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ASSESSMENT OF THE PSYCHOACOUSTIC PERFORMANCE OF THE VENUS PROJECT DISTRIBUTED ELECTRIC PROPELLERS CONFIGURATION

Alessandro Di Marco[1*] **Luana G. Stoica**[1]
Giorgia Capobianchi[1]
[1] DICITA, University of Roma Tre, Roma, Italy

ABSTRACT

The increasing use of aircraft concepts driven by distributed propulsion for urban and regional air mobility raises the issue of new sources of community noise and the prediction of the resultant annoyance. This paper addresses the assessment of the experimental measurements on a distributed electric propellers configuration in the framework of the EU project VENUS from a psychoacoustic point of view, framing the engineering design of these systems in a perception-driven perspective. The VENUS project was aimed to the aerodynamic and aeroacoustic design of a distributed electric propulsion aircraft. Acoustic, aerodynamic and wall pressure measurements were carried out on a wing model equipped with a flap and three propellers powered by electric motors in an open jet wind tunnel. The parameters changed during the tests included five blade pitch settings, an angle of attack sweep, take-off and landing flap configurations, a phase delay between the propellers, different relative distances between the propellers and with respect to the wing. An optimized liner was installed on the wing for acoustic mitigation, in selected configurations. The optimal geometric configuration was determined based on psychoacoustic metrics (i.e. loudness, fluctuation strength, roughness, sharpness and tonality) and psychoacoustic annoyance models.

*__Corresponding author__:
alessandro.dimarco@uniroma3.it.
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1. INTRODUCTION

The main objective of the present study is to investigate to what extent a model based on sound quality metrics (SQMs) can predict the noise annoyance caused by a set of distributed electric propulsion layouts. The human perception of noise is influenced not only by personal qualities but also by their aesthetic and cognitive inclinations, along with their psychophysiological condition. While it's challenging to assess the latter factors, one can consider the unique aspects of how sounds are perceived acoustically, defining them through a model based on subjective qualities [1]. In psychoacoustic studies, different subjective qualities independent of each other have been identified: sharpness, fluctuation strength, roughness and tonality. By combining these qualities, a quantitative measure was established: the psychoacoustic annoyance (PA) can be calculated from a global point of view. The benefit of this approach is that it provides an overall estimate of the perceived annoyance level from a recorded sound without identifying the noise annoyance level among public residents through questionnaires. Additionally, the PA performance is compared to commonly used conventional noise metrics. The use of the PA approach in combination with the noise certification metric makes a perception-influenced acoustic design possible, in which the new vehicle design can simultaneously meet noise certification requirements while achieving low annoyance [2].

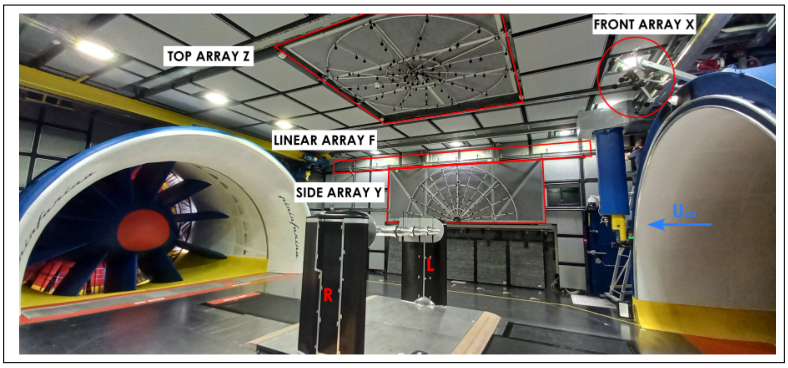

Figure 1. VENUS experimental setup.

2. METHODOLOGY

2.1 Wind Tunnel Aeroacoustic Measurements

Measurements in wind tunnels (WT) have been one of the main methods for aeroacoustic testing for the last decades, as they offer controllable conditions (flow velocity, angle of attack, etc.) repeatability of the results and, in most cases, accurate knowledge of the model position. One of the main challenges for wind-tunnel experiments is to replicate the exact conditions at full-scale. The smaller scale and usually less-detailed geometry of the wind-tunnel models, together with the typically lower flow velocities, can lead to a discrepancy in the Reynolds number. This effect was not taken into account. A model with three wing installed propellers (Fig. 1) was mounted on the floor of the Pininfarina WT test section with the central plane aligned with the WT balance.

Two aerodynamically shaped struts sustained the upside-down wing. The wing consisted in a non symmetric constant chord airfoil (NACA 63(2)415) with a deployable flap. The three propellers could be arranged in different geometrical configurations. The lateral propellers had two degrees of freedom on the wing whereas the central could be translated only in longitudinal direction. The propellers rpm were remotely controlled by an home-made software able to syncrophase the lateral propellers (followers) with respect to the central one (the leader). The model was instrumented with pressure taps, pressure transducers and load cells for thrust and torque measurements. During the test campaign, fluctuating pressure was acquired with four microphone arrays (Fig. 1) and the global aerodynamic coefficients were measured with the WT balance. Different DEP configurations were tested, those of interest are summarised in section 3 The reader is referred to [3] for more details on the experimental set-up.

Table 1. Parameters varied during VENUS wind tunnel tests.

Parameter	Value
AoA α	$-1° \rightarrow 11°$
Flap angle δ	$0°$ (SL), $20°$ (TO), $35°$ (LA)
Phase shift $\Delta\varphi$	$0°, 35°$
DEP layout	XY1 $\rightarrow$ XY11
Low noise device	on, off

Tab. 1 provides a description about the tested conditions during the whole campaign. A reduced subset of the VENUS database is used here for to the psychoacoustic analysis. The data analysed herein correspond to an angle of attack (AoA) of $5°$, as it is the design angle in the landing phase. Regarding the nacelles layout, only the geometrical dispositions relevant to the study are selected as individuated in a preliminary numerical aeroacoustic study performed before the realization of the WT model. $XY*$ is a conventional name given to a specific combination of nacelle positions with respect to the baseline configuration, which is indicated with $XY1$.

The phase shift indicates the de-phasing of the lateral propellers with respect the central one. The wind tunnel air speed velocity was set at 20 $\mathrm{m/s}$ and the rotational speed of the three propellers was kept constant at 3300 rpm in all tests in order to guarantee the same advance ratio of $J = 0.65$.

2.2 Aeroacoustic and Psychoacoustic Sound Quality Metrics

Conventional acoustic/aeroacoustic metrics were used as a first ranking discriminant of the most/less annoying DEP configuration. To better assess the actual annoyance experienced by people, more sophisticated SQMs from the field of psychoacoustics were also implemented. In addition to SQMs, the relationship between annoyance of the sounds in this test and aircraft noise certification metrics was explored. Since the sounds were of short duration and constant, (those certification metrics involving summation and integration over time) metrics such as the effective perceived noise level were not analysed. Instead, the constituent metrics of these certification metrics were analysed. These constituent metrics are A-weighted sound pressure level ($L_{p,A}$), Z-weighted (or unweighted) sound pressure level ($L_{p,Z}$), perceived noise level (PNL) and tone-corrected perceived noise level (PNLT). In synthesis, without entering into the definitions, for each sound signal the following metrics were calculated:

- Loudness (N);
- Tonality (K);
- Sharpness (S);
- Roughness (R);
- Fluctuation strength (FS);

In this paper, a subset of these metrics is reported for the sake of conciseness. To reduce amplitude variation in some metrics, the 5 percent excess in the levels of the metrics are used to describe the metric levels for the duration of sound. If an SQM value is nearly constant over the sound duration the exceeded level will be approximately equal to the constant level [4].

From the SQMs, the PA metrics were calculated according to the models introduced by [5] and improved by [6]. The conventional sound metrics, SQMs and PA metrics were computed using the open-source MATLAB toolbox SQAT (Sound Quality Analysis Toolbox) [7].

3. TEST CASES

Three comparison scenarios are considered: (i) clean model versus model with installed propeller blades, (ii) five nacelle layouts for the take-off configuration with respect to the baseline layout, four nacelle layouts for the landing configuration with respect to the baseline layout and (iii) wing with/without noise reduction device for a selected nacelle layout. The clean configuration was obtained from the baseline layout removing the propellers blades and carrying out the tests with motors off. For this specific comparison a side-line (SL) configuration with the flap not deployed was also tested and presented in section 4. Take-off (TO) and landing (LA) configurations were obtained deploying the flap at 20° and 35° respectively. Fig. 2 shows the possible nacelle movements in $X-$ and $Y-$ direction. The central green lines indicate the positions of the baseline configuration. Note that the central nacelle can only translate in the streamwise direction.

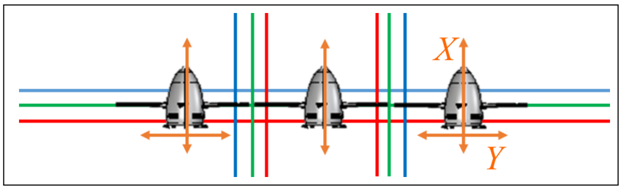

Figure 2. Sketch of the nacelles translation directions.

The nacelle layouts considered in this study are summarised in Tab. 2. ΔX and ΔY corresponds to the position variation with respect to the baseline configuration. Arrows indicate the longitudinal and transversal translation directions of the three nacelles (left L, central C and right R) for each layout. The values of the nacelle translations considered here were set at $\Delta X = 6$ cm for streamwise movements and $\Delta Y = 4$ cm for spanwise movements.

Table 2. Nacelle layout movements with respect to the baseline configuration.

Conf	ΔY_L	ΔX_L	ΔX_C	ΔX_R	ΔY_R
XY1	-	-	-	-	-
XY2	-	⇓	⇓	⇓	-
XY3	-	⇓	⇑	⇓	-
XY4	-	⇑	⇓	⇑	-
XY6	-	-	⇑	-	-
XY10	⇒	⇓	⇑	⇓	⇐
XY11	⇒	⇑	⇓	⇑	⇐

Table 3. Acoustic and Psychoacoustic metrics comparison of the baseline, clean and installed configurations.

	DEP Conf	$L_{p,A}$ [dBA]	PNLT [dB]	N [phon]	K [t.u.]	S [acum]	PA [-]
SL	Clean	63.3	76.9	19.6	0.07	1.10	21.2
	Installed	72.9	87.7	35.8	0.12	1.39	40.0
TO	Clean	64.6	78.3	21.5	0.07	1.11	23.4
	Installed	73.0	88.1	36.5	0.12	1.38	40.5
LA	Clean	65.8	79.5	23.3	0.08	1.11	25.5
	Installed	74.3	88.9	39.0	0.10	1.35	42.4

Table 4. Effect of the mitigation device on acoustic and psychoacoustic metrics.

	DEP Conf	$L_{p,A}$ [dBA]	PNLT [dB]	N [phon]	K [t.u.]	S [acum]	PA [-]
$\delta\varphi = 0°$	No Liner	75.2	89.4	40.5	0.1	1.33	44.1
	Liner	74.4	89.0	39.4	0.1	1.33	43.4
$\delta\varphi = 35°$	No Liner	74.8	89.2	40.1	0.11	1.33	44.0
	Liner	74.5	89.1	40	0.11	1.34	43.7

The noise reduction device consisted in a series of micro-perforated inserts mounted on the wing leading edge of the pressure side. The holes distribution and size and the cavities beneath the wing surface were specifically designed through an optimization procedure focused on the attenuation of the propeller tonal noise in a wide range of frequencies.

4. RESULTS

All the results presented in the following sections are obtained analysing the signal acquired by the central microphone from the array on the ceiling of the WT. In this way, the noise is perceived as an observer underneath the wing, similar to a fly-over manoeuvre. Sound propagation effects are not taken into account. All the signals are band-pass filtered in the range of interest of the installed propellers, discarding effects of the low frequency wind tunnel noise and high frequency disturbance due to the microphones and acquisition system. Furthermore, the signals are downsampled at 48 kHz in order to be compatible with psychoacoustic software requirements.

4.1 Clean vs Installed Configuration

Tab. 3 summarises the results of the comparison between the clean wing model and the wing with the propeller blades installed. The $L_{p,A}$ are found to be larger when the propellers are running, as expected, due to the noise contribution from the propeller rotation. The average level of this difference between the configurations amounts approximately to 8.8 dBA. For the clean model, the values increases with the flap deployment angle by 1 dBA when moving from SL to TO to LA. The effect of the flap with the propellers running only causes a rise of the $L_{p,A}$ in landing configuration, due to the greater deflection of the propeller wake. Similar trends are found for the PA. It is worth noting that installing the propellers doubles the estimated annoyance with respect to the clean model, for each manoeuvre setup.

4.2 Noise Mitigation Device Effect

The acoustic and psychoacoustic effects of the noise mitigation devices are summarised in Tab. 4. The results do not indicate a substantial modification of the perceived noise. The best performances are obtained for the in-phase propellers ($\delta\phi = 0°$). The noise reduction device causes a slight reduction of the loudness, whereas the other metrics remain substantially unchanged.

4.3 Psychoacoustic Sound Quality Metrics of TO and LA setups

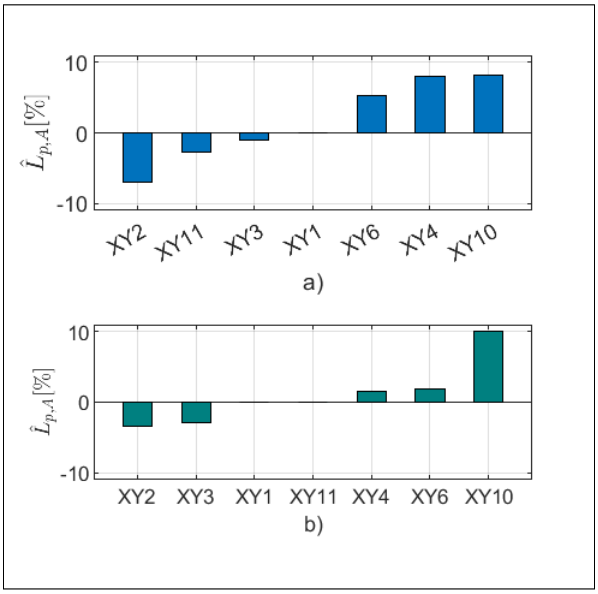

Figure 3. Normalized $L_{p,A}$ in TO for a) $\Delta\varphi = 0°$ and b) $\Delta\varphi = 35°$.

The results presented in this section for both setups are all referred to the baseline $XY1$ configuration. In order to adjust values measured on different scales to a comparable scale, the conventional metrics ($L_{p,A}$) and the psychoacoustic annoyance (PA) values are normalized as follows:

$$\hat{\sigma}_{p,A} = \frac{\sigma_{p,A,XY*} - \sigma_{p,A,XY1}}{\sigma_{p,A,XY1}} \tag{1}$$

and

$$\hat{PA}_{p,A} = \frac{PA_{XY*} - PA_{XY1}}{PA_{XY1}} \tag{2}$$

where XY^* indicates a generic nacelle layout, $XY1$ corresponds to the baseline layout and $\sigma_{p,A}$ is obtained from the A-weighted sound pressure level with the inverse formula assuming a reference pressure of 20 µPa.

The analysis of the conventional metrics and the PA model revealed some differences among the various layouts as illustrated in Fig. 3 and Fig. 4 for TO and in Fig. 5 and Fig. 6 for the LA setup. In the figures, negative values express a reduction in the emitted noise compared to the baseline layout whereas positive values are an increment. On the abscissa, the layout ranks from the quietest to the noisiest; in each figure, results obtained at the two relative phase angles between the propellers are shown.

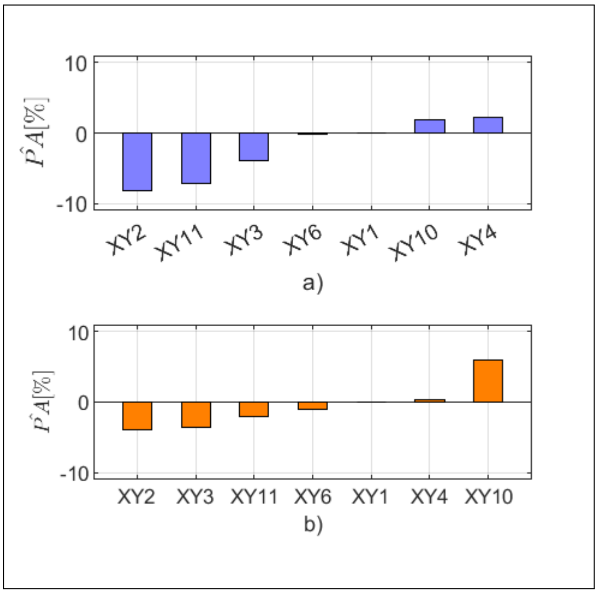

Figure 4. Normalized PA in TO for a) $\Delta\varphi = 0°$ and b) $\Delta\varphi = 35°$.

In TO, the quietest layout is the $XY2$ independently of the phase or the approach used. The layout consists of the three propellers discs aligned with each other at their closest position with respect to the wing. The noisiest configuration is the $XY10$ examining most metrics, although this result is questionable for the PA at $\Delta\varphi = 0°$ (Fig. 4). In this layout, the propeller discs are overlapping, with the two external propellers closest to the wing and the central at the farthest longitudinal position. Comparing the acoustic and psychoacoustic metrics at $\Delta\varphi = 0°$, the layout ranking remains almost unvaried, whereas changes occur when the propellers are not running in phase. A moderate noise reduction is obtained de-phasing the propellers in most cases.

For LA conditions, the worst case in terms of noise with respect to the baseline is represented by layout $XY4$. In this layout, the central nacelle is in the closest and the external nacelles in the farthest streamwise position. The estimated annoyance for this case is considerably lower than the conventional metric $L_{p,A}$. The quietest layout is

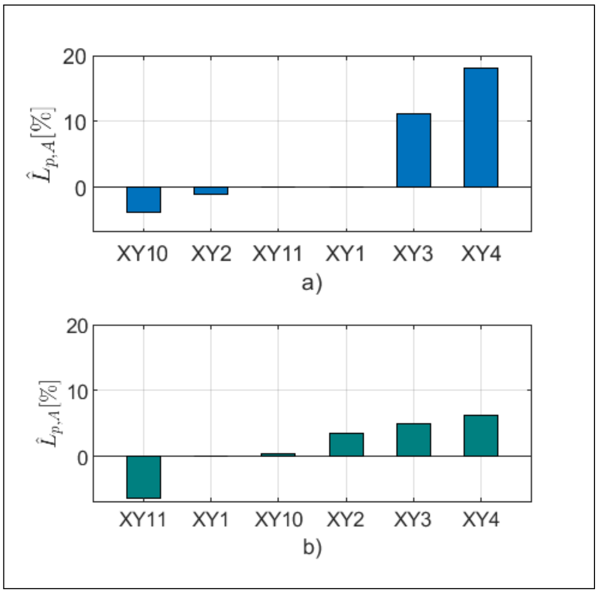

Figure 5. Normalized $L_{p,A}$ in LA for a) $\Delta\varphi = 0°$ and b) $\Delta\varphi = 35°$.

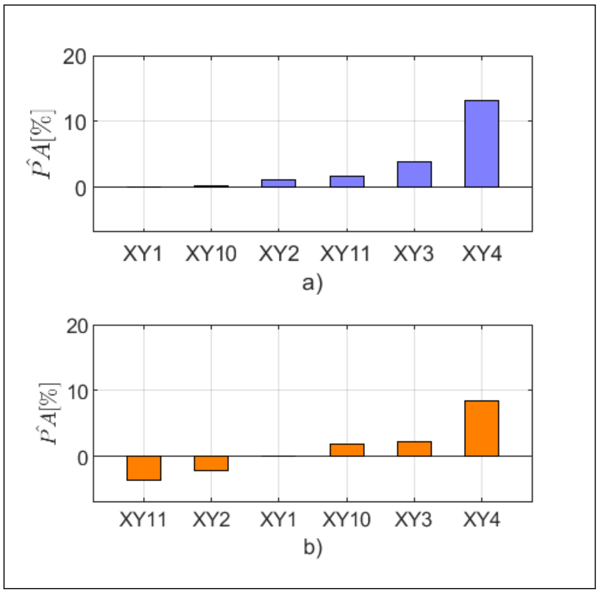

Figure 6. Normalized PA in LA for a) $\Delta\varphi = 0°$ and and b) $\Delta\varphi = 35°$.

not uniquely determined as it is the ranking.

Table 5. Overall ranking.

Tot points	Layout
15	XY2
20	XY11
27	XY1
30	XY3
37	XY10
48	XY4

In order to define the best and worst performing layout, a score was assigned based on the performances in both TO and LA configurations, for all the relative phase angles and for all the metrics used. The total points were counted summing each placement in the different rankings considered. The best overall configuration is thus found to be $XY2$ and $XY4$ as the worst. The overall ranking is reported in Tab. 5.

5. CONCLUSIONS

The aim of the paper is to gain insight into the wide variety of experimental tests performed within the VENUS project from a psychoacoustic perspective and compare it to classical aeroacoustic metrics. The model tested is a wing of a regional aircraft with an optimized distributed electric propulsion system composed of three tractor propellers powered by electric motors. The objective of the study was to compare different methods analysing the annoyance of noise perception. The classical method for annoyance estimation is to apply the A-weighting to the SPL, which roughly corresponds to the perceived loudness level. However, this method may only be suitable for certain types of noise.

Measurements of loudness are used to put policies in place that limit noise levels below reasonable bounds. But because of the informational value of noise and the notable decrease in noise levels that has already been attained, there are now additional techniques for measuring noise-induced irritation that supplement the conventional approaches. These include the rapid and effective computation of short-term psychoacoustic annoyance based on various subjective noise properties.

Results demonstrated that the noise emitted by the model with the installed propellers with respect to the airframe only notably increases the human annoyance as confirmed by the conventional metrics. The effects of the noise mitigation device showed a moderate impact reduction on both conventional metrics and short-term annoyance. It was shown that the estimated human perception of the noise is different from the conventional approach, leading in some case to different results. A critical role is also held by the phase between the propellers. A deeper study on the phase effect and a hearing experiment would complete and validate this study.

6. ACKNOWLEDGMENTS

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