Aircraft lining panels with low-cost hardware for active noise reduction

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***Abstract*—Passive structures are augmented with actuators, sensors and control to implement the task of active noise or vibration reduction. Such systems are considered smart because they have advanced functionalities compared to conventional structures. A smart aircraft lining is able to reduce the low-frequency cabin noise induced by tonal or multi-tonal external noise sources. Such noise sources are for example fuel-efficient rotor engines like counter-rotating open rotors. Research on smart systems starts on a laboratory scale by using low-noise sensors and high-performance rapid control prototyping systems. The replacement of such costly and bulky laboratory hardware is one important precondition for the commercialization of smart structures. The increased internal noise, the reduced computational performance and other restrictions of low-cost hardware must be taken into account during the design of a smart system. Experimental results on the noise reduction of a smart lining with low-cost hardware show that a replacement of laboratory hardware will not lead to a loss of performance. The smart lining achieves tonal interior sound pressure level reductions of up to 25 dB with a mass increase of only 2 percent. Even a mass neutral implementation seems possible, if conventional loudspeaker-driven passenger announcements are realized with smart linings.**

***Index Terms*—active noise control; smart structures; low-cost hardware; aircraft; lining**

I. Introduction

The active control of rotor noise in aircraft has been successfully implemented in the past. Different strategies were pursued to reduce the disturbing noise in the aircraft cabin. One approach uses loudspeakers to reduce the interior sound pressure by altering the radiation impedance or by anti-sound (ANC). Early results of ANC in aircraft are documented by Elliott et al. [1]. There, loudspeakers and microphones are used in different configurations in the cabin. Maximum sound pressure level (SPL) reductions of 13 dB at the fundamental blade passage frequency (88 Hz) are reported. A different approach is the active structural acoustic control (ASAC) of the fuselage structure by means of shakers or piezoelectric patch actuators. Early results on ASAC in aircraft are documented by Fuller and Jones [2]. In this work, a model aircraft fuselage (downscaled unstiffened aluminum cylinder) is mounted in an anechoic chamber and excited by a monopole sound source. A mini-shaker is used as the actuator of the ASAC system. Strong reductions of interior SPL are reported with only one properly tuned actuator. A related approach for active interior noise reduction uses active trim panels (linings) instead of actuated fuselage structures. This method, which is also the focal point of this paper, has gained less attention by researchers in the past. One reason might be the unsatisfactory performance of such systems reported by Lyle and Silcox [3] and by Tran and Mathur [4]. In the experimental work of Lyle and Silcox [3], the 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. The linings are generic sandwich structures extending from floor to floor. A loudspeaker is used for the excitation of the fuselage barrel, which is sealed with end caps to prevent flanking transmission. The whole setup is located in an anechoic chamber. Piezoelectric patch actuators are applied to the outer surface of the linings. A global SPL reduction of up to 5 dB is achieved by the active system, which is considered unsatisfactory, especially in view of the promising results documented by Fuller and Jones [2]. The limited performance of the active linings is explained (at least in parts) by the different coupling of primary excitation and active linings into the cavity modes. A similar behavior, although expected, was not observed in the experiments of Fuller and Jones [2]. In Tran and Mathur [4], full-scale experiments in a McDonnell Douglas DC-9 aircraft (on ground) are described. The active control system uses 16 piezoelectric patch actuators on the linings (aft section) and 32 microphones placed at the headrests and in the aisle.

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The measured noise reduction was basically limited to one frequency (out of eight), which is much less compared to loudspeaker-based systems (ANC) and systems with actuators on the fuselage that were implemented on the same aircraft (see [4, Fig. 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. Yet the results are very important, since, unlike in Lyle and Silcox [3], a real aircraft is used for the experiments, which provides a test environment with realistic structural and acoustic damping. In a recent publication of the lead author of this presentation [5], 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 the present work, the aircraft is substituted by a fuselage panel with coupled lining, 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 focus of this contribution lies on the acoustic performance of an active lining equipped with low-cost hardware relative to a system using high-precision laboratory hardware, which is considered as the benchmark.

II. Experimental Setup

The experiments take place in a sound transmission loss facility. A schematic of the experimental setup is provided in Fig. 1. A loudspeaker array (LSA) is positioned in front of the test opening where the fuselage panel is mounted. The LSA induces a pressure field in front of the panel. Acoustic foam (blue) is applied to reduce the acoustic feedback of the surrounding reverberation room on the synthesized pressure field. The induced pressure transmits through the fuselage with the coupled lining structure into a semi-anechoic room which represents the aircraft cabin.

More information on the real experimental setup is provided in Fig. 2. The CFRP fuselage panel 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 (stiffener of the panel) 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 (see Fig. 3). Three pairs of collocated laboratory and low-cost microphones are installed at the head rest positions of the three seats in front of the lining. Two different active lining systems are investigated. First, a low-cost system using low-cost microphones and a microcontroller board; and second, a laboratory system using laboratory microphones and a dSPACE rapid control

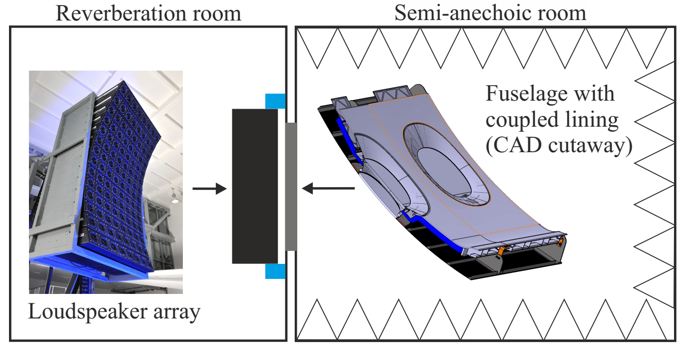

Fig. 1. Schematic of the experimental setup in the transmission loss facility showing the loudspeaker array in the reverberation room and the fuselage-lining-system mounted in the test opening between reverberation and semi-anechoic room.

prototyping system. The actuators and the amplifiers are equal in both cases. Furthermore, the laboratory microphones are used for evaluation of the noise reduction performance of the active systems. Two exciters are applied at positions on the lining skin fields below the window units. The main parts of this setup will be described in more detail in the following subsections.

A. Excitation

In the experiments, a low-frequency multi-tonal acoustic excitation typical for a counter-rotating open rotor (CROR) engine is realized with the LSA. Rotor engines are energy-efficient and might become more important in the future if the prices of primary energy carriers increase. One drawback of rotor engines is the high sound radiation of the engines leading to unacceptably high SPL in the aircraft cabin. The noise generated by typical rotor engines is multi-tonal, meaning that it contains multiple frequencies of the rotational speed with respect to the number of rotor blades. Simulation results for a generic 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 an LSA and a sound field reconstruction (SFR) method. As shown in Fig. 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].

B. Test Specimen

The test specimen consists of a primary CFRP fuselage panel and a secondary lining panel. Whereas the lining panel is an original aircraft part from DIEHL Aviation, the fuselage

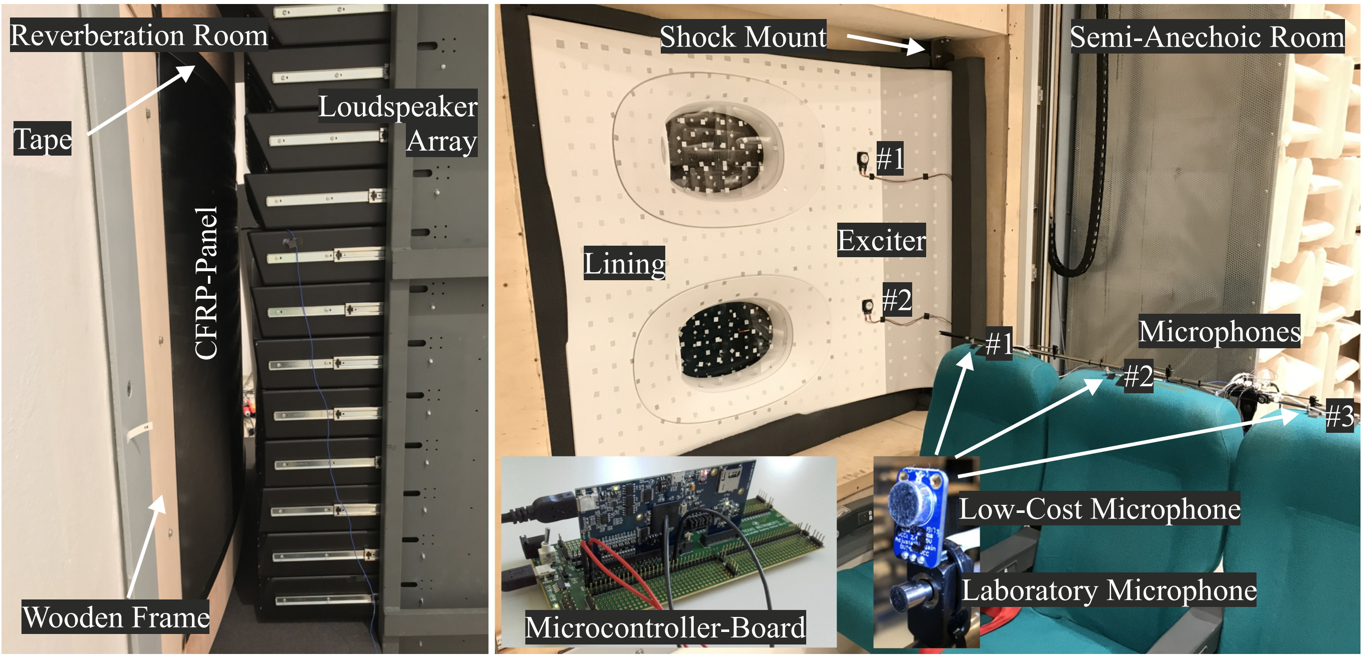

Fig. 2. Experimental setup in the transmission loss facility with the loudspeaker array placed in front of the CFRP fuselage panel (left) and the active lining in the semi-anechoic room with the low-cost components (right).

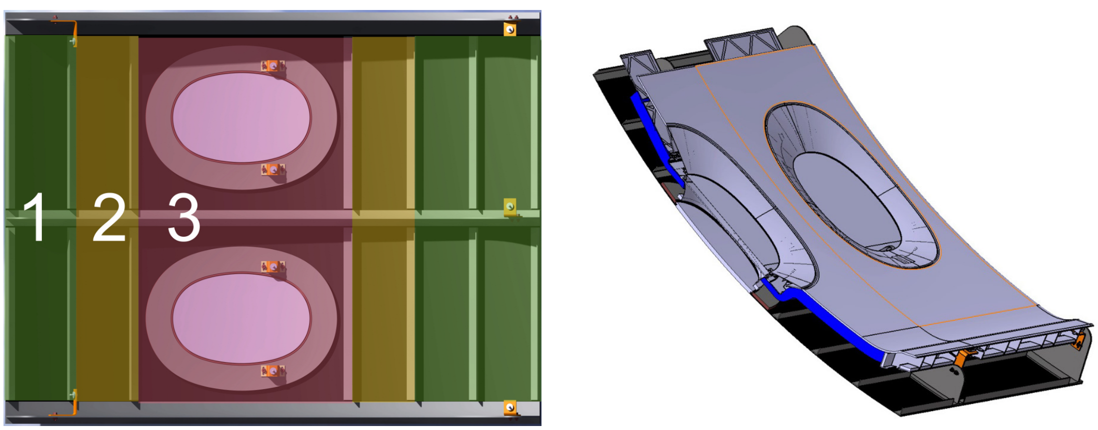

Fig. 3. CFRP fuselage panel with three zones of increasing skin thickness (left) and Airbus A350 side panel coupled to fuselage with secondary thermo-acoustic isolation in blue (right). The primary isolation is suppressed in this view.

panel is largely simplified compared to an original Airbus A350 part. The CFRP fuselage panel must be seen as a compromise between manufacturing costs and vibro-acoustic similarity to the original part. The 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 (see Fig. 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 an L- and T-shape geometry. The spacing of the stringers is 200 mm and the spacing of the frames is 635 mm. 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 counterparts on the fuselage. The 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 Fig. 3.

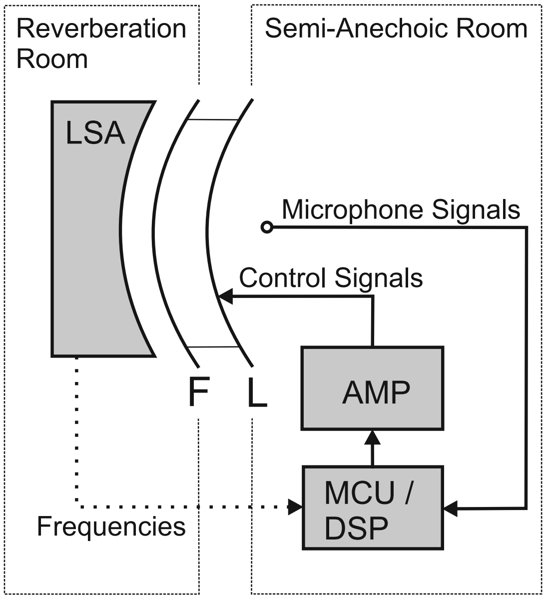

Fig. 4. Schematic of the experimental setup in the transmission loss facility showing the main signals and systems.

C. Active Lining

Each smart lining is equipped with two inertial force actuators of the type Visaton EX 45 S. With these actuators, the active system is able to induce forces to the lining structure and to alter the vibration behavior. The chosen 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 fuselage lining 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 Fig. 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 [7]. A simple approach is also followed with regard to the microphones. Each head rest is equipped with one microphone (see Fig. 2). The signals of the microphones are used as error signals to control the adaptation of the active feedforward controller. A scheme of the experimental setup showing the main signals and systems is shown in Fig. 4. Two different control system configurations are investigated here. The first configuration is called low-cost system, because it uses low-cost electret microphones with preamplifier units of the type MAX 4466 as error sensors and a TI Delfino microcontroller unit (MCU) of the type TMS320F2837xD for the control algorithm implementation. The second configuration is called laboratory system, because it uses calibrated laboratory microphones of the type PCB T130D21 and a dSPACE real-time system (DSP) for the control algorithm implementation. The amplifier (AMP) and the actuators are equal in both cases. A tiny low-cost class D stereo audio amplifier is able to drive the actuators. Before the integration of these components into the lining structure, 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.

III. 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 Fig. 5, the choosen hardware is shown. The MCU 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 a 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. [8]. 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, $r = 1, \dots, R$), 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 suitably stable. With this algorithm each actuator is individually controlled by one adaptive complex finite impulse response (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 FIR filter of the x-LMS algorithm. The square $J(n) = |\boldsymbol{e}(n)|^2$ of the error signal

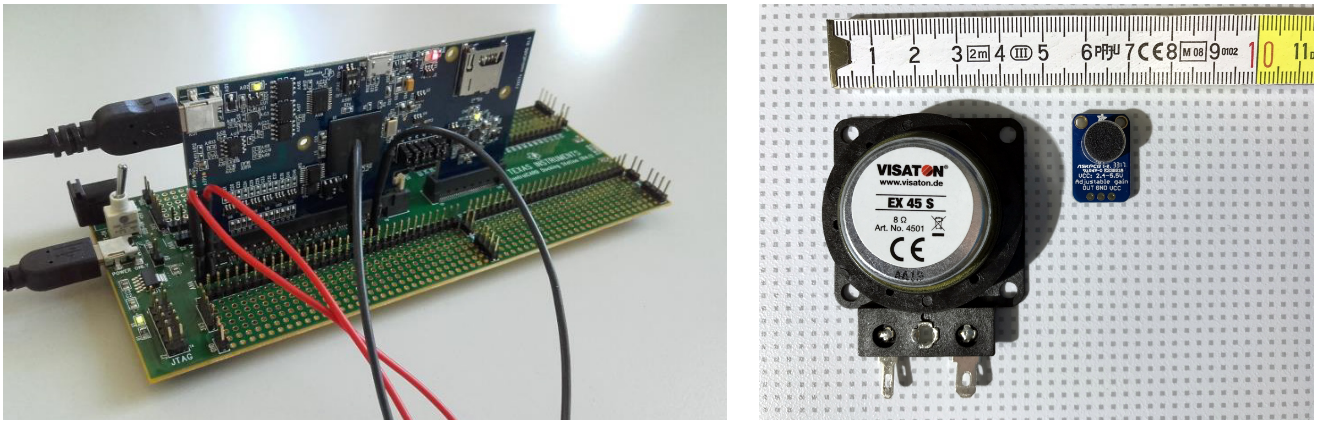

Fig. 5. Evaluation board with low-cost microcontroller unit TI Delfino TMS320F2837xD (left) and exciter Visaton EX 45 S and electret microphone with preamplifier unit MAX 4466 (right).

vector

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

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

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

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 [8]. 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.

IV. Results

One important conclusion that can be drawn from the experimental results is, that the use of low-cost hardware will not lead to a performance degradation of the active lining. According to Fig. 6 (left), both active systems achieve similar SPL at the CROR frequencies. The main reduction occurs at the fundamental blade-passing frequency of 119.4 Hz. There, the mean SPL reduction of the low-cost systems amounts to 23 dB and the maximum SPL reduction measured at microphone 2 is 25 dB. It is shown in Misol [5] 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 the largest at microphone 1 and the 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 Fig. 6 that shows the SPL reductions of the low-cost system measured by the three laboratory microphones at the CROR frequencies.

V. Conclusion and Outlook

In this work, an active feedforward control system for a serial production Airbus A350 lining coupled to a CFRP fuselage panel 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. The comparison of the acoustic performance of the low-cost system with a system using bulky and expensive laboratory hardware shows almost no difference. It is therefore possible to use cheap, small and lightweight parts that can be integrated into the lining structure to build up a highly autonomous smart lining module. Besides the main functionality of noise reduction, other tasks such as passenger announcements or noise masking could be realized. In such a case, the conventional speakers are obsolete

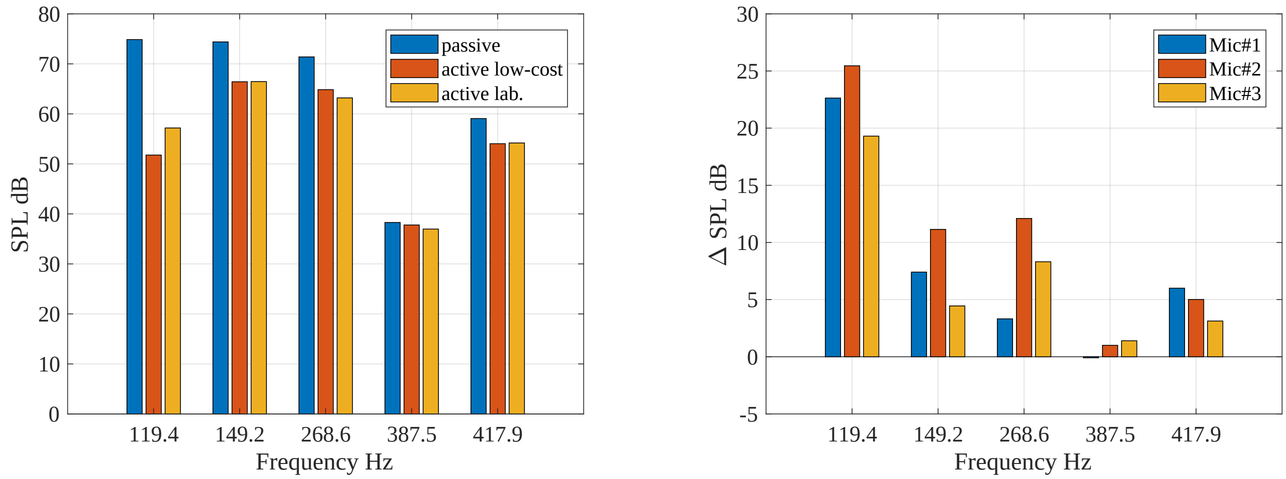

Fig. 6. Mean SPL measured at the head rest positions with inactive (passive) and active control with low-cost hardware (active low-cost) and with laboratory hardware (active lab.) (left) and tonal SPL reductions of the active low-cost system measured at the head rest positions (right).

and a mass neutral realization of the proposed system seems possible.

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 integration of the smart lining components suitable for production. These topics are currently addressed within the project Advanced Concepts for Aero-Structures with Integrated Antennas and Sensors (ACASIAS) funded by the European Union under grant agreement number 723167.

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