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Analysis of SPL Reduction Possibilities Inside the WFI ATHENA Filterwheel Assembly

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ABSTRACT

Ariane 5 rocket produces very high sound pressure levels during launch, what can influence structures located inside the fairing. In Wide Field Imager (WFI) project, the main part of the filterwheel assembly (FWA) is an extremely thin (~240 nm) filter of large area (170 × 170 mm), very sensitive to noise and vibrations. The aim of this study was to minimize the sound pressure affecting filter surface. Several modifications of the filterwheel assembly including e.g. different filterwheel angular position or height were analysed using finite element method (FEM) simulations. The possible modification options were greatly limited by non-acoustical design factors. The results from computer simulations were compared with measurements of the prototype FWA. The results will be used in further design process of WFI filterwheel assembly.

Keywords: Rocket, Noise, FEM, Athena, WFI

1. INTRODUCTION

Space telescope ATHENA is an X-ray telescope, which maps hot gas structures, determines their physical properties, and searches for supermassive black holes. Wide Field Imager (WFI) – one of the key instruments of ATHENA – will provide imaging in the X-ray energy range of 0.2–15 keV over a field of view with the size of 40 arc min squared in combination with spectral and time-resolved photon counting. The WFI detector, based on arrays of DEPFET active pixel sensors, apart from sensing X-Rays, is also sensitive to photons in the UV and VIS range. To manage this problem, an appropriate blocking filter is needed for the large field of view detector. Due to the large area/dimension (170 × 170 mm) and minor thickness (~240 nm), the filter of WFI is very vulnerable to acoustic and vibration loads, which are generated during rocket launch (1). Therefore, the estimation and minimalization of acoustic load is crucial for designing the WFI Filter Wheel structure.

Common solution to problem of excessive sound pressure levels during rocket start is to enclose the object in vacuum chamber, what leads to significant increase of weight and fault probability. In case of WFI ATHENA a decision was made to protect the filter, instead of enclosing it in vacuum, so that the impact of acoustic wave on fragile blocking filter is minimized. Such approach makes the design lighter and less complicated but the reduction of the SPL on the filter surface must be provided by other means.

2. FILTERWHEEL ASSEMBLY

Detailed structural models of the Filterwheel Assembly (FWA) were provided by Space Research Centre, Polish Academy of Sciences (2). The important elements appearing in all variations of the assembly (Figure 1) are a baffle which shapes the light beam, top cover, filterwheel and the filter.

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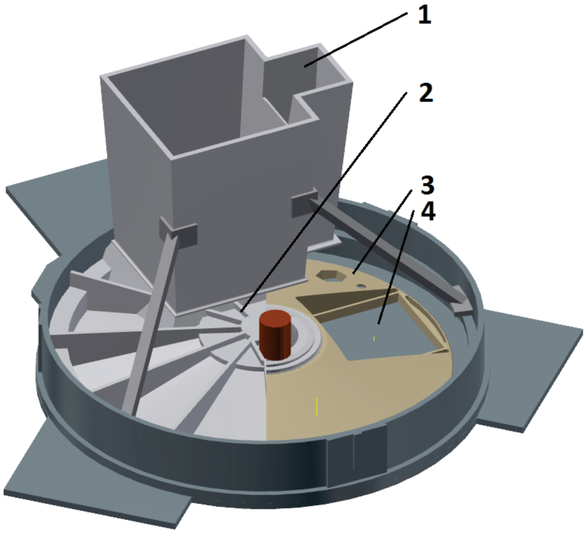


Figure 1 – Geometry of WFI Filterwheel Assembly 1 – Baffle, 2 – Top Cover, 3 – Filterwheel, 4 – Filter on which the SPL must be minimized. The top cover is shown in half section to show the filterwheel

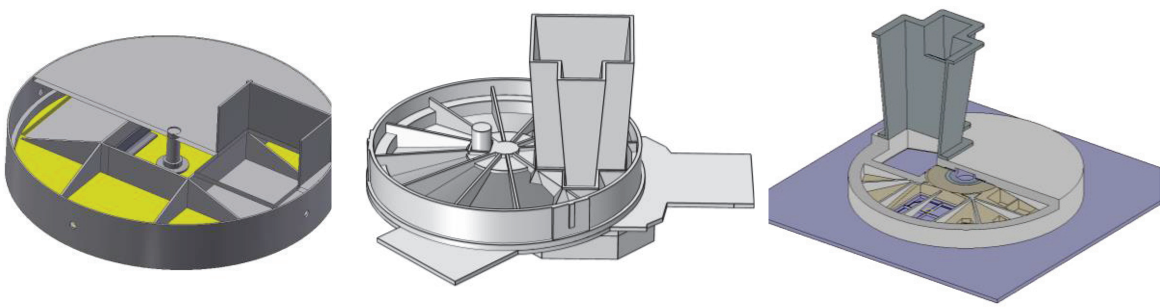
2.1 Analysed WFI Athena FWA Configurations

Three main WFI Athena Filterwheel Assembly models were tested. Due to significant differences in the design of each version the results from different models are not comparable, however the impact of individual modifications within one primary design can be assessed.

The first design (V1) was a prototype used to create and calibrate the Finite Elements Method (FEM) model (Figure 2a). A physical model of the FWA was build and tested in both the reverberation and anechoic chamber of AGH University of Science and Technology (3). Measurement results were used to verify and calibrate the computer model. Finally, an acceptable agreement between the measurement in anechoic chamber and simulation was obtained. The FEM model conditions derived at this stage are described in detail in chapter 3.1 and were used in further simulations without significant modifications.

Second model (V2) was a first proposition of the functional FWA design providing required mechanical properties (Figure 2b). The model was used to analyse the impact of multiple design factors on the sound pressure level inside the assembly. Based on simulation results of the second model, a third geometry was created.

Third model (V3) has a modular design allowing for verification of some of the proposed SPL minimalization solutions by measurements (Figure 2c). It also meets the functional and mechanical requirements and a non-modular version of the geometry can be used as final solution. This model will be built and tested in June 2019. The results from testing third model will be used to re-evaluate the finite elements model.



a) b) c)

Figure 2 – Main tested FWA variants a) prototype model (V1), b) functional model (V2), c) modular model (V3)

3. FEM MODELLING

The WFI Filter Wheel Assembly (FWA) is still in design phase therefore most of the analysis must be carried using numerical simulation methods. The measurements were made only to provide a calibration data for computer modelling.

In order to run simulations provided models have been simplified. We removed all joint elements (screws, bolts and holes), replaced gears and bearings with rings and deleted the chamfered and rounded edges. Such modifications resulted in significant reduction elements number and simulation time. All simplifications were carried so that their impact on the results would be neglectable.

3.1 Finite Elements Method Models

Base FEM model is simulating the anechoic chamber conditions. The geometrical model is filled and surrounded by the cylinder of air (Figure 3a). Outside layer of the air cylinder is the perfectly matched layer (PML) providing the sound radiation condition. Excitation is realized by incident pressure field condition on the top of the cylinder. The structure is simulated using linear elastic material model. The material properties describe aluminium with density of $2700\,\text{kg/m}^3$, 70 GPa Young modulus and 0.33 Poisson ratio. Damping was included as isotropic loss factor $0.64 * 10^{-3}$. Filter membrane is modelled separately using 0.2 mm thick shell component with density of $280\,\text{kg/m}^3$, Young modulus 3.3 GPa and Poisson ratio 0.33. The material properties of the shell were tuned to match the predicted first resonance frequency of the filter (4). Interactions between acoustic pressure filed, linear elastic and shell domain were included in calculations and modelled by suitable interactions. This model provided good agreement with measurements (Figure 3b).

Mesh size was calculated so that the maximum element size was equal to one eight of the 1000 Hz wavelength. Calculations were carried in COMSOL Multiphysics 5.3 software.

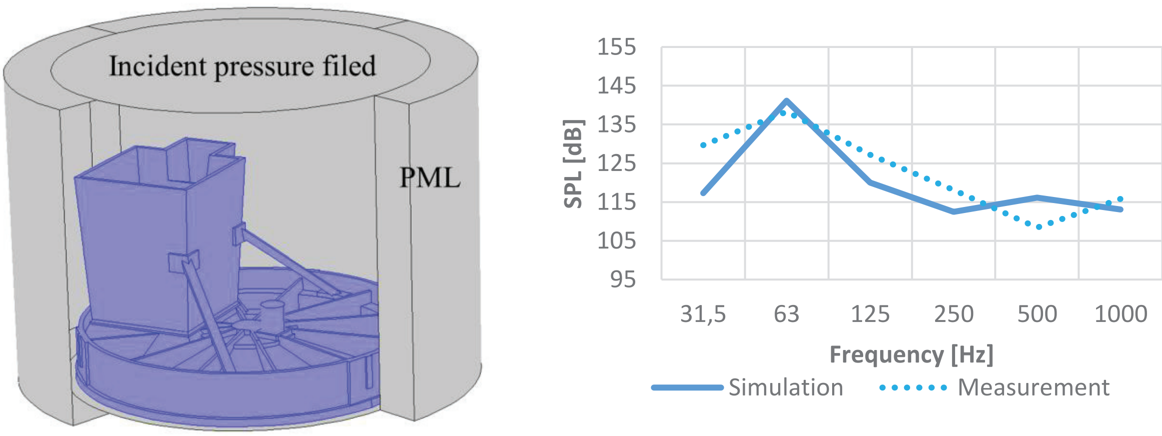


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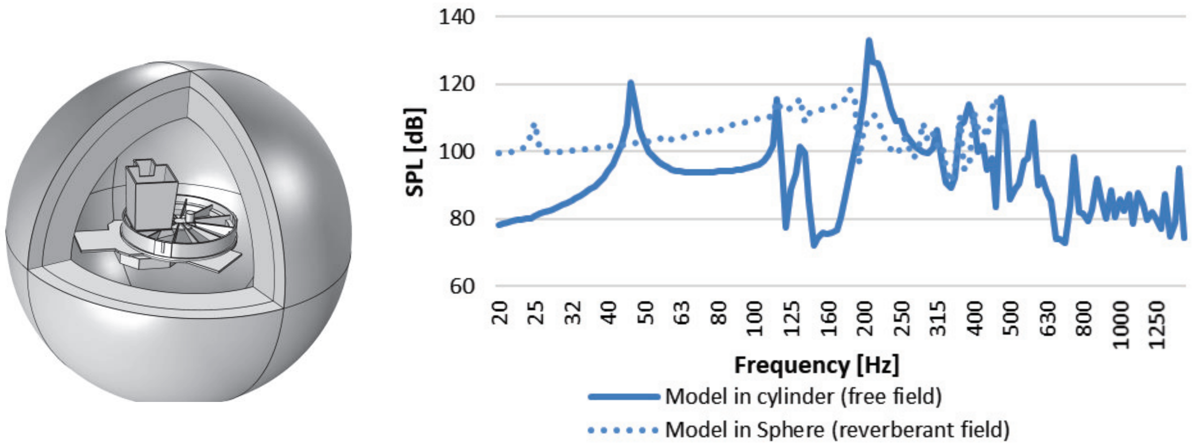
Figure 3 – Base FEM model a) Model geometry with highlighted structure, b) Comparison of measured and simulated SPL on filter surface (model V1)

Because real conditions inside the rocket fairing area are more alike reverberant field than free field, additional model was created to check the impact of the field surrounding the element on the SPL inside the FWA. In the alternative model, the FWA geometry is filled and surrounded by sphere of air with outer layer acting as background pressure filed. To achieve random wave direction the simulated excitation pressure filed is modelled as sum of 200 plane waves with random phases and directions. Because the excitation is partially random, in order to maintain energy, a correction factors based on simulated excitation SPL and target excitation SPL are calculated and applied.



a) b)

Figure 4 – Reverberant field model a) geometry of the model b) comparison of sound pressure levels on filter surface in free field and reverberant field model (model V3)

The simulated SPL for free field and reverberant filed model is significantly different (Figure 3b). Higher overall SPL combined with lower values for resonance frequencies in reverberant field model may be caused by the fact that random excitation is less likely to induce specific resonances but on the other hand it will excite the model more evenly.

For the simulations presented in further chapters the free field model was used. It was compared and calibrated to free field measurements and it allows for comparison of different geometry variants. The measurement session planned on June is supposed to clarify weather the free field or reverberant field model fits the free field measurement better and therefore should be used in future simulations.

3.2 Verification of Structure Transmission Impact

In order to assess the impact of sound transmission via the structure, a model with closed baffle was created. This sealed inside of FWA blocking direct airborne transmission of sound wave to the filter. Additionally, we tested the model with rigid structure.

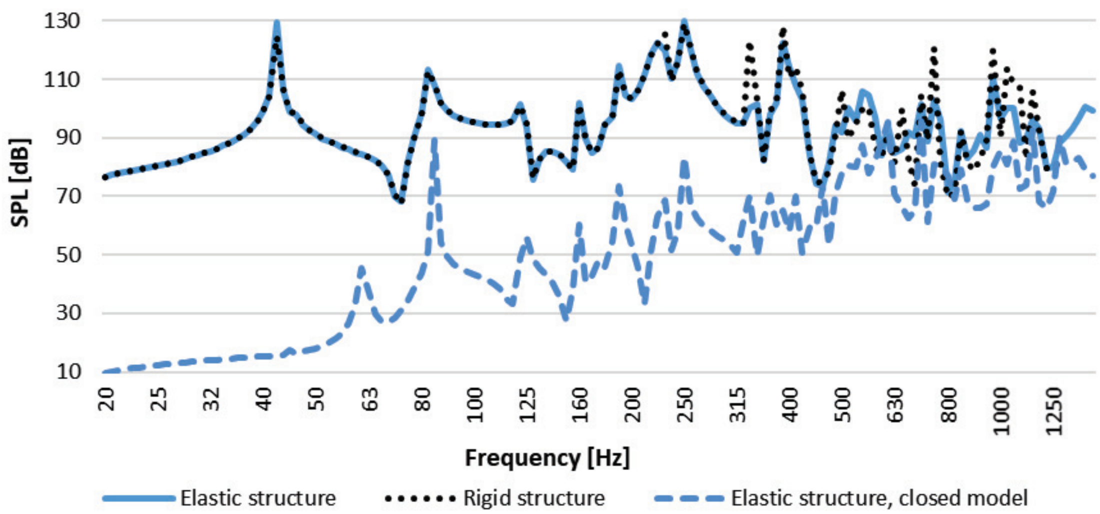


Figure 5 – Impact of structure modelling on the SPL on the filter surface (model V2)

The observed impact of structure-borne transmission is neglectable (Figure 5). SPL on the filter surface with rigid and elastic structure is almost identical. The analysis of closed model shows that for frequency range under 500 Hz the energy transmitted by the structure is orders of magnitude smaller than the energy transmitted through air.

4. ANALYSYS OF FILTER WHEEL ASSEMBLY MODIFICATIONS

4.1 Baffle closing

Based on results of structural transmission analysis, a new model with collapsed (partially closed) baffle was proposed (Figure 6). This allows for some direct access of the airborne sound wave into the model but the exposed area is significantly smaller.

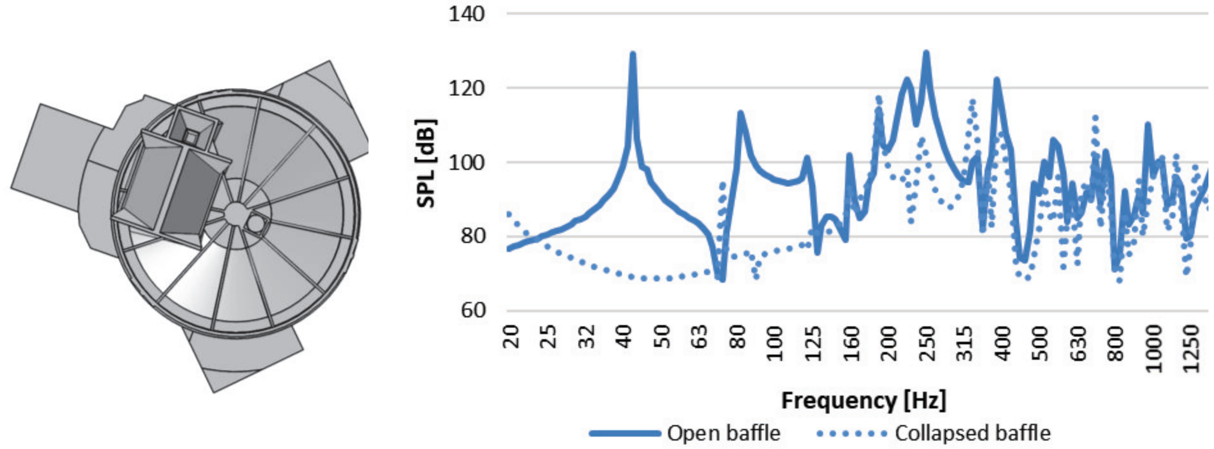


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Figure 6 – Collapsed baffle model a) geometry of the model, main baffle is closed, small baffle remains open b) comparison of the SPL on filter surface for model with open baffle and collapsed baffle (model V2)

Collapsing the baffle leads to significant decrease of the SPL affecting the filter especially in frequency range around 100 Hz where the first resonant frequency of the filter is expected. Although collapsing the baffle reduces the SPL inside the FWA for now this solution is rejected due to complexity and high possibility of fault of the baffle closing and opening mechanism.

4.2 Moving Ribs Inside the Filterwheel Assembly

Another proposed solution was changing the location of the ribs stiffening the top cover from the outside to the inside of the model. It was achieved by moving the surfaces between ribs from the bottom of the ribs to their top (Figure 7a). Such modification increased the overall volume of the FWA and created the expansion chambers inside the filterwheel assembly leading to SPL reduction (Figure 7b). The presented solution was included in the V3 model and is supposed to be included in final FWA design.

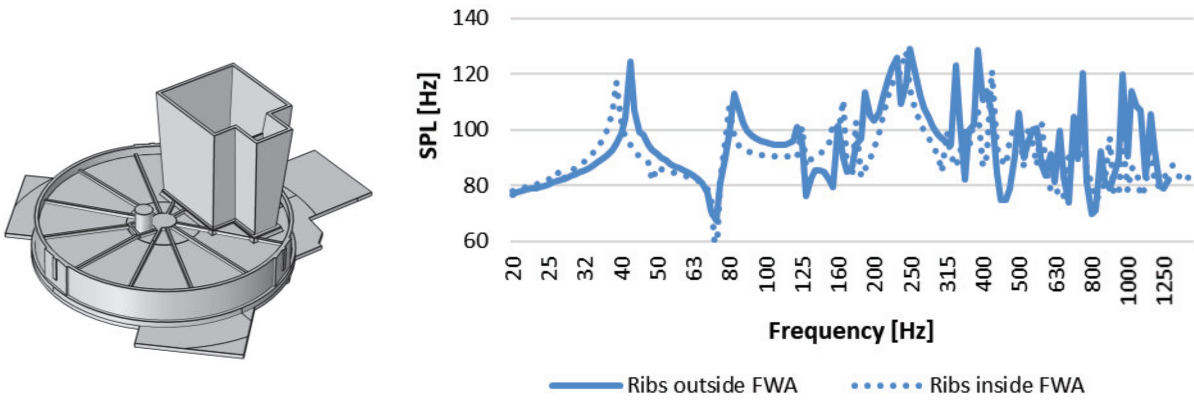

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Figure 7 – Model with ribs inside the FWA, a) geometry of the model, b) comparison of the SPL on the filter surface with ribs outside and inside the FWA (model V2)

4.3 Filter position

The filterwheel can be designed so that during launch the filter is placed either at 90° or 180° from axis connecting the centres of the FWA and baffle. The simulated SPL on the filter surface is lower for 90° configuration (Figure 8). This result is surprising, as the filter in 90° configuration is closer to the baffle than in 180° variant. It may be caused by the fact that the clockwise and counterclockwise sound transition paths inside the FWA are different in the 90° configuration, resulting in different phase shifts of the incoming waves. Setting filter at 90° during the take-off is additionally preferable as it allows for symmetrical and balanced filterwheel design.

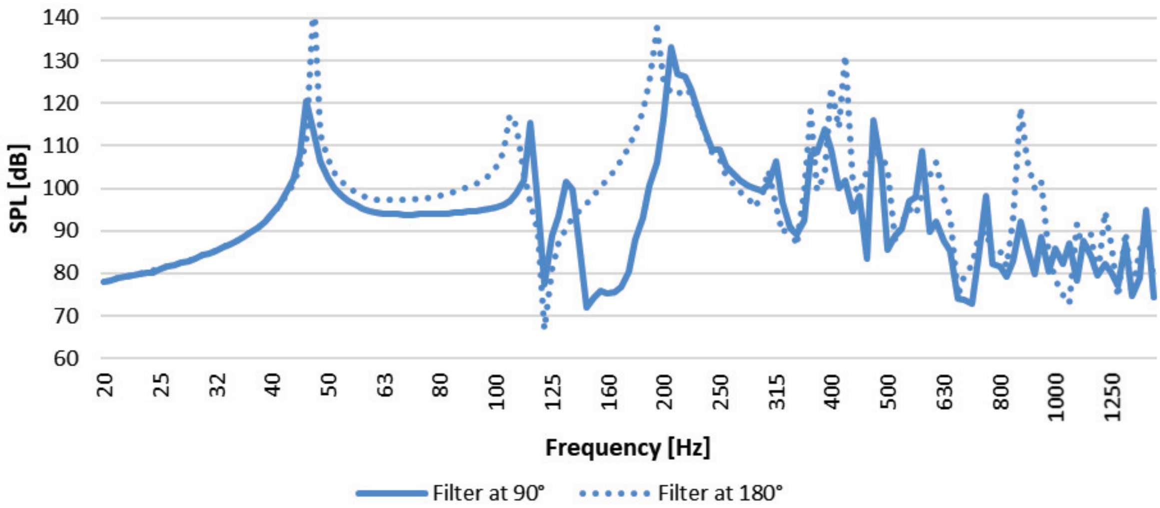

Figure 8 – Impact of filter position on the SPL on filter surface (model V3)

4.4 Modification of Spacing Between Filter Wheel and the Cover

Minimal distance between the filterwheel and the cover is chosen so that the filterwheel, vibrating during the rocket launch, would not touch the cover. The estimated minimal distance is 2 mm. To minimize overall SPL affecting the filter the gap should be as small as possible, however increasing the gap shifts the resonance frequencies. This effect can be used to tune the geometry and move the air volume resonances further from filter mechanical resonance, what may be preferable even at the cost of overall SPL increase. The optimal values of the distance between FW and cover will be identified when the final geometry of the filter and the filterwheel assembly is established.

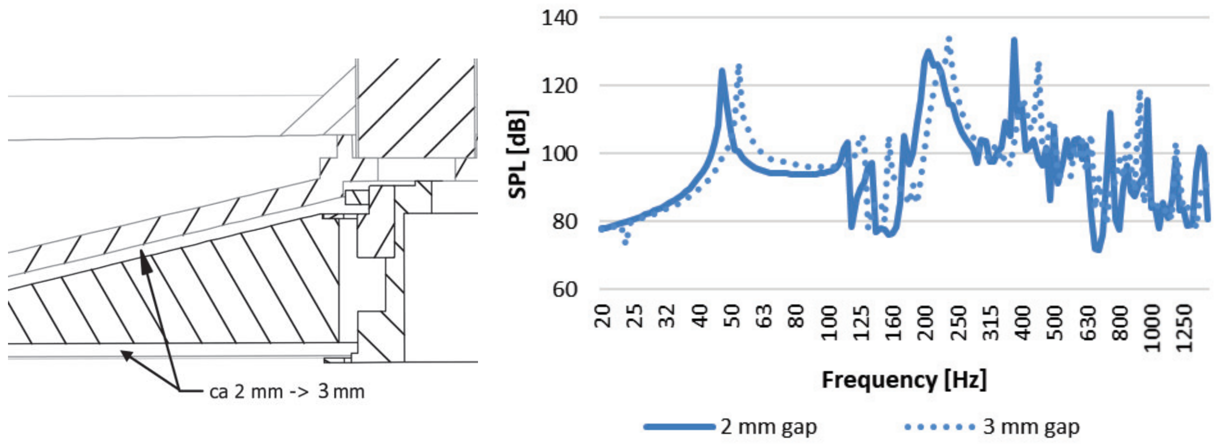

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Figure 9 – Model with ribs inside the FWA, a) geometry of the model, b) comparison of the SPL on the filter surface with ribs outside and inside the FWA (model V2)

5. CONCLUSIONS

Using the FEM simulations, many geometrical variants and potential noise reduction solutions were tested and the number of configurations to be verified in physical measurements was narrowed. Impact of the FEM model conditions on the simulation results is significant and often greater than the impact of proposed FWA modifications. It is crucial to verify which of the proposed models is better suited to reverberant conditions during the upcoming measurement session. Nevertheless, free field model allows for the comparison of different FWA designs.

The SPL reduction on filter surface can be obtained by adding expansion chambers inside the assembly and changing the filter position during rocket launch. Modifying the gap between the filterwheel and the cover can be used to shift the resonance frequencies of the air inside the FWA at the cost of overall SPL increase. Closing the baffle leads to significant SPL reduction but it complicates the design of the FWA and increases the risk of fault, therefore currently it is not considered as acceptable solution.

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