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EXPERIMENTS ON NOISE REDUCTION IN AIRCRAFT WITH ACTIVE SIDEWALL PANELS

Malte Misol
German Aerospace Center, Institute of Composite Structures and Adaptive Systems, Braunschweig, Germany
email: malte.misol@dlr.de

The present work focuses on the active reduction of aircraft interior noise by means of smart lining (sidewall panel) modules. In general, the interior noise floor of jet-driven aircraft is on an acceptable level. This, however, might change, if energy-efficient engines with open rotors are used in combination with stiff lightweight fuselage structures. In such a case, unacceptably high noise levels might arise especially at low frequencies (< 500 Hz). In this frequency range, passive sound insulation methods are usually incompatible with the mass and volume restrictions of aircraft. The linings are coupled to the fuselage and radiate sound into the cabin. They have large sound-emitting surfaces and many passengers are sitting directly in front of them. Therefore, it is reasonable to reduce the low-frequency sound emission of linings with active control. Furthermore, smart linings could be used for secondary tasks like passenger announcements or noise masking. Multiple functionalities can be realized in parallel. This contribution describes recent experimental research work on smart linings conducted in the DLR test aircraft Dornier Do728. The Do728 provides a fully equipped cabin with a realistic acoustic environment. The external acoustic excitation is realized with a loudspeaker array placed directly in front of the fuselage. A synthesized counter-rotating open rotor (CROR) noise containing the first five harmonics (< 500 Hz) is used to emulate the acoustic fuselage excitation of a real CROR engine. Two smart lining modules are driven in parallel, each with two inertial actuators and an independent adaptive feedforward control unit. Microphones are used as error sensors and for capturing the sound emission and noise reduction capability of the smart linings. Mean sound pressure level reductions up to 10 dB are achieved in the monitored area of the cabin.

Keywords: aircraft, interior noise, active control, lining, sidewall panel

1. 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 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. 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. It is also the aim of the present contribution to assess the noise reduction performance of active linings in a realistic full-scale experiment. Preliminary tests of the active lining are done in a sound transmission loss facility using a serial production Airbus A350 lining coupled to a carbon-fibre reinforced plastic (CFRP) fuselage panel with two windows[5]. Mean SPL reductions of up to 25 dB are achieved in the anechoic room in front of the lining, which can be considered as promising results regarding the full scale tests in the Dornier Do728 aircraft.

2. Experimental Setup

The DLR test aircraft Dornier Do728 is a ground test facility with a complete primary structure and a fully equipped cabin. Although most parts of the Do728 are original, it must be noted that this is not true for the linings. Therefore, the mass and stiffness characteristics differ from conventional lining structures. Furthermore, the structural links and the fixation on the fuselage are not original. In the author's opinion, this will not lead to a loss of validity of the obtained results. The functionality of the smart lining with an original part and original structural mounts was proven prior to the experiments in a sound transmission loss facility [5]. For reasons of convenience, the last four seat rows are removed. The configuration of the cabin is shown in Fig. 1. Important components of this setup are the loudspeaker array (LSA), the aircraft fuselage (F) and the aircraft cabin with the two independent smart linings (L1 and L2). These parts will be described in more detail in the following subsections. A microphone array with 18 microphones of the type PCB T130D21 is placed in the cabin in front of the lining at a height of approx. 1.2 m.

Figure 2 shows a schematic of the experimental setup including the active components and signals of a smart lining. Inputs to the digital signal processing (DSP) are the microphone signals and the information about the excitation frequencies. The microphone signals are used as error signals for the adaptive feedforward control algorithm, while the frequencies of the LSA are used for the synthesis

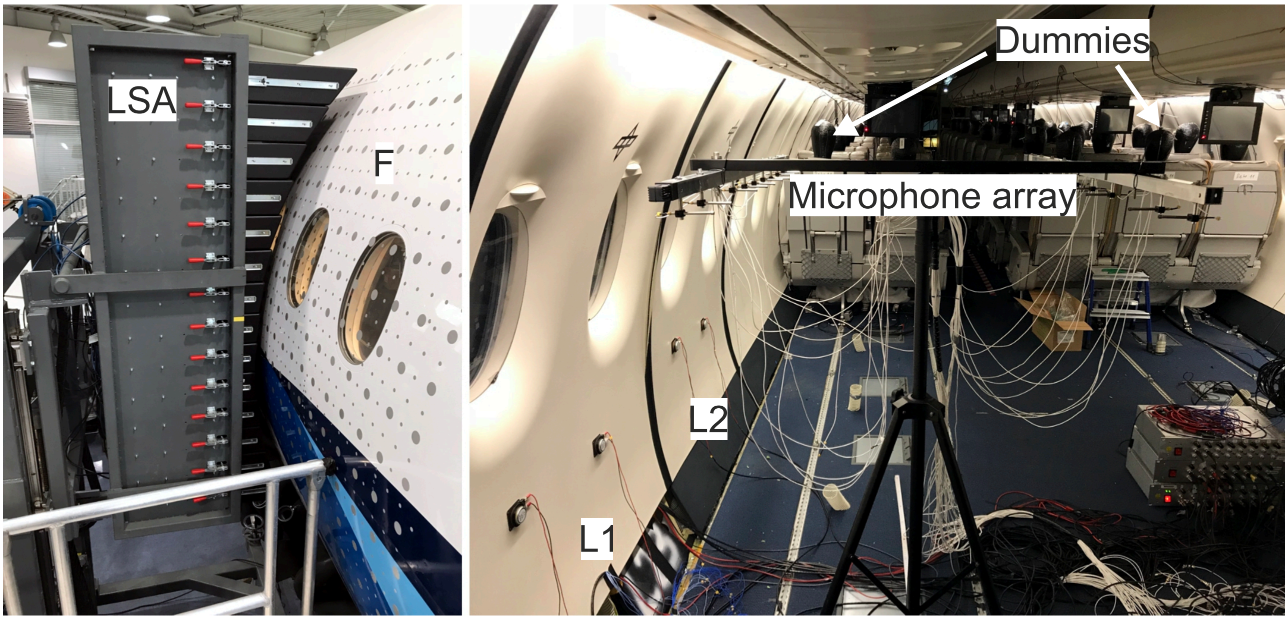

Figure 1: Experimental setup with loudspeaker array (LSA), aircraft fuselage (F) and smart linings (L1 and L2).

of the harmonic reference signals. The amplified (AMP) control signals are fed to the actuators of the smart lining. For the experiments, it is assumed that the frequencies of excitation do not vary over time.

2.1 Excitation

Rotor engines of aircraft induce high acoustic loads on the fuselage, which transmit into the cabin. The excitation frequencies depend on the rotational speed and the rotor geometry. 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 (see first row of Table 1). The synthesis of the calculated pressure distribution on the fuselage was done with a loudspeaker array (LSA) and a sound field reconstruction (SFR) method. As shown in Fig. 1, the LSA was placed in front of the fuselage at a distance of 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].

Table 1 lists the SPL measured outside and inside the aircraft at the CROR frequencies. The exterior SPL is measured with a microphone placed between LSA and fuselage in the center of the area covered by the LSA. The interior SPL was measured with a microphone placed in front of the lining at a distance of approx. 1 m. The values are intended to give a rough impression of the external and internal noise levels.

Table 1: Sound pressure levels outside and inside of the aircraft induced by the loudspeaker array.

Frequency [Hz]	119.4	149.2	268.6	388.0	417.9
SPL fuselage [dB]	109	110	108	93	106
SPL cabin [dB]	69	72	62	48	62

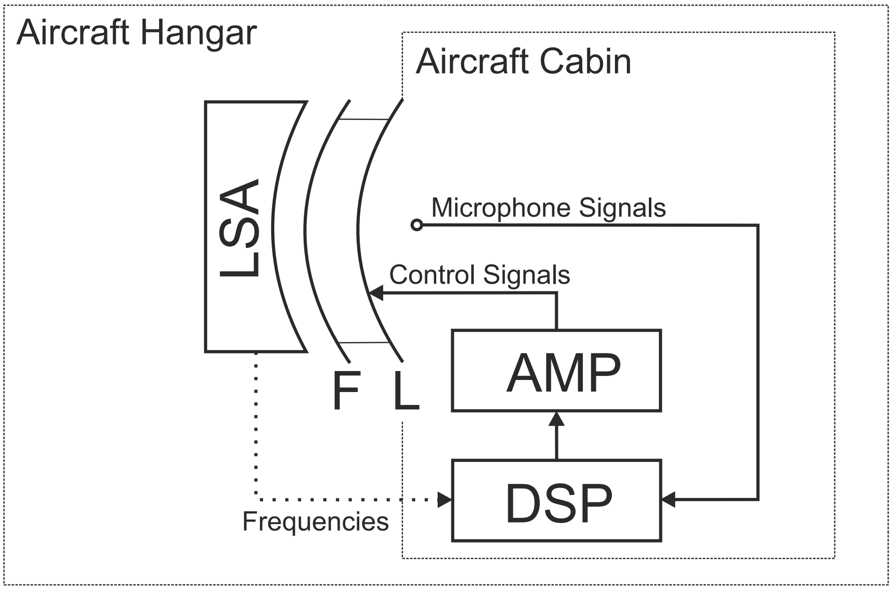

Figure 2: Schematic of the experimental setup showing the main signals and systems.

2.2 Aircraft

Preliminary tests of the smart lining were done in a sound transmission loss facility [5]. Tests in a fully equipped aircraft cabin provide the opportunity to achieve a more realistic acoustic environment compared to the acoustic laboratory (semi-anechoic room). Furthermore, two (or more) smart linings can be driven in parallel to assess robustness and cross-coupling between the individually controlled units. For the present investigation, the interior acoustics of the Do728 cabin is quantified by the reverberation time T_{60}. The measurement of T_{60} was done with a B&K Investigator 2260 with the reverberation time software BZ 7220, an OmniPower 4296 sound source and an amplifier 2716. The excitation noise was generated by the Investigator 2260 and fed to the amplifier. The whole process was controlled by the B&K measurement system. The output are the reverberation times in third-octave bands as given in Table 2. It can be seen that at frequencies below 200 Hz, the value of T_{60} strongly depends on the actual measurement position. This is attributed to the modal behavior of the cabin. Expected values of T_{60} of a single-aisle aircraft cabin (fully equipped but without passenger) lie in the range of 0.25–0.3 s. Values of T_{60} of an occupied cabin are not available, but it is assumed that the acoustic absorption of the human body will induce additional damping, which decreases T_{60}. Apparently, for frequencies above 160 Hz, the damping in the Do728 cabin is higher than the expected values. This is explained by the presence of dummies, which were installed in most parts of the cabin and might induce additional acoustic absorption. Although the dummies were designed for the thermal behavior of humans and hence will not correctly reflect the acoustic influence of a human body, they might increase the damping, which decreases T_{60}. Under this assumption, the obtained mean values of T_{60} are considered reasonable for the approximation of the acoustic environment of a fully occupied aircraft cabin.

Table 2: Measured reverberation times T_{60} in the aircraft cabin in third-octave bands.

Frequency [Hz]	125	160	200	250	315	400	500
T_{60} [s]	0.37	0.41	0.14	0.19	0.18	0.21	0.22

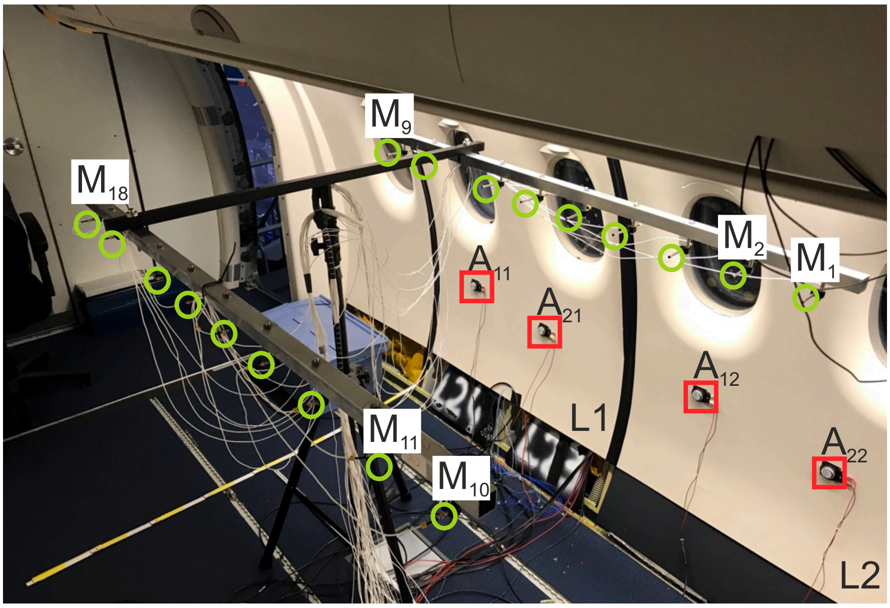

Figure 3: Smart linings (L1 and L2) with actuators (A) and sensors (M).

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 were 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 was considered appropriate to position the actuators in a straightforward manner. In order to ensure sufficient control authority, the structural vibration and interior SPL induced by the loudspeaker array were compared to the values generated by the actuators. A more elaborate actuator placement based on genetic optimization is described in [5]. A simple approach was also followed with regard to the error microphones. The control system configuration described here uses eight microphones as error sensors. Each of the two smart linings uses the same microphones: M_1, M_4, M_7, M_9, M_{10}, M_{13}, M_{16} and M_{18}. This choice ensures an almost even spacing of microphones along the two linings and permits the measurement of SPL close to the lining and close to the aisle. The height of the microphones corresponds to the ear positions of the dummies (see Fig. 1). The control algorithm is adopted from Johansson et al. [7, Eq. 5]. It is based on the complex filtered-x LMS algorithm and approximates the Newton algorithm by using the diagonally dominant property of the Hessian matrix ([7, Eq. 8]). 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 ten adaptive complex filter weights to control the five frequencies. The adaptive feedforward controllers of the smart linings are implemented on a dSPACE rapid control prototyping system.

3. Results

A microphone array is used for error sensing and control performance evaluation. As described in subsection 2.3, not all microphones are used as error sensors for the adaptive control. Fig. 4 shows the mean SPL spectra of all microphones in the uncontrolled as well as in the controlled case. The peak average SPL reduction was achieved at 149.2 Hz with 9.3 dB. The reductions at 119.4 Hz and

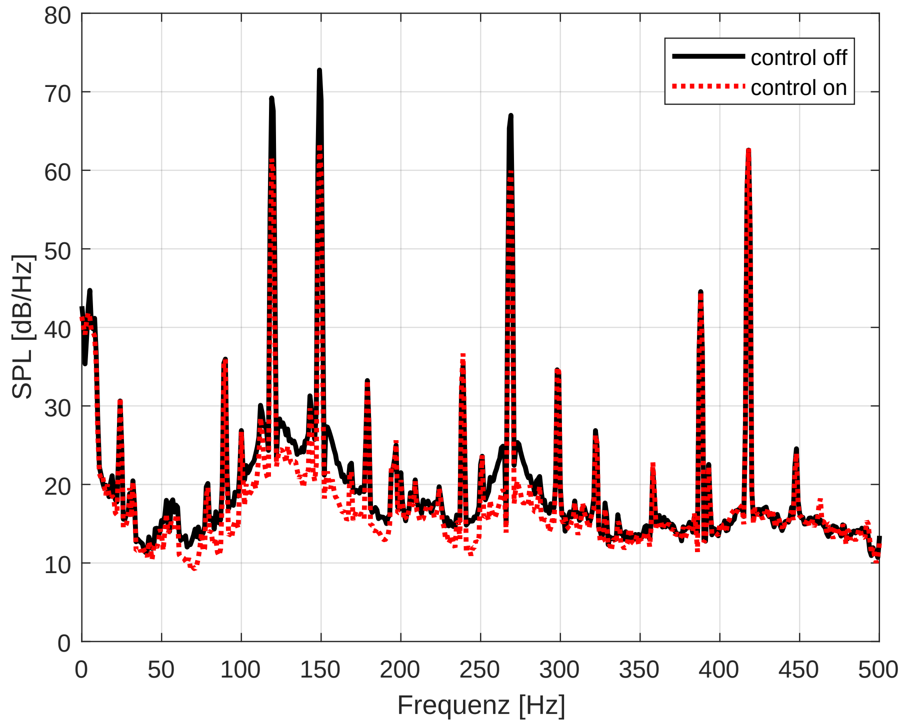

Figure 4: Mean SPL (average of M_1 to M_{18}) with inactive (black) and active (red) smart linings.

268.6 Hz are 7.7 dB and 7.1 dB. At 388 Hz and 417.9 Hz, no reductions were achieved. At these two frequencies, the uncontrolled SPL is relatively small, which forces the adaptive control to focus on the first three frequencies. Consequently, the strongest SPL reduction occurs at the second frequency because it has the maximum uncontrolled mean SPL. In the controlled case, the mean SPL at all frequencies (except the fourth) is on a similar level. The mean SPL reduction of all microphones in the configuration shown in Fig. 3 is 6.8 dB.

Table 3 lists the measured SPL of all microphones in the uncontrolled case and the SPL reduction achieved by the two smart linings working in parallel. It is clear that the maximum SPL reductions are achieved directly in front of the linings. This is due to the higher SPL monitored by the microphones M_1 to M_9 (see Fig. 3 and Table 3). The decreasing SPL for an increasing distance between microphone and lining is seen as a consequence of the sound radiation of the lining and of the acoustic excitation of the fuselage partition the linings are mounted to. The first microphone row (M_1 to M_9) is approx. 0.4 m from the lining and the second microphone row (M_{10} to M_{18}) is approx. 1.2 m from the lining. Under ideal conditions, in an acoustic free field, the distance increase of a factor of three from the sound source would result in a SPL decrease of approx. 9.5 dB. In the monitored area, the microphones show a SPL decrease normal to the lining surface of up to 8.4 dB (for microphones M_4 and M_{13}). The observed SPL decrease in the direction normal to the lining surface indicates that the main part of the acoustic energy is transmitted through and radiated by the linings. More measurements might be necessary to corroborate this assumption.

4. Conclusion

In this work, a full-scale aircraft test setup is used to assess the noise reduction performance of so-called smart linings. A maximum SPL reduction of 11.3 dB is achieved in the controlled area. The mean SPL reduction over 18 microphones is 6.8 dB. At the most critical second frequency, a mean SPL reduction of 9.3 dB is achieved by the two smart linings working in parallel. It is observed

Table 3: Sound pressure levels and reductions in the monitored area.

Microphone	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9
SPL [dB]	80.4	77.4	77.9	79.1	77.9	80.2	79.4	79.9	81.0
SPL reduction [dB]	9.3	7.9	9.1	9.7	8.2	9.2	11.3	9.9	8.5
Microphone	M_{10}	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	M_{17}	M_{18}
SPL [dB]	75.2	73.0	71.5	70.7	70.9	72.6	73.6	74.0	74.5
SPL reduction [dB]	3.6	3.8	3.2	3.7	4.3	3.4	3.0	2.2	2.2

that the SPLs near the lining surfaces (at the window seats) are significantly higher than the SPLs near the aisle. This leads to the conclusion that the major part of the sound energy is transmitted through the linings, which is seen as an argument for the suitability of the smart lining concept. The activated smart linings achieve a smooth and nearly uniform SPL distribution in the monitored area with an average SPL of 69.8 dB. The standard deviation of the SPL values drops from 3.6 dB in the uncontrolled case to 1.7 dB when the control of the smart linings is switched on.

Future work will focus on an increase of the technology readiness level of the smart lining. Important steps towards this goal are the replacement of laboratory hardware by low-cost components (e. g. replacement of dSPACE with a microcontroller unit) and further experiments in the Do728 to assess the performance and robustness of a larger amount of smart lining modules.

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