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INFLUENCE OF THE SURFACE ROUGHNESS ON THE AERODYNAMIC, AEROACOUSTIC AND PSYCHOACOUSTIC PERFORMANCES OF DRONE PROPELLERS

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ABSTRACT

The increasing air traffic of small multi-rotor UAVs for urban activities has led to a growing interest in the study of the flight noise emitted by these vehicles. Propeller noise has been recognized as a crucial issue, prompting efforts by the scientific community to search for mitigation strategies to reduce noise without compromising the propeller aerodynamic performance. The current research aims to analyze the effect of the propeller blades surface roughness on their aerodynamic, aeroacoustic and psychoacoustic performances. In order to carry out the study, an experimental campaign is conducted on a propeller, in isolated configuration at different rotational speeds. Tests involved the simultaneous measurements of the propeller thrust and noise, through a load cell and an array of microphones respectively. For each combination of parameters, a time-frequency analysis is performed, and a psychoacoustic annoyance model is used to evaluate five psychoacoustic metrics, loudness, sharpness, roughness, tonality and fluctuation strength.

Keywords: *propeller, roughness, psychoacoustics, noise, noise mitigation strategies.*

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1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have experienced a significant increase in popularity over the last decade, due to the wide range of applications they can be used in. They are employed in military operations as well as civil applications such as traffic surveillance, packages delivery, wildfire monitoring, medical purposes, exploration of inaccessible areas etc. [1,2] Despite the advantages of using drones, noise is considered a crucial factor that limits their employability on a large-scale in urban environments. The main source of noise in multirotor vehicles is caused by the propulsion system, i.e. propellers. Since propellers are the components responsible for generating lift, in the effort to reduce propeller noise, particular attention must be paid to ensure that the aerodynamic performance of the propeller does not deteriorate. Noise reduction can be achieved by modifying the blade shape and structure, leading to a deep interdependence of noise and propeller efficiency.

Several studies have been conducted in order to achieve a better understanding of the noise generation mechanism of small rotating blades [3] and to explore the relationship between the aerodynamic performance and the acoustic signature of propellers [4]. These two aspects are naturally in competition. Therefore, to avoid that the reduction of noise is obtained to the disadvantage of the efficiency, multidisciplinary optimization algorithms are often employed in order to achieve a trade-off between the two aspects [5, 6].

Recent researches have focused on the impact assessment on propeller aeroacoustics of the addition of roughness on the blade surface [7–9]. The application of a microfiber

coating on the propeller blades [7], or the use of propellers with high surface roughness values [8] have been found to lead to a noise reduction if compared with the baseline propeller. Hasegawa et al. [7], in particular, demonstrated that the application of a microfiber coating effectively reduces the broadband noise emitted by the propeller in the frequency range between 3 kHz and 10 kHz. The noise reduction becomes more pronounced as the position of the microfiber coating moves towards the blade tip. This, combined with the fact that the reduction occurs at high frequencies, suggests that the microfiber coating modifies the characteristics of the flow associated with the turbulent boundary layer trailing-edge noise (TBLTE) and the laminar boundary layer vortex-shedding noise (LBLVS).
Moreover, noise generated by UAVs is strongly related to a sense of annoyance in human listeners. The annoyance that people experience when exposed to UAVs noise is found to be greater than the one related to other vehicles, such as road vehicles [10]. Evidence highlights that environmental noise pollution significantly affects public health, well-being, and quality of life [11]. Recent focus on public health, encompassing both physical and mental dimensions, plays a crucial role in directing research and innovation in this area, aiming to ensure an improved quality of life and psychosocial well-being.
The indicators typically used to assess the acoustic behavior of a source, such as the overall sound pressure level (OASPL), calculated by integrating the power spectral density over the audible frequency range (between 20 Hz and 20 000 Hz), although very useful to determine the acoustic efficiency of a vehicle, can not be fully representative of the human perception. To evaluate the annoyance perceived under laboratory conditions, participants were exposed to specific noises and asked to numerically rate their level of annoyance. Statistical indicators were then derived from these ratings [10, 12–14]. Specifically, the mean annoyance indicator (MA) was calculated as the primary parameter, based on the average rating of all those involved in the study. However, the MA obtained from a specific laboratory trial can not be directly compared with the same parameter from another trial, unless additional tests are performed.
For this reason, psychoacoustic models have been developed to mathematically calculate and directly compare the relative annoyance degree of different sounds.
Since the perceived annoyance is found to be strongly dependent on the spectral characteristics of the sound, specific metrics are used to quantify these properties [15–17]. These metrics include loudness, sharpness, roughness, tonality and fluctuation strength. A weighted combination of these parameters enables the calculation of psychoacoustic annoyance (PA). According to Zwicker [18], PA can be described as a function of loudness, sharpness, fluctuation strength and roughness. This model, however, does not take tonality into account. To address this limitation, Di et al. [19] enhanced the model by including tonality as a dependency in the PA function, making it suitable for comparing tonal and atonal noises.
The present study intends to investigate the influence of the surface roughness on the aerodynamic, aeroacoustic and psychoacoustic behaviour of a propeller. The aim is to determine if an improvement can be achieved from the aeroacoustics and psychoacoustics point of view without compromising the propeller aerodynamic performance.
To this purpose, an experimental campaign has been carried out in the Fluid dynamics Laboratory of the University of Roma Tre. A load cell was used to measure thrust under static conditions while a linear microphone array was installed to collect acoustic data and, hence, to perform an analysis in terms of OASPL and psychoacoustic indicators.
The paper is organized as follows. Details about the experimental set-up and the measurement techniques are reported in Sec. 2. The results of the aerodynamic characterization and the acoustic and psychoacoustic measurements are presented in Sec. 3, with the conclusions drawn in Sec. 4.

2. METHODOLOGY

2.1 Experimental Setup

The experimental investigation was carried out in the Fluid dynamics Laboratory of the University of Roma Tre. The propellers used in this campaign are APC 8x6 E, with a diameter D of 20.48 cm and a pitch of 15.3 cm. Each propeller features a different surface roughness value. Apart from the commercial off-the-shelf propeller, the other roughness values were achieved by applying materials with varying grain sizes to the blades near the tip and in correspondence of the trailing edge in the suction side, as in Fig. 1, following the methodology in [7]. The grain sizes are equal to 27 µm, 50 µm, and a mixture of particles ranging from 70 to 110 µm. Tab. 1 provides a summary of the different values of the propeller's surface roughness along with the corresponding labels used in the graphs in Sec. 3.

The propellers were operated in static condition and

Table 1. Values of the propeller's surface roughness and the corresponding labels.

Roughness 1	R1	27 µm
Roughness 2	R2	70-100 µm
Roughness 3	R3	50 µm
Roughness 4	R4	baseline

in a pusher configuration at a maximum chord-based Reynolds number of about 7×10^4, based on the chord at 75% of the blade. The rotational speed of the propellers was set equal to six different values: 5500 RPM – 6000 RPM – 6500 RPM - 7000 RPM – 7500 RPM – 8000 RPM for the current experiment. The RPM control was managed through a LabVIEW program, which ensures that the RPM variation remains within 1.5% of the desired value.

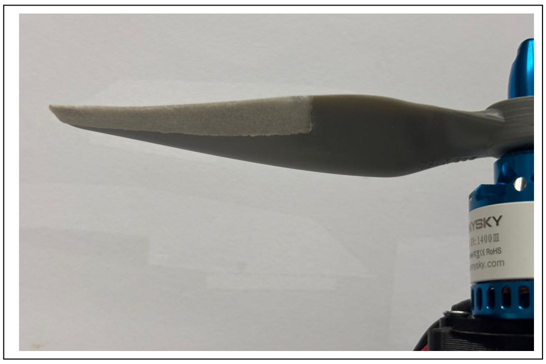

Figure 1. Propeller APC 8X6 E with a roughness value of 50 µm

2.2 Acoustic measurements

Four Microtech Gefell M360 electret microphones were used to perform the acoustic acquisitions. Each microphone has a diameter of 7 mm and has a flat frequency response in a range between 20 and 20 kHz with a maximum sound pressure level of 130 dB. The reference pressure is 20 µPa and the microphones have an integrated preamplifier. Microphone signals were recorded for a total of 10 s at 100 kHz. The microphones were mounted on a linear stand parallel to the propeller rotational axes and positioned at 0.7 m from it, that is equal to 3.5 D. The first microphone was aligned with the propeller plane, the others were positioned at 15°, 30° and 45° with respect to the propeller plane, in the outlet region. Fig. 2 shows in detail the setup used to perform the acoustic measurements. A fifth microphone was then placed in the nearfield of the propeller to perform the RPM control.

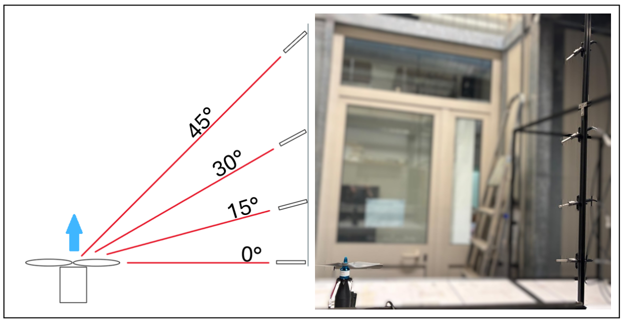

Figure 2. Schematic (left) and photo (right) of the experimental setup.

2.3 Thrust acquisitions

A RoHS low force compression load cell FS20 was used to perform thrust measurements. It can measure up to 1500 Grams-Force and the sensitivity was determined through the utilization of known weights. The signals were recorded for a total of 10 s at 100 kHz and the average values were calculated. The load cell was positioned into the propeller support specifically created to allow the transmission of the force in the x direction. Fig. 3 shows the load cell and the motor support.

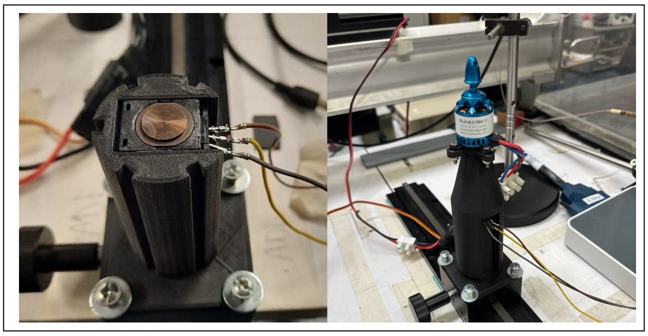

Figure 3. Load cell (left) and motor support (right).

2.4 Analysis

To perform the acoustic analysis, the sound pressure spectrum level (SPL) and the OASPL were calculated according to Eqn. (1) and Eqn. (2), respectively.

$$SPL(f) = 10\log_{10}\frac{PSD(f)}{p_{ref}^2} \tag{1}$$

$$OASPL = 20\log_{10}\frac{\sigma(p_m)}{p_{ref}} \tag{2}$$

where PSD is the power spectral density of the signal, calculated with a frequency resolution of $\Delta f = 3$ Hz, p_{ref} is the reference pressure and it is set equal to 20 µPa and $\sigma(p_m)$ is the standard deviation of the pressure signal from which the mean value has been subtracted.
Moving on to the psychoacoustic analysis, the open-source MATLAB toolboxSQAT (Sound Quality Analysis Toolbox) [20] was used. In particular, the model implemented here to calculate the perceived annoyance is the one proposed by Di et al. [18]. Psychoacoustic annoyance is defined as in Eqn. (3).

$$PA = N_5\left(1+\sqrt{w_S^2+w_{FR}^2+w_T^2}\right) \tag{3}$$

where w_S, w_{FR} and w_T are defined as in Eqn. (4), Eqn. (5) and Eqn. (6).

$$w_S = \begin{cases}(S-1.75)(0.25\log_{10}(N_5+10)), & S > 1.75\\ 0, & S \leq 1.75\end{cases} \tag{4}$$

$$w_{FR} = \frac{2.18}{N_5^{0.4}}(0.4F+0.6R) \tag{5}$$

$$w_T = \frac{6.41}{N_5^{0.52}}T \tag{6}$$

where N_5 is the fifth percentile loudness and S, FS, R and T are the other psychoacoustic metrics: sharpness, fluctuation strength, roughness and tonality respectively.

3. RESULTS AND DISCUSSION

In this section the results are analyzed and commented. Starting from the analysis of thrust, Fig. 4 shows that the two propellers R1 and R2 exhibit better aerodynamic performance than the baseline propeller at all rotational speeds tested, with a maximum thrust gain of 0.3 N at 6000 RPM. The same cannot be said for the propeller R3, which instead shows lower performance than the baseline propeller at low RPM, but recovers from 7500 RPM onward, achieving the best overall performance at 8000 RPM.

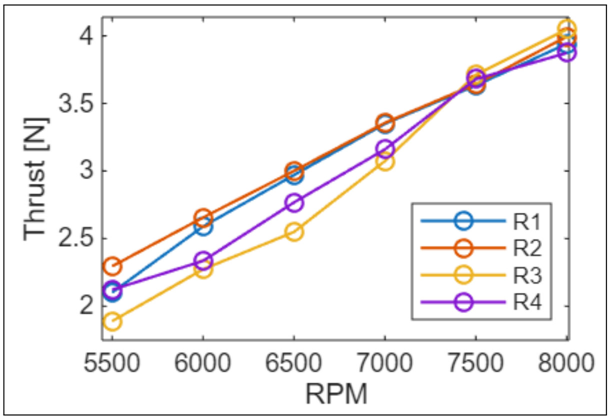

Figure 4. Thrust vs RPM

Fig. 5 shows the sound pressure spectrum level for a rotational speed of 7000 RPM and for all the propellers tested. The propellers with the add-on show a reduced broadband noise contribution than the baseline one, especially at the lower frequencies, up to 5 kHz. The same behavior is observed for all the rotational speeds tested and it is particularly pronounced for the propellers R1 and R2.
A zoom of the first 15 BPFs at 7000 RPM is provided in Fig. 6. In addition to the lower broadband noise, it can be observed that, in correspondence of the harmonics of the BPF, the propellers with the add-on reach higher values of SPL than the baseline (R4), i.e. the tonal noise contribution is higher, especially for R1 and R3.
In agreement with this observation, the values of tonality, the psychoacoustic indicator that evaluates the proportion of pure tones in a noise signal, are found to be higher for the propellers with the add-on compared to the baseline, which exhibits lower values across all RPM, as shown in Fig. 7. The greatest difference is observed at 7000 RPM, where the tonality value of the propeller R1 is 50% higher than the tonality of the baseline. Furthermore, it is worth emphasizing that the R2 propeller exhibits both a significantly reduced broadband noise and a relatively minor increase in tonal noise. This combination of contributions is expected to provide a good trade-off for achieving a better overall acoustic performance.

The OASPL values of the four propellers are com-

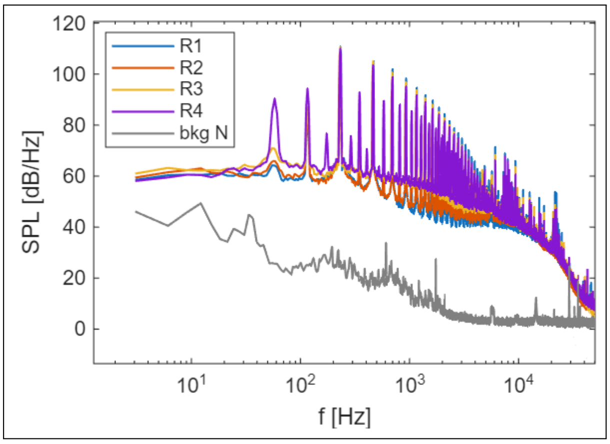

Figure 5. Spectra of the nearfield microphone at 7000 rpm

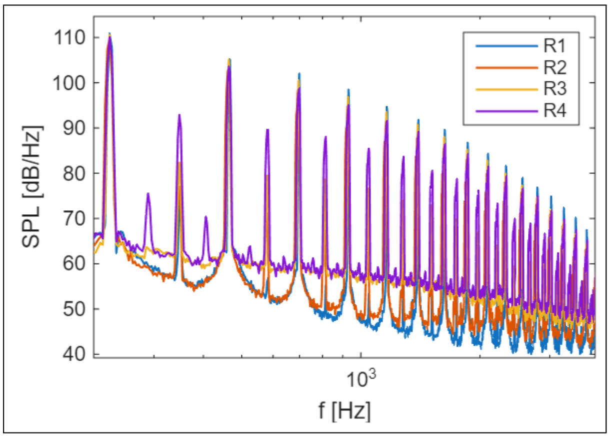

Figure 6. Zoom of the first 15 BPF at 7000 rpm

pared in Fig. 8 for all microphones and all the rotational speeds tested. As a general trend, we observe that the OASPL values tend to increase as the RPM increases, as expected. The baseline propeller has the worst aeroacoustic performance, exhibiting a higher acoustic energy content than the other propellers. Moreover, for most conditions, the R2 propeller appears to have the best acoustic performance, as previously suggested, with an average OASPL reduction of 0.9 dB compared to the baseline, versus an average reduction of 0.6 dB for the R1 propeller and 0.5 dB for the R3 propeller. However, at low speed, around 5500 RPM, and at high speed, around 8000 RPM, the lower value of OASPL is achieved by the R3 propeller. In the range between 6500 RPM and 7500 RPM, the R3

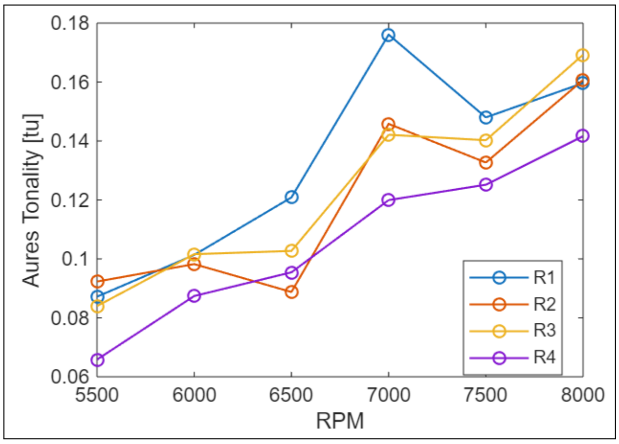

Figure 7. Tonality vs RPM for the microphone on the rotational plane of the propeller

OASPL values became similar to the ones of the baseline, deteriorating its overall acoustic performance. The maximum OASPL reduction, equal to 2.3 dB, with respect to the baseline, is achieved by the R2 propeller in correspondence of microphone 3 at 8000 RPM.

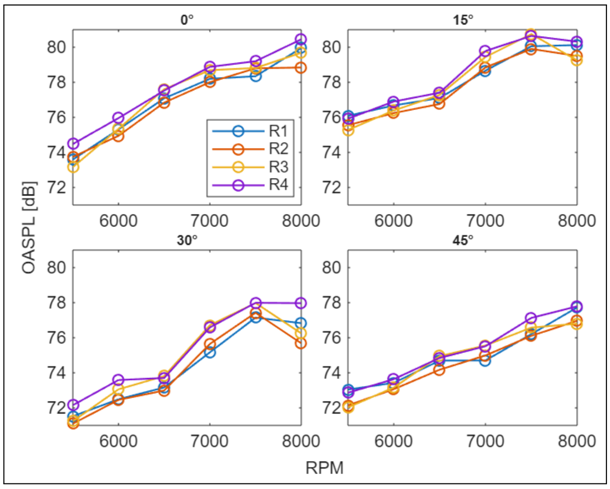

Figure 8. OASPL vs RPM for each microphone

From the psychoacoustic perspective, only the psychoacoustic annoyance (PA) is reported here, as it is calculated as a linear combination of all the other psychoacoustic parameters (see Eqn. 3). In Fig. 9, in particular, the annoyance versus the RPM is plotted for all the microphones. It can be observed that the trend of the PA curves is quite similar to the trend of the OASPL curves,

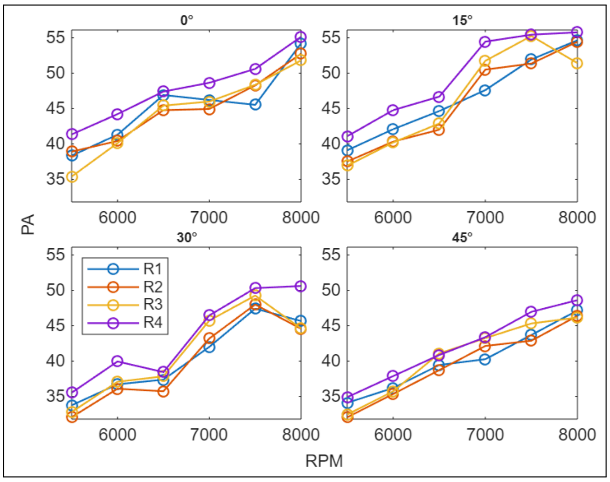

Figure 9. Psychoacoustic annoyance vs RPM for each microphone

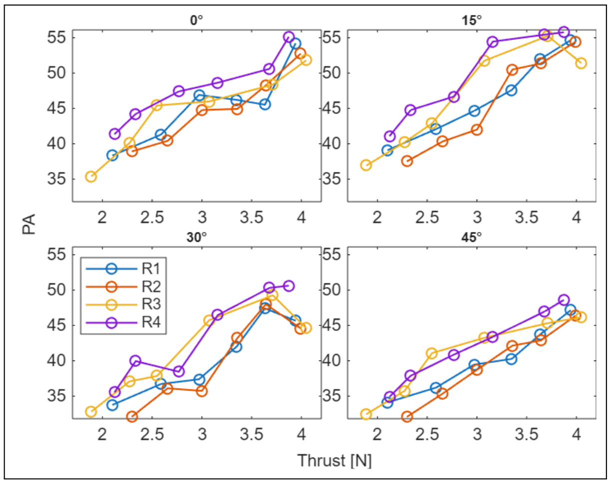

Figure 10. Psychoacoustic annoyance vs Thrust for each microphone

but the differences are more pronounced: the curves of the propellers are more spaced apart, revealing significant differences in terms of the annoyance caused. First, it is clearly visible that the baseline propeller is the most annoying along all the RPM and at all the locations. Regarding the lowest values, the situation is somewhat less clear. At low speed, between 5500 and 6000 RPM, the best psychoacoustic performance is reached by the roughness 3 and roughness 2 propellers. At 7000 and 7500 RPM the roughness 3 propeller became more annoying reaching, in some cases, values equal to the baseline. In this range of RPM, the best performance is prerogative of the R1 and, again, of the R2 propellers. At the maximum speed, 8000 RPM, once again the roughness 3 propeller achieves the best result. Anyway, the propeller with an overall greater average decrease in PA, compared to the baseline, is the R2 propeller, with a decrease of 3.2 units, whereas the other two propellers, R1 and R3, show a decrease of about 2.6 units.
As final comparison, Fig. 10 shows the psychoacoustic annoyance of the four propellers as function of the thrust produced. Here the situation is a bit different. For the same thrust, the most annoying propeller is, quite always, the baseline, but the values are often matched by the R3 propeller. For almost all the cases, the best psychoacoustic performance is achieved by the R2 propeller, followed by the R1. Only at the maximum thrust, the roughness 3 propeller achieves the best performance, since it combines the highest thrust at 8000 RPM (Fig. 4), if compared to the other propellers, and a relatively low psychoacoustic annoyance at 8000 RPM, as highlighted previously (Fig. 9).

4. CONCLUSIONS

An experimental investigation of the influence of the surface roughness on the aerodynamic, aeroacoustic and psychoacoustic behaviour of a propeller was carried out in the Fluid dynamics Laboratory of the University of Roma Tre. Four APC 8X6 propellers were tested: an off-the-shelf propeller and three propellers with an add-on of 27 µm, 50 µm, and a mixture of particles ranging from 70 to 110 µm, respectively. Thrust measurements were performed by means of a load cell, whereas 4 microphones were placed in the farfield, at a distance of 3.5 D from the hub of the propeller, for the acoustic characterization. Moreover, a fifth microphone was placed in the nearfield of the propeller. The psychoacoustic analysis was performed using the open-source MATLAB toolboxSQAT (Sound Quality Analysis Toolbox) that implemented the model proposed by Di to calculate the psychoacoustic annoyance. From the study of the spectra measured by the nearfield microphone, the propellers with an add-on show a reduced broadband noise contribution at the lower frequency, up to 5000 Hz. In the same frequency range, in correspondence of the BPF and its harmonics, the propellers with an add-on exhibit higher peaks than the baseline, showing an increased tonal noise contribution. In particular, the R2

propeller, with the add-on roughness ranging from 70 to 100 µm, displays both a significantly reduced broadband noise and a relatively minor increase in tonal noise, a combination that ensures a good performance overall from an aeroacoustic point of view, as demonstrated by the analysis of the OASPL. From the psychoacoustic perspective, the roughness 2 propeller shows an excellent performance relative to the psychoacoustic annoyance as function of the thrust produced. For the same RPM, R2 produces a greater thrust and a lower psychoacoustic annoyance than the other propellers tested, resulting in the best choice to improve the propeller performances.
Therefore, the addition of material which increases the surface roughness on the propeller's tip trailing edge surface is shown to improve the aerodynamic, aeroacoustic and psychoacoustic performances of the off-the-shelf propeller. In particular, among the particles sizes tested in this study, the best results were provided using the mixed particles ranging from 70 to 100 µm.

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