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GLOBAL NOISE ATTENUATION THROUGH THE COMBINATION OF LOCAL ACTIVE NOISE CONTROL SYSTEMS IN THE CABIN OF AN AIRCRAFT

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The excessive noise level at the interior of aircrafts' cabins is an important issue, that can affect the comfort of the passengers during flight. Although modern aircrafts are manufactured using technologically advanced soundproofing materials and quitter engines, the Sound Pressure Levels (SPL) in the cabin can sometimes exceed 80 dB. Especially in tilt-rotor aircrafts, the cabin SPL can reach 90 dB-95 dB, because of the existence of low frequency harmonics that are related to the rotor's Blade Passage Frequency (BPF) and cannot be attenuated by conventional passive techniques because of weight and volume issues. For this reason, the use of Active Noise Control Systems (ANCS) in such aircrafts is a very promising method in order to reduce SPL without increasing the aircraft's weight and the fuel consumption. The combination of local ANCS is being investigated in this work for global noise control around all seats. Two different ANC architectures have been modeled using FEM. The results of 2D and 3D simulations have shown that both ANC architectures create a more than 10 dB quiet zone in front of the seat's head-rest for a multi-tone acoustic disturbance. However, the multichannel approach, where systems of adjacent seats cooperate with each other, can achieve even bigger SPL attenuation, more uniform quiet zones in combination with the usage of less microphones comparing to the stand-alone systems. Thus, the present work proposes an efficient and easily implemented solution for the active noise control around the seats' headrests of small aircraft cabins.

Keywords: active noise control, aircraft cabin, global control simulations

1. Introduction

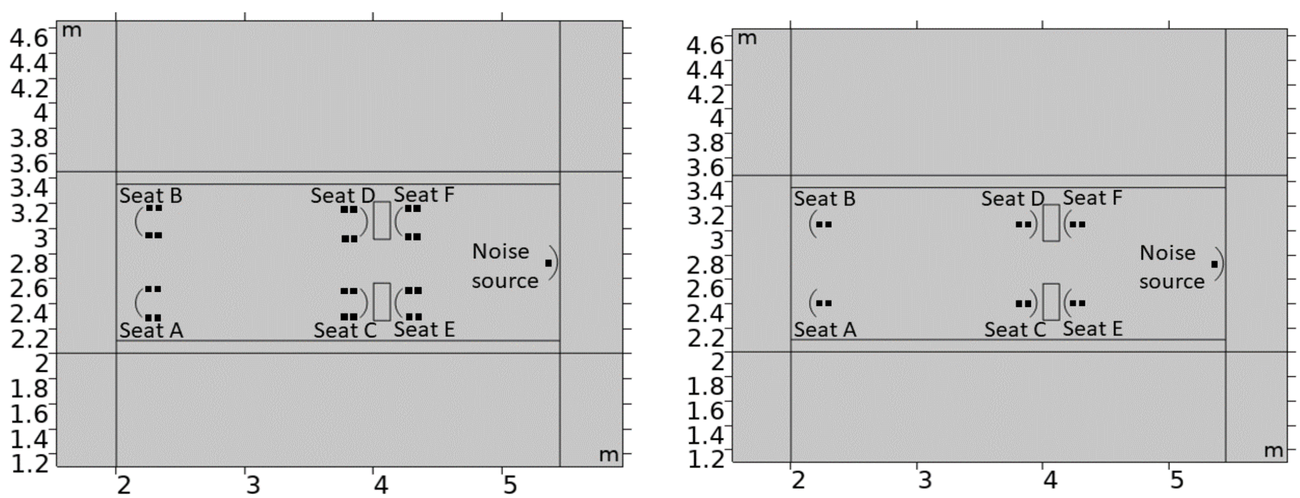
For more than three decades, scientists have been studying the suppression of noise in aircraft cabins using active sound control techniques. The most established approach, which has also been tested during inflight experiments [1], [2], is to minimize the potential acoustic energy, which is computed by summing the squares of the acoustic pressures captured by microphones evenly distributed in the cabin. In this way a global attenuation of the acoustic pressure is achieved. Another approach that has gained particular attention in recent works tries to create quiet zones around the headrest of the aircraft seats, using local active noise control systems (LANCS). In [3] two microphones and two loudspeakers along with multiple input multiple output (MIMO) FxLMS algorithm have been used to attenuate the low frequency acoustic disturbance created by the propellers of a turboprop aircraft, while in [4] several Active Noise Control (ANC) algorithms have been investigated for a headrest system installed in a wooden cabin mock-up. In addition, a feedforward system with headtracking capability and multiple reference signals has been proposed in [5] for the attenuation of broadband recorded airplane noise.

The aforementioned works attempt to provide solutions to the major issues of ANC headrests related to the control algorithm, the virtual sensing technique used to estimate the acoustic pressure at the passenger's ears, and system disturbances caused by head movement, resulting in improved sound pressure level (SPL) attenuation performance. However, there is no reference of the LANCS' overall effect on the cabin's soundfield and the interference between them. Thus, if adjacent headrests are very close to one another, this interference can cause stability issues, and sound levels can be greatly increased in remote areas of the cabin, far from the quiet zones created by the LANCS. In addition, separate systems can be combined in order to enhance the performance of the overall system and to save hardware, depending on the geometry of the cabin and the position of the seats.

In the present work, the effect of six ANCS on the soundfield of a tiltrotor aircraft cabin is investigated through simulations using finite element method (FEM). The major objective is to provide a suitable configuration that ensures the stability of the systems and establishes a sufficient quiet area in front of each seat without significantly raising the SPL in other regions of the cabin. The paper is structured as follows: In paragraph 2 a brief description of the model and the control algorithm is given, while in paragraph 3 the 2D and 3D simulation results are discussed. Finally, in paragraph 4, a brief discussion of the simulation results is provided, followed by the conclusions in paragraph 5.

2. Description of the model

Both 2D and 3D simulations have been implemented in an attempt to investigate the behaviour of the local systems. The solution for all of them was obtained using the time domain FEM. Furthermore, the acoustic disturbance was composed of four harmonics (48 Hz, 72 Hz, 96 Hz and 119 HZ) of the aircraft's rotor blade passage frequency (BPF) at 24 Hz and was obtained during inflight measurements. The frequency at 119 Hz has been chosen instead of 120 Hz because it appears at the frequency spectrum measured in the cabin. The noise source is positioned at the rear end of the cabin and a microphone in front of it in order to obtain the reference signal for the feedforward control algorithm. Finally, the simulation time was set to be 4 seconds, which is enough time to test the system's stability.



(a) (b)

Figure 1: The two different system setups investigated during the 2D simulations. (a) At the first setup, every system consists of 2 microphone pairs (black rectangles) and 1 loudspeaker (arc) and is dedicated to one seat. (b) At the second setup every system consists of 2 microphone pairs and 2 loudspeakers which cooperate to attenuate noise in front of adjacent seats.

2.1 Geometry of the model

The 2D model's geometry consists of a rectangular cabin and a perfectly matched layer (PML) that is positioned around it to simulate free space (Fig. 1). The PML has a thickness of 2 m to absorb low frequency acoustic disturbances and the cabin dimensions are 3.45 m long by 1.25 m wide. In addition, the cabin walls have a thickness of 0.1 m and its material was set to be aluminium. The primary and secondary sources are also modelled as arcs with a normal acceleration boundary condition. One or two microphone pairs (Fig 1) are positioned 3cm in front of them depending on the chosen setup. The distance between each pair's microphones is also 3 cm. Each of the six secondary sources corresponds to a different headrest, with the goal of creating a quiet zone in front of it. Additionally, a wooden rectangle is placed behind the adjacent systems to reduce their interference and to simulate reflections that may exist in the real cabin.

On the other hand, the geometry of the 3D model is semicylindrical with the same length and width as the 2D model (Fig. 2). The height of the cabin is 1.7 m. Moreover, absorbing layers are placed at the front and rear ends of the model to add sound dampening, while the cabin walls are supposed to be acoustically rigid. Finally, the loudspeakers are modelled as circles with 22 cm diameter.

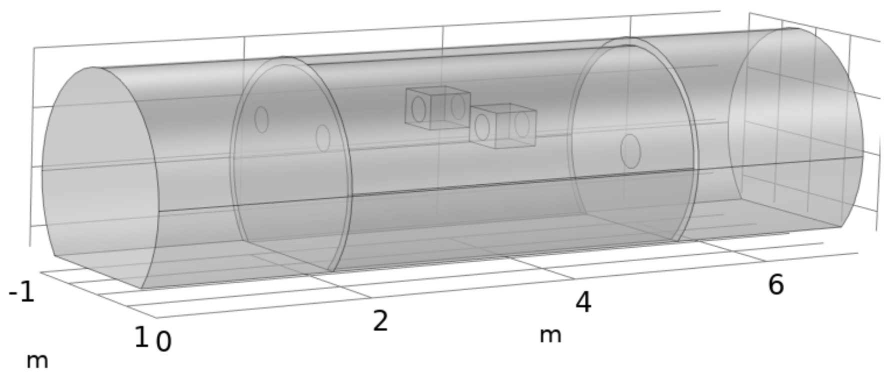


Figure 2: The geometry of the 3D model. The loudspeakers are modelled as circles, and the noise source is located at the back of the cabin.

2.2 The control algorithm

The control algorithm, which is used for the computation of the antinoise signal of each loudspeaker is the multiple input-multiple output FsLMS algorithm presented in [6]. This algorithm is practically a functional link artificial network (flann) with trigonometric functional expansion. As a result, the expanded reference signal becomes:

$$\begin{aligned} s(n) = [&x(n)\ \sin\big(\pi x(n)\big)\ \cos\big(\pi x(n)\big) \ldots \sin\big(P\pi x(n)\big)\ \cos\big(P\pi x(n)\big) \\ &x(n-1)\ \sin\big(\pi x(n-1)\big)\ \cos\big(\pi x(n-1)\big) \ldots\ \sin\big(P\pi x(n-1)\big)\ \cos\big(P\pi x(n-1)\big) \ldots \\ &x(n-N+1)\ \sin\big(\pi x(n-N+1)\big)\ \cos\big(\pi x(n-N+1)\big) \ldots \\ &x(n-N+1)\ \sin\big(P\pi x(n-N+1)\big)\ \cos\big(P\pi x(n-N+1)\big)] \end{aligned} \quad (1)$$

where P is the order of the flann and $x(n)$ is the signal obtained by the reference microphone in front of the noise source. The reference signal is then filtered by the secondary paths between each loudspeaker and each microphone in order to form the update equation of the multichannel FsLMS. Although there are not non-linearities in the model this algorithm has been chosen in order to check its stability when it controls multiple separate systems. In the case of real-world conditions, where non-linearities are present, the advantages of the flann comparing to linear FxLMS has been shown in [7].

In addition, linear extrapolation is used for the prediction of the acoustic pressure at the passenger's ear [8]. The formula that gives the acoustic pressure at the virtual location is:

$$e_v(n) = \frac{e_{p2}(n) - e_{p1}(n)}{a} * x + e_{p2}(n) \tag{2}$$

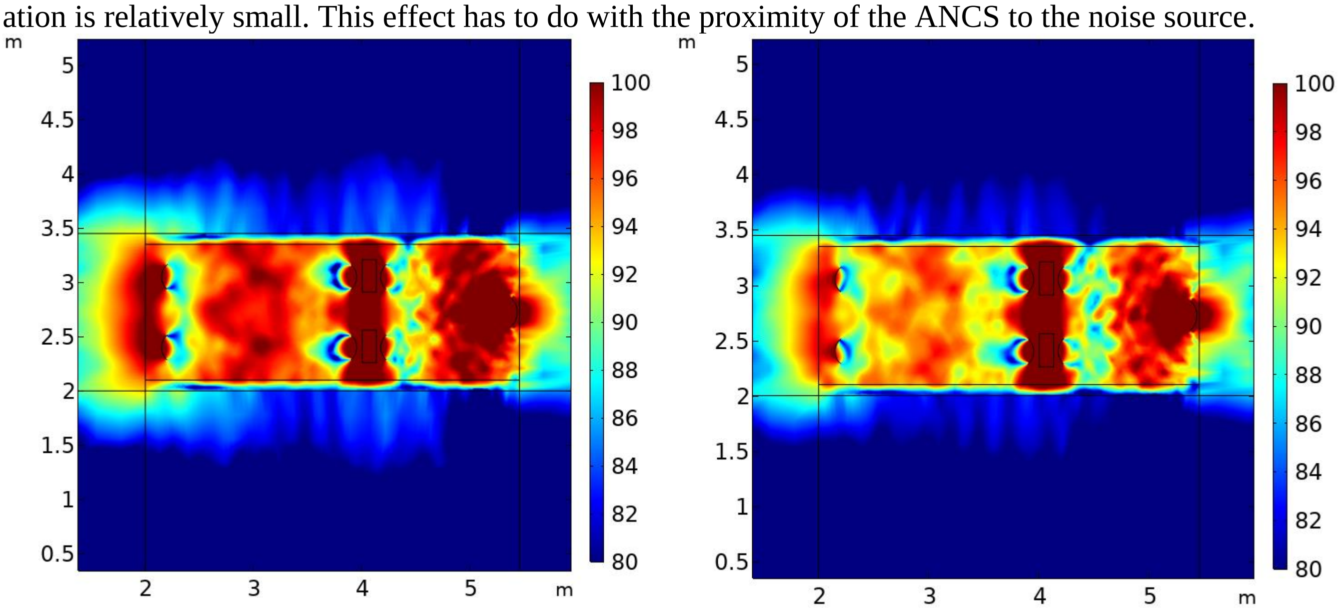
where $e_{p1,2}$ are the acoustics pressures obtained by one pair of error microphones, a is the distance that separates the two microphones and x is the distance between the error microphones and the virtual location.

Finally, it should be mentioned that two scenarios have been simulated. At the first scenario, one multichannel system with 2 inputs and 1 output corresponds to every seat, while at the second one ANCS with 2 inputs and 2 outputs is responsible for the creation of the quiet zones in front of adjacent seats. In other words, at the second case, adjacent loudspeakers cooperate with each other saving hardware and computing power.

3. Simulation results

3.1 2D simulation results

The simulation results for the standalone systems (Fig. 1a) show that the SPL attenuation ranges between 9 and 16 decibels, forming a quiet zone with dimensions of about x=15 cm and y=33 cm (Fig. 3a), while without them the sound pressures level is around 96 dB. The best performance is achieved for seats C and D and the worst for E and F, where the quiet zones are not uniform and the SPL attenuation is relatively small. This effect has to do with the proximity of the ANCS to the noise source.



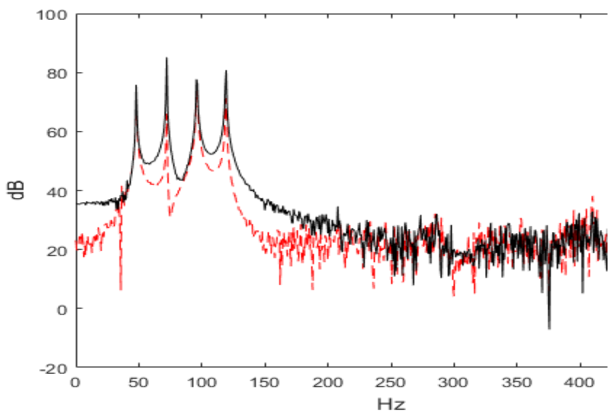
(a) (b)

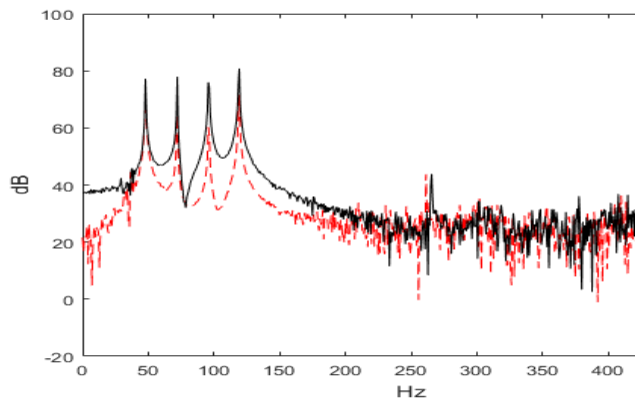
Figure 3: Sound pressure level after the activation of active noise control systems in (a) standalone systems dedicated to each seat, and (b) cooperative systems of adjacent seats.

Furthermore, at 10 cm away from the microphones, the amplitude attenuation of the majority of the BPF harmonic is around 10 dB (Table 1). However, some harmonics' attenuation does not meet the 10 dB threshold. Furthermore, an increase in acoustic pressure is observed in areas far from the quiet zones and between opposite seats. The SPL rises by 5 decibels as a result of this event.

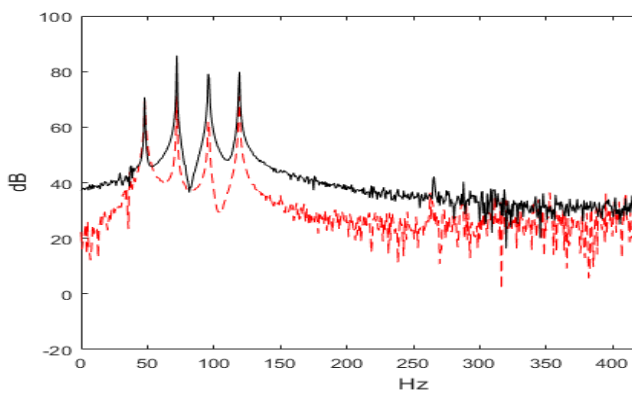
In an attempt to address these issues, the solution of the cooperative adjacent loudspeakers was investigated (Fig. 1b). It is clear in (Fig. 3b) that the quiet zones in front of seats E and F are larger, and the SPL is lower between opposite seats, indicating that the global system is working more effectively. Furthermore, the total number of microphones used is reduced from 12 in the standalone system setup to 6.

Finally, the mitigation of BPF harmonics (Fig 4) is bigger at seats C and D where ranges between 10 and 17 decibels.





(a) (b)

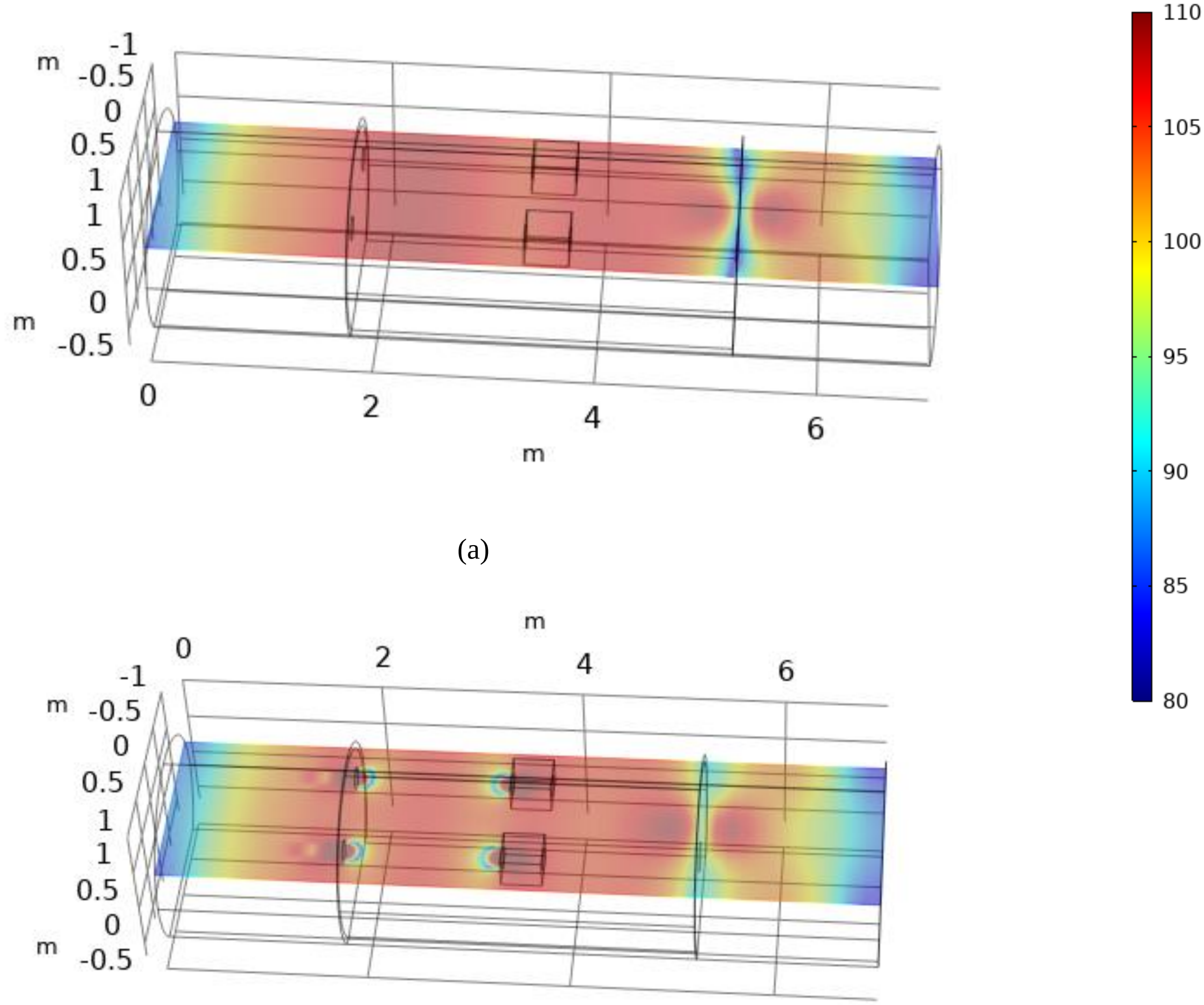


(c)

Figure 4: Frequency spectrums before (black line) and after (red dotted line) the activation of the ANCS in the case of cooperative adjacent systems. Spectrum (a) corresponds to seat B, spectrum (b) corresponds to seat D and spectrum (c) corresponds to seat F.

3.2 3D simulation

The 3D simulation was conducted to investigate the behaviour of the ANCS when the acoustic wave is not plane, as it is in 2D geometry. Because of the model's high computational demands, only the systems of seats A, B, C, and D were active in this simulation. In addition, the setup of the adjacent cooperative loudspeakers was deployed. The results on the reduction of the acoustic pressure are shown in (Fig. 5). In front of each loudspeaker, a quiet zone with dimensions (x=25cm, y=35cm, z=25cm) is formed, with SPL attenuation greater than 8 dB. At the blue areas of Fig. 5b the reduction is more than 10 dB. These results are consistent with the 2D simulations, with the exception of the width of the quiet zone, which appears to be larger in the 3D model, and the similarity of the shape of the quiet zones of different seats.



(a)

(b)

Figure 5: 3D simulation when the ANCS is (a) not activated and (b) activated. The height of the slice is at 1.28m and the maximum attenuation reaches 20 dB.

Table 1: Attenuation of the BPF harmonics for the two ANC setups.

	SPL reduction* (dB)	Harmonic attenuation* (dB)			
		48 Hz	72 Hz	96 Hz	119 Hz
Stand-alone systems					
Seats A-D	12	10	18	2	12
Seats B-E	16	4	18	17	10

Seats C-F	9	-	10	16	3
Cooperative systems					
Seats A-D	11	6	14	4	13
Seats B-E	15	10	17	16	10
Seats C-F	15	11	14	15	8
* It refers to the left ear that is assumed to be placed at 110 cm high, 10 cm far from the headrest’s surface					

4. Discussion

The results of the two and three-dimensional simulations show that the problem of noise attenuation around the seat headrests of a small aircraft cabin can be addressed by combining local active noise control systems. Given the relatively large diameter of the loudspeakers, the quiet zones are large enough to cover gentle head movement. In addition, the reduction of the sound pressure level is more than 10 dB within a big area and the systems’ stability is maintained. The noise attenuation far from the headrests is either small or does not exist at all. However, in a small cabin like the one studied in present work the crucial areas are the ones in front of the seats, where the large SPL reduction is achieved. Furthermore, the noise source was arbitrarily placed at the back end of the cabin because the goal of this work is to investigate the interference between local ANCS rather than the propagation of the propeller-rotor noise. In real-world situations, when the noise source is the rotor, the reference microphone must be placed in a position that ensures high correlation with the acoustic disturbance at source.

5. Conclusion

In the present work, two setups of local active noise control systems were investigated in order to attenuate the acoustic pressure in front of the seat headrest in 2D and 3D models of a tilt-rotor aircraft cabin. In the first setup one system is dedicated to every seat, while in the second adjacent loudspeakers cooperate forming a multichannel system with two inputs and two outputs. The second setup seems to have better performance, while at the same time uses less microphones. Thus, it seems to be a promising solution for the active noise control in small aircraft cabins. Future research will be focused on the experimental verification of the simulation results, using real world acoustic disturbances.

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