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AEROACOUSTICS EFFECTS OF THE WAVY LEADING EDGE ON A FAN-RIG SDT STATORS

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Abstract. *The interaction between the turbulent wake of the rotor and the stator vanes has been identified as one of the main sources of broadband noise in a turbofan engine, in addition to the tonal noise. Studies inspired by the owl's silent flight have shown that the application of certain natural properties of its wings, such as the serrated pattern on the leading edge (Wavy Leading Edge), are effective techniques for reducing aircraft noise. The objective of this work was to analyze it on the stator vanes Source Diagnostic Test (SDT) Low-Noise model of the EESC/USP Rig-Fan bench. The geometry of the new vanes was defined and printed for the experimental tests and the analysis of noise emissions. The bench has acoustic instrumentation for data acquisition, and for its spectral analysis, the Welch method is used in signal processing. Tests were carried out with rotations from 800 to 1800 rpm for both stators. The acoustic measurements of the WLE stator when compared to the Low-Noise stator had a reduction of 1.5 to 4 dB in low and medium frequencies, while there was an increase in high frequencies of up to 1.2 dB. It is understood by this study that there is no ideal serration that reduces noise for all types of conditions that are imposed, but it is more efficient at low rotation speeds, which could be used to improve the landing or takeoff conditions of aircraft.*

Keywords: *Wavy Leading Edge, SDT, Reduction Noise, Rig Fan.*

1. INTRODUCTION

One of the main sources of noise in the landing and takeoff of an aircraft is the engine, which produces noise of the tonal and broadband type. Between the years 1940 to 1990 the most common among aircraft was the jet engine, but in 1970 turbofan engines were introduced in the market proposing better fuel efficiency and lower noise emission. With the high bypass technology - high derivation rate - defined by the ratio between the air flow that passes through the duct and through the center of the engine, the aircraft became silent, because with the increase of the bypass the speed of the jet. As a result, new sources of noise predominated, such as fan noise. Its main source is located in the interaction between the turbulent wake generated by the rotor blades incident on the stator vanes (GLEGG; DEVENPORT, 2017).

One of the applications to reduce noise radiation is the serrations devices on the leading edge (Wavy Leading Edge) in aerodynamic profiles, which gradually reduces the flow over the upper surface of the profile, smoothing the local pressure gradient and, thus, reducing the emission of associated noise. These devices originate from the physical characteristics of the wings of owls (Figure 1), being identified as an effective collaborator in the reduction of sound sources and for a better aerodynamic performance (WANG et al., 2019).

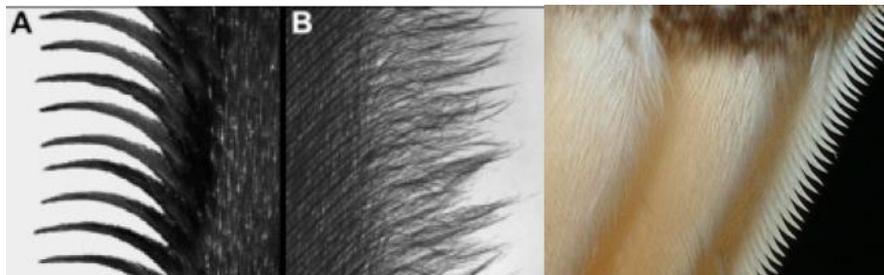


Figure 1. Physical characteristics of the owl's wing.

The use of these geometric modifications depends on parameters such as the wavelength (λ) and amplitude (A) of the serration (Fig. 2a). Broadband noise reduction is more sensitive to amplitude measurements than wavelength measurements (CHONG et al., 2015). Also, when (λ) decreases, noise reduction is greater at low and mid frequencies,

while smaller at higher frequencies. If this parameter is large enough, an increase in noise at high frequencies may occur (WANG et al., 2019). This can be observed in Fig. 2b.

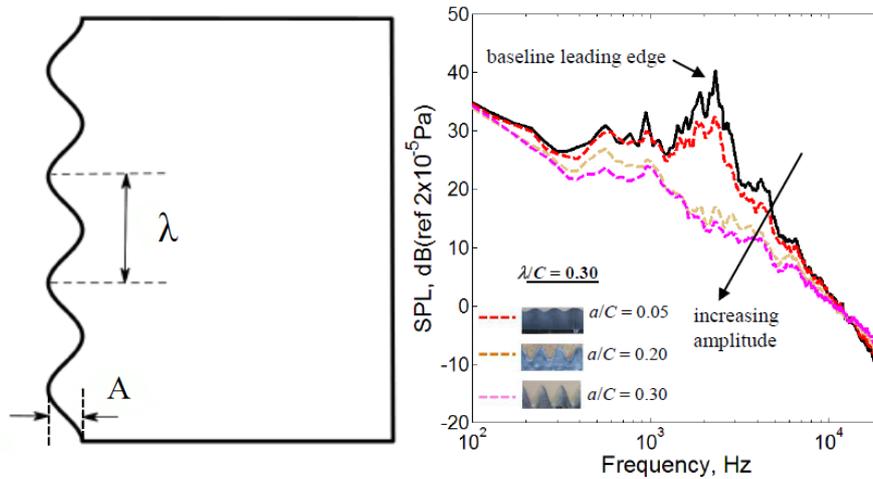


Figure 2a. Serrations on leading edge –WLE; Figure 2b. Noise levels with variation of serration amplitude, Chong. et al. (2015).

Claire et al. (2013) also studied the acoustic effects of three WLE models on the NACA 65 airfoil to reduce turbofan interaction noise. At high flow velocities, the WLE behaved like a low-pass filter, as they were more efficient above 1000 Hz. They demonstrated a reduction of about 3 to 4 dB without changing aerodynamic performance and their tested configurations performed better with the larger amplitude model. Noise reduction was about 6 dB at 3 kHz.

The broadband noise is generated by the turbulent flow, associated with the high Reynolds number and the main source of turbulence is the wake of the rotor blades (SMITH, 1989). When this disturbance interacts with the stator vanes, pressure fluctuations are generated in the vanes that produce tonal and broadband noise, known as rotor/stator interaction noise (OLAUSSON, 2011). In the fan stage, tonal noise is produced by the periodicity of the rotor wake, which is noise concentrated in a narrow part of the spectrum and contains a high proportion of energy at a single frequency.

The experimental study of aircraft engine noise can be performed using aeroacoustic tunnels. Reference models such as the Source Diagnostic Test (SDT) from NASA have a rotor/stator set with distinct geometries for simulations: baseline, Low-Count and Low-Noise (Fig. 3). The main function of the stators is to direct the flow to the compression stage, thus maximizing the thrust.

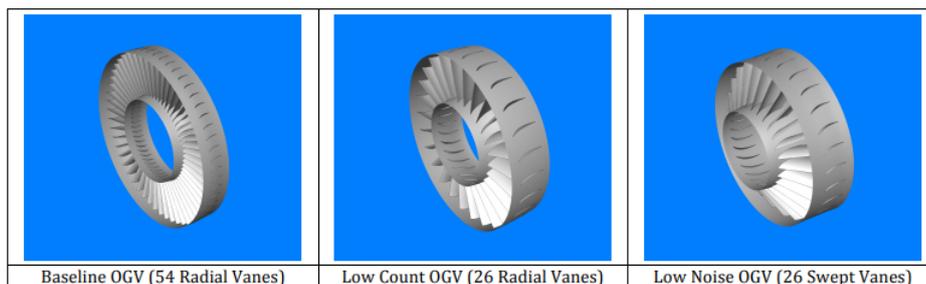


Figure 3. Stator geometries, NASA Glenn (2016).

Thus, the analysis of the aeroacoustic effects in a turbofan was carried out, after modifying the geometry of the blades of the Low-Noise model stator in the EESC/USP Rig-Fan bench (the only one in Brazil). The specifications for the tests are described in the following sections.

2. EXPERIMENTAL SETUP

The tests were carried out at the Aircraft Laboratory of the Department of Aeronautical Engineering at EESC-USP, using the Rig-Fan bench. The rotor/stator set uses the Low-Noise geometry of the SDT configuration as a reference. Contains 22 blades on the rotor and 26 vanes on the stator, with a sweep angle of 30° on the leading edge. Due to equipment limitations, the maximum speed reached by the fan during the tests was 1800 rpm.

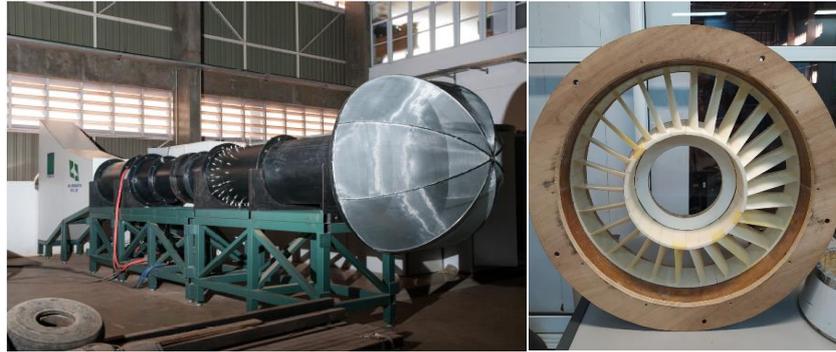


Figure 4a. Rig-Fan bench; Figure 4b. Low-Noise model stator.

Initially, the acoustic campaign of the Low-Noise model stator was carried out without the geometric modifications in its vanes. The tests were performed by changing the fan speed every 200 rpm. Table 1 describes the operations performed in this test:

Table 1. Test operations – Low-Noise stator.

Parameter	Especificação
Fan speed	800 : 200 : 1800
Throttle	0%, 25%, 40%, 55%

For flow control, a throttle following the ISO-5136 standard is used for exhaustion, which can restrict the outlet area by up to 70%. There is a tendency to reduce broadband noise levels by decreasing the flow rate (CUENCA, 2017).

In aeroacoustic instrumentation, the Rig-Fan has G.R.A.S 40PH-S2 $\phi 7$ mm model condenser microphones of high precision in the frequency range from 20Hz to 20kHz, which can be divided into 3 rings on the wall of the fan module. The acquisition system is composed of an NI PXI-1042Q board and data acquisition is performed by cDAQ on the bench computer. For aerodynamic measurements, a pitot tube and a TSI model 8705 DP-Calc micromanometer are used. In addition, there is a meteorological station for data on pressure, density and flow velocity.

2.1. Modified Stator

For the geometry of the vanes, the leading edge of the Low-Noise model was modified by adding serrations (Fig. 5a), following the literature by Chong et al. (2015), Clair et al. (2013) and Wang et al. (2019). The vanes were designed and printed in PLA material (Fig. 5b), following the geometries in Table 2. The λ value was defined so as not to be small enough to increase noise at high frequencies (above 6 kHz) and nor large enough to be greater than amplitude (A). According to Howe (1991), the ratio of the parameters of the serrated devices must be $A/\lambda > 1$.

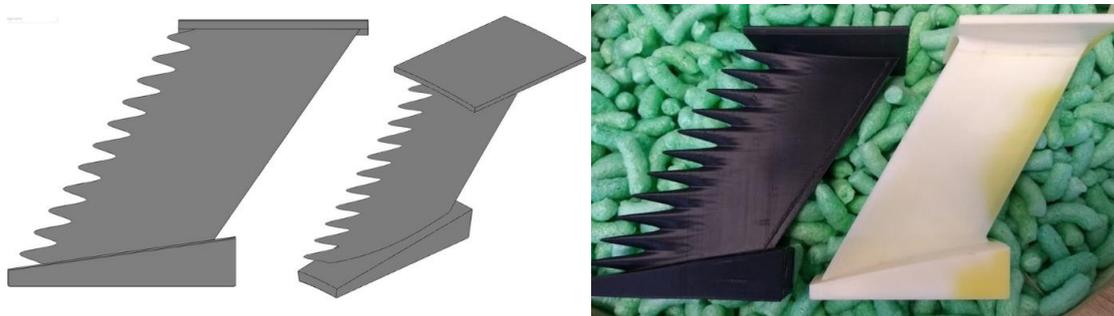


Figure 5a. Vane model WLE; Figure 5b. Vane modified x Low-Noise.

Table 2. Geometry WLE vanes (in % of chord)

Parâmetro	%C
λ	15
A	20
A/λ	1,33

All 26 vanes were printed and mounted on the duct's fan module, which is 600mm in diameter (Fig. 6). The same test operations carried out with the Low-Noise stator are also used for the modified stator model.



Figure 6. Stator WLE.

2.2. Acoustic Processing and Testing

The acoustic measurements performed by the Rig-Fan instrumentation refer to the noise power, being necessary to carry out conversions and data processing to obtain the desired type of signal. Microphones respond to pressure fluctuations by converting them into electronic signals. These signals arrive at the acquisition system and a time series is recorded and discretized at an acquisition rate of 52.1k samples per second. The analysis is carried out by converting the signal from the microphones to the frequency domain, in order to obtain its spectrum in Sound Pressure Levels (SPL) (Eq. 1).

$$SPL = 10 \log_{10} \left(\frac{p^2}{p_{ref}^2} \right) \quad (1)$$

where p^2 is the estimated PSD and the reference pressure $p_{ref} = 20 \mu\text{Pa}$.

For this, it is necessary to obtain the Power Spectral Density (PSD), which shows how the power is distributed along the frequencies. The spectra consist of methods for obtaining the PSD estimate (periodograms) without signal parameterization, and one of them is the Welch method, which is used for data processing:

$$[p_{xx}, f] = pwelch(x, \text{window}, \text{noverlap}, f, fs)$$

The input data (x) are exported from the bench acquisition system, where p_{xx} is the power spectral density. Signal (x) is segmented into eight sections of equal length, each with 50% overlap, using the Hanning window (determines the estimator resolution and minimizes Leakage effects). The frequency is the Nyquist frequency which is half of the sampling rate used.

For the acoustic measurements, 9 microphones were used, positioned in circles on the duct wall (Fig. 7) and calibrated for data processing. The first ring, with 8 microphones, is at a distance of 0.70 m from the fan module and the second with 1 microphone at 0.10 m from the first. Acquisitions were performed at a sampling rate of 51.2 kHz with a duration of 10 seconds for each rotor speed.

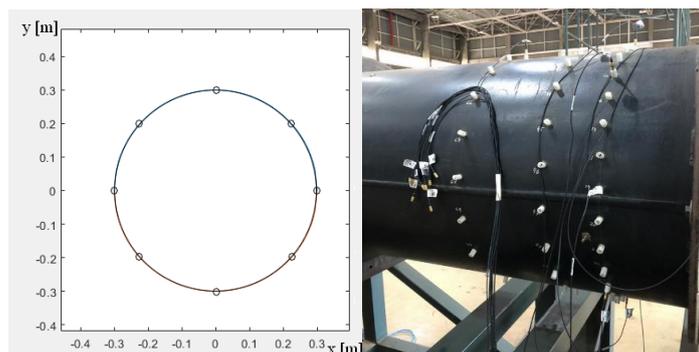


Figure 7. Microphones array.

3. ACOUSTICS TESTS

The first tests were carried out with the Low-Noise stator, which is used as a baseline for comparing the noise measurements with the new geometric model. In figure 8, it is possible to verify that with the increase in fan speed, there is also a considerable increase in noise levels, which was already expected. Through these spectra it is possible to observe both tonal and broadband noise.

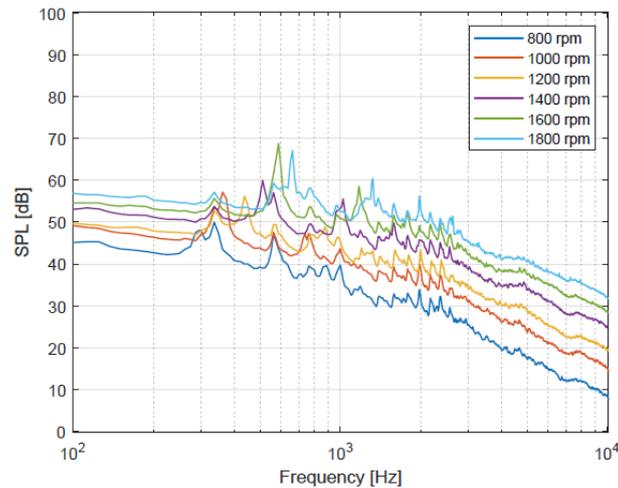


Figure 8. Rotor noise levels.

Another parameter changed during the tests was the exhaust area of the duct. Three throttles (plates) were used for flow control. This area restriction reduces broadband noise compared to open duct (0% throttle). The first plate causes about 25% restriction in the duct output, which causes a reduction in noise levels at low frequencies – 100 to 500 Hz, when tested at a speed of 800 rpm (Fig. 9).

Increasing the throttle (40% and 55%) generates an increase in noise at low frequencies, but a reduction in broadband noise, in the range of medium to high frequencies – 1.5 kHz to 6 kHz, because the turbulence in the wake is smaller due to the reduction of the axial velocity of the flow for the same rotation (CUENCA, 2017).

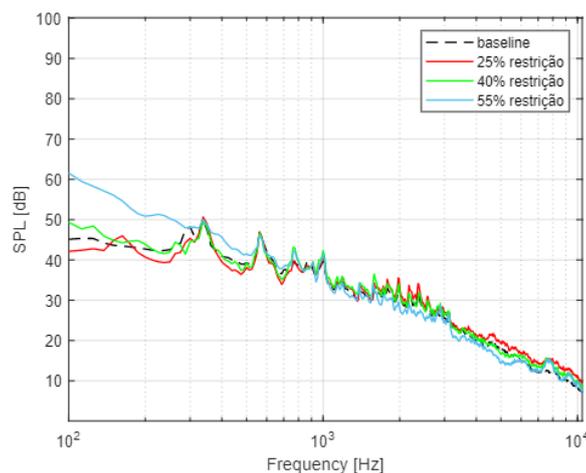


Figure 9. Sound pressure levels at 800 rpm in all area restrictions.

Results of the sound pressure levels emitted by the WLE model stator can be seen in Figure 10, with tested speeds from 800 to 1800 rpm, without area restriction (throttle). It was found that serrations are more effective at lower rotational speeds, as well as studied by Soderman (1973) having better noise reductions at low and medium frequencies.

Given the conditions imposed in these tests, serrations were more sensitive in reducing sound radiation at low rotation speeds (800 to 1000 rpm), because at high speeds, SPL levels are also higher, with more energy in the flow. Noise reduction decreases as the velocity of this flow increases. Because of this, the vortices that are generated in the serrated valleys (where the pressure is lower) were insufficient to reduce the periodicity of the turbulent wake.

The frequencies that had the highest $|\Delta\text{SPL}|$ calculated from 100 Hz to 10 kHz, which indicates a reduction or increase in sound pressure levels (Fig. 11), the noise reduction reached 1.5 to 4 dB in low and medium frequencies, while an increase was verified in high frequencies in the order of up to 1.2 dB. Insignificant changes were found in all frequency bands when tests were performed using throttle.

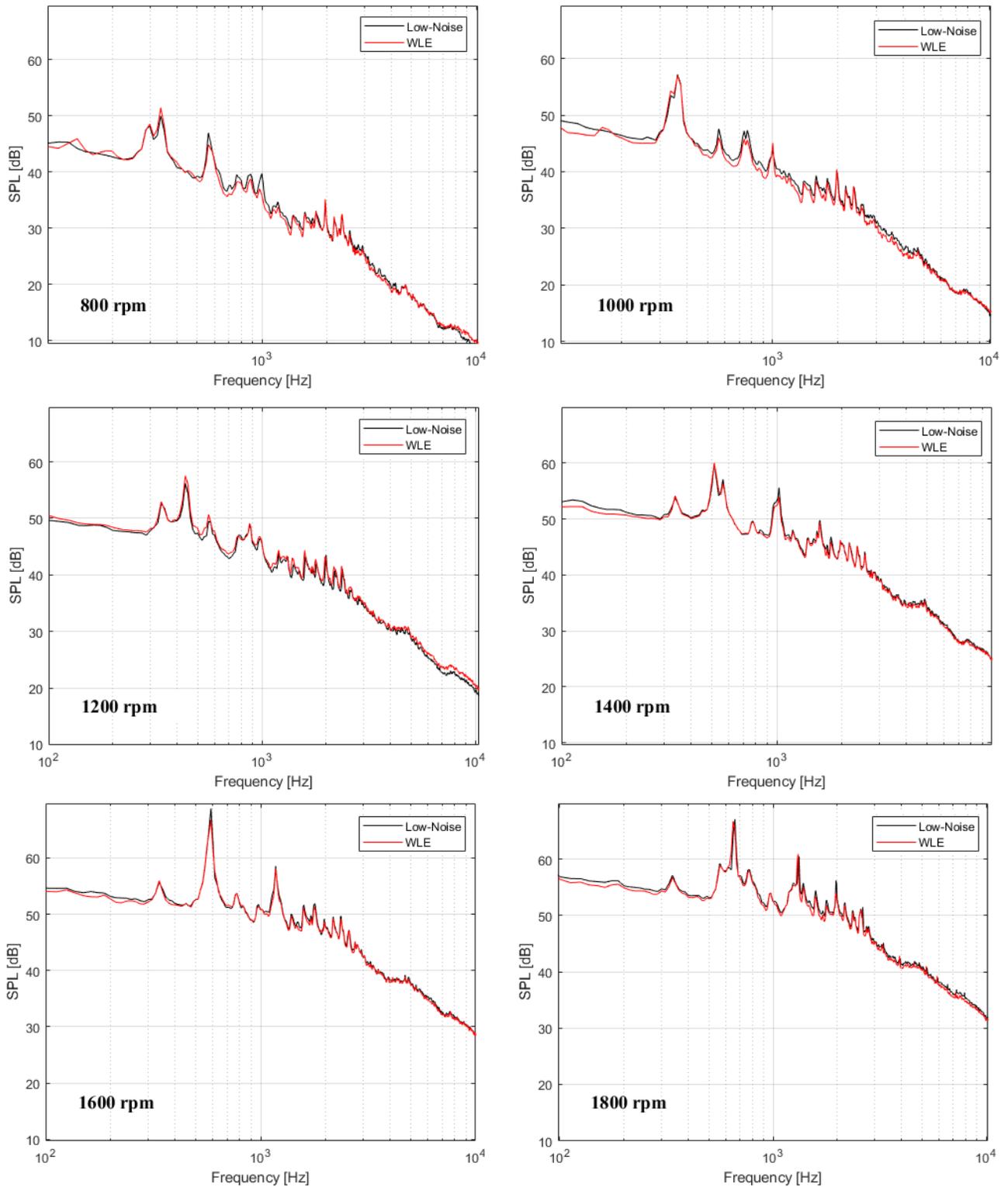


Figure 10. Comparisons – Low Noise and WLE (800 to 1800 rpm).

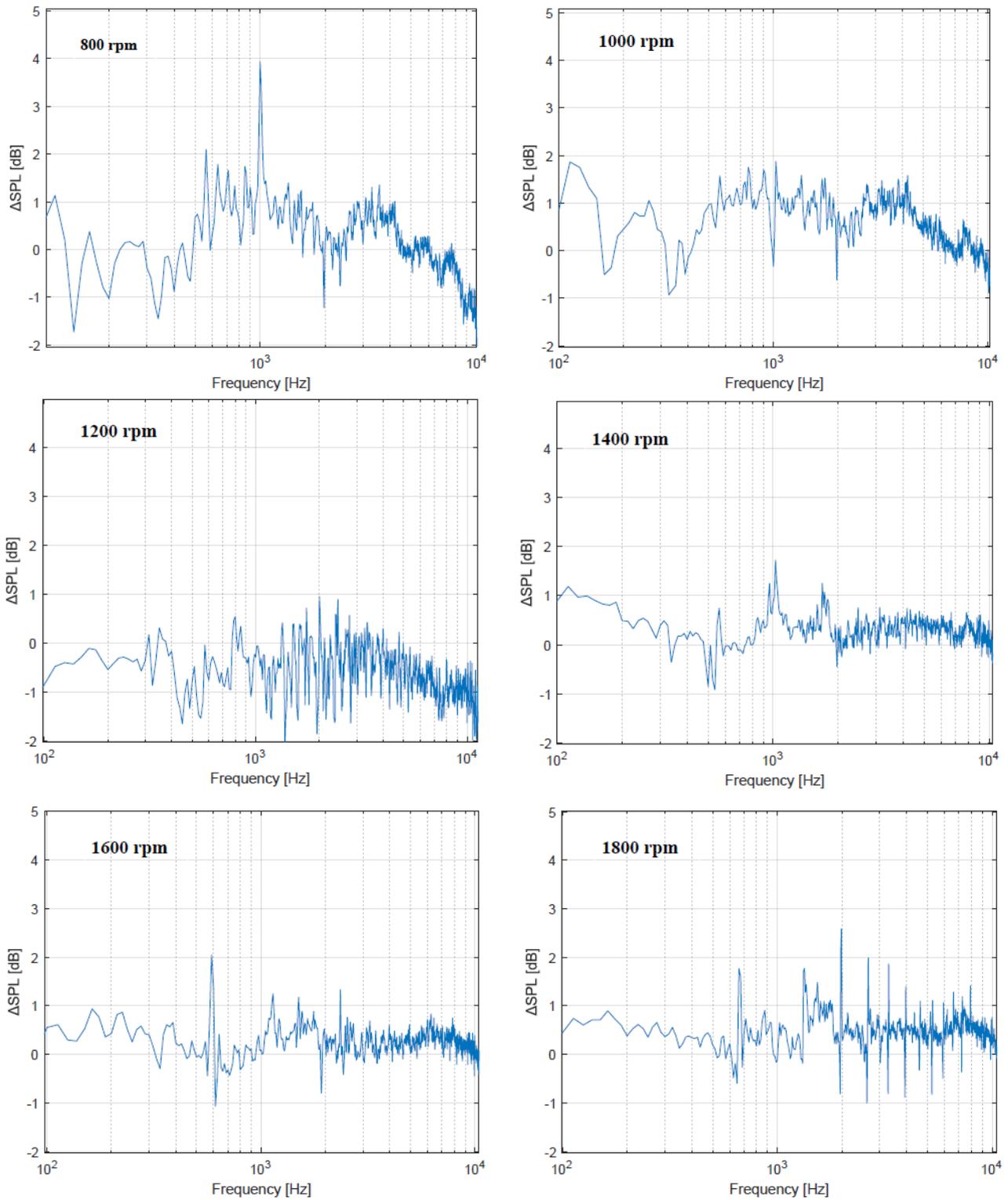


Figure 11. ΔSPL (800 to 1800 rpm).

4. RESULTS

In this research dedicated to the reduction of rotor-stator interaction noise, it was proposed the use of bio-inspired devices physical characteristics of the owl's wing, applied to the leading edge vanes in order to reduce the sound radiation coming from the rotor. Referenced research on leading edge WLE has proven to be an effective application for noise reduction, on the order of up to about 10 dB depending on configuration and frequency.

Equipment used for aerodynamic and acoustic measurements are tunnels or aeroacoustic benches, where it is possible to change the conditions for tests such as rotor speed, stator geometry, flow control, turbulence levels, etc. With the Rig-Fan bench it was possible to measure the sound pressure levels of the Low-Noise geometry SDT stator and also of the new stator model with WLE.

To process the data obtained by the microphones, it was necessary to use mathematical tools, such as the Welch method, which uses Fourier transforms to decompose the temporal function and thus process the spectrum of interest over frequencies.

It was experimentally analyze that at low and medium frequencies the sound pressure levels were reduced, although a small increase in noise at high frequencies was observed. It is considered, therefore, that a deeper investigation is necessary on the geometry of the serrations that caused this increase in noise at high frequencies, using more sensitive instruments or techniques for the location and behavior of sound sources.

It is understood from this study that there is no ideal serration that reduces noise for all types of conditions that are imposed, however, as efficiency is better at lower rotation speeds, it is believed that the serrations on the leading edge could be used to improve aircraft landing or takeoff conditions.

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