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DESIGN OF AN ACTIVE NOISE CONTROL SYSTEM FOR A BUSINESS JET WITH TURBOFAN ENGINES

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An active noise vibration control (ANVC) system is designed for a Dassault Falcon 2000LX business jet. Measurement data from ground tests and recordings from cruise flight reveal narrowband and tonal cabin noise in the bandwidth from 50 Hz to 500 Hz. In both conditions the sound pressure level (SPL) of the tonal components is up to 10 dB above the cabin noise floor. The designed ANVC system is expected to reduce the tonal components to the noise floor. The system is realized on the ceiling panel in the aft of the cabin. A frequency domain filtered-x least mean squares algorithm (FxLMS) is used for control. The main design task is the definition of actuator (inertial exciter) and error sensor (microphone) locations on the ceiling panel and in the cabin fluid. Measurement data from a ground vibration test of DLR test aircraft iSTAR is used for the identification of suitable actuator and sensor locations. The system performance is predicted with numerical simulations using sampled sound pressures and identified frequency response functions (FRF). The sound pressures are recorded at 312 locations in the volume of the aft cabin. FRF from 48 actuator locations to 312 microphone locations are available for optimization. The system will be realized in the iSTAR in July 2023. Ground tests will be performed with engine excitation up to 80% N1 (rotational speed of low the pressure compressor shaft).

Keywords: aircraft, interior noise, active control, experiments, ground vibration test

1. Introduction

Active noise control (ANC) systems are able to reduce tonal or multi-tonal aircraft interior noise effectively up to a few hundred Hertz. Most research has been published related to propeller aircraft since the propeller blades of the running engines cause high sound pressure levels (SPL) in the cabin at the blade passing frequency (BPF) and multiples of the BPF. Early flight test results of ANC are reported in Dorling et al. [1] and Elliott et al. [2]. Both groups use the same BAe 748 twin turbo-prop aircraft but with different ANC systems. Dorling et al. [1] use 24 loudspeakers and 72 microphones to realize SPL reductions of 8–13 dB at three frequencies. In Elliott et al. [2], 16 loudspeakers and 32 microphones are used to achieve SPL reductions of 3.7–14 dB at two frequencies. More details on the flight tests can be found in Elliott et al. [3]. Results on ANC in a Saab 2000 aircraft are reported by Emborg at al. [4]. The active control system uses 36 loudspeakers and 72 error microphones. The measured SPL reductions are 8–14 dB at the blade-passing frequency (BPF) and approx. 8 dB summed over the first three frequencies.

Instead of using loudspeakers, as was done in the publications mentioned before, the aircraft interior parts, for example the sidewall panels so-called linings, can be excited by inertial actuators (exciters) to realize panel speakers. If these interior parts are equipped with actuators, sensors and signal processing they are called smart structures. Research with active linings has been published in the 1990s by Lyle et al. [5]. In this work 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. The performance limitations of the active linings is explained (at least in parts) by the different coupling of primary excitation and active linings into the cavity modes. More recent research work of Misol [6] with active linings equipped with inertial exciters instead of piezoelectric patches show promising results in a full-scale experiment. In this work 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 dominant second harmonic a mean SPL reduction of 9.3 dB is achieved by two smart linings working in parallel.The concept of a smart lining with integrated actuators, sensors and virtual error microphones is described in Misol [7].

This contribution describes the acquisition and the post-processing of measurement data obtained during a ground test with a business jet with turbofan engines. Based on this data an active noise vibration control (ANVC) system is designed and the performance is evaluated. Tonal components around 137.5 Hz and 404 Hz are identified in the interior sound field for engine excitation with 80% N1 (rotational speed of low the pressure compressor shaft). The effect of a chosen actuator and sensor configuration on the reduction of the SPL at these two tones is described.

2. Experimental setup

The experiments take place in the aft of the cabin of DLR's research aircraft Dassault Falcon 2000LX MSN 006 "iSTAR" (In-Flight Systems and Technology Airborne Research, see Fig. 1). Figure 2 shows a sketch of the experimental setup in the iSTAR cabin. The microphone stand and the actuators on the ceiling panel are shown in Fig. 3. The microphone measurements are repeated sequentially at six different locations and two orientations of the microphone stand (configurations C1 to C12). Figure 3 shows the orientation of the microphone stand for the uneven configurations (starboard side of the aircraft). In the even configurations the microphone stand is rotated by 180 degrees along the Z axis (port side of the aircraft). By using 26 microphones in each configuration at total of 312 microphone locations is realized in the aft of the cabin. The spacing of the microphones is chosen small enough to fulfil the Nyquist criterion of having at least two spatial samplings per wavelength for frequencies up to 500 Hz. The inertial exciters are distributed regularly on the ceiling panel in the investigated region of the cabin as can be seen in Fig. 3. The microphone array is built of PCB T130D21 ICP microphones. The ICP support is provided by analog low-pass filters of the type Kemo CardMaster 255G. The cut-off frequency of the low-pass filters is set to 500 Hz for the multi-reference tests and to 4 kHz for the disturbance sound

Figure 1: Test aircraft Dassault Falcon 2000LX MSN 006 "iSTAR" on DLR apron of Research Airport Braunschweig. The location and measurement direction of the accelerometer mounted to the starboard pylon is indicated by the red arrow.

pressure measurements. The sampling frequency of the dSPACE MicroLabBox system is set to 2000 Hz for the multi-reference tests and to 10 kHz for the disturbance sound pressure measurements. The 16 analog outputs of the dSPACE are fed through the low-pass filters and amplified by two eight-channel power amplifiers to drive the 16 inertial exciters of the type VISATON EX 45 S 8 Ohm. A real-time FFT-Analyzer of the type Ono Sokki CF-9200 is used to monitor the spectra of selected signals. An accelerometer of the type Kistler 8000M095 is mounted on the starboard pylon at the location indicated in Fig. 1 to measure the engine induced structural vibration in z-direction. The signal of this accelerometer serves as phase reference for the calculation of the interior sound pressure field from the 12 sequential measurements and it is also taken as the reference signal for the active feedforward control system. Since both engines are running without synchronization, the rotational speeds N1 and N2 (rotational speed of the high pressure compressor shaft) of the engines might be slightly different. However, the spectrogram in Fig. 4 provides no evidence of close tones around 137.5 Hz or 404 Hz. Therefore, only one reference sensor is taken to synthesize the disturbance pressure field in the cabin.

3. Numerical design

For the numerical design of the ANVC system it is required to have access to the FRF matrix of all exciters to all microphones. Furthermore, the correct amplitudes and relative phases of the disturbance pressure field in the cabin must be available. The derivation of these quantities based on the acquired measurement data is described in the following subsection.

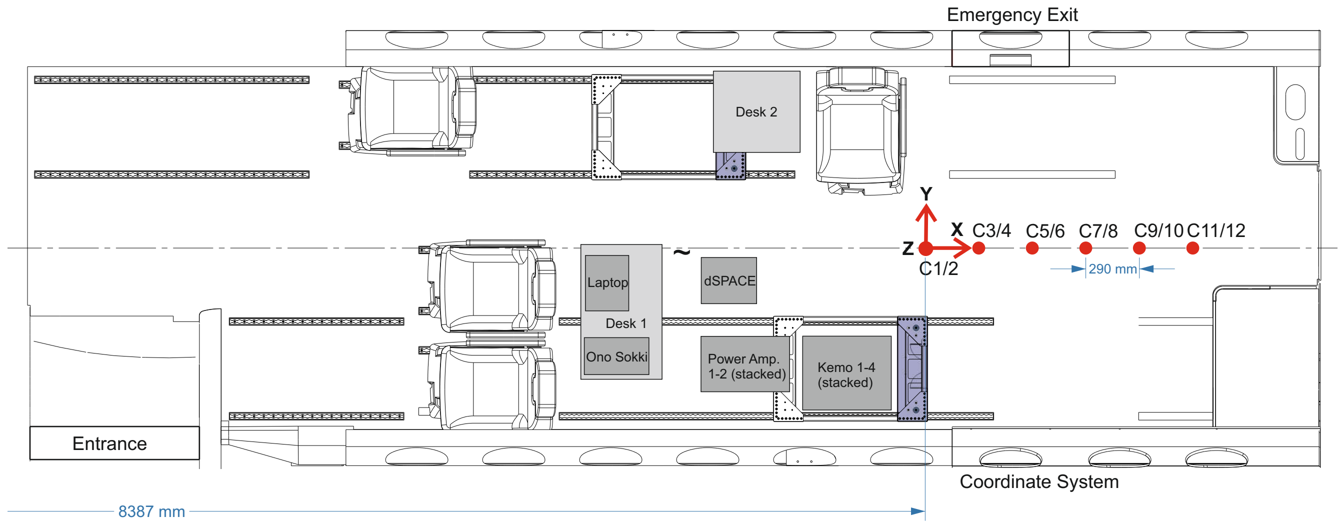

Figure 2: Sketch of the test setup in the iSTAR cabin. The two port seats are rotated by 180 degrees along the z-axis during the experiments. The local coordinate system is shifted by 8387 mm from the aircraft nose to the aft. The z-location of the coordinated system is 620 mm above the floor. The microphone stand location is indicated by red dots. The 312 microphone locations are measured sequentially in 12 configurations from six translations with two rotational angles at each location (C1 to C12).

3.1 Acquisition and post-processing of measurement data

According to Fig. 5 a total of 48 different exciter locations and 312 microphone locations are considered. Since the dSPACE system is limited to 16 analog outputs, the FRF matrix is assembled from three subsequent identification steps. In each step a multi-reference test with 16 uncorrelated bandlimited white noises and 26 microphones is repeated for all 12 configurations (C1 to C12 see Fig. 2). This leads to a total of 36 sequential multi-reference tests for the whole FRF matrix. These tests were performed in the aircraft hangar over a time span of two to three hours for each step. Mainly due to the reconfiguration of actuators, each step required a full day resulting in a total system identification time of three days. It is assumed that the system is linear and time-invariant for the duration of the test. The sampling rate is 2 kHz and the sampling duration is five minutes for each multi-reference test. The FRF are calculated using the H1 estimator with 75 complex averages. The frequency resolution of the FRF is 0.25 Hz. The FRF at the two frequency bins containing 137.5 Hz and 404 Hz are stored in the three dimensional matrix $\mathbf{G} \in \mathbb{C}^{i,j,k}$ for the control system design. The index $i = 1, \ldots, 312$ indicates the microphone, the index $j = 1, \ldots, 48$ indicates the exciter and the index $k = 1; 2$ indicates the harmonic.

The disturbance pressure field is assembled from 12 sequential measurements (C1 to C12 see Fig. 2). The sampling rate is 10 kHz and the sampling duration is two minutes. The signal from the accelerometer mounted to the starboard pylon serves as phase reference for this task. For each configuration the FRF of the reference signal to the 26 microphones is calculated using the H1 estimator with 30 complex averages.The frequency resolution of the FRF is 0.25 Hz. Here, the FRF values of the frequency bins close to the two harmonics with the highest magnitude squared coherence values are picked and stored in the two dimensional observer matrix $\mathbf{O} \in \mathbb{C}^{i,k}$. The selected frequency bins must not necessarily coincide with the bins containing 137.5 Hz and 404 Hz. Due to slight deviations of N1 and N2 from one to the other configuration, the highest coherence values occur at slightly different frequencies.

The spectra Y_{1k} of microphone 1 and the corresponding values O_{1k} of the observer at harmonic

Figure 3: Photo of test setup in aft of iSTAR cabin. 16 inertial exciters on the ceiling panel market with red dots and 26 microphones on a movable stand in configuration 11 (C11) of Fig.2.

$k = 1; 2$ are used for the calculation of the complex amplitude of the reference signal X_k (Eq. 1).

$$X_k = \frac{Y_{1k}}{O_{1k}} \quad \text{with} \quad k = 1; 2 \tag{1}$$

This leads to the matrix of disturbance pressure spectra $\mathbf{Y} \in \mathbb{C}^{312x2}$ consisting of the elements $Y_{ik} = O_{ik} X_k$. The choice of microphone 1 is arbitrary and any other microphone out of the 312 microphones could be used as well in Eq. 1. The derived matrices $\mathbf{G}$ and $\mathbf{Y}$ will be used in the following subsection for the design of an ANVC system.

3.2 Control design

The real-time implementation of the control algorithm will be a complex filtered-xLMS algorithm described in Misol [6]. It is assumed that the real-time controller will converge towards the optimal solution for tonal disturbances Eq. 2 (see Elliott [8, p.179ff]). This assumption is valid because the disturbance excitation from the engines is deterministic and changes of N1 and N2 are tracked fast enough by the adaptive algorithm.

$$\mathbf{U}_{opt,k} = -[\mathbf{G}_k^H \mathbf{G}_k]^{-1} \mathbf{G}_k^H \mathbf{Y}_k \quad \text{with} \quad k = 1; 2 \tag{2}$$

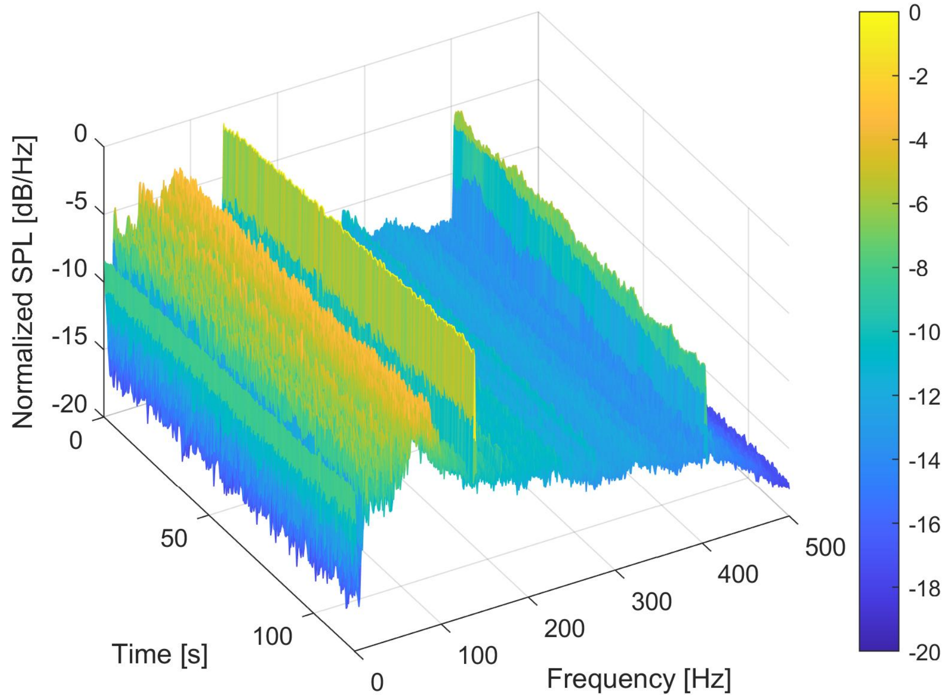

Figure 4: Normalized spectrogram of cabin sound pressure for 80% N1 averaged over all 312 microphones. The frequency resolution of the FFT is 1 Hz computed with 50% overlap (block size 0.5 s).

The residual error $\mathbf{E} \in \mathbb{C}^{312x2}$ follows directly from $\mathbf{E}_k = \mathbf{Y}_k + \mathbf{G}_k\mathbf{U}_{opt,k}$. The ANVC system performance is evaluated based on its global (all microphone) and local (error microphones) noise reduction. The required control voltages and the consumed electric power will also be taken into account. These performance metrics can be used to guide an optimization routine to derive the best system design. Besides the number and location of actuators also the number and location of error microphones play an important role. It was agreed with the industry partner Dassault to restrict the actuator locations on the ceiling panel. Restrictions on the spatial distribution of error microphones in the cabin have not been defined so far. The following section shows the results of one exemplary system design.

4. Results

The performance of a system with 16 exciters on the ceiling panel and 60 error microphones is numerically evaluated by using the synthesized data set and applying Eq. 2. The actuator and sensor locations are defined in Fig. 5. Figure 6 shows the distribution of normalized SPL in the error sensor plane. The left hand side shows the distribution in the uncontrolled case ($\mathbf{Y}$) and the right hand side shows the distribution in the controlled case ($\mathbf{E}$). For each harmonic, a normalization constant was taken to limit the values to one. The ANVC systems achieves a local SPL reduction of 13.6 dB and a global SPL reduction of -2.9 dB (i.e. an amplification of 2.9 dB). The maximum control voltage amplitude is 7.5 V. The maximum electric power of one exciter is 3.4 W (rms) and the total electric power of all 16 exciters is 9.9 W (rms). These values are below the exciter limits of 12.6 V and 10 W (rms). Considering the system design, it is concluded that the chosen exciters of the type Visaton EX 45 S are oversized and the exciter mass of 0.96 kg (16$\times$ 0.06 kg) could be further reduced in the final design. However, different system design could have higher voltage and power demands.

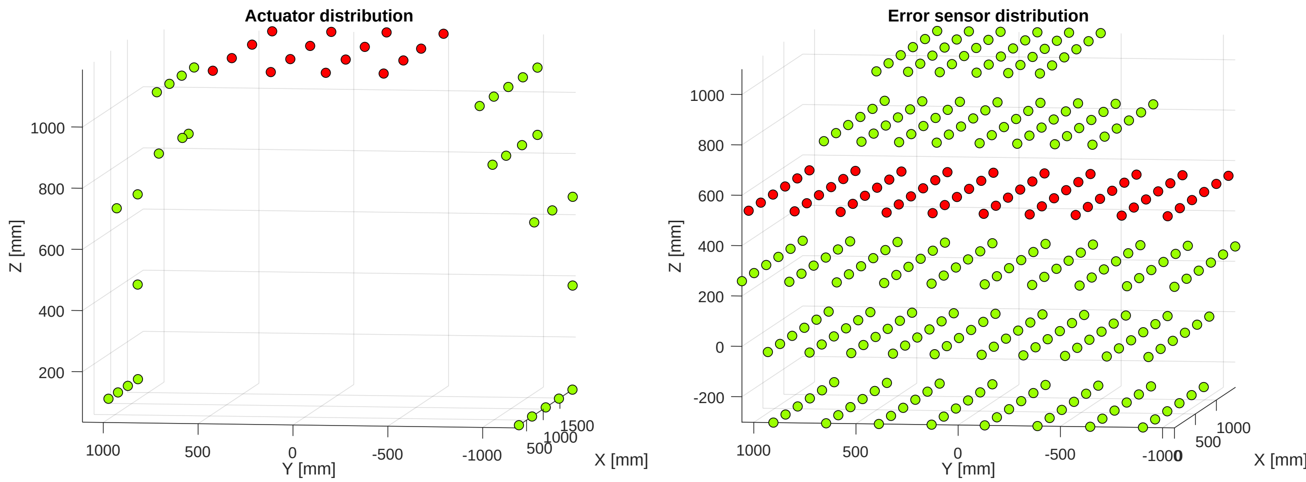

Figure 5: Actuator distribution on the sidewall structures (z-values below 800 mm), on the valence panels (z-values above 800 mm and below 1100 mm) and selected actuators on the ceiling panel marked by red dots (left). Distribution of 312 microphones in the cabin (right) The selected 60 error microphones are located in plane four (z-value 539 mm) which is assumed to coincide with the head plane of the passengers. The z-location of the microphone planes can also be seen in Fig. 3.

5. Conclusion and Outlook

A ground test with DLR's research aircraft Dassault Falcon 2000LX MSN 006 "iSTAR" (In-Flight Systems and Technology Airborne Research) is described. During the ground test, the sound pressures induced by the two engines running at 80% N1 (rotational speed of low the pressure compressor shaft) are captured in the cabin aft. Inertial exciters are mounted to the cabin interior parts and the FRFs to the cabin microphones are obtained from multi-reference tests. The interior sound field is synthesized from sequential measurements and an ANVC system is designed and evaluated based on the synthesized data.

Future work concentrates on the derivation and realization of an optimized ANVC system for a ceiling panel. Real-time control tests of the active ceiling panel will be performed in a sound transmission loss facility. A second ground test campaign is planned in July 2023 to validate the system performance.

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REFERENCES

1. Dorling, C. M., Eatwell, G. P., Hutchins, S. M., Ross, C. F. and Sutcliffe, S. A demonstration of active noise reduction in an aircraft cabin, *Journal of Sound and Vibration*, **128** (2), 358–360, (1989).

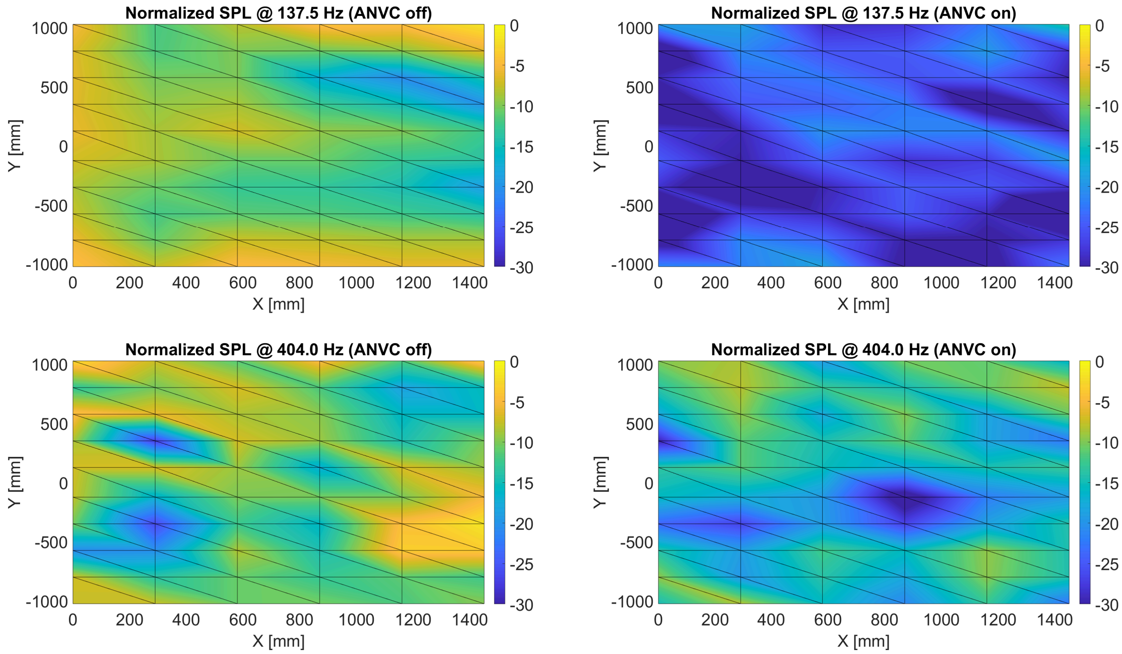

Figure 6: Distribution of normalized SPL in plane four with and without ANVC at 137.5 Hz (top) and 404 Hz (bottom).

2. Elliott, S. J., Nelson, P. A., Stothers, I. M. and Boucher, C. C. Preliminary results of in-flight experiments on the active control of propeller-induced cabin noise, *Journal of Sound and Vibration*, **128** (2), 355–357, (1989).

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

4. Emborg, U., Samuelsson, F., Holmgren, J. and Leth, S. Active and passive noise control in practice on the saab 2000 high speed turboprop, *4th AIAA/CEAS Aeroacoustics Conference*, Reston, Virigina, American Institute of Aeronautics and Astronautics, (1998).

5. Lyle, K. H. and Silcox, R. J. A study of active trim panels for interior noise reduction in an aircraft fuselage, *SAE Technical Paper Series*, SAE Technical Paper Series, SAE International400 Commonwealth Drive, Warrendale, PA, United States, (1995).

6. Misol, M. Full-scale experiments on the reduction of propeller-induced aircraft interior noise with active trim panels, *Applied Acoustics*, **159**, 107086, (2020).

7. Misol, M. Active sidewall panels with virtual microphones for aircraft interior noise reduction, *Applied Sciences*, **10** (19), 6828, (2020).

8. Elliott, S., *Signal Processing for Active Control*, Elsevier (2001).