the structural behavior by means of the vibro-acoustic coupling problem. To predict the vibro-acoustic response of the metamaterial, the approach is to simplify the model by obtaining a simplified panel with equivalent acoustic and mechanical responses on the frequency range of interest. The mechanical behavior is characterized by the engineering constants of the detailed system. The most relevant eigenfrequencies have been found to be those that have an asymmetric mode shapes, being the first one the most important. The acoustic absorption of the equivalent systems has been modelled through an impedance boundary condition. The present findings confirm that the SRA panel effectively reduces the noise transmitted at the design frequency and that the RTA panel reduces the reflection and transmission of the incident waves. Moreover, the results show the effect of the vibro-acoustic coupling. The structural frequencies depend on the dimensions and boundary conditions of the panel. Hence, the boundary conditions of the metamaterials are an important aspect to consider regarding acoustic performances. The suggested methodology simplifies noise control analysis and allows for its application in other areas.

Acknowledgements

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References

[1] J. P. Arenas and R. N. Margasahayam, "Noise vibration of spacecraft structures," *Revista chilena de ingeniería,* vol. 14, no. 3, pp. 251-264, 2006.

[2] European Cooperation for Space Standarization, "Space Engineering. Spacecraft mechanical loads analysis handbook," 2013.

[3] J. Angevain, A. Ihle, G. Rodrigues and J. Santiago-Prowald, "Present Status and Future Outlook of the Large Deployable Space Borne Reflector Antennas in Europe," in *Proceedings of the 3rd International Conference,"Advanced Lightweight Structures and Reflector Antennas", ESA Conference Bureau*,, 2018.

[4] Arianespace, "Vega User's Manual. Issue 4. Revision 0," 2014.

[5] N. Jiménez, V. Romero-García, V. Pagneux and J.-P. Groby, "Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems," *Scientific reports,* vol. 7, no. 1, pp. 1-12, 2017.

[6] N. Jiménez, W. Huang, V. Romero-García, V. Pagneux and J.-P. Groby, "Ultra-thin metamaterial for perfect and wuasi-omnidirectional sound absorption," *Applied Physics Letters,* vol. 109, no. 12, p. 121902, 2016.

[7] p. Malbéqui, R. Davy and C. Bresson, "Experimental characterization of the acoustics of the future Ariane 6 launch pad," in *7th European Conference for Aeronautics and Space Sciences*, 2015.

[8] J. M. Requena Plens, N. Jiménez, A. Cebrecos, R. Picó and V. Sánchez-Morcillo, "Acoustic field prediction during the launch of rockets," in *Tecniacustica*, 2020.

[9] B. H. Song and J. S. Bolton, "A transfer-matrix approach for estimating the characteristic impedance and wavenumbers of limp and rigid porous materials," *The Journal of the Acoustical Society of America,* vol. 107, 2000.