On the noise reduction of active sidewall aircraft panels using feedforward control with embedded systems

M. Misol [1], **S. Algermissen,** [1], **M. Rose** [1]
[1] German Aerospace Center, Institute of Composite Structures and Adaptive Systems,
Lilienthalplatz 7, 38108 Braunschweig, Germany
e-mail: **malte.misol@dlr.de**

Abstract

Keeping aircraft interior noise on an acceptable level is an important aspect for the passenger comfort and health in modern aircraft design. Generally there is a trade-off in the achievable transmission loss of aircraft and the additional weight of the insulation provision, especially at low frequencies below 500 Hz. In this frequency range, passive methods for sound insulation usually have high weight and volume requirements for suitable performance in aircraft. The present work focuses on aircraft with rotor engines having characteristic low frequency narrow banded noise sources due to the rotational speed of the rotors. A major transmission path of the noise is given by the linings of the aircraft cabin, which are coupled to the fuselage. These large sound emmitting surfaces radiate the noise directly into the passenger zone. Active control is a promising method to reduce at least the low-frequency noise radiated by the panels. These so-called smart linings, augmented with suitable actuators and sensors, are also usable for additional tasks, such as e.g. passenger announcements and noise masking. The feasibility of active feedforward control to reduce narrow banded frequencies below 500 Hz has already been tested successfully at DLR on test panels and in a fully equipped test aircraft on ground, which are excited externally by a loudspeaker array. This paper is dedicated to a discussion of the recent activities to simplify the underlying control strategies in a way that they can be implemented on small embedded systems with limited performance. In the future, such microprocessor units enable the integration of the actuators, sensors and control algorithms directly into smart lining modules, having a positive effect on maintainability and weight footprint of the smart panels.

1 Introduction

A major goal in modern aircraft design is the suppression of disturbing noise in the cabin. One promising way to reduce low frequency content is the use of active control. Different strategies have been successfully implemented in the past. The so-called active noise cancellation (ANC) uses loudspeakers to reduce the interior sound pressure by emitting anti-sound or by alternating the radiation impedance (see [1] for early results with loudspeakers and microphones in different configurations). Focusing on blade passage frequencies of around 88 Hz, reductions of 13 dB sound pressure level (SPL) have been achieved. Substituting loudspeakers by shakers or piezoelectric patch actuators in combination with the structure itself, the second major approach of active structural acoustic control (ASAC) can be used. Early results with respect to aircraft are given in [2]. In that work, a model aircraft fuselage (downscaled unstiffened aluminium cylinder) is mounted in an anechoic chamber and excited by a monopole sound source. A strong reduction of interior SPL was achieved, using as actuator one properly tuned attached mini-shaker. In this paper, a related approach for active interior noise reduction using active trim panels (linings) instead of actuated fuselage structures is investigated. In the past, experimental work of Lyle and Silcox [3] and by Tran and Mathur [4] reported unsatisfactory performance of such systems, which might be the reason, that this method has not gained much attention by researchers. In the former work, active linings are coupled to a stiffened fuselage barrel (3.66 m long with a diameter of 1.68 m) made of filament-wound graphite-epoxy composite, stiffened with frames and stringers and equipped with a plywood floor. As linings, generic sandwich structures extending from floor to floor are used. The external excitation of the fuselage barrel was realized by a loudspeaker, sealed with end caps to prevent secondary transmission pathes. The whole setup was embedded in an anechoic chamber. Augmenting the outer surface of the linings by piezoelectric path actuators, a global SPL reduction of up to 5 dB has been documented. In view of the promising results given by Fuller and Jones [2], this was considered unsatisfactory. One explanation of the limited performance of the active linings was related to the different coupling of the primary excitation and the active linings into the cavity modes. In the latter work of Tran and Mathur, full-scale experiments in a McDonnell Douglas DC-9 aircraft on ground are described. As control actuators, 16 piezoelectric patches have been attached to the linings (aft section) and 32 microphones placed at the headrests and in the aisle served as sensors. Basically only one frequency out of eight have been reduced, which is not competitive to equivalent loudspeaker based ANC systems and systems with actuators on the fuselage being implemented on the same aircraft (see [4], figure 4). In conclusion, the unsatisfactory performance of the active linings is explained by the unsuitable structural dynamics of the linings, the sub-optimal actuator positions and the flanking paths. As there is no further elaboration on these possible explanations, it remains unclear, which factors are most important for the limited performance and how these limitations could be overcome. Unlike in Lyle and Silcox [3], the results are very important as reference, because a real aircraft is used in the experiments with realistic structural and acoustic damping.

In a recent publication of the lead author of this presentation [8], the noise reduction performance of active linings has been investigated in a full-scale experiment based on a Dornier Do728 aircraft. Mean SPL reductions of up to 6.8 dB are reported and in the controlled area, maximum SPL reductions of up to 11.3 dB have been achieved. In this work, the aircraft is substituted by a fuselage panel, which is mounted in a sound transmission loss facility. The aim here is to better characterize the active system in a controlled laboratory environment. A serial production Airbus A350 lining coupled to a carbon-fibre reinforced plastic (CFRP) fuselage panel with two windows was used, allowing mean SPL reductions of up to 12 dB in the anechoic room in front of the lining. A special focus of this paper is given by the control algorithm (based on Johansson [7]) and its properties to be implementable on low cost microcontroller hardware.

2 Experimental setup

The principle experimental setup is shown in figure 1. A loudspeaker array (LSA) located in the reverberation room induces the external excitation onto the primary structure (F) being a testrig of a typical aircraft fuselage segment. The active lining (L), mounted on the fuselage segment in the semi-anechoic room radiates the transmitted sound. These parts will be described in more detail in the following subsections. The real experimental setup is shown in figure 2. Three pairs of laboratory and low-cost microphones are installed at the head rest positions of the three seats in front of the lining (cp. figure 2). The signals of the three low-cost microphones are fed to the TI Delfino microcontroller unit (MCU) of the type TMS320F2837xD. These signals are A/D-converted, processed, D/A-converted and finally fed to the amplifiers (not shown) controlling the two inertial force exciters of the type Visaton EX 45 S. As can be seen in figure 2 (right), the exciters are applied at positions on the lining skin fields below the window units. The collocated laboratory microphones of the type PCB T130D21 are used for the performance evaluation of the smart lining. More details on the signal processing and the implemented control algorithm are provided in section 3.

2.1 Excitation

Currently, most aircraft are jet-driven because fuel is cheap and jet engines still have potential for improvements. Rotor engines are energy-efficient and might become more important in the future. One major drawback of rotor engines like counter-rotating open rotors (CROR) is the high sound radiation of the engines. The excitation generated by typical rotor engines of aircraft consist mainly of tonal frequencies, which are

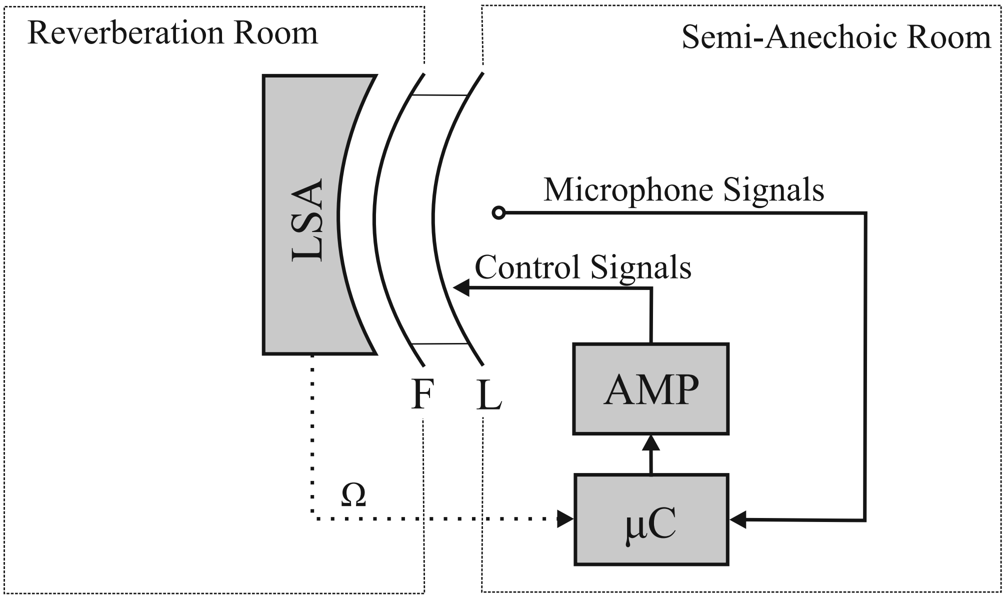

Figure 1: Schematic of the experimental setup showing the main signals and systems.

multiple of the rotational speed with respect to the number of rotor blades. These tonal frequencies induce high acoustic loads on the fuselage being transmitted into the cabin. Simulation results for a generic counter-rotating open rotor (CROR) engine suggest that the strongest excitation occurs in the frequency range of 100–500 Hz [6]. Therefore, the investigated active noise reduction system is designed for this frequency range, which contains the first five CROR frequencies: 119.4 Hz, 149.2 Hz, 268.6 Hz, 388 Hz and 417.9 Hz. The synthesis of the calculated pressure distribution on the fuselage is done with a LSA and a sound field reconstruction (SFR) method. As shown in figure 2 (left), the LSA is placed in front of the fuselage. The mean distance between the loudspeaker plane and the fuselage panel is approx. 0.14 m. The LSA has 14 rows with eight loudspeakers each. In total, there are 112 loudspeakers, which can be individually controlled to facilitate the SFR. More information on the calculation and the synthesis of the CROR pressure field can be found in [6].

2.2 Primary structure

The primary structure is defined together with DIEHL Aviation and Airbus. The main goal is the derivation of a CFRP fuselage panel that approximates the vibro-acoustic properties representative for an Airbus A350 aircraft. The CFRP panel has the dimensions 1690 mm x 1300 mm (direction: frame x stringer) and a radius of 2980 mm. The skin is made of unidirectional (UD) CFRP tapes with different thicknesses in the areas 1, 2 and 3 (cp. figure 3). The skin is thinnest in area 1 and thickest in area 3. The fuselage has two windows with 15 mm thick plexiglass window panes and two 12 mm thick aluminum window frames. The window frames are glued to the CFRP skin. The stringers and frames are made of aluminum in a L- and T-shape geometry. The spacing of the stringers is 200 mm and the spacing of the frames is 635 mm. The primary structure is mounted in the test opening of the transmission loss facility by means of four shock mounts located near the corners of the panel. Each shock mount is connected to the outer frame on one side and to the embrasure of the test stand on the other side. A small air gap between the four panel edges and the test opening is sealed with flexible tape. This kind of mounting leads to a dynamic decoupling in the frequency range of interest. The lining itself is mounted to the primary structure at 9 positions near the frames or the windows (cp. figure 3). The secondary structure is a serial production sidewall panel from DIEHL Aviation for the Airbus A350 series. It has 9 structural holders which are connected to the counterparts on the fuselage. The

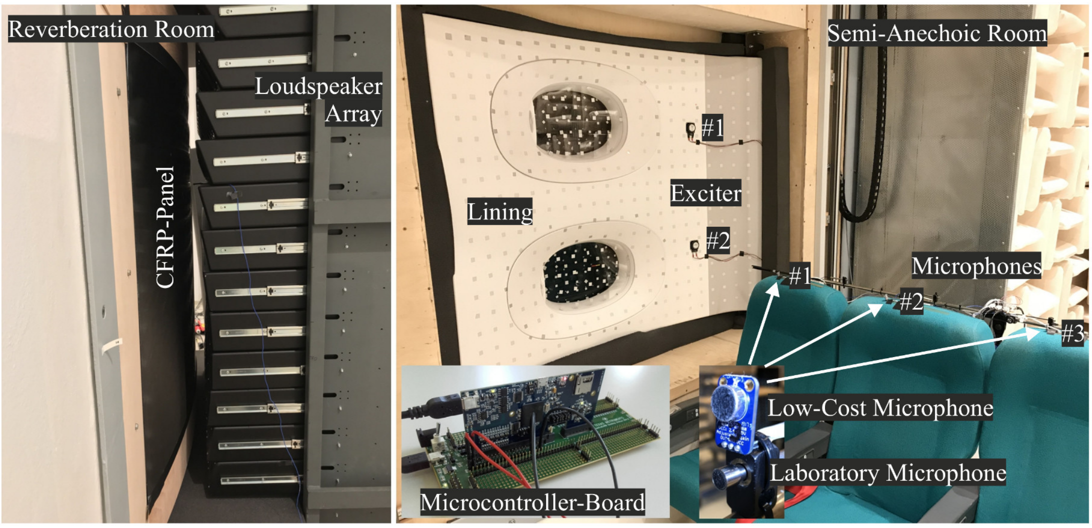

Figure 2: Excitation in reverberation room (left) and cabin side in anechoic chamber (right).

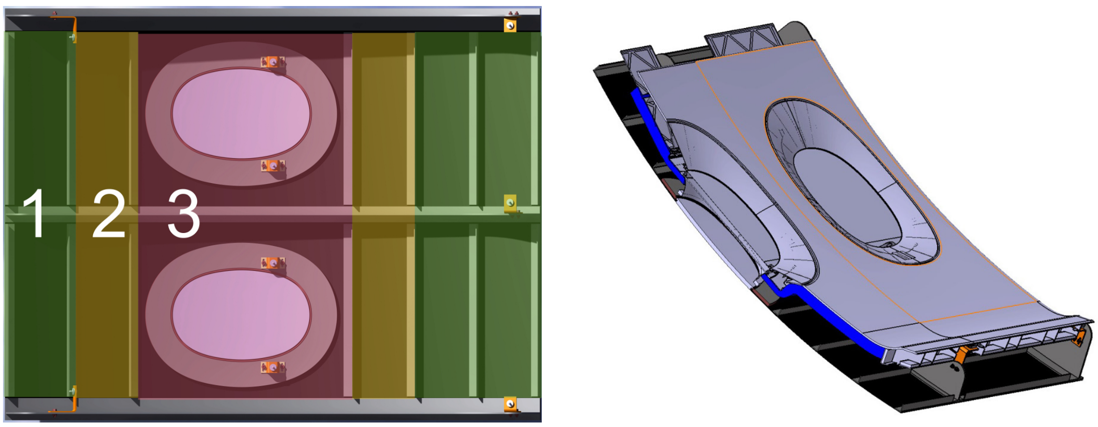

Figure 3: CFRP fuselage panel with three zones of increasing skin thickness (left) and Airbus A350 side panel coupled to fuselage with secondary thermo-acoustic isolation in blue (right). The primary isolation is suppressed in this view.

lining is equipped with a thermo-acoustic isolation bag applied at the backside. Prior to the mounting of the lining a primary thermo-acoustic isolation is applied to the fuselage. A sectional view of the coupled system without primary isolation is shown in figure 3.

2.3 Active lining

Each smart lining is equipped with two inertial force actuators of the type Visaton EX 45 S. This type of actuator has a maximum rms power of 10 W and a mass of 0.06 kg. The number and positions of the actuators are not optimized. It is known from preliminary tests that – because of the relatively high structural damping of the double panel system – the modal behavior is weakly pronounced. Therefore, it is considered appropriate to position the actuators in a straightforward manner. The positions can be seen in figure 2. In order to ensure sufficient control authority, the structural vibration of the lining and the SPL at the seats induced by the loudspeaker array are compared to the values generated by the actuators. A more elaborate actuator placement based on genetic optimization is described in [5]. A simple approach is also followed with regard to the error microphones. Each head rest is equipped with one microphone (cp. figure 2). The control system configuration described here, uses three electret microphones with preamplifier unit of the type MAX 4466 as error sensors. The error sensor signals are processed by the TI Delfino microcontroller unit (MCU) of the type TMS320F2837xD and fed to the actuators via the amplifier. A cheap and small class D stereo audio amplifier can be used to drive the actuators. Before the integration of these components into the smart lining, the microphones have to be replaced by a number of structural sensors and a suitable observer filter. This task is not part of the research work described here.

3 Control algorithm

In view of manageable and mostly autonomous units, it is desirable to integrate the control hardware in the active panel substructures. To additionally minimize the overall costs, the use of cheap and small microcontroller boards is of high interest. In figure 4, the choosen hardware, a TMS320F2837xD board from *Texas Instruments*, is shown. It consists of two 32 bit CPUs with 200 MHz clock frequency and has four sixteen bit analog digital converters (ADC) and three twelve bit digital analog converters (DAC). To enable quick changes in the algorithm, the use of the simulation environment *MATLAB/SIMULINK* is convenient. A suitable toolbox is available to compile and run the control algorithms via USB connection on the evaluation board. The underlying overhead using this toolbox can be avoided by coding the algorithms directly in the C language, but this was not necessary yet.

The control algorithm itself is adopted from Johansson et al. [7]. It is based on a complex filtered-x LMS algorithm, which realizes a narrowband multiple-reference feedforward controller. We have R complex reference signals $x_r(n)$ (the engine drives including their harmonics at angular frequency ω_r, $r = 1, \ldots, R$), A actuators and S sensors. n denotes the sample number in the discrete time domain. The system dynamics are described by R complex matrices $\boldsymbol{F}_r$, each of dimension $S \times A$. These matrices can be obtained from the measured frequency response functions at the given frequencies. Johansson describes a method to keep the reference signals in sync with the engines using suitable filters based on fast fourier transformations (FFT). For simplicity, in our implementation the reference signals are completely software generated and the phase drifts are also adapted by the LMS algorithm with only minor degradation in performance, if the frequencies ω_r are suitable stable. With this algorithm each actuator is individually controlled by one adaptive complex FIR filter weight per frequency. This permits a very efficient implementation even in the case of close frequencies (beating), which might arise if the rotors are not perfectly synchronized. Hence, each smart lining uses $A \cdot R = 2 \cdot 5 = 10$ adaptive complex filter weight to control the five frequencies. There are R complex weight vectors $\boldsymbol{w}_r(n)$ of dimension $A \times 1$ as parameters for the finite impulse response (FIR) filter of the x-LMS algorithm. The square $J(n) = |\boldsymbol{e}(n)|^2$ of the error signal vector

$$\boldsymbol{e}(n) = \boldsymbol{d}(n) + \sum_{r=1}^{R} \Re\left\{\boldsymbol{F}_r \boldsymbol{y}_r(n)\right\} = \boldsymbol{d}(n) + \sum_{r=1}^{R} \Re\left\{\boldsymbol{F}_r \boldsymbol{w}_r(n) x_r(n)\right\}, \quad \text{with} \quad \boldsymbol{y}_r = \boldsymbol{w}_r x_r, \tag{1}$$

should be minimized by the filtered-x LMS algorithm. Here $\boldsymbol{d}(n)$ denotes the external disturbances, which has the same dimension $S \times 1$ as the error vector $\boldsymbol{e}(n)$. The adaptation of the weight vectors

$$\boldsymbol{w}_r(n+1) = \boldsymbol{w}_r(n) - \boldsymbol{M}_r \frac{\partial J(n)}{\partial \overline{\boldsymbol{w}}_r}. \tag{2}$$

is done using some damped Newton type method or a scaled steepest descend direction in the simplest case, depending on the choice of the scaling matrix $\boldsymbol{M}_r$ of dimension $A \times A$. The gradient is simply

$$\frac{\partial J(n)}{\partial \overline{\boldsymbol{w}}_r} = 2\overline{x}_r(n) {\boldsymbol{F}_r}^H \boldsymbol{e}(n). \tag{3}$$

Here $(\cdot)^H$ denotes the conjugate transpose. The Newton-like algorithm needs a fully populated matrix

$$\boldsymbol{M}_r = \mu_0 \left(\rho_r {\boldsymbol{F}_r}^H \boldsymbol{F}_r\right)^{-1}, \quad \text{with} \quad \rho_r = E\{|x_r(n)|^2\}. \tag{4}$$

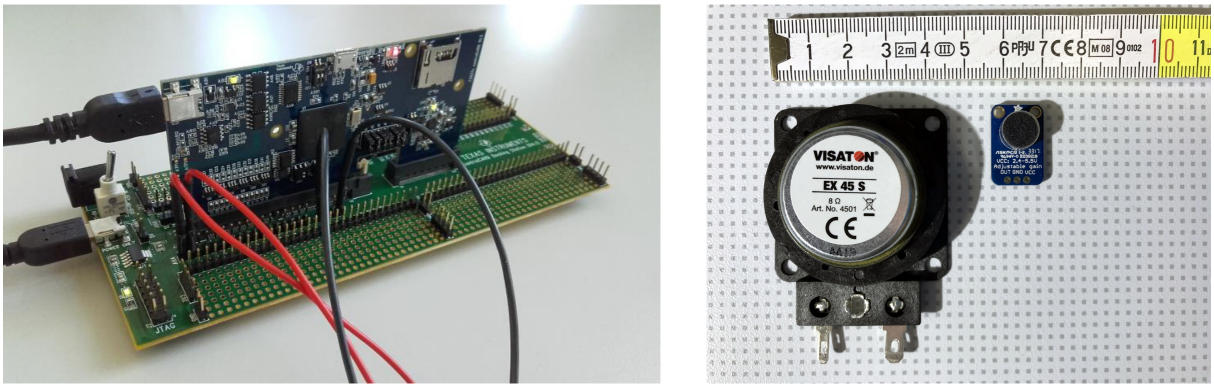

Figure 4: Evaluation board with low-cost microcontroller unit TI Delfino TMS320F2837xD (left) and exciter Visaton EX 45 S and electret microphone with preamplifier unit MAX 4466 (right).

To avoid the costly matrix multiplication in equation (2), a diagonally dominant approximation

$$\boldsymbol{M}_r = \mu_0 \left(\rho_r \mathrm{diag} \left(\boldsymbol{F}_r{}^H \boldsymbol{F}_r \right) \right)^{-1} \tag{5}$$

of $\boldsymbol{M}_r$ is choosen, according to equation (8) of [7]. Stability of the algorithm can be expected for positive values μ_0 smaller then one (though not guaranteed). In fact only substantially smaller values $\mu_0 \approx 0.001$ provided convergence. One reason could be the strong coupling of the actuators to the sensors and the corresponding weak approximation of $\boldsymbol{M}_r$ by a diagonal matrix. In further studies, equation (4) will be used to investigate this hypothesis and as a result possibly increasing the performance.

4 Results

The acoustic performance of the smart lining with low-cost hardware is shown in figure 5. The main reduction occurs at the first blade-passing frequency 119.4 Hz. There, the mean SPL reduction amounts to 23 dB and the maximum SPL reduction measured at microphone 2 is 25 dB. It is shown in Misol [8] that in a real aircraft cabin, the SPL drops about 10 dB from the window to the aisle seat. Therefore, it was expected that the SPL reduction is largest at microphone 1 and smallest at microphone 3. This, however, is not the case because the results show mean SPL reductions of 8.3 dB at microphone 1, 12.2 dB at microphone 2 and 5.1 dB at microphone 3. This effect is also visible in the right hand part of figure 5 that shows the SPL reductions measured by the three microphones at the CROR frequencies. Although the smart lining processes the signals of the low-cost microphones, the results are based on the laboratory microphone signals.

5 Conclusion and Outlook

In this work, an active feedforward control system for a serial production Airbus A350 lining coupled to a CFRP fuselage panel with two windows has been discussed. The experimental setup is realized in a sound transmission loss facility with an semi-anechoic room on the cabin side. The chosen control algorithm is described and successfully realized on a low-cost microcontroller unit allowing tonal reductions up to 23 dB mean SPL and reductions up to 12 dB mean SPL for the energetic sum of all five frequencies. Further investigations will be done to enhance robustness by advanced choices of the feedforward adaptation gain factors. Ongoing research aims at the replacement of microphones by a number of structural sensors and the integration of the smart lining components suitable for production.

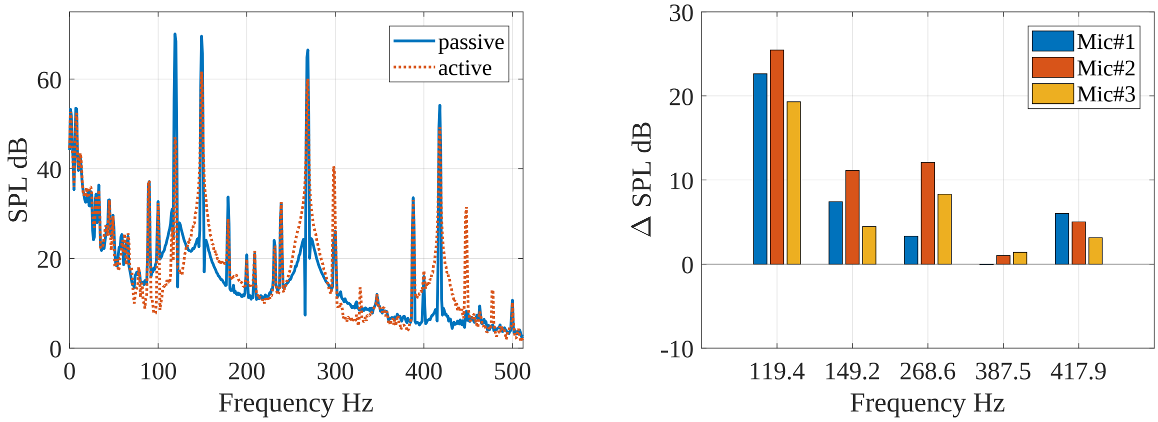

Figure 5: Mean SPL with de-activated (passive) and activated smart lining (active) (left) and SPL reductions achieved by the active system at the five CROR frequencies measured at the head rests (right).

Acknowledgements

This project was funded by the Bundesministerium für Wirtschaft und Energie (BMWi) under grant number 20K1301D.

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

References

[1] S. J. Nelson, P. A. Nelson, I. M. Stothers, C. C. Boucher, *In-flight experiments on the active control of propeller-induced cabin noise*, Journal of Sound and Vibration, 140 (2), 219–238, (1990).

[2] C. R. Fuller, J. D. Jones, *Experiments on reduction of propeller induced interior noise by active control of cylinder vibration*, Journal of Sound and Vibration, 112 (2), 389–395, (1987).

[3] K. H. Lyle, R. J. Silcox, *A study of active trim panels for interior noise reduction in an aircraft fuselage*, SAE Technical Paper, 05, SAE International, (1995).

[4] B. N. Tran, G. P. Mathur, *Aircraft interior noise reduction tests using active trim panels*, Proceedings of Noise-Con 96, pp. 395–400, (1996).

[5] M. Misol, T. Haase, S. Algermissen, V. Papantoni, H. P. Monner, *Lärmreduktion in Flugzeugen mit aktiven Linings*, Smarte Strukturen und Systeme – Tagungsband des 4SMARTS-Symposiums, Shaker Verlag, 329–339, (2017).

[6] S. Algermissen, S. Meyer, C. Appel, H. P. Monner, *Experimental synthesis of sound pressure fields for active structural acoustic control testing*, Journal of Intelligent Material Systems and Structures, 140 (7), 881–889, (2014).

[7] S. Johansson, P. Sjsten, S. Nordebo, I. Claesson, *Comparison of multiple-and single-reference mimo active noise control approaches using data measured in a dornier 328 aircraft*, International Journal of Acoustics and Vibrations, 5 (2), 77–88, (2000).

[8] M. Misol, *Experiments on noise reduction in aircraft with active sidewall panels*, Proceedings of 25th International Congress on Sound and Vibrations, 8-12 Juli, Hiroshima, (2018).