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Development of an innovative noise generation system for turboprop aircraft fuselage testing

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Abstract. This paper presents the development of a cabin noise testing equipment that will be used to evaluate the interior noise of regional aircraft as well as to aid the development of noise reduction techniques. The innovative noise generation system consists of three loudspeaker arrays positioned around the fuselage circumference to synthesize a pressure field that is similar to the pressure field seen by the fuselage during a flight. The acoustic pressure field generated by the loudspeakers is measured by a number of microphones scattered on the fuselage surface. These microphone signals are then fed back to the controller with the purpose of minimising the error between the target pressure field and the measured one by means of an iterative learning approach. The number and location of the microphones used in the control loop are selected through a pre-test optimisation analysis, which aims to reduce the time and cost of the set-up. A small-scale electroacoustic demonstrator has been built to develop the feedback control approach. A frequency domain multi-input multi-output feedback controller is used to replicate the random pressure field generated by the turbulent boundary layer excitation. The multi-harmonics of the propeller induced excitation are then added to the time histories of the broadband noise using a time waveform replication technique. Different arrangements of the driving signal distribution are investigated, and the results are then presented in terms of accuracy of the pressure field reproduction.

1. Introduction

This paper presents the development and detailed test results of a feedback control approach for the replication of tonal components on random noise applied to a small-scale electroacoustic demonstrator. This electroacoustic demonstrator is a small-scale version of the innovative noise generation system (iNGS) initially presented in [1], and it has been built for the purpose of developing the control strategy and carrying out the preliminary tests.

On-ground tests using near-field acoustic sources to replicate the dynamic pressure field acting on the fuselage surface of aircraft during a flight have been researched in the past [2,3] as well as in recent years [4,5] given the revived interest in fuel efficient, but usually noisy, turboprops.

Current systems, however, still rely on manual inputs for each loudspeaker and frequency band, can replicate only either the random or the harmonic excitations, or their acoustic load covers only a portion of the full circumference of the fuselage [6]. The iNGS tries to overcome these obstacles making use of three rings of loudspeaker arrays that cover the full fuselage section and a feedback control approach to replicate both the tonal and the random noise accounting for any uncertainties and disturbances in the system. A pre-test analysis based on the study in [7] is also implemented, which allows to select the optimum microphone locations to use in the control loop, therefore reducing the time and cost for the test set-up.

This paper builds on a previous conference paper [1] by presenting novel contributions that focus on the development of the strategy to replicate both the tonal and the random noise, and the test results when all three rings of loudspeakers are implemented with different signal distributions.

The electroacoustic demonstrator set-up is briefly recalled in section 2.1. Section 2.2 presents the generation of the target time histories that include both the tonal and random noise components. The test configurations and the results are reported in section 2.3 and section 2.4, respectively. The conclusions are then summarised in section 3.

2. Small-scale electroacoustic demonstrator
In this section are presented the test set-up, the strategy for the replication of tones on random noise and the results of the tests on the small-scale electroacoustic demonstrator with different signal distributions.

2.1. Experimental set-up
The experimental set-up of the small-scale electroacoustic demonstrator was first introduced in [1], and is shown in figure 1. With respect to the set-up presented in [1], all three rings of loudspeakers were activated for the present study and the number of microphones was increased to 48.

(a)   (b)
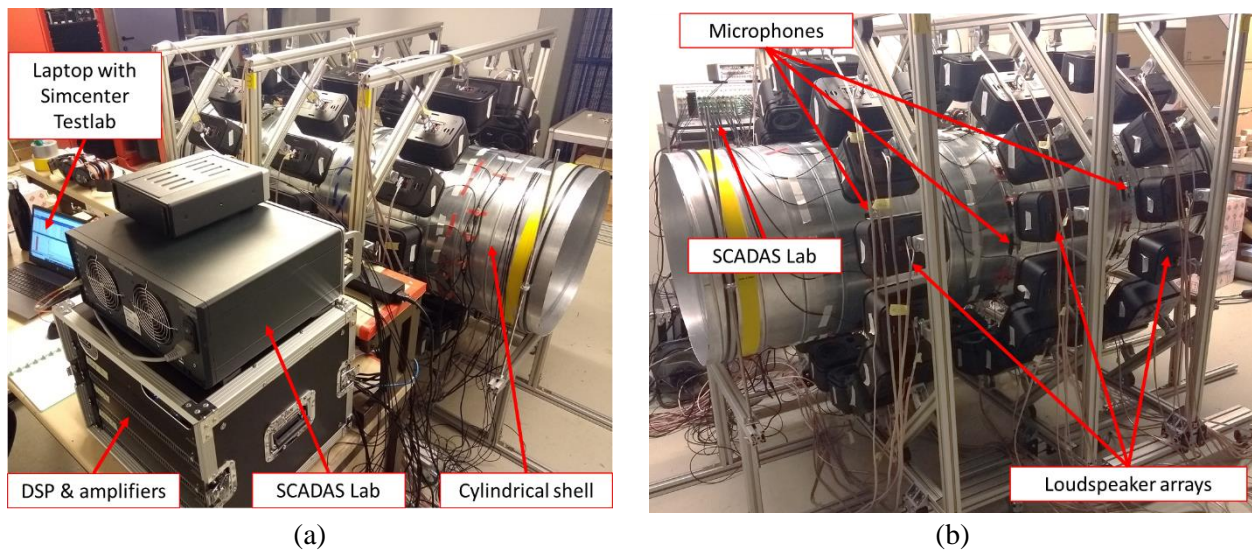
Figure 1. Small-scale electroacoustic test rig with a cylindrical shell as device under test.

The set-up comprises a 0.8 mm thick steel cylindrical shell of 630 mm diameter. A laptop running Simcenter Test.Lab is connected to a SCADAS Lab data acquisition system with 48 inputs and 16 independent outputs. The SCADAS outputs are connected to an Auvitran switching matrix that distributes the 16 drives to 48 amplification channels, which are linked one-to-one to 48 loudspeakers. The loudspeakers are uniformly distributed in three rings equally spaced around the centre of the cylindrical shell. The acoustic field generated by the loudspeakers is measured by a set of 48 collocated microphones attached on the device under test and the measurements are then fed back to the SCADAS.

During this test campaign several types of microphones were used, precisely: twenty-one GRAS 40PH-10, six PCB 130A10, thirteen PCB 130B10, seven GRAS 40PF, and one GRAS 40PQ.

2.2. Replicator of tones on random

The purpose of this research is to replicate an acoustic pressure field on the cylindrical shell of figure 1 using the loudspeaker arrays controlled via a feedback loop with the outputs of a number of control microphones positioned around the device under test.

The required pressure field to be replicated comes with two types of specification: 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. The former is related to one of the dominant noise sources in turboprops, which is the propeller blade passage that generate a tonal disturbance and harmonics thereof. The latter, instead, represents the pressure fluctuations generated by the turbulent airflow that excites the fuselage.

The target tonal and broadband components used in this study are reported in table 1 and table 2, which are the same for all the microphones at any location on the outer surface of the device under test. It should be noted that the phase of the tonal components among different microphones has been set to zero. In general, different target profiles can be specified for different microphone locations for both the tonal and the broadband components.

Table 1. Target tonal components of the acoustic pressure field.

Frequency (Hz)	Amplitude (Pa)
120	1
240	0.5
360	0.25

Table 2. Target profiles for the broadband component of the acoustic pressure field.

1/3 octave centre frequency (Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k	6.3k	8k	10k
Sound Pressure Level (dB)	60	61	62	63	65	66	67	68	70	73	75	78	80	83	85		83	80	75		70	65	60	55	50	50

The multi-input multi-output (MIMO) control strategy that is used in this study to drive the loudspeakers is called time waveform replication (TWR) [8]. As the name suggests, TWR is a time-domain method, which requires the test specifications given in table 1-2 to be transformed into multiple time histories before being used as target signals. A reduced number of control microphones that will be used in the feedback loop is first selected out of the full set of 48 microphones using a pre-test analysis, as detailed in [7]. In this study 20 microphones were selected as control microphones and the remaining ones were used for monitoring purposes, hence they were not involved in the feedback loop.

The target time histories are then generated following the schematic shown in figure 2, which we also refer to as the replicator of tones on random noise. A system identification is first conducted on the electroacoustic demonstrator exciting the loudspeakers with 16 random uncorrelated driving signals. Secondly, the third octave SPLs in table 2 are translated into power spectral densities (PSDs) with a flat spectrum for each band, using the same frequency resolution and bandwidth adopted for the system identification. These PSDs are then combined with the cross-power spectral densities (CSDs) of the system identification measured at the microphone locations to form a full spectral density matrix. In general, the target CSDs could also be specified, for example if a particular spatial cross-correlation is sought. The resulting spectral density matrix is then transformed into time histories using the MIMO

random time trace generation approach, which is documented in [9]. The sine waves at each control microphone with the specifications given in table 1 are also calculated using the same sampling frequency of the random noise time histories. Finally, the time traces of the broadband component are superimposed onto the time traces of the tonal components to create a set of target time histories.
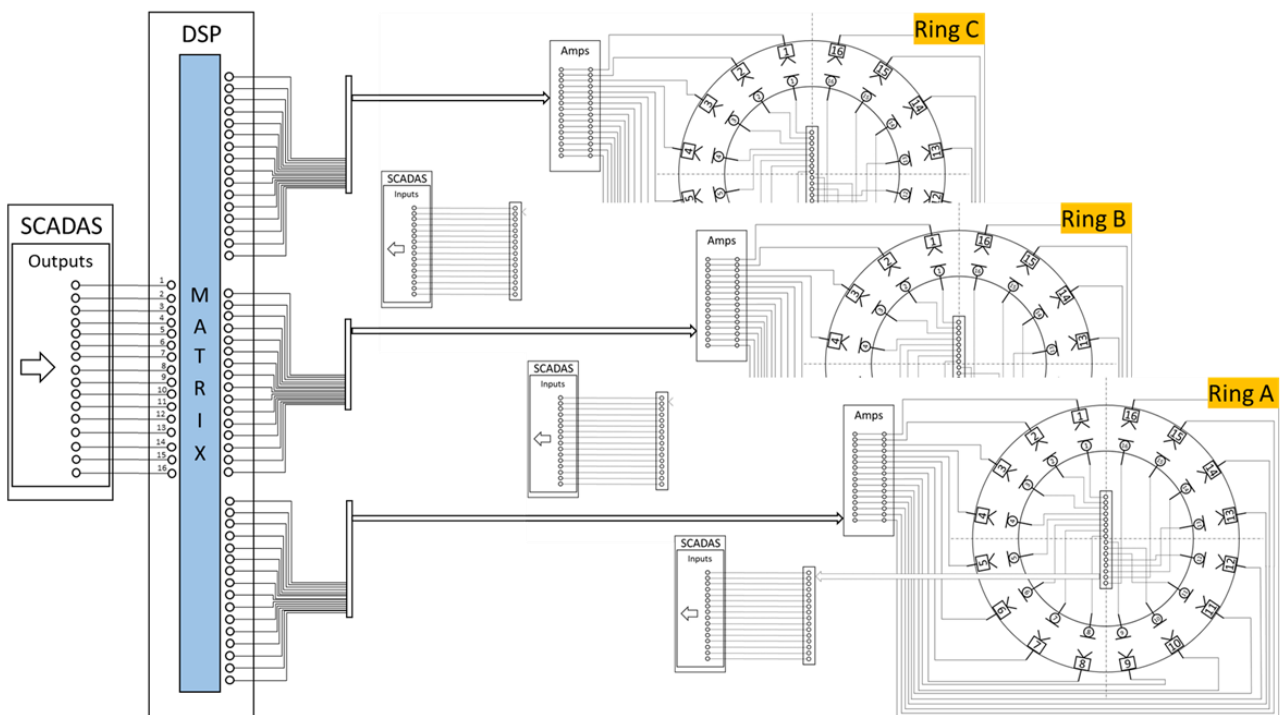
Once the reference time traces have been generated, the TWR algorithm is applied as in [1].
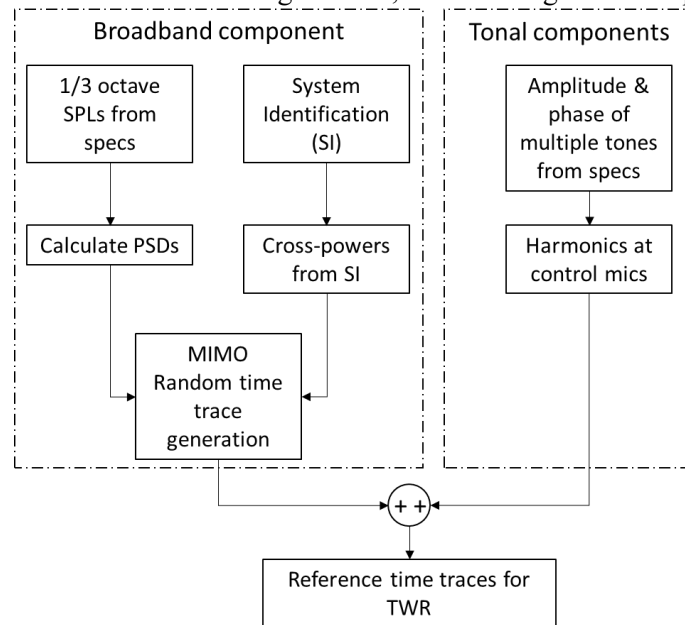
Figure 2. Generation of the time traces needed for the Time Waveform Replication (TWR) algorithm.
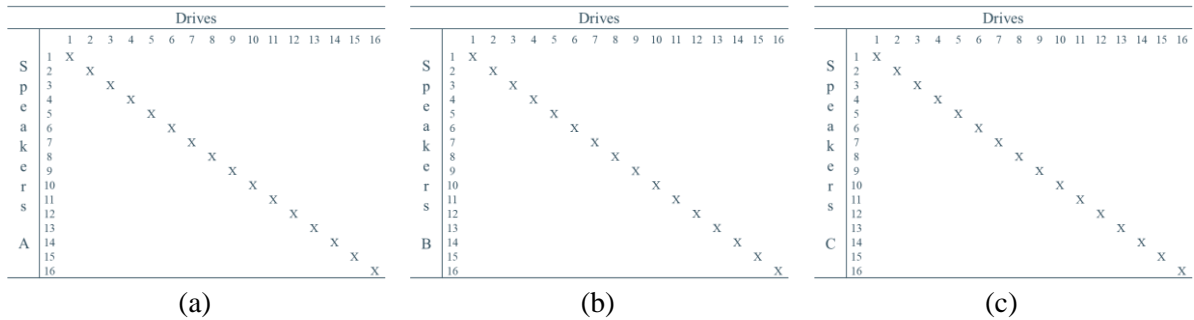
2.3. Test configurations
The tests were set-up according to the schematic in figure 3.

Figure 3. Schematic of the test configuration and loudspeaker-microphone arrangement.

The switching matrix that connects the 16 SCADAS outputs to the 48 amplifier's channels was set-up with two different logics of signal distribution for two different experiments with the same specifications.

2.3.1. Identical signal distribution repeated on each ring. The first arrangement of the switching matrix is the one shown in figure 4, where the 16 drives are distributed on a one-to-one mapping with the 16 loudspeakers of each ring. In this case the diagonal signal distribution is repeated identically on each ring. Hence, for example, drive 4 will be connected to the loudspeakers A4, B4 and C4.

(a)   (b)   (c)

**Figure 4.** Switching matrix (DSP) configuration for first test.

2.3.2. Signals distributed among rings. The second arrangement of the switching matrix is the one shown in figure 5, where the 16 drives are roughly equally distributed among the rings, specifically: 5 drives on ring A, 5 on ring B and the remaining 6 on ring C. In this case adjacent loudspeakers share the same driving signal, for example, drive 4 will be connected to the loudspeakers A10, A11, A12.


(a)   (b)   (c)
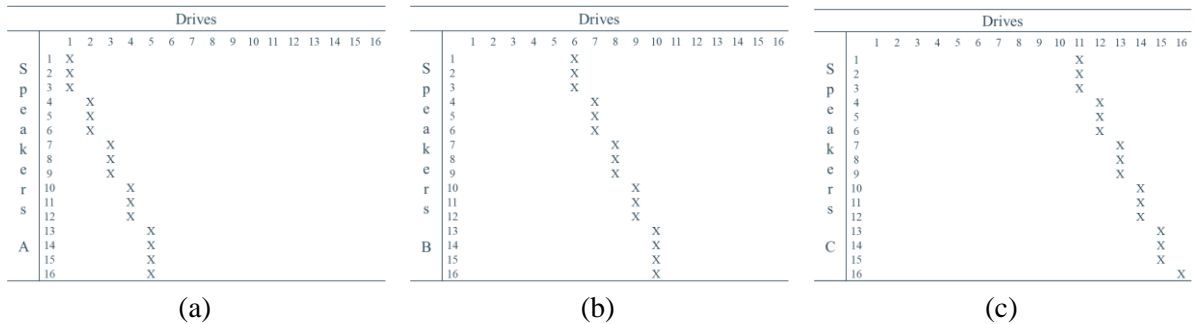
Figure 5. Switching matrix (DSP) configuration for second test.

2.4. Results

2.4.1. Identical signal distribution repeated on each ring. The results of the first test using TWR control on the reference profiles given in table 1 and table 2 are illustrated in figure 6. The plots of figure 6 show the comparison between the PSD of the reference signal (magenta solid line) and the measured ones (blue solid line) at the 20 control microphones after the 5th iteration of the TWR algorithm. In order to assess the accuracy of the sound field reproduction, the error between the target profiles and the measured sound pressures at each control microphone location has been calculated for each third octave band, as shown in figure 7. In this scenario, the error is always lower than 3 dB at all microphones and the spread of the error across microphones is within ± 1 dB over most of the frequency range considered (50 Hz – 10 kHz). The average error across all microphones and the complete frequency range sits below 1.5 dB.
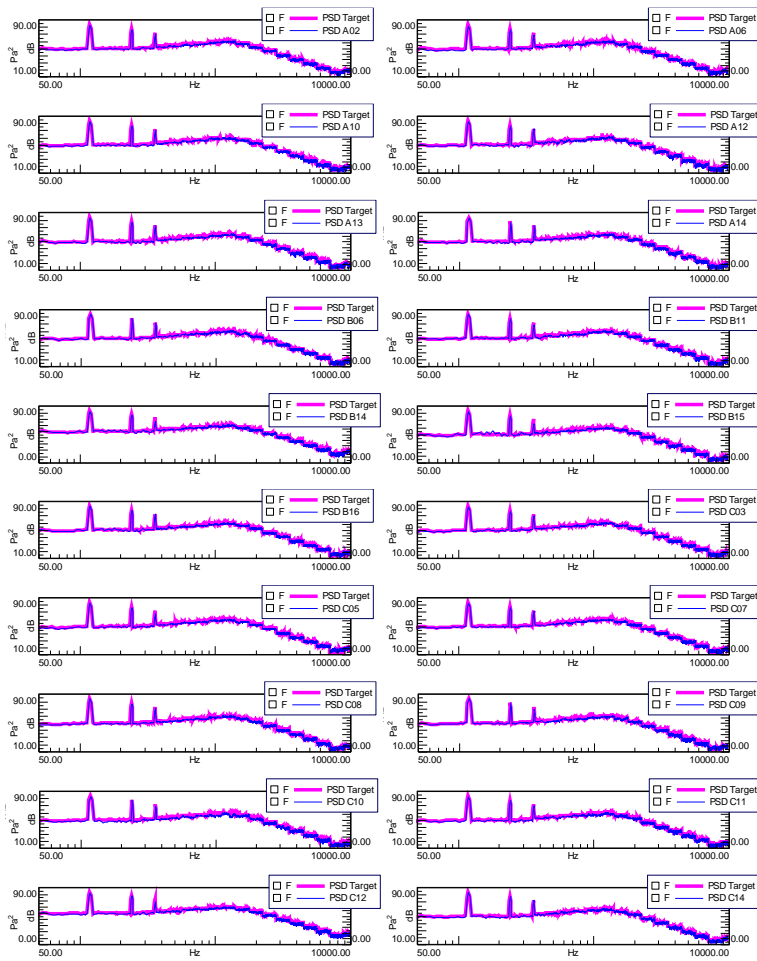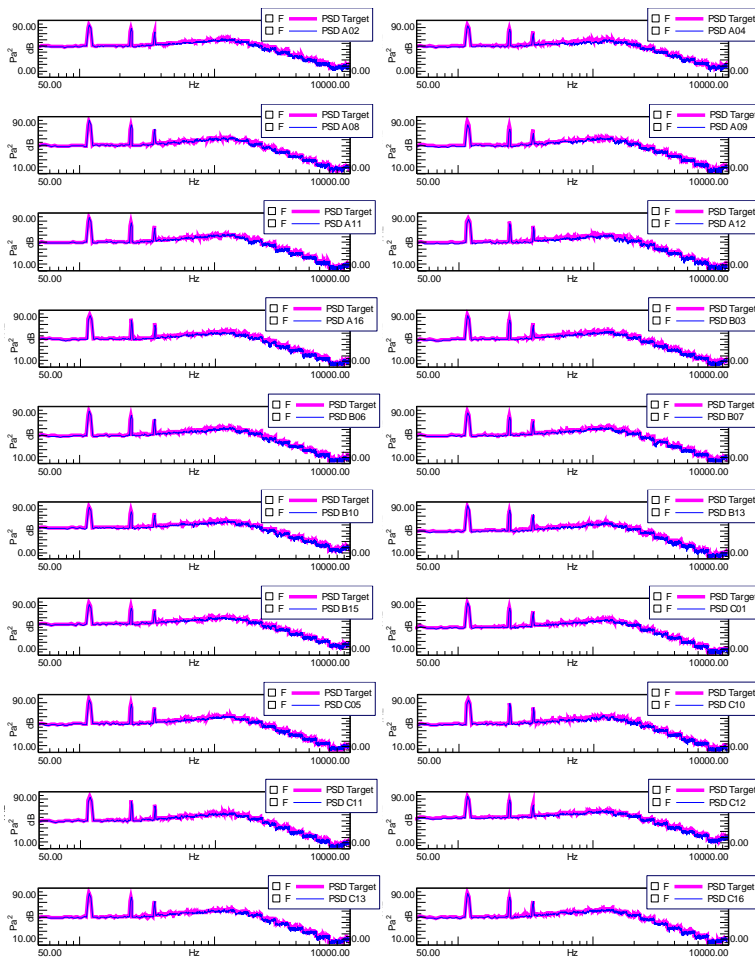
Figure 6. PSD of reference signal (magenta solid line) versus measured PSDs (blue solid line) at the 20 control microphones for the first test.
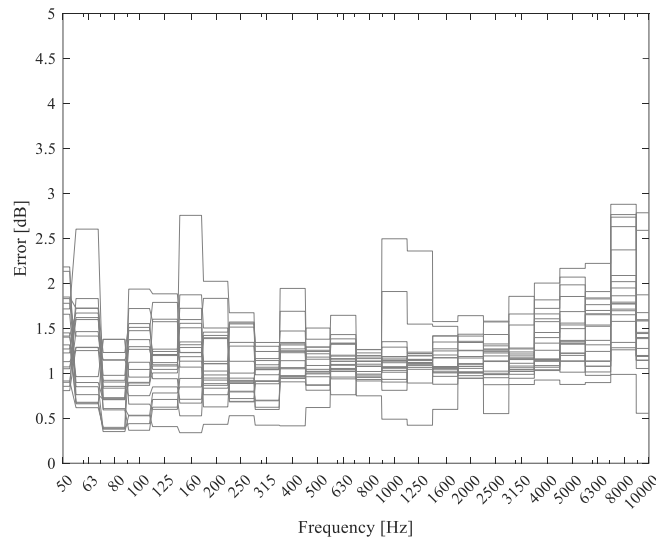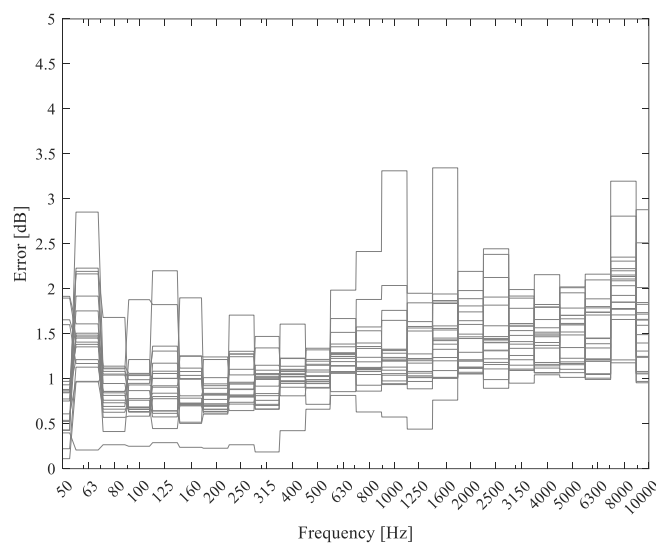

Figure 7. Error in 1/3 octave bands between the target signal and the measured signal at the 20 control microphones for the first test (each line represents a microphone).

2.4.2. Signals distributed among rings. The results of the second test are illustrated in figure 8.

Figure 8. PSD of reference signal (magenta solid line) versus measured PSDs (blue solid line) at the 20 control microphones for the second test.

Figure 9. Error in 1/3 octave bands between the target signal and the measured signal at the 20 control microphones for the second test (each line represents a microphone).

Similarly to figure 6, figure 8 also shows the comparison between target profiles (magenta solid line) and the measured PSDs (blue solid line). The error at each control microphone and third octave band is then displayed in figure 9. It can be noticed that even though the overall degree of accuracy is comparable to the scenario reported in section 2.4.1, in this case the 3 dB level is exceeded on three occasions by three different microphones. Also, the spread of the error across different microphones is higher than in the previous case, and there is a tendency of the average error to increase over frequency in this case.

3. Conclusions and future work

This paper presented the development of an innovative noise generation system for on-ground turboprop fuselage testing, which was facilitated by a small-scale electroacoustic demonstrator. Firstly, the experimental set-up of the electroacoustic test rig was recalled. Secondly, the algorithm that is used to generate the target time traces for both the random and tonal noise has been described, starting from the frequency domain specifications. The target time traces are then used as references in the TWR feedback control approach during the tests, as reported in [1]. Two different driving signal distributions were investigated as part of the switching matrix arrangement. Finally, the results of the tests were reported and the errors between target spectra and measured ones at the control microphones were calculated for each third octave band. It is shown that this system is able to replicate the target pressure field with a high degree of accuracy. In particular, a specific configuration of the signal distributions led the error to be lower than 3 dB at all control microphones for the entire frequency range (50 Hz – 10 kHz) and the average error to stay below 1.5 dB. Future work will concern the implementation and testing of this feedback control strategy on the full-scale iNGS.

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