Noise-shield with membrane-type metamaterials for low-frequency sound insulation.
Part II: Numerical investigation of the full-scale acoustic panel assembly

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Introduction

In the context of a counter-rotating open-rotor (CROR) aircraft design, a need of measures for reducing high-amplitude low-frequency noise, generated by the propellers, arises. Considering the traditional sound attenuation techniques at low frequencies, the lightweight requirements for a fuselage-mounted noise shield cannot be satisfied.
To challenge this problem, new generations of metamaterials have emerged as a possible solution for sound attenuation well beyond the limit of the conventional acoustical mass law.[3] Locally resonant acoustic materials of membrane-type with negative dynamic mass are recently reported being able to increase sound transmission loss significantly when compared to mass law based sound reduction means. Based on the analytical results obtained for a single-celled multi-layer arrangement in part I of the contribution, series of numerical investigations involving finite element analyses have been performed aiming to verify the adequacy of the material arrangement as a middle layer of a double panel structure for low frequency noise protection. The sound transmission loss calculations are carried out for structures with different complexity and with varying parameters.

Noise shield structure

The proposed and investigated noise shield structure is a multi-layered panel with a predefined thickness of 57 mm and a size of 1000 mm by 1200 mm, it is mounted on the outside of the aircraft body in the CROR propeller plane. The panel includes two aluminium sheets and an air cavity with two membrane-cell layers. The geometrical details with respect to the arrangement, which can be seen in Fig. 1, are as follows: h_0=20 mm, Δh=10 mm, t_1=5 mm, t_2=2 mm, and membrane masses M_1=3.2 g and M_2=1.9 g. A single-celled mass-loaded membrane is constructed from a very thin prestressed square membrane, attached to an aluminium frame, and a centrally located steel mass. The single-celled membrane has an edge length of 50 mm and is prestressed with 6.4 MPa, the steel mass is a square with an edge length of 10 mm. The membrane material properties are as follows: Mass density $\rho = 1270$ kg/m^3, Young's modulus $E = 2.9$ GPa, Poisson's ratio $\mu = 0.44$, and membrane thickness 25 μm. The width and thickness of the membrane-cell aluminium frame are 5 mm and 1 mm, respectively. The air properties considered in the study are: Density ρ_0=0.458 kg/m^3 and speed of sound c_0=298 m/s for a cruise flight at 35 000 ft. In the present contribution, numerical results for the transmission loss of a single-celled structure are compared to the multi-celled array arrangement, and a layered structure cell, which can be seen in Fig. 1. The aim is to estimate the transmission loss behaviour of a full size noise shield panel.

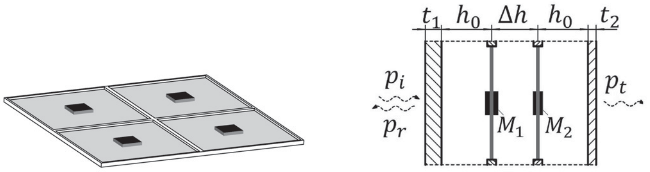

Figure 1: Multi-celled and multi-layered membrane structures.

Finite Element Models

A vibro-acoustic finite element analysis is used for the evaluation of the transmission loss properties of the configurations discussed above. Both, modal based and direct vibro-acoustic calculations, under time-harmonic uniform pressure excitation and a fully clamped boundary condition for the edges of the membranes were performed for the model depicted in Fig. 2. In this model, solid elements are used for the fluid, while surface elements are chosen for the structures. A non-reflecting impedance boundary condition is assigned at the outer faces of the fluid.

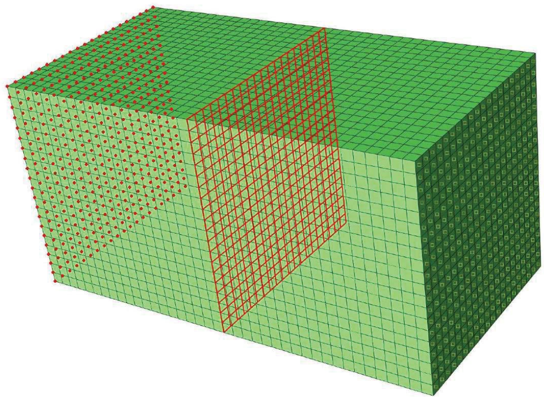

Figure 2: Finite element model for the single layer geometry.

Modal-based vibro acoustic response analyses were proven to be faster and more effective for single layer structures. For the multi-layered configuration, only direct vibro-acoustic forced response analyses have been executed. At this stage, the investigations are performed under a normal field excitation with an incident pressure of 1 Pa, while no damping is considered for the membrane material. The membranes are discretized by membrane-type finite elements, accounting for the lack of bending and shear stiffness of the thin material. The transmission loss was defined by the means of the relationship:

$$\mathrm{TL} = 10 \log \left| \frac{\hat{p}_i(f)}{\hat{p}_t(f)} \right|^2 , \tag{1}$$

where $\hat{p}_i(f)$ is the incident sound pressure of 1 Pa and $\hat{p}_t(f)$ is the transmitted sound pressure. The fluid-structure coupling is realized as face to face with the help of Lagrange multiplier technique, providing mesh matching-free continuity at the interfaces.

Results

Transmission loss calculations have been executed to compare the results, achieved for the different arrangements. In Fig. 3, the single-celled membrane TL behavior is compared to a four-celled panel with different areas of the added mass. Thus, the influence of the frame and of an increasing number of cells can be studied. The appearance of additional TL drop-offs and peaks between the resonance frequencies has not been observed in the case of single-celled samples, hence it can be attributed to the frame properties. The additional drop-off is found to be a result of the first eigenmode of the frame. The increased size and mass of the aluminium frame, due to the four cells, leads to a decrease of the first frame eigenfrequency. The variation of the area covered by the centrally located mass influences both first and second resonance frequencies, as for smaller area they are shifted to lower frequencies. The TL drop-off and TL peak, connected with the eigenmode of the frame, are not affected by these variations, as it was expected. The TL profile of the multi-layered panel, depicted in Fig. 4, consists of the two TL peaks, corresponding to the TL peaks of the individual membranes. The three TL drop-offs for a single cell layered structure are probably caused by the resonance modes of the double wall and the two membranes. For the four-celled arrangement, an additional TL peak and drop-off have been observed, in connection to the membrane frame eigenmodes. The overall TL for the multi-layered configuration is higher as for a double wall, excluding the above mentioned TL drop-offs. For frequencies above the second TL peak, the TL magnitude preserves relatively high values and maintains an increase towards higher frequencies following the double wall trend. The magnitude of the TL drop-off, driven by the membrane frame eigenmode, is smaller in comparison with the ones attributed to the layers interaction.

Conclusions

The proposed noise shield panel consists of approximately 640 membrane single-cells splitted into two layers. Based on the observation for smaller sized multi-celled and multi-layer arrangements, the following conclusions about the transmission loss of the full scale panel can be drawn: An increasing number of membrane cells leads to a decrease of the TL peaks magnitude and bandwidth, together with an introduction of cell array frame resonances. In view of this, for a larger number of cells the frame stiffness becomes an issue. Stacking membranes with different peak frequencies preserves the main TL properties from the individual layers. Further investigation in a diffuse sound field are needed to provide a more realistic view of the noise shield acoustic behaviour.

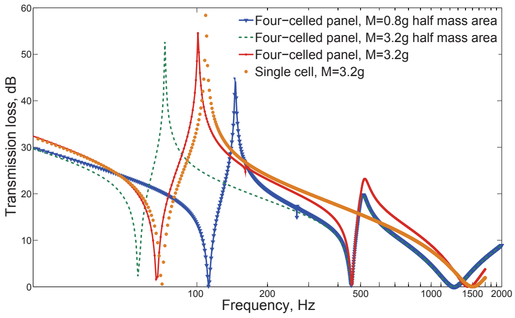

Figure 3: Transmission loss for the membrane arrays.

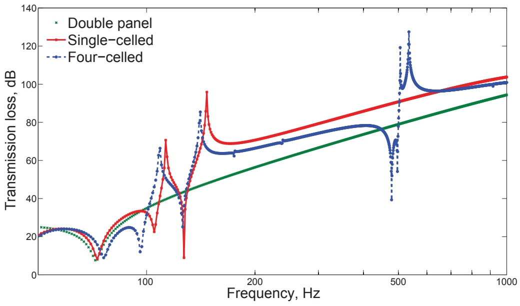

Figure 4: Transmission loss for the multi-layered structure.

Acknowledgement

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