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DESIGN OF AN INNOVATIVE FUSELAGE CABIN NOISE TESTING SYSTEM FOR REGIONAL AIRCRAFT

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The current interest in sustainable aviation is motivating the development of aircraft with better environmental performance. Within this context, advanced turboprops offer higher fuel efficiency compared to conventional turbofan engines. However, the cabin noise levels of propeller driven aircraft are significantly higher than those in common fanjets. The dominant noise sources in turboprop aircraft are the turbulent boundary layer noise, which is generated by the turbulent airflow exciting the fuselage, and the propeller induced noise caused by the periodic pressure fluctuations produced by the propeller blades passing near the fuselage. This paper presents the design of an innovative noise generation system that will be able to replicate, with a set of loudspeakers, the dynamic excitation given by both the turbulent boundary layer noise and the blade passing noise on a fuselage. The novelty of this system is the use of MIMO feedback controllers to simultaneously achieve desired sound pressure levels and spatial correlations at specific fuselage locations. The aim of the CONCERTO project (GA886836) is to develop cabin noise testing equipment that will be used to evaluate the interior noise of regional aircraft and to aid the development of noise reduction solutions. Firstly, a preliminary analysis of the noise generation system is carried out for a small-scale noise generation set-up. The system components are investigated and MIMO feedback control strategies are introduced. MIMO random control is used to replicate the random pressure field generated by the turbulent boundary layer excitation. The tonal components of the propeller induced excitation are then added to the broadband noise using a time waveform replication technique. The preliminary results for the small-scale set-up show that the power spectral densities of the measured microphone signals converge to those of the references within acceptable tolerance (±1.5 dB). Finally, the design of the modular mechanical structure for the full-scale innovative noise generation system is discussed.

Keywords: MIMO feedback control, turboprop aircraft

1. Introduction

The high noise level inside the cabin of turboprop aircraft is a major disadvantage for their widespread adoption [1], [2]. Cabin noise reduction is a very active field of research [3], [4], which heavily relies on experimental tests [5]–[7]. In-flight test campaigns are expensive, thus undesirable, especially during the initial development phase of a noise attenuation technique. An alternative approach is offered by ground tests in which arrays of loudspeakers are placed around the aircraft fuselage. These loudspeakers are then driven such that they can replicate the in-flight dynamic pressure field on the fuselage surface [8].

The dominant noise sources are propeller blade passage pressures and turbulent pressure fluctuations. The former noise source is generated by the propulsion system, whereas the latter is due to wind noise [9].

This paper presents the design of an innovative noise generation system (iNGS) that will be used to replicate the dynamic pressure loads due to both the turbulent boundary layer and the blade passage on a fuselage of a turboprop aircraft.

The paper begins by describing the system configuration for a small-scale demonstrator of the iNGS in Section 2.1. Section 2.2 introduces the Multi-Input Multi-Output (MIMO) feedback control strategies that are used to drive the loudspeakers. Preliminary results are then presented in Section 2.3. Finally, the design of the iNGS mechanical structure is illustrated in Section 3.

2. Preliminary analysis using a small-scale electroacoustic demonstrator

In this section, the system configuration, the MIMO control strategies, and the preliminary results are presented for a small-scale version of the iNGS.

2.1 System configuration

The experimental set-up of the small-scale electroacoustic demonstrator is shown in Fig. 1, where the test object is a steel cylindrical shell of 630 mm diameter. The set-up comprises a laptop with Simcenter Testlab software. MIMO Random Control and Time Waveform Replication worksheets of Testlab Dynamic Environmental Testing workbook are used for signal generation, recording and, in particular, for the implementation of the MIMO feedback control laws. The laptop is connected to a SCADAS Lab SYSCON Vibco with 16 inputs and 12 independent outputs. The SCADAS acts as an Analogue-to-Digital (ADC) and Digital-to-Analogue (DAC) converter. The output signals from the SCADAS are connected to a Digital Signal Processor (DSP), which is an Auvitran AVBx7 toolbox. This device is used as a switching matrix in order to redistribute the SCADAS outputs to their corresponding amplifier inputs.

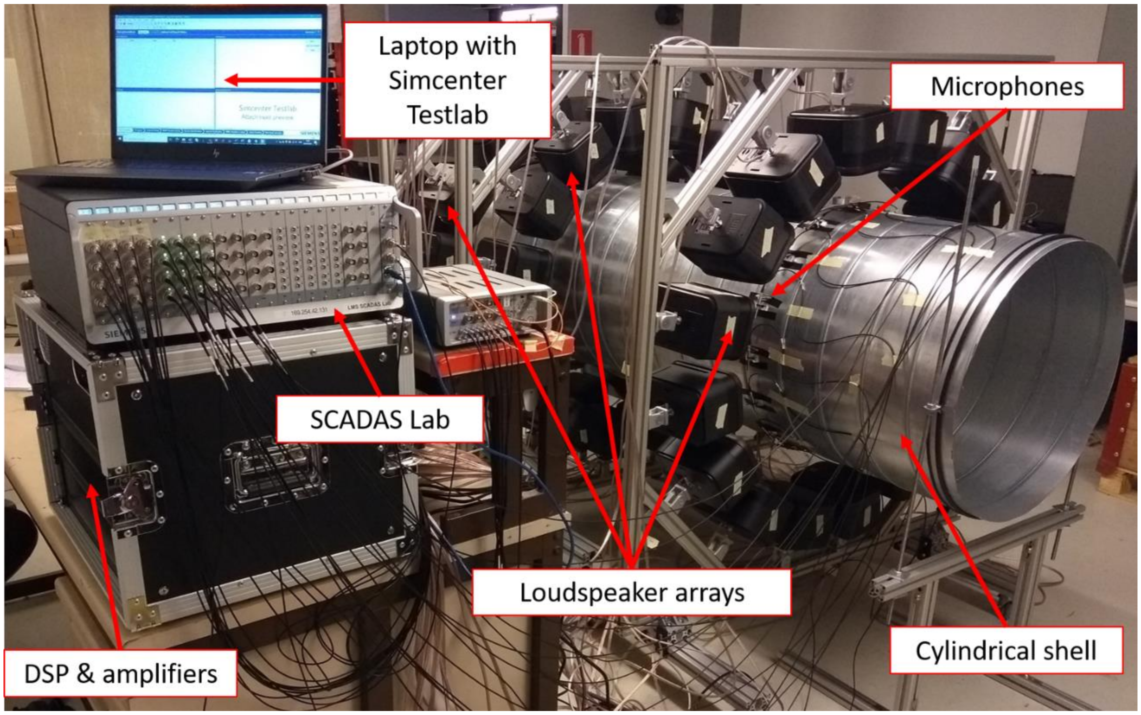

Figure 1: Picture of the small-scale electroacoustic test rig.

The switching matrix allows to use a number of independent drives (SCADAS outputs) that is different from the number of acoustic sources (loudspeakers). The switching can be conveniently performed with a Graphical User Interface (GUI) provided by the manufacturer.

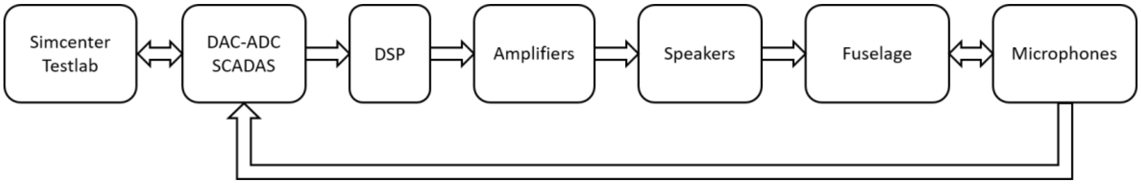

Figure 2: Block diagram of the iNGS configuration.

This device is then connected to three Audac DPA616 16-channel audio amplifiers. The amplified signals are then sent to 48 JBL Control 1 Pro loudspeakers subdivided in three rings of 16 equally spaced loudspeakers each. The acoustic field generated by the loudspeakers is measured by a set of collocated microphones attached on a cylindrical shell whose dimensions are 630 mm diameter and 2000 mm length. The cylindrical shell was considered as a test object since it mimics the outer surface of a fuselage. During this test campaign one loudspeaker ring and one microphone ring were activated, hence 16 microphones were used: fourteen GRAS 40PH-10 and two PCB 130A10. The microphone measurements are then fed back in real time to the SCADAS. The block diagram of the whole system configuration is illustrated in Fig. 2.

2.2 MIMO control strategies

The aim of this research is to replicate the acoustic loads on the cylindrical shell of Fig. 1 using a set of loudspeakers, controlled via a feedback loop with the outputs of a number of control microphones scattered around the test object. The MIMO control techniques that are used to drive the loudspeakers are MIMO Random Control [10] and Time Waveform Replication (TWR) [11]. The first of the two approaches is a frequency-domain method that targets a user-specified Spectral Density Matrix (SDM). The second approach, instead, is a time-domain method, where the test specifications are transformed into multiple time histories that are used as the target signals. In this paper, we focus on the TWR control strategy, which is used to replicate a set of time series that contain information on both the broadband excitation and the multiple tonal components [11].

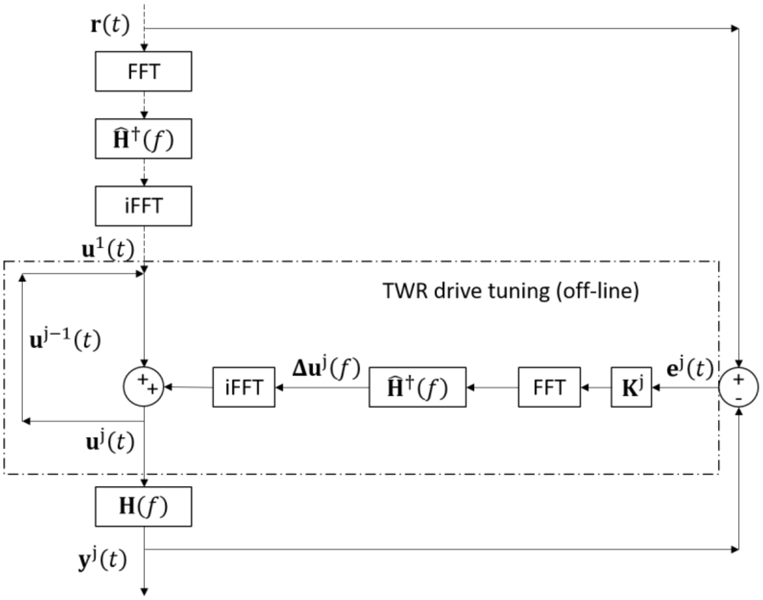

Figure 3: Block diagram of the time waveform replication control strategy.

The control target of TWR is a set of pressure time histories $\mathbf{r}(t)$ that have to be replicated. Firstly, a system identification is performed in order to estimate the matrix of FRFs $\widehat{\mathbf{H}}(f)$. Then the first set of drives is calculated as,

$$\mathbf{u}^{\mathbf{1}}(\boldsymbol{t}) = \mathrm{IFFT}\{\widehat{\mathbf{H}}^{\dagger}(\boldsymbol{f})\mathbf{r}(\boldsymbol{f})\}, \tag{1}$$

Where $\widehat{\mathbf{H}}^{\dagger}(f)$ indicates the pseudo-inverse of the system matrix. However, in practice, a difference between the estimated and the real system's dynamic behaviour exist. Hence, it is required to iteratively correct the drives in order to reduce the error $\mathbf{e}^{j}(\boldsymbol{t})$ between the recorded responses $\mathbf{y}^{j}(\boldsymbol{t})$ and the reference signals, as shown in Fig. 3. An entire recording of the time histories of the error needs to be used to update the drives with the error correction. In fact, this control loop takes place off-line between each iteration. A diagonal matrix of control gains $\mathbf{K}^{j}$ (with entries between 0 and 1) can be used to weight the error correction in order to prevent control instabilities.

2.3 Results

Preliminary results were obtained on the test rig shown in Fig. 1 where a single ring of 16 loudspeakers was activated and the acoustic field was measured by 16 collocated microphones. The switching matrix that connected the 12 SCADAS outputs to the 16 amplifier's channels was set up according to Figure 4. This signal distribution was selected based on the uniformity of the target acoustic field and the axisymmetric geometry of the set-up. Different logics of signal distribution will be investigated in future work.

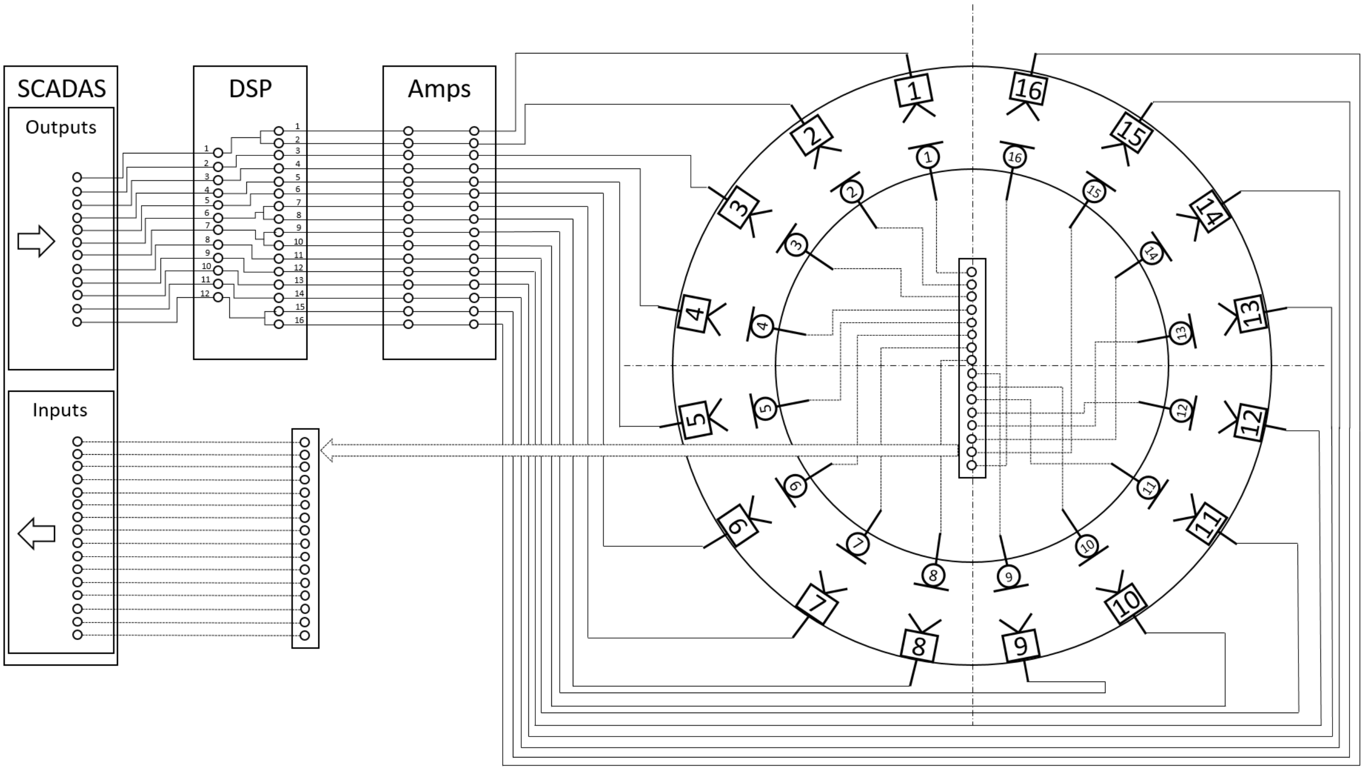

Figure 4: Switching matrix (DSP) configuration and loudspeaker-microphone arrangement.

The target profiles for the broadband excitation were specified as a uniform power spectral density (PSD) for each 1/3 octave band starting from 60 dB at 50 Hz and increasing to 85 dB at 1250 Hz, before ramping down to 50 dB at 10 kHz. On top of the broadband excitation, three tonal components were specified. The first one at 120 Hz with an amplitude of 1 Pa and then two harmonics at 240 Hz and 360 Hz with amplitudes of 0.5 Pa and 0.25 Pa, respectively. Both the broadband and the tonal target profiles are defined as equal at all the sixteen control microphones. The results of the experimental tests using TWR control are presented in Fig. 5.

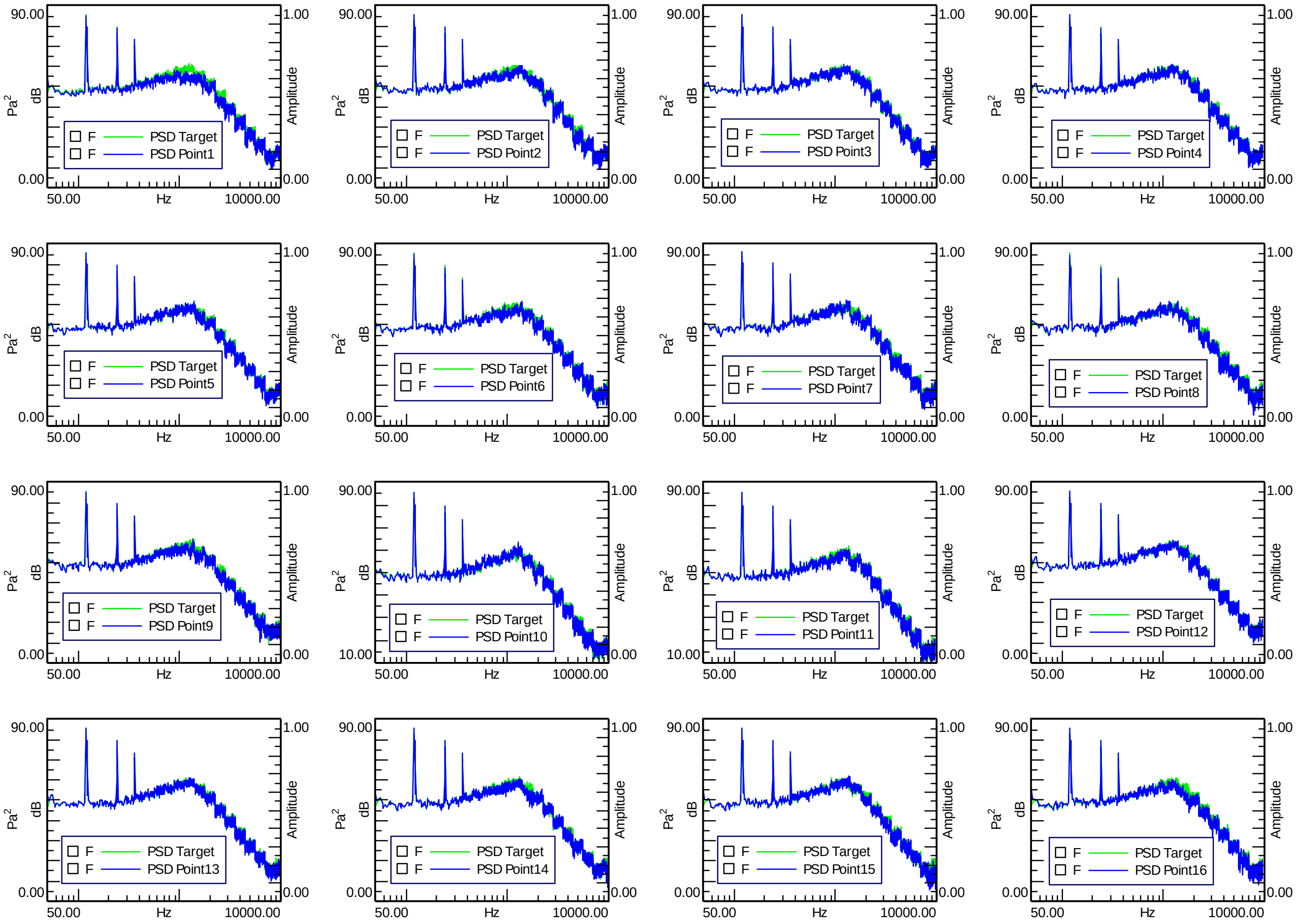

Figure 5: PSD of reference signal (green solid line) versus measured PSDs (blue solid lines) at the 16 control microphones.

The plots of Fig. 5 show the comparison between the PSDs of the reference signal (green solid line) and the measured ones (blue solid line) at the 16 control microphones after the 15th iteration of the TWR algorithm. The measured profiles provide an accurate replication of the target profiles at all the control locations for both the broadband and the tonal components of the spectra.

3. Design of the iNGS mechanical structure

The design of the full-scale iNGS includes a reconfigurable mechanical structure that supports arrays of loudspeakers around aircraft fuselages of differing diameters. The main design requirements for the iNGS mechanical structure are the following:

- Modular and adjustable frame that allows to install a variable number of loudspeakers around the fuselage barrel based on its diameter, which ranges from 2.5 m to 4.0 m;
- Three rings of loudspeaker arrays are placed around the fuselage barrel. These rings can be moved freely along the longitudinal direction (parallel to the fuselage axis), so that the distance among rings can be defined independently;
- Minimise the set-up time, in particular for the positioning of the loudspeakers.

The reference configuration of the mechanical structure, which will be used within the CONCERTO project to validate the MIMO feedback control algorithms, features three arrays of 22 loudspeakers each, around a fuselage barrel with a diameter of 3550 mm [12].

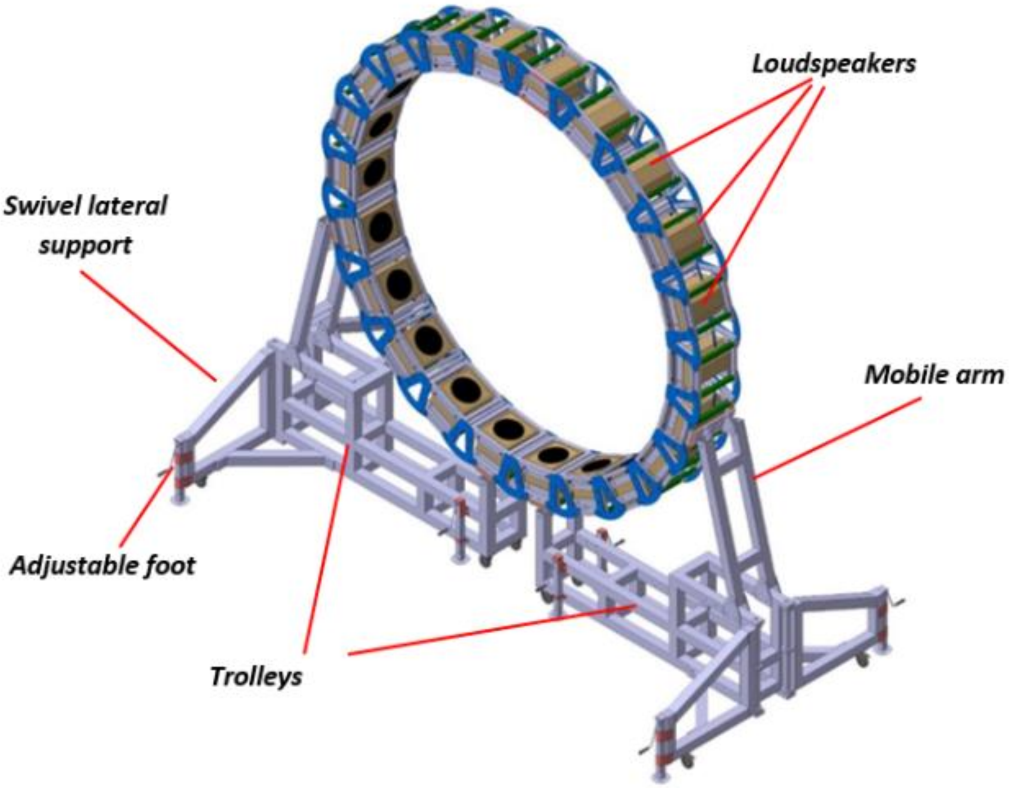

Figure 6: Array of 22 loudspeakers suitable for CleanSky1/CleanSky2 fuselage barrels.

A complete single array of 22 loudspeakers, mounted on two identical trolleys with swivel lateral supports, is represented in Fig. 6. The structure can be easily adapted to also fit around fuselages of non-circular cross-section.

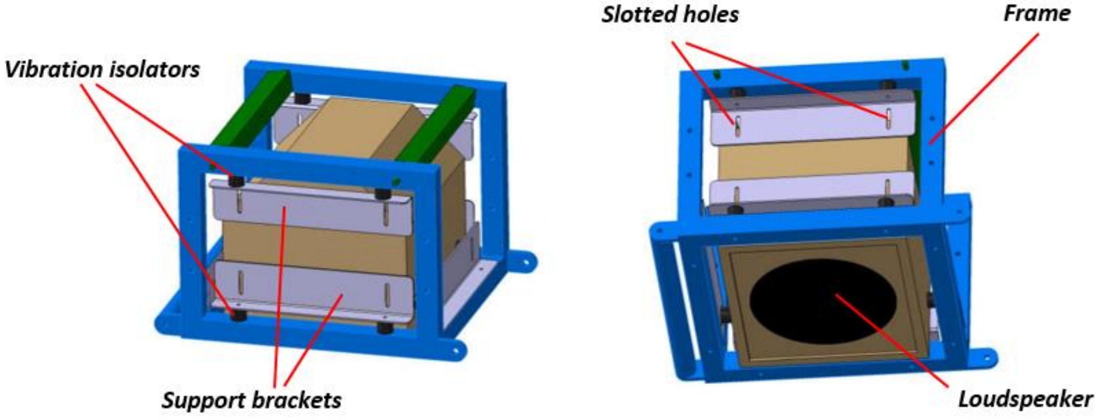

Figure 7: Views of loudspeaker module; several identical modules are hinged to one another to form one array.

Each loudspeaker is contained in a frame, as shown in Fig. 7. Slotted holes on special support brackets allow to adjust the loudspeakers radial position. In this way, the distance between each loudspeaker and the fuselage surface can be finely tuned. Vibration isolators are then used to connect the loudspeakers to the rigid frames. The loudspeaker frames are identical and hinged to one another so that the angle between the two adjacent loudspeakers can be adjusted, continuously, within the range of 10 to 40 degrees. This allows to easily change the internal diameter of the array, by adding or removing modules and adjusting the angle between these modules accordingly. The curvature is adjusted using the mechanism shown in Fig. 8. Connection plates are then used to add rigidity to the loudspeaker array by locking the modules firmly together.

Two identical trolleys support each array, as shown in Fig. 6. The same support trolleys are used for all the diameters of the circumferential arrays without requiring any component changes. The trolleys are equipped with swivel wheels and adjustable feet as well as swivel lateral supports, which allow to move the three arrays adjacent to one another. In this way, the acoustic excitation can be directed on a given section of the fuselage, and the desired spatial correlation in the streamwise direction can be achieved. The swivel lateral supports are rotated when two arrays must be placed side by side, otherwise, they are rigidly connected to a removable strut, increasing the stability of each array.

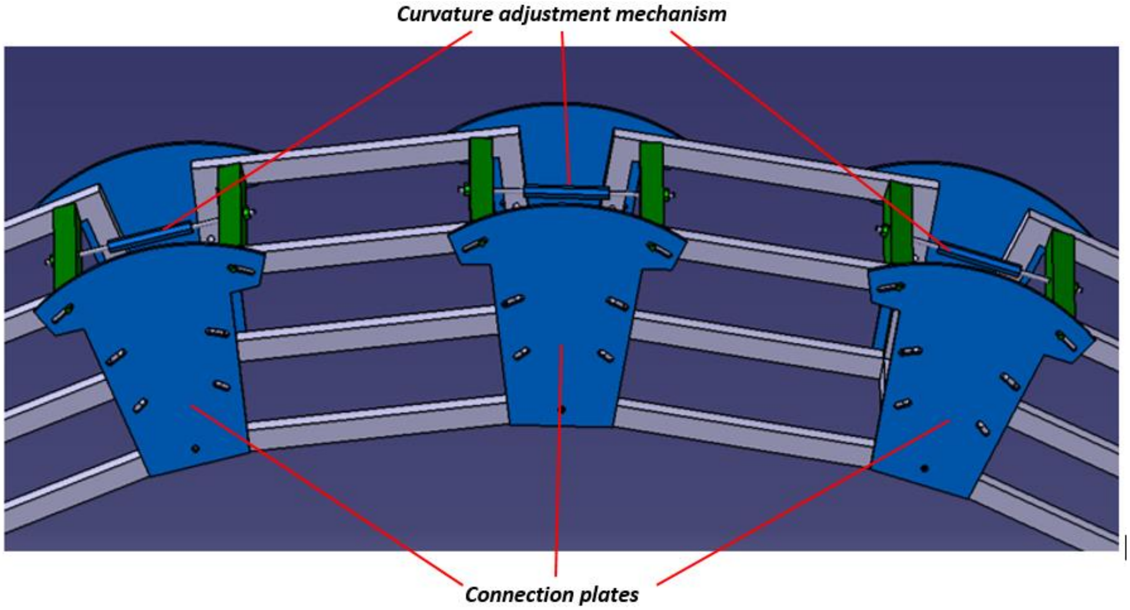

Figure 8: Curvature adjustment and locking mechanism.

Hence, the advantages of this iNGS mechanical structure design can be summarised as follows:

- Modular self-supporting system that does not require supporting bridges or cranes;
- Uniform density of loudspeakers per unit fuselage diameter;
- The same components are used for all fuselage geometries;
- Geometrical adjustments are possible without disassembling the arrays;
- Light and robust mechanical structure that can be adapted to differing fuselage cross-sections.

4. Conclusions and future work

This paper presented the design of an innovative noise generation system that will be able to replicate, with a set of loudspeakers, the dynamic pressure excitation given by both the turbulent boundary layer noise and the blade passing noise on a fuselage. Firstly, the experimental set-up of a small-scale electroacoustic demonstrator has been described. Secondly, the MIMO control strategies used to drive the loudspeakers from the measured microphone signals have been briefly introduced. Then the preliminary results of the TWR control approach applied on one ring of the small-scale electroacoustic demonstrator have been reported and discussed. This feedback control approach provided an excellent agreement between the recorded microphone spectra and the specified reference profiles for both the broadband excitation and the tonal components. Finally, the design of the mechanical structure of the full-scale iNGS has been presented. Its versatility and modularity has been highlighted, as well as its adaptability for differing fuselage diameters and cross-sections. In particular, this solution will provide a fast and accurate experimental set-up for noise test campaigns. Future work will concentrate on implementing the control strategies on all the three rings of the small-scale electroacoustic demonstrator and on the full-scale iNGS.

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REFERENCES

1 Johansson, S., *Active Control of Propeller-Induced Noise in Aircraft*, Blekinge Institute of Technology, Sweden, (2000).

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

3 Janssens, K., Vecchio, A. and Van der Auweraer, H., Synthesis and sound quality evaluation of exterior and interior aircraft noise, *Aerosp. Sci. Technol.*, **12**, (1), 114–124, (2008).

4 Van der Auweraer, H. *et al.*, Derivation of experimental vibro-acoustical models for ANC configuration design, *Proceedings of the 3rd AIAA/CEAS Aeroacoustics Conference*, Atlanta, GA, U.S.A., 12-14 May, (1997).

5 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, *J. Sound Vib.*, **128**, (2), 355–357, (1989).

6 Van der Auweraer, H., Otte, D., Brughmans, M., Waterman, E. and Reijnen, J., Primary sound field characterization of the Fokker 100 using experimental and numerical vibro-acoustical models, *Proceedings - National Conference on Noise Control Engineering*, **1**, 187–192, (1996).

7 Van der Auweraer, H., Martens, T., Waterman, E., Olbrechts, T., and Augusztinovicz, F., Comparison of structural and acoustical active noise control performance of the fokker 100 based on experimental simulation models, *in INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 1020–1027, (1996).

8 Hackstein, H. J., Borchers, I. U., Renger, K. and Vogt, K., The Dornier 328 Acoustic Test Cell (ATC) for interior noise tests and selected test results, *in Fourth Aircraft Interior Noise Workshop*, 34–43, (1992).

9 Wilby, J. F., Aircraft interior noise, *J. Sound Vib.*, **190**, (3), 545–564, (1996).

10 Peeters, B. and Debille, J., Multiple-input-multiple-output random vibration control: Theory and practice, *Proc. 2002 Int. Conf. Noise Vib. Eng. ISMA*, 507–516, (2002).

11 De Cuyper, J., *Linear feedback control for durability test rigs in the automotive industry*, PhD Thesis, Katholieke Universiteit Leuven, (2006).

12 CONCERTO Project [GA886836], (2020). *Analysis phase : Requirement matrix and support documentation*, [Online]. Available: https://www.project-concerto.eu/wp-content/uploads/2021/01/D1.1-Analysis-phase.pdf.