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NOISE CONTROL FOR A BETTER ENVIRONMENT

Design of an Adaptive Dynamic Vibration Absorber for acoustic levels reduction of a regional aircraft passengers 'cabin

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ABSTRACT

This study concerns a design procedure for the definition of an ADVA aimed at reducing the interior acoustic field within a regional propeller aircraft. At low frequency, sound excitation is dominated by the Blade Passage Frequency (BPF) and

its harmonics. Because in that range the structural acoustic coupling is significant, it is reasonable that a structural device can absorb acoustic energy. As well-know, tones are very critical for passengers' well-being and comfort. DVA are simple and effective devices for extracting energy from the structure. Providing them with some adaptive potentiality may further improve their performance levels. Adaptive DVA could be used for following the small variations occurring in the BPF during cruise (around 2%), to modify the device characteristics for different regimes of the propeller to tune the absorption peak at the optimal frequency.

Moving from previous analyses, the author develop the assessed procedure to take into account the peculiarity of a fuselage of a turboprop aircraft, and define size, material, number and position of the selected system. After a parametric study to identify DVA optimal mass and stiffness, its geometrical layout is defined and an architecture to give it adaptive property thank to SMA system.

Keywords: Adaptive Dynamic Vibration Absorbers, SMA, Active-Passive noise control, Turboprop aircraft

I-INCE Classification of Subject Number: 34

1. INTRODUCTION

In turboprop aircraft, the low frequency engine vibration is one of the major contributor to interior noise [1-2]. These vibrations originate from engine and propeller shaft imbalance and are transmitted to the cabin by several paths influencing the overall interior noise level and hence the comfort perception of passengers. The major part of the acoustic energy affecting the interior fuselage radiates directly from the source; it is concentrated in the low frequency range (0-300 Hz) and it is due to the propeller tone frequencies (fundamental and harmonics). The excitation of the interior fuselage vibro-acoustic modes determines noise transmission inside the cabin due to the fluid-structure coupling between the fuselage panel and the enclosed cavity. On the other hand, structure-borne noise also radiates from the fuselage panels due to the random excitation caused by air turbulence and due to the tonal frequencies caused by the rotating imbalances within the engines.

The eighties and nineties saw much work on adaptive devices for aircraft interior control, especially for turboprop applications [3]. This occurred because traditional acoustic noise reduction techniques, such as sound-absorbing materials, require relatively large and costly materials and are ineffective at low frequencies. The first commercial turboprop aircraft in the world in which this technique was used is the SAAB 340 and its successor, the SAAB 2000 [4]. The use of silent seats driven by ANC technology has also recently gained increasing interest due to the adaptive capability to generate comfort bubbles around passengers' head [5].

The recent advances in engine technologies and composite materials pose new challenges on anti-noise and anti-vibration concepts, whose combination raise unsolved questions in regard to vibration and acoustic passenger comfort. They involve both the effectiveness of acoustic and vibrational control concepts and the associated design methodologies to optimize the acoustic benefits and minimize their mutual interference at aircraft level. The new generation lightweight structures, for instance, result in poor transmission loss properties in the lower frequency range and significantly affect interior comfort.

Furthermore, the noise reduction performance may be strongly affected by the frequency content, amplitude and phase of the primary noise and their capabilities shall be capable to adapt to such time varying conditions. Mistuned vibration absorbers, indeed, could in principle even increase the vibration of its host structure and, more in general, every deviation from the design ("tuned") conditions degrades the performance of a dynamic absorber [7].

Moving from previous analyses, the author herein presents numerical investigations for the design and validation of a Dynamic Vibration Absorber with adaptive capabilities (ADVA) to reduce the vibration field of a turboprop aircraft fuselage. Conceptually, the device is a classical DVA, but with the property of being able to change its stiffness by taking advantage of the Shape Memory Alloy material properties. This allows to recover optimal performance in case of mistuning conditions due to, for instance, a drift in the forcing frequency (with impact on acoustic benefits as for takeoff (having different propeller rotational speed compared to cruise conditions) or due to a drift in tuned frequency caused by environmental factors (e.g. temperature change with altitude, etc). Moreover, the resonance conditions of an aircraft fuselage may vary depending on the mass distribution inside them and therefore on how people and things are allocated inside the fuselage. For these reasons, the possibility of installing noise control and absorption systems capable of tracking changes in the acoustic field during a flight appears of great interest.

2. ADVA AND ITS FUNCTIONALITY

Typically, a DVA is tuned to a certain frequency band and this greatly limits the application field in case of frequency changes in the sound to be controlled. A Dynamic Vibration Absorber with adaptive capacity has the objective of being able to absorb mechanical vibrations and therefore produce considerable reductions in the acoustic field within a certain frequency range. Its adaptive capacity makes it possible to attenuate resonance peaks with a good bandwidth and which can oscillate by a maximum of 20% around the nominal design value.

To give adaptive propriety to a conventional DVA, the proposed concept is based on a DVA shank with certain thicknesses of two types of material, aluminum or SMA (Shape Memory Alloy) or steel and SMA. The two materials can be placed concentrically with a cylinder full of aluminum in the center and an SMA tube on the outside (Fig. 1).

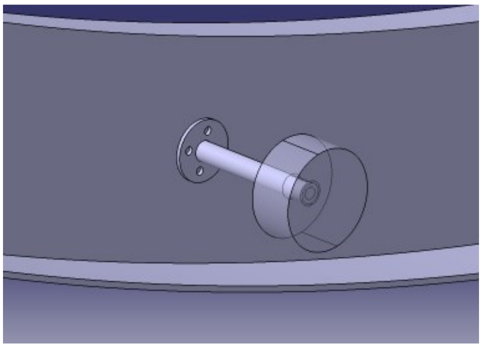

Fig. 1 - ADVA CAD Model

Once completed the sizing phase, the system must be flanked by a control logic for the SMA activation. SMA is a material that is activated thanks to its heating that allows it to change phase from austenite to martensite or vice versa. The two phases of SMA have different stiffness, allowing the whole system to vary its resonance frequencies and therefore move the absorption band of the DVA system. The heating system takes place by Joule effect with a control logic sensitive to the variation of the type of size that is going to undermine the variation of the acoustic properties of the primary structure.

The ADVA CAD model consists of three main parts: a tip mass, a shank and a fixing flange. The tip mass guarantees inertial properties of the system, the shank consists of a precise value of the relationship between the two materials and of geometric properties in order to obtain a certain stiffness value while the fixing flange is designed to constrain the device to the frame of the aircraft and to realize the coupling zone between the control and heating systems and the ADVA system. The tip mass has a fixed mass value which comes out of parametric optimization and has the stocky cylinder shape. It is made of aluminum and is mounted on the stem of the DVA through a system of screws. The stem, which has the adaptive characteristic, consists of an internal aluminum bar and an external SMA tube. The bar thus assembled is welded to the circular plan locking flange. Through the use of 4 screws, the whole system is fixed on the frame of the fuselage in a precise position and in number determined by topological optimization based on considerations made on the modal form of the aircraft itself.

2.1 ADVA application at cabin level for a regional aircraft

The design of an isolated ADVA can be made very easily with a single-dof system for the determination of the stiffness and mass parameters to be applied to the components of the resonator such as the shank and the tip mass. When a system of ADVA is installed on a fuselage for noise control emerge a series of variables that must be taken into account so that the absorption system continues to work for the project resonance peak. First of all, it should be noted that the introduction of the ADVAs on the primary structure changes the inertial properties of the system itself, so that once the properties of the isolated ADVA are defined with the 2-D model, these are last ones must be further optimized on the assembly structure. The number and position along the frame also play a crucial role in terms of absorption efficiency. Typically, for the control of the vibrations of a turboprop, the ADVA, or adaptive pendulums, are mounted on the first frames closest to the longitudinal position of the propeller and for each position chosen along the frame two pendulums are mounted on opposite faces of the same frame.

The noise of the forcing, coming from the propellers, is formed by more tonal, of which the first are those with the highest intensity. The noise of the forcing, coming from the propellers, is made up of several tones, of which the first are those with the highest intensity. An excellent integration of the ADVA with the fuselage is strongly influenced by numerous factors, so that the design conditions with respect to the operating conditions are subject to deviations. Some parameters that may vary the design conditions from the operating conditions are: The different flight phases, the weather conditions, changes in engine speed, changes in mass distribution (luggage and passengers) and so on...

A normal DVA is not able to follow such oscillations, so outside the nominal conditions it is ineffective, rather it could introduce amplification phenomena such as to increase the equivalent level of noise and therefore worsen the comfort conditions. Thanks to the use of an ADVA with an appropriate control law, it is possible to follow variations from nominal parameters up to a maximum of ± 20%.

3 FE Model of regional aircraft cabin

The structural FEM model of the turbo-prop aircraft fuselage includes airframe skin, reinforcement components (axial stringers, circumferential frames) and the interior sandwich lining (Fig. 2-a). An acoustic FEM model is finally generated to fill the three main fuselage interior cavities, cabin area, cargo area and air-gap separating the airframe from the lining (Fig. 2-b).

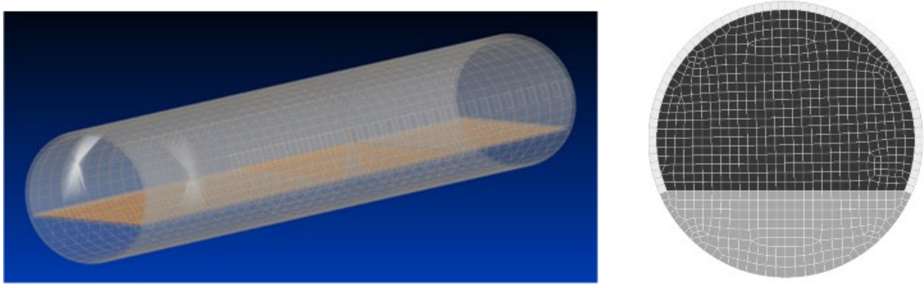

Fig. 2 – Structural and acoustic FEM models of the fuselage. Structural model (left), Acoustic cavities model (right)

3.1 Vibro-acoustic Loads and reference response

The response of the entire fuselage to the pressure field generated at the main Blade Passage Frequencies (BPFs) by the two propellers was achieved through a FEM Direct Frequency Response. The propellers acoustic loads at the first three BPFs, acting on the fuselage skin, are computed with a BEMT+FW-H approach [8,9]. Fig. 3 shows the external acoustic pressure loads distribution at the 1st BPF and the corresponding SPL distribution achieved with the aero-vibro-acoustic approach, without installing DVA. Despite external acoustic loads are mainly concentrated at the propeller plane, the cabin response is more uniformly distributed along.

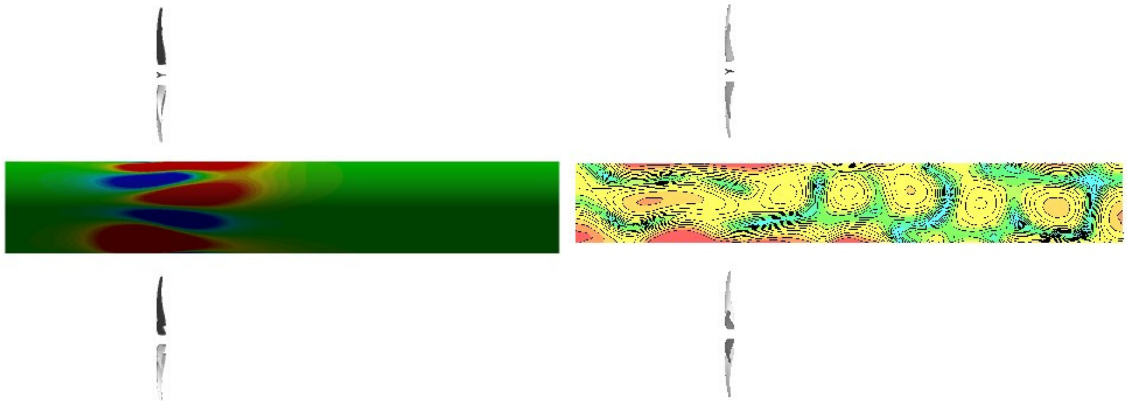

Fig. 3– Cabin noise achieved with the aero-vibro-acoustic approach – On the left, external acoustic pressure loads distribution at the 1st BPF. On the right, cabin acoustic field at passengers' ear level.

3.2 Modal analysis and considerations

In order to determine the best positions of the ADVAs on the frames, a modal analysis of the entire structure was carried out in the frequency range up to 1st BPF. By analyzing the various mode shapes close to the first BPF, a mode shape near 1st BPF was selected, because it is considered a global mode and with a somewhat symmetrical shape (Fig. 4). At this frequency, the structure has 2 coexisting 4-lobe modes, offset by 90 degrees, one with respect to the other. Taking into account this modal shape, we have come to the consideration of positioning the ADVAs at the points where the maximum displacement was recorded.

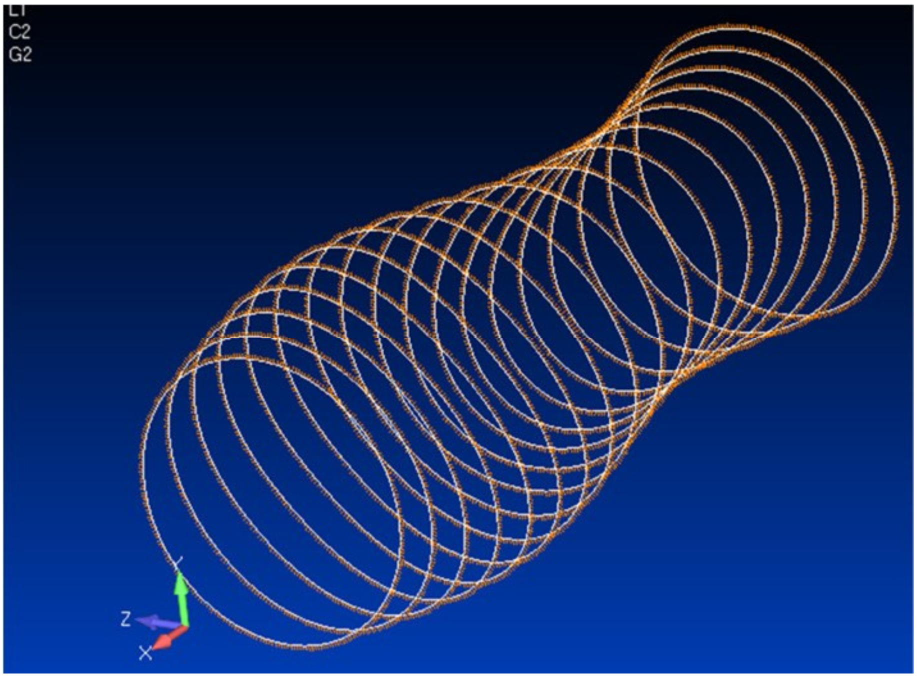

Fig. 4 - Modal shapes of frames at a frequency near 1st BPF

Considering the cross-section of the frame, 4 points were identified with maximum displacement for each modality at this frequency for a maximum of 8 points angularly displaced by 45°. In this way it was easy to identify 8 points on the circumference of the frame, 45 degrees from each other. In Fig. 5, it is possible to notice the positions of the DVAs along the circumference of the single frame and the same sequential pattern repeated on the rest of the other frames of the fuselage.

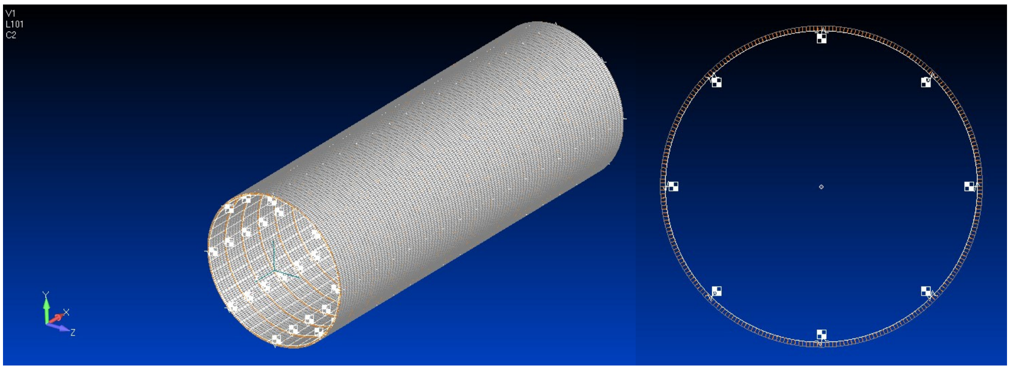

Fig. 5 - DVA positions and Fuselage cross section with DVAs

4. ADVA FOR CABIN NOISE REDUCTION

The ADVA is made of two scalar parameters, K and M. The stiffness, K, may in turn equal two values, representative of the non-activated and activated part, representative of the austenite and martensite state. A standard damping is associated to its characteristics, classically set equal to 1% equivalent viscous damping. With the application of a preliminary procedure to identify an initial pair of values (K and m) [6], the isolated system with a single frame was optimized. After having identified the main design parameters of the ADVA, the estimate of its effect in terms of noise abatement within the fuselage was performed. To this scope the FE model of the fuselage barrel, described in section 3.1, was integrated with a simplified model of the single ADVAs, each one represented through a lumped mass, connected to the frame by an elastic element, enabling only radial excursions. CONM2 and CELAS MSC/Nastran elements were used. This approach implies that each mass moves symmetrically with respect to the frame plane. This, with reference to Fig. 1, means that couples of masses-springs must be symmetrically mounted on the two sides of the web of the frame, to represent each single ADVA.

As shown in Fig. 6 only 5 frames were taken into account, one at the propeller plane and other two upward and downward. Eight ADVAs (yellow spots) were placed on each frame for a total additional mass of 28 kg.

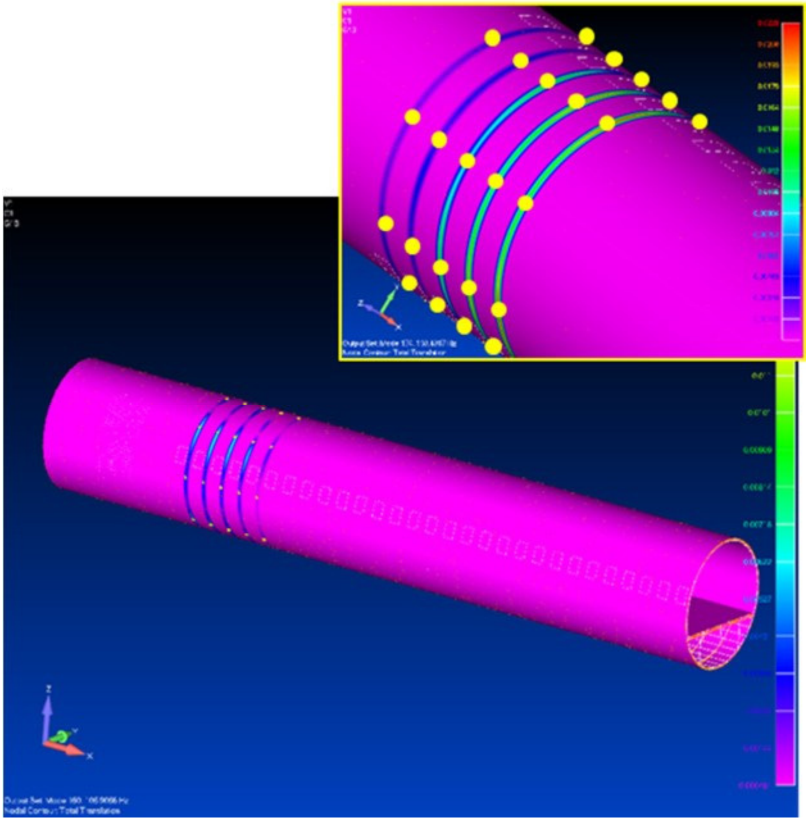

Fig. 7 - Frames integrates with 8 ADVAs, close to the propeller plane

The ADVAs were optimized for the fuselage structure setting three design parameters: the mass and the rigidity to fit the frequency of the mode (namely “nominal mode”) to be controlled in switched-off configuration and the tangential position on the frame to assure the maximum transfer of energy between the frame and the ADVA. The nominal mode was selected on the basis of its participation to the interior noise generated, and as close as possible to the tonal excitation of the propeller (1st BPF).

In practice, the SPL associated to each mode near 1st BPF was estimated and averaged along the horizontal plane at the level of the ears of the passengers. In the following plot, the abatement obtained within the selected bandwidth and tuning the ADVAs on the modes within the range is illustrated. Fig. 8 illustrates the results obtained through a frequency response analysis performed through the assigned excitation in the frequency and space domain of interest. The thicker red curve, referring to a tuning frequency near 1st BPF, highlights the best result obtained on the excitation peak, assuring a local abetment of 9,2 dB. Assuming that the ADVA elastic element is made of SMA alloy, adequate temperature changes will enforce the phase transformation (martensite into austenite and vice versa) and will produce also remarkable variations of the stiffness (up to 3 times the martensitic value), with a consequent shift of the tuning frequency. The blue curve represents the envelope of the abetment attainable moving from pure martensite to pure austenite conditions. The bandwidth at which a SPL attenuation greater than 3 dB is attainable ranges of 30 Hz of band frequency. A power consumption of 820 W has been estimated through engineering considerations on the power per unit volume necessary to increase the temperature of the SMA from the lowest aircraft operational temperature (-50 °C) to the austenite finish temperature; in this case to prevent any undesired activation event, an alloy with an austenite start temperature higher than the maximum operational temperature (+80 °C) has been considered. This estimate is however very conservative, since it refers to the temperature ramp, but in the realty, as the activation is achieved, a thermostat keeps the desired temperature, regulating the power supply.

A modest increase of 1.1 dB was found out at the 2nd BPF, as shown by the red thick curve in the plot of Fig. 9.

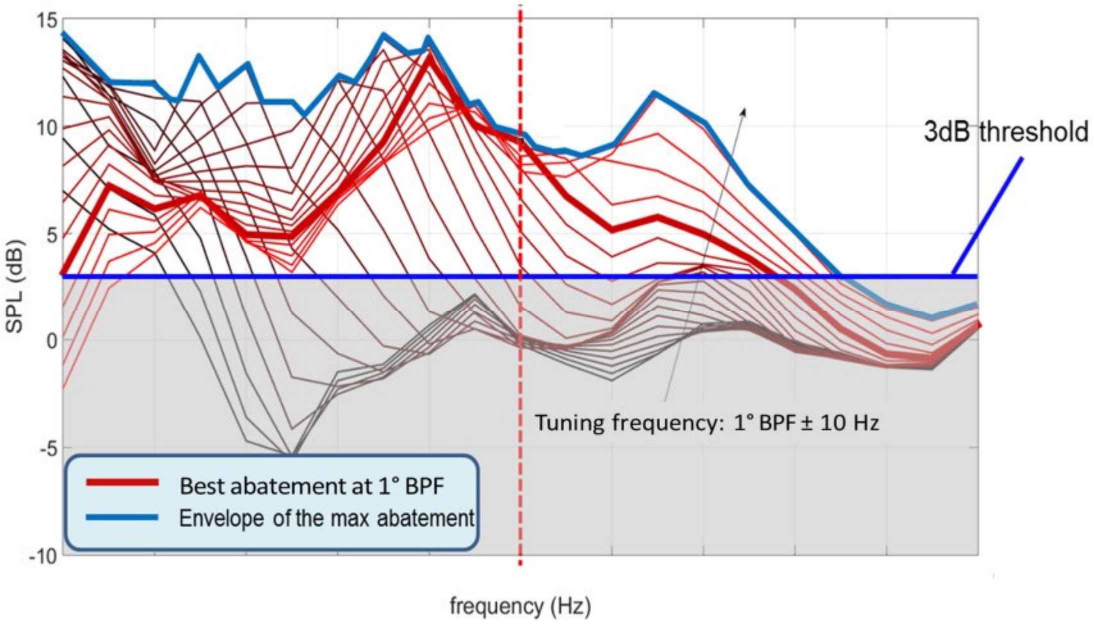

Fig. 8 - Parameterization of the ADVA tuning frequency vs SPL abatement on the 1st frequency of excitation of the propeller (1st BPF)

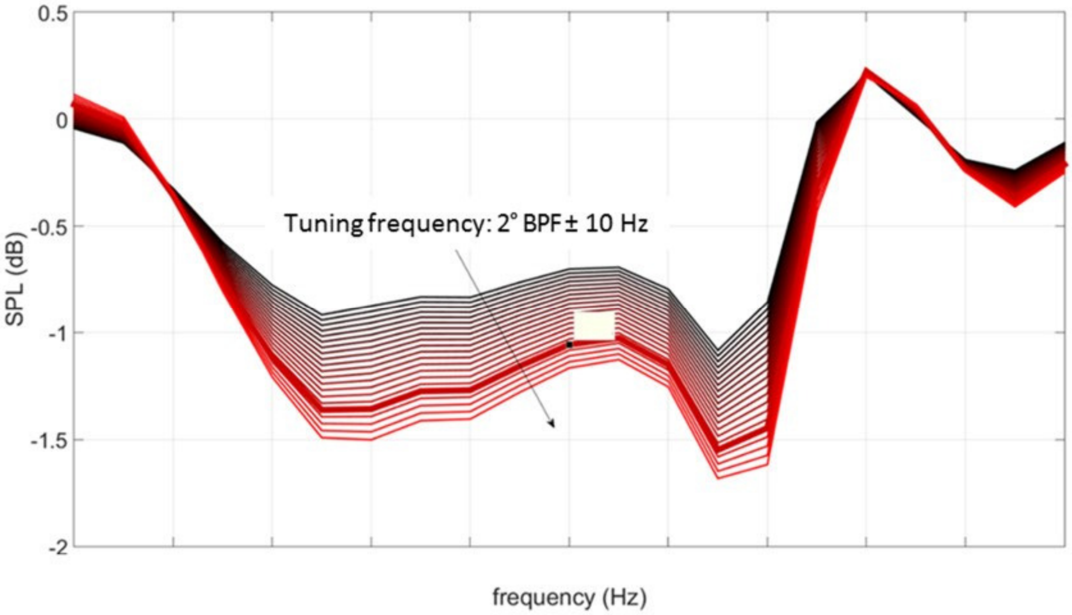

Fig. 9 - Parameterization of the ADVA tuning frequency vs SPL abatement on the 2nd frequency of excitation of the propeller (2nd BPF)

5. CONCLUSIONS

This paper detailed the design procedure and its numerical implementation for a development of an ADVA aimed at reducing the interior acoustic field within a regional propeller aircraft. Firstly, the acoustic response of a regional aircraft fuselage to the pressure field generated at the main Blade Passage Frequencies (BPFs) has been predicted. A reliable FE model of the entire fuselage has been generated by including airframe, skin, linings and the air-gap between the double wall structure. Such a model has been equipped with a number of ADVA whose positions have been optimized to adaptively reduce the vibro-acoustic response for the 1st BPF. Assuming that the ADVA elastic element is made of SMA alloy, adequate temperature changes have been assumed to enforce the phase transformation (martensite into austenite and vice versa), thus producing remarkable changes in the stiffness and hence a shift in the tuning frequency. The ADVA device stiffness has been numerically simulated as equal two values, representative of the non-activated and activated part, representative of the austenite and martensite state. The results showed that at least a 3 dB noise attenuation may be achieved moving from pure martensite to pure austenite conditions in the frequency range of interest. The best SPL abatement has been achieved at the 1st BPF where the noise reduction reaches up to 9.2 dB. The design of a control algorithm and its actual implementation into an experimental set-up will be the key point for the future development of the proposed technology.

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The FEM model developed for the numerical analysis has been derived from the CAD model of the Clean Sky 2 demonstrator, provided by LDOVEL as one of the project input data.

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