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MULTIPLE-INPUT MULTIPLE-OUTPUT ACOUSTIC TESTING OF TURBOPROP FUSELAGE STRUCTURES

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ABSTRACT

This paper presents a novel cabin noise testing equipment that is used to evaluate the interior noise of regional aircraft and to aid the development of noise reduction solutions. The innovative noise generation system consists of three modular frames that hold evenly distributed loudspeakers at a given distance around a fuselage. The near-field array of loudspeakers is used to synthesize a pressure field on the fuselage surface that is representative of the in-flight conditions. Hence, the target pressure profiles include the random pressure fluctuations of the turbulent boundary layer, and, at the same time, the periodic pressure fluctuations caused by the propeller blades passages.

The sound pressure is measured by a certain number of microphones collocated with the loudspeakers. The number and location of the microphones used in the control loop are selected using an optimisation analysis. The controller uses an iterative learning approach to minimise the error between the target and the measured pressure fields. The implementation and validation of the full-scale innovative noise generation system are presented.

Keywords: *sound synthesis, control, loudspeaker array.*

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1. INTRODUCTION

Cabin noise in turboprop aircraft is dominated by two sources: the tonal components generated by the periodic propeller blade passages near the fuselage, and the random pressure fluctuations generated by the turbulent boundary layer (TBL) around the fuselage [1]. Research focused on cabin noise reduction relies on either in-flight test campaigns, or ground tests with an accurate replication of the acoustic field [2-4]. On-ground tests use an array of loudspeakers around a turboprop fuselage to replicate the dynamic pressure field that acts on the fuselage surface during a flight [5-8]. To date, existing ground testing systems are characterised by a number of limitations that can be summarised in three categories: the manual tuning of the individual loudspeakers, the simultaneous replication of either harmonic or random excitations, and the partial coverage of the full fuselage circumference with the acoustic load [9]. This paper presents an innovative noise generation system (iNGS), object of CONCERTO project (GA 886836), that tries to address these limitations using three rings of loudspeaker arrays that cover the full fuselage section, a multiple-input multiple-output (MIMO) closed-loop controller for the automatic tuning of the loudspeakers, and the simultaneous replication of both the TBL noise and the blade passage noise. This work builds on previous research [10-11] and it focuses on the validation of the proposed approach on a full-scale iNGS. The design and the realization of the iNGS mechanical structure are illustrated in Sect. 2, whereas Sect. 3 describes the configuration of the system used during the validation tests. Sect. 4 presents the MIMO control strategy used to drive the loudspeakers and the generation of the acoustic target profiles including both tonal and random components. The results of the validation tests are reported in Sect. 5, and the conclusions are then summarised in Sect. 6.

2. INNOVATIVE NOISE GENERATION SYSTEM

The iNGS mechanical structure consists of three rings that can be placed around a fuselage trunk. Each ring, which is shown in Fig. 1, supports 22 loudspeakers that are joined together to form a modular assembly. As shown in Fig. 2, an adjustment mechanism is present between any two adjacent loudspeakers to modify the angle between the modules and thus the diameter of the ring. In this way, rings of various sizes can be realized by adding or removing modules to closely fit fuselages of differing diameters. The modular structure can also be easily adapted to fit also around fuselages that have a non-circular cross-section. Each ring is mounted on a couple of trolleys with wheels, swivel lateral supports and adjustable feet.

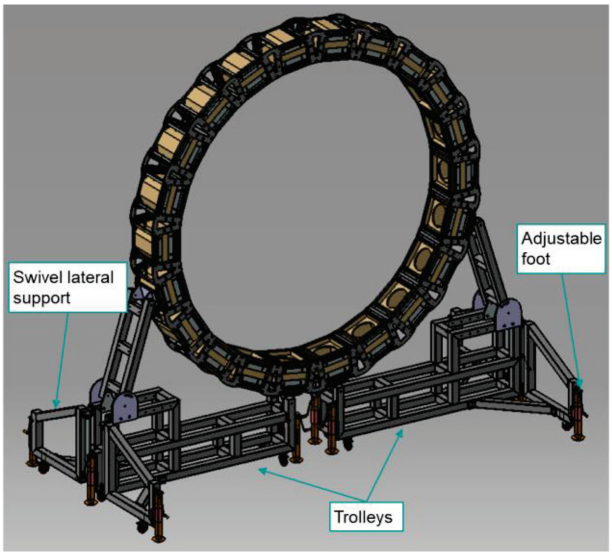

Figure 1. CAD of the ring structure holding the loudspeaker array. Three such structures have been built to be placed around a fuselage barrel.

The trolleys allow to freely move the rings along the longitudinal direction (parallel to the fuselage axis), such that the distance among rings can be defined independently. Also, the swivel lateral supports 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.

The iNGS has been built as shown in Fig. 3. The characteristics of the design described in this section target the minimisation of the time it takes to set-up a test, especially regarding the positioning of the loudspeakers around a fuselage.

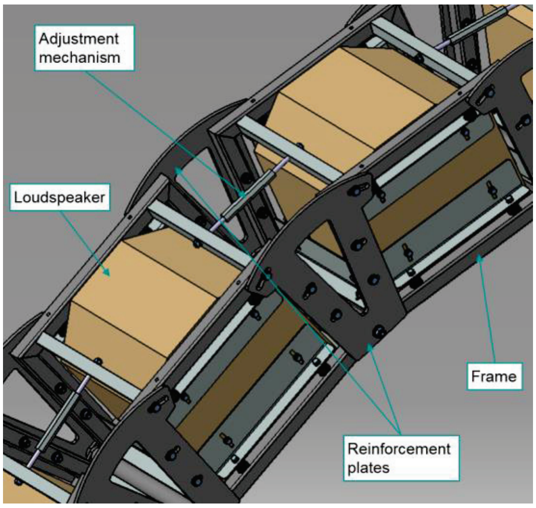

Figure 2. View of the loudspeaker modules that have been hinged one another to form an adjustable array.

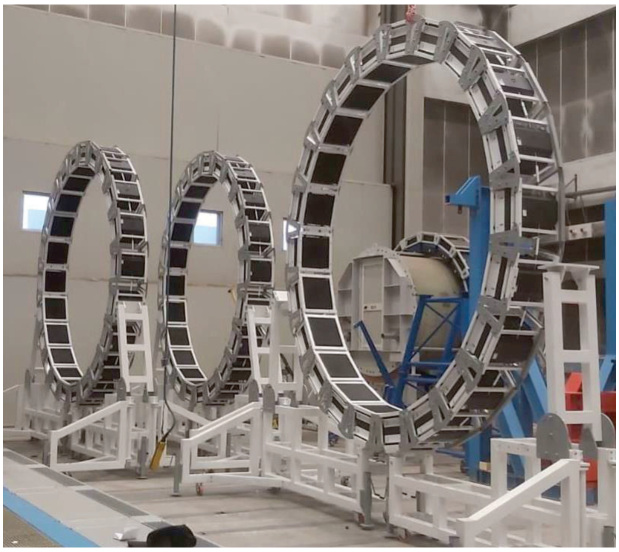

Figure 3. Picture of the iNGS with 3 rings of 22 loudspeakers each.

3. SYSTEM CONFIGURATION

The schematic of the system configuration is shown in Fig. 4. The set-up comprises a control station with a laptop with Simcenter Testlab software, which is used to for the 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 independent outputs and 66 inputs. The SCADAS outputs are connected to a Digital Signal Processor (DSP), also called switching matrix here, which is an Auvitran AVBx7. This device redistributes the SCADAS outputs to their corresponding loudspeakers through the amplifiers. Both the amplifiers and the loudspeakers have been custom built by Sonora Srl. The switching matrix maps the 16 independent drives (SCADAS outputs) to the 66 loudspeaker excitations. The switching can be conveniently performed through a software interface using AVS-Monitor, which is an application provided by the DSP manufacturer. The acoustic field generated by the loudspeakers is measured by 66 collocated PCB microphones attached on the external surface of the fuselage. The microphone signals are then fed back to the SCADAS Lab.

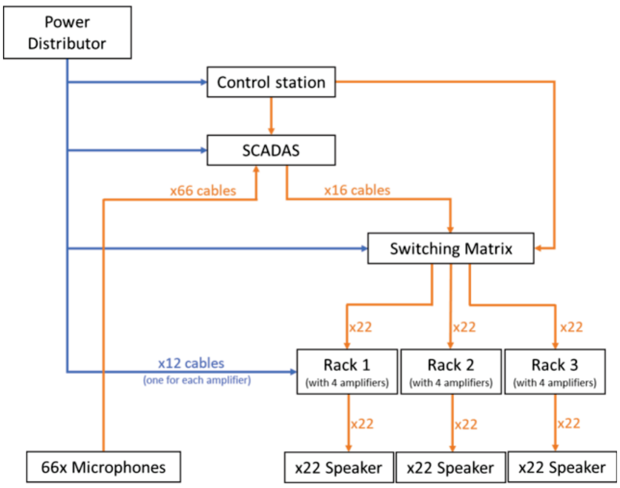

Figure 4. System diagram.

During the validation phase, the iNGS was tested without the presence of the fuselage. For this reason, the microphones were positioned at 10cm from the corresponding loudspeakers using tensioned cables across the diameter. This also means that there is no reflection of the sound waves on the outer fuselage skin, therefore, the MIMO system is highly coupled, and it is more difficult for the controller to accurately replicate the different targets at the different locations because of these interactions. The tests were set-up according to the schematic in Fig. 5 for ring #3.

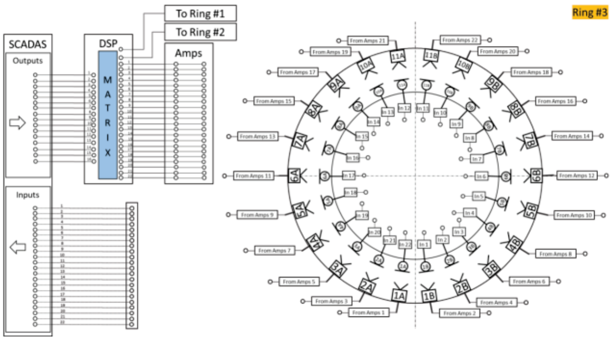

Figure 5. Schematic of test configuration of ring #3.

The switching matrix that connects the 16 SCADAS outputs (drives) to the 22 loudspeakers (amplifier's channels) of ring #3 was configured according to Tab. 1. Since only ring #3 was tested, the number of independent drives needed was reduced to 11. The gains of each input and output channel have been defined and fixed during preliminary open-loop ground tests.

Table 1. Configuration of drive's distribution to loudspeakers.

		Drive #										
Loudspeaker # of ring #3		1	2	3	4	5	6	7	8	9	10	11
	01A											X
	01B	X										
	02A											X
	02B	X										
	03A										X	
	03B		X									
	04A										X	
	04B		X									
	05A									X		
	05B			X								
	06A									X		
	06B			X								
	07A								X			
	07B				X							
	08A								X			
	08B				X							
	09A							X				
	09B					X						
	10A							X				
	10B					X						
	11A						X					
	11B						X					

4. CONTROL STRATEGY

4.1 Selection of control channels

The number of control channels used in the feedback loop during the test can be optimized to improve the performance of the controller. If all the measurement microphones were used in the control law calculations, the memory usage would increase and the processing would be slower. It is more efficient to reduce the number of control sensors using a pre-test analysis tool [12], which allows to perform an optimal selection. In this paper, 20 control channels were selected out of the 22 available. The two channels used only for monitoring purposes are microphone 03A and microphone 08A of Fig. 5.

4.2 Generation of tones on random profiles

The acoustic pressure field to be replicated comes with two requirements: a tonal noise component at determined frequencies, amplitudes and phases, and a broadband noise component with given sound pressure levels (SPLs) at each third octave band. These specifications can be different for each control microphone location. A dedicated tool, Simcenter Replicator of Tones on Random (ROTOR), has been developed specifically for this purpose of generating target time histories by combining these references simultaneously. Fig. 6 shows the target definition in Simcenter ROTOR in terms of broadband components and tonal components at each control microphone location.

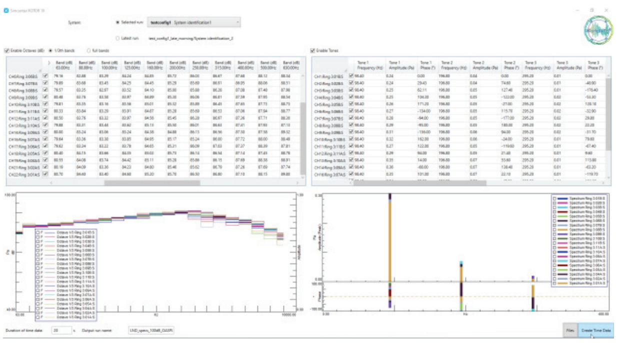

Figure 6. Target definition in Simcenter ROTOR and generation of the time traces for the 20 control channels.

The target time traces generation is described schematically in Fig. 7. A system identification is first carried out on the iNGS exciting the loudspeakers with 11 uncorrelated pseudo-random signals. Secondly, the specified third octave SPLs are translated into power spectral densities (PSDs) with a flat spectrum for each band. These PSDs are then combined with the cross-power spectral densities (CSDs) of the system identification. In general, the target CSDs could also be specified, for example if a particular spatial cross-correlation is sought. The resulting spectral density matrix for the broadband component is then transformed into time histories [13].

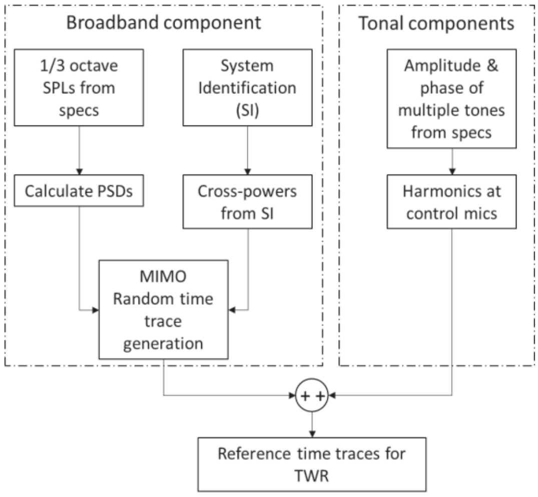

Figure 7. Schematic of the process to generate the target acoustic time traces at each control location.

The specified harmonic components in terms of frequency amplitude and relative phase are also translated in time domain with the same sampling frequency of the random noise time histories. Finally, the time traces of both the broadband component and the tonal component are combined to generate the target time traces for each control microphone that will be the references for Simcenter Testlab time waveform replication (TWR) control algorithm.

4.3 Time waveform replication

Once the reference time traces have been generated using Simcenter ROTOR, the TWR algorithm can be applied during a test as described in [10]. Fig. 8 shows the block diagram of the TWR approach, which can be briefly summarized with the following steps. The first set of driving signals that are sent to the loudspeakers are calculated from the target time traces $\mathbf{r}(t)$ and the matrix of frequency response functions (FRFs) $\hat{\mathbf{H}}(f)$ measured during the system identification, as

$$\mathbf{u}^{1}(t) = \mathrm{IFFT}\{\hat{\mathbf{H}}^{\dagger}(f)\mathbf{r}(f)\} \quad (1)$$

where $\hat{\mathbf{H}}^{\dagger}(f)$ indicates the pseudo-inverse. The error $\mathbf{e}^{j}(t)$ between the target time trace and the measured response $\mathbf{y}^{j}(t)$ at each control microphone is corrected iteratively by adjusting the driving signals via a matrix of control gains $\mathbf{K}^{j}$ between 0 and 1 to reach faster convergence or to prevent possible divergence.

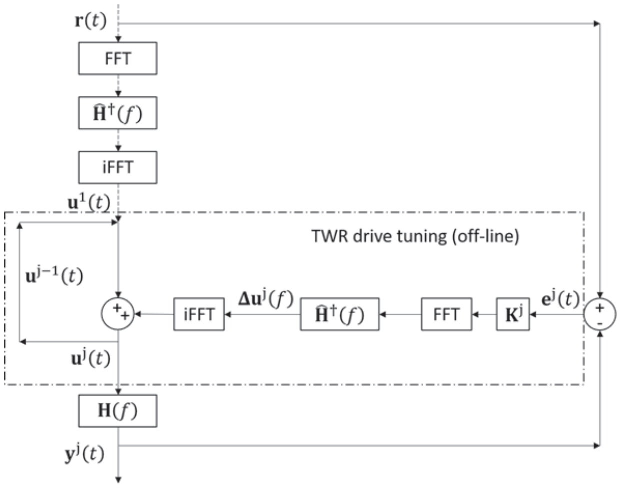

Figure 8. Block diagram of the time waveform replication control strategy.

5. RESULTS AND SYSTEM VALIDATION

The validation test using the TWR controller converged after 10 iterations. The results are shown in Fig. 9-10 in terms of PSDs between the reference profiles (green solid line) and the measured signals (blue solid line) at the 20 control microphone locations after the tenth iteration of the TWR algorithm. The results show an accurate replication of the target profiles at all control locations over the entire frequency range, except around 100Hz for the microphones 09B, 10B, 06B and 05B, which is close to the frequency of the first tonal component. The reason for this error can be attributed to the MIMO system being highly coupled and suffering from destructive interference at certain frequencies. The wavelength at 100Hz is about 3.44m and the internal diameter of the ring is 4.4m, since the reflecting surface (fuselage) was not present during these validation tests, the tonal component at certain microphone locations can suffer from destructive interference from almost diametrically opposed loudspeakers. Including the fuselage in future tests would certainly increase the accuracy with which the acoustic field can be replicated.

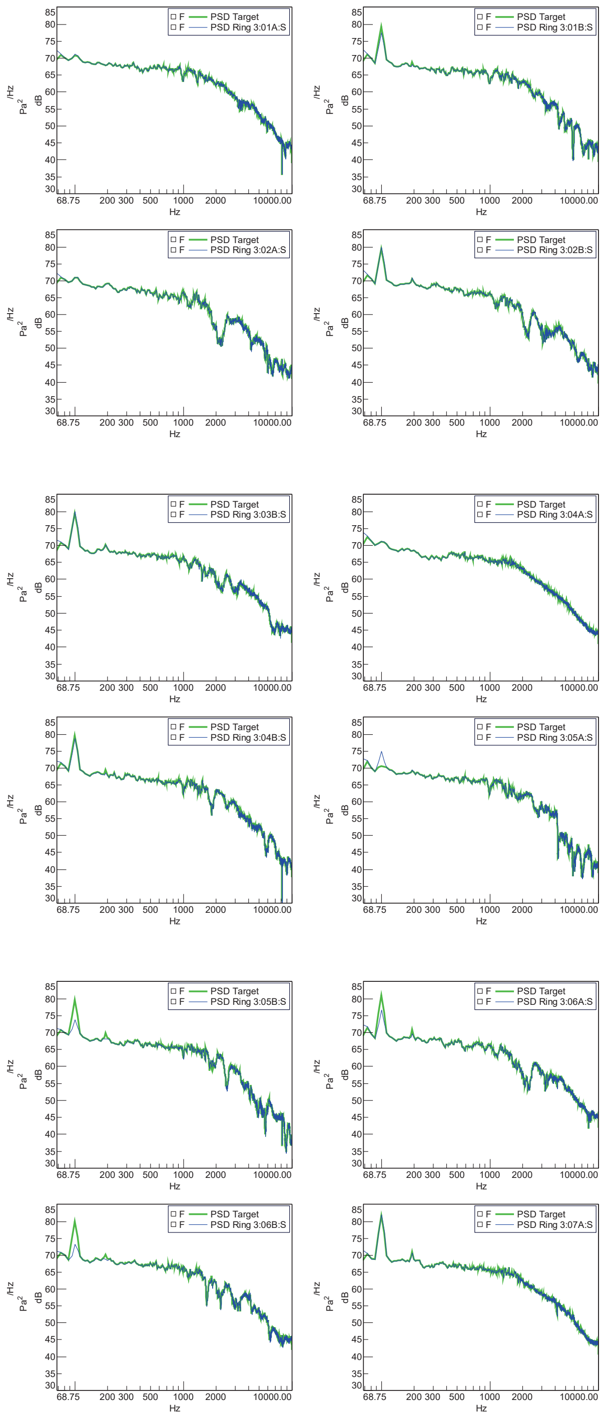

Figure 9. PSDs of reference signals (green solid line) versus measured PSDs (blue solid line) at the first 12 control microphones.

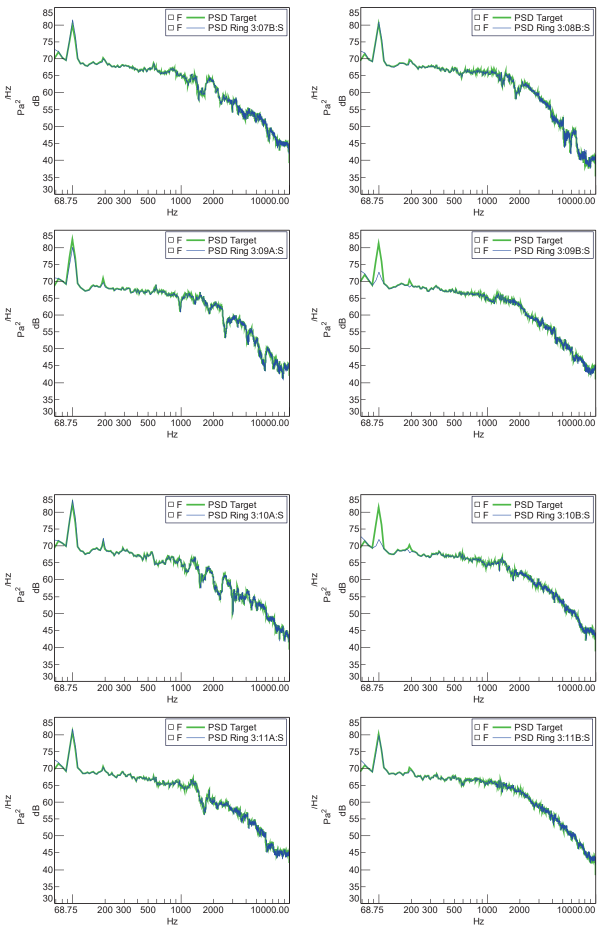

Figure 10. PSDs of reference signals (green solid line) versus measured PSDs (blue solid line) at the remaining 8 control microphones.

6. CONCLUSIONS

This paper presented the validation tests of an iNGS for on-ground turboprop fuselage testing. Firstly, the design and realisation of the full-scale iNGS mechanical structure has been presented. Secondly, the configuration of the electroacoustic system has been described as well as the set-up of the validation tests. The approach for the optimal selection of the control channels has been introduced and the process of generating target time traces combining the required SPLs for broadband noise and the harmonics for the tonal components has been discussed. The generated time traces are then used as target profiles for the TWR closed-loop controller during the test. Finally, the results of the validation tests were reported and the errors between target PSDs and measured ones at the control microphones were calculated. Although the absence of the fuselage as reflecting surface made the MIMO system highly coupled, it is shown that the control algorithms used for the iNGS can replicate the target pressure field with a high degree of accuracy. Future work will focus on testing a turboprop fuselage inside the iNGS.

7. ACKNOWLEDGMENTS

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