Experimental Analysis of Small-Scale Rotors with Serrated Trailing Edge for Quiet Drone Propulsion

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Abstract.
Drones are a growing business in Europe, delivering services in all environments, including urban areas: delivery of goods and e-commerce, precision agriculture, mapping, infrastructure inspections. In order to allow the integration of this platform in urban areas and to obtain public acceptance, it is necessary to significantly reduce the noise produced by the propellers. Currently, the level of noise generated by propellers is too relevant in terms of annoying effects induced on living beings. In particular, low altitude flights have been found to disturb citizens and frighten animals. With the aim to tackle such an issue, this paper describes an experimental parametric analysis of a passive noise control technique to reduce the signature generated by small-scale propeller employed for mini unmanned aerial propulsion.

The noise control strategy here proposed is based on a serration pattern realized at the trailing edge (TE) of the blade. Despite the same approach has already been successfully employed to mitigate noise generated by wind turbines and fixed wing aircraft, few studies have been devoted to investigate the effects of a serration pattern on small propellers.

A large number of different serration were realized by varying height, width and teeth distribution. The idea is to find the optimal serration geometry in terms of acoustic requirements and to highlight the role of teeth number.

Results shows a sensible reduction in the noise propeller signature. Serration effects seems to depend strongly from the polar angle identifying different region of operation. Spectral Analysis points out that the serration affect the low frequency region and even the tonal component of aerodynamic noise. Statistical analysis shows a departure from a gaussian distribution and an effect of damping on distribution tails.

1. Introduction
In the last few years, Unmanned Aerial Vehicles (UAVs), usually referred as drones or Micro Aerial Vehicles (MAVs), have been becoming a central issue in several application fields due to their versatility for different tasks. The contexts where drones find possible application are manifold. Indeed, they are currently employed for military aims (e.g. surveillance or reconnaissance missions), as well as for civil purposes, such as: infrastructure inspections, precision agriculture, geographical mapping, goods delivery and e-commerce. Regardless from the particular application, the noise produced by UAVs is one the most important aspect which is slowing down the actual spread of these vehicles. The problem is exacerbated especially in the proximity to civil areas.
The standard UAV electric propulsion system is composed of: the propeller, the brushless electric motor, the energy source (i.e. batteries) [1]. The propeller and the engine are known to be the main noise source. In this regard, most MAVs use electric motors, which contribute to simplify operations and significantly reduce the noise signature due to engine. This effect has further increased in brushless motors [2, 3]. In 2018 the European Aviation Safety Agency (EASA) published a document that establishes the noise level requirement for drones at a fixed value of 60 dB(A), measured at a distance of 3 m from the source [4].

The reduction of noise impact, as well as the increase of flight endurance, is generally identified as the main goal to achieve for a serious growing of drone market. This is far from easy task, because endurance increase and noise reduction appear as contradictory objectives, but they represent key issues for the future improvement of this technology. Actually, the reduction of noise from the propulsive system of small rotors has been the subject of several works in literature [5, 2, 3, 1, 6, 7, 8, 9, 10, 11]. However, particular care is required in the design stage because any structural change must not affect the generation of aerodynamic forces.

For these reasons, UAVs provide a great challenge to the task of noise characterization and prediction. Indeed, although the main noise sources stay the same associated with helicopters, there are numerous unknowns which need to be investigated. Examples of interesting features deserving particular attention are the effect of size reduction and the balance between tonal and broadband noise.

An important difference between small size UAVs and conventional rotor-craft is the flow speed regime of flight, identified by the chord-based Reynolds number at 75% span:

$$Re_c = \frac{0.75 c \omega R}{\nu}$$  \hspace{1cm} (1)

where $c$ is the rotor blade chord, $\omega$ is the rotational regime, $R$ is the rotor tip radius and $\nu$ is the air kinematic viscosity. For a full-scale helicopter, a representative $Re_c$ is in the order of $10^6$, while for a UAV it may range from $10^4$ to $10^5$. In terms of conventional flat plate aerodynamics, the former Reynolds number explicates in a turbulent flow regime while the latter in a laminar-transitional flow regime [12]. This discrepancy calls into question the applicability of traditional noise prediction tools.

As said before, UAV and MAV propeller noise is a central and challenging issue that has to be taken into account in system design. Strategies for noise control are basically of two kinds: active and passive. For large scale airfoils and propellers active flow control methods have been widely employed, but these solutions are energy-consuming. On the other hand, passive flow control techniques enable the boundary layer to be manipulated without further consumption of external energy, and it can be employed to reduce noise generation. For this reason, in the last decade, several studies have been devoted to passive control systems for noise reduction [13].

In this paper, we propose a control system based on a sawtooth pattern applied at the TE of the blade. Serrations applied to the TE of an airfoil reduce noise generation due to the destructive interference of the pressure fluctuations produced by the flow structures conveacting along the slanted edge.

The idea for this original geometry was inspired by nature, in particular by the silent flight of owls [14][15][16]. The quietness of their flight is due to their characteristic wings, with three main physical features: a suction wing surface with a soft downy coating, a comb of stiff feathers at the wing leading edge, and TE feathers and wings with a fringe of flexible filaments. The sawtooth pattern employed by manufacturers is the simplest geometric way to mimic the permeability of owls’ wings.
2. Propeller aeroacoustics: noise decomposition and trailing edge noise focus

2.1. Propeller noise decomposition

This section provides a brief explanation of the most common noise prediction model and a description of the passive noise control strategy presented. The aim is to understand the noise generation mechanism and how the serration may mitigate it. Generally, the propeller aerodynamic noise is split into two main components: narrow and broad-band contributions [7, 17, 18, 2]:

\[ p'(x,t) = p'_{NB}(x,t) + p'_{BB}(x,t) \] (2)

where \( p'_{NB}(x,t) \) is the narrow-band component of pressure fluctuations, whereas \( p'_{BB}(x,t) \) is the broad-band counterpart.

Narrow (or tonal) components are directly related to the periodic motion of the blade in the surrounding fluid. Therefore, the frequency and magnitude of the radiated noise is related to rotational velocity. The production of the tonal contributions is related to blade thickness and aerodynamic loading. For thin blades and low Mach numbers (\( M < 1 \)), the narrow-band contribution is given by the sum of a sound source related to blade thickness, \( p'_T \), and one related to aerodynamic loading, \( p'_L \):\n
\[ p'_{NB}(x,t) = p'_T(x,t) + p'_L(x,t) \] (3)

The thickness term takes into account the fluid displacement due to the body, while the loading counterpart takes count of the unsteady force distribution over the body surface.

On the other hand, broad-band noise of a propeller is radiated by the interaction of turbulent flow structures with the blade edge. Therefore, it is either generated at the blade leading/trailing edge or at the blade tip, and it is generally produced by three main sources: i) noise related to the turbulence of the incoming flow (\( LE \) noise); ii) noise produced by the interaction of the turbulent boundary layer over the blade surface with the trailing edge (\( TE \) noise) and iii) noise generated by the possible separation of the flow (\( Separation \) noise) [7]. Therefore, the broad-band contribution can be further split as:

\[ p'_{BB}(x,t) = p'_{TE}(x,t) + p'_{LE}(x,t) + p'_{S}(x,t) \] (4)

where \( p'_{TE}(x,t) \) is the trailing edge component, \( p'_{LE} \) is the leading edge component and \( p'_{S} \) is the due to laminar separation bubble term.

Several authors have already addressed the prediction of trailing edge broad-band noise. A relation between the Power Spectral Density of the trailing noise, \( S_{TE}^{pp} \), and the spanwise velocity correlation length, \( l_y \), is reported in [7] as:

\[ S_{TE}^{pp}(r,\theta,\omega) = \frac{B}{8\pi} \left( \frac{\omega c}{2af} \right)^2 \Delta R D(\theta,\phi) |I|^2 \Phi_{pp}l_y \] (5)

where \( r \) is the observer position vector, \( \omega = 2\pi f \) is the angular frequency, \( f \) is the rotational frequency, \( B \) is the number of the blades, \( c \) is the chord, \( a \) is the speed of sound, \( \Delta R \) is the spanwise length of the blade, \( D(\theta,\phi) \) is the directivity function, \( I \) is the radiation integral function, th operator \( || \) is the square of the absolute value and \( \Phi_{pp} \) is the wall power spectral density of the pressure fluctuations.

There are different models for \( S_{TE}^{pp} \) estimation, e.g. the one proposed by Schklinker and Amiet [19], or the more recent one proposed by Rozenberg et al. [20], which takes into account the effect of the adverse pressure gradient. On the other hand, \( l_y \) is usually evaluated by means of the Corcos’ model [21].

The noise control strategy analyzed and hereafter described is based on the model proposed in eq.5. More specifically, since \( S_{TE}^{TE} \sim l_y \), a significant reduction of \( l_y \), provided by varying TE geometry, should correspond to a noise reduction in the far field.
2.2. Serrated Trailing Edge noise

In fig.1 a two blades are rendered in their three dimensional geometry: one is a commercial blade (APC 9x4e) hereafter denoted as baseline (see fig.1a), the other is the custom–made blade obtained removing material from the baseline. All blades were made by removing material from the trailing edge of the baseline as represented in fig.2, where the main geometrical serration parameters are reported: tooth height \( h \), width \( b \) and characteristic angle \( \alpha \).

To ensure that the mitigation of propeller noise is effective, the geometrical serration must obey three specific constraints:

i) the dimensionless tooth height, defined as the ratio between the tooth half-height and the boundary layer thickness, \( h^* = h / 2\delta \), must be bigger than 0.25, otherwise the serration height is too small to have an interaction with the larger eddies convected into the boundary layer;

ii) the serration angle, \( \alpha \) (see fig.2), must be smaller than 45\(^\circ\), to obtain a sharp saw–teeth [22, 23]. For the sake of clarity, latter condition is equivalent to \( AR_t = 2b / h < 4 \);

iii) the Strouhal number, defined as the ratio between the boundary layer thickness and reference flow velocity, \( St_\delta = f\delta / U \) must be grater than one, as stated by Howe’s theory for significant noise reduction.

The effect of tooth height the aeroacoustics and aerodynamics of propeller, with particular attention to the influence on noise, thrust and torque generation, has been currently investigating and discussing by scientific community.

Recently, Intravartolo et al.[18] carried out an experimental analysis on serrated TE showing that an increase in serration height produces a reduction in the intensity of the trailing edge wake. Nevertheless, benefits from the height of the serrations diminished with respect to the overall noise signature of the propeller. When serration height reaches a value comparable to half of the Mean Aerodynamic Chord (MAC), no further gain in aeroacoustic effect can be observed. On the contrary, an increase in the overall noise may occur due mainly to aerodynamic effects.

Serration height effect was also analysed by Pagliaroli et al.[2], observing a significant noise reduction in the low frequency region of the pressure spectra followed by a loss in propeller aerodynamic efficiency as a main drawback. Furthermore, an analysis of the noise directivity shows that the sawtooth pattern effect is more important in the propeller wake region.
3. Experimental Setup

For experimental campaign, performed in anechoic chamber $3 \times 3 \times 1.6 \, m$ in size, a custom–made test bench for measuring both the aerodynamic and aeroacoustic behaviour of small scale propeller was implemented. Thrust time series were acquired by National Instrument ACQ board type USB-6002 from a load cell, whereas pressure fluctuations were sampled by using Microphone Gefell M360 and National Instrument ACQ board type. All signals were acquired for 10 s at sampling frequency $f_s = 51200\, Hz$. The microphone was installed on a rotating support allowing to vary the polar angle $\theta$ in a range $[0^\circ : 150^\circ]$. The polar angle $\theta$ is defined in fig.3.

The propeller baseline selected for the experimental campaign, type APC $9 \times 4e$, was machined to realize the different test cases: totally 23 propellers with different serration strategy obtained by varying the teeth height $h$, the teeth basis $b$ and the number of teeth along the blade $n$ in spanwise direction (see tab.1) were realized.

![Figure 3. Sketch of the experimental setup and of the anechoic chamber used for the test campaign. Microphone was located on angular traversing 1.2 m far from the propeller.](image)

| $i$ | $b_i \, [mm]$ | $h_i \, [mm]$ | $n \, [-]$ |
|-----|---------------|---------------|------------|
| 1   | 4             | 4             | 5          |
| 2   | 5             | 3             | 10         |
| 3   | 6             | 6             | -          |
| 4   | 3             | 8             | -          |

Table 1. Values assumed by width, height and number of the teeth.
4. Results

In this section the results of the aeroacoustic measurements are reported. Figs. 4 and 5 shows the effect of the teeth geometrical parameters on the Overall Sound Pressure Level (OASPL) for several polar angles. The OASPL is defined as follows:

\[
OASPL = 10 \log_{10} \left( \frac{\langle p'^2 \rangle}{p_{ref}} \right) \tag{6}
\]

where \( \langle \cdot \rangle \) denotes an ensemble average and \( p_{ref} \) is a reference pressure equal to 2 \( \mu \)Pa.

In fig. 4 the value assumed by OASPL is reported upon \( h \) keeping constant \( b = b_1 \), while in fig. 5 the tooth height is fixed at \( h = h_3 \) and \( b \) is the independent variable. These figures shows that it is not possible to identify a trend and suggest that \( n \) has not a strong influence on the noise generated, probably because some of the teeth are in stall condition and they does not affect the pressure field. A strong directivity of the pressure signal can be observed. The \( b \) and \( h \) parameters singularly seems not to give information to design a quiet propeller so in the following analysis the focus is on the \( AR_t \).

![Figure 4. OASPL trend at different polar angle \( \theta \) for STE propeller with \( b = b_1 \) and \( h \) variable.](image-url)
Figure 5. OASPL trend at different polar angle $\theta$ for STE propeller with $h = h_3$ and $b$ variable.

In order to achieve a better understanding of the noise generation mechanism, further analysis was carried out. Thereby, in fig.6 the OASPL for each propeller was reported as a function of $AR_t$. In addition, in order to make a comparison with the baseline propeller, a red dotted line was plotted. Even in this case, it is impossible to define a characteristic trend, nonetheless it is interesting to underline that when the polar angle reaches a value of 90 degrees (fig.6(d)), the experimental points obtained for almost all propellers are situated under the red dotted line, that can be interpreted as a better aeroacoustic behaviour. Furthermore, in fig.6 the best and the worst propeller for each case was highlighted with a red circle and for these test cases further investigations were carried out.

In particular, spectral and statistical analysis were performed, and the related results are shown in figs.7-8. The spectra are calculated in terms of the Sound Pressure Spectrum Level ($SPSL$) and the Harmonics of the Blade Passing Frequency ($HBPF$), which are defined as:

$$SPSL = 10 \log_{10} \left( \frac{PSD \cdot \Delta f}{p_{ref}^2} \right)$$  \hspace{1cm} (7)$$

$$HBPF = \frac{2\pi f}{\Omega B}$$  \hspace{1cm} (8)$$

where $p_{ref} = 20\mu Pa$ is the threshold of human hearing, $PSD$ is the power spectral density of the pressure signal, $\Delta f$ is the frequency resolution set at 1 Hz, $B$ is the number of blades and $\Omega$ is the rotational regime in rad/s.
Figure 6. OASPL for each blade by varying the $AR_t$. The red dotted line is representative of the baseline blade. (a)=$0^\circ$, (b)=$30^\circ$, (c)=$60^\circ$, (d)=$90^\circ$, (e)=$120^\circ$ and (f)=$150^\circ$.

Figure 7. SPSL trend for the best (green line), the worst (blue line) and the baseline propeller (red line) for each polar angle. (a)=$0^\circ$, (b)=$30^\circ$, (c)=$60^\circ$, (d)=$90^\circ$, (e)=$120^\circ$ and (f)=$150^\circ$.

Fig. 7 reports the worst (blue line), the best (green line) and the baseline blade for the case highlighted with the red circle in each plot of fig. 6. Plots in fig. 7 point out a strong reduction in broadband noise in the low frequency region and an unexpected reduction even in the tonal component. As seen in §2.1, tonal noise is related to the aerodynamic loading over the blade thus a decrease of this component it is likely connected with a loss in aerodynamic performance. Fig. 8 shows the results obtained from statistical analysis in terms of Probability Density Function.
in a logarithmic scale, where pressure is represented in a reduced form in order to have zero mean and unitary standard deviation. A deviation from a gaussian distribution is the first feature which should be noted. In particular, in particular the effect of serration is to mitigate the tales of the PDF that are generally related to intermittency. This effect could give a physical interpretation of the behaviour of this propeller: the serration seems to mitigate the frequency of strong energetic events in the turbulent field.

![Graphs showing Probability Distribution Function for different propellers](image)

**Figure 8.** Probability Distribution Function for the best (green line), the worst (blue line) and the baseline propeller (red line) for each polar angle. (a)=0°, (b)=30°, (c)=60°, (d)=90°, (e)=120° and (f)=150°.

5. Conclusions & Future Development

In this paper, the aeroacoustic behaviour of several propellers was investigated by using a test bench specific for the characterization of drones propulsive systems. The first step was given by the realization of the setup and of the propellers, followed by a microphone measurement campaign.

The trailing edge geometry of the rotor blade was modified by means of a sawtooth pattern by mimicking the owls’ wing in order to obtain a loss in the noise radiated by the rotor. Results show that is possible to achieve a sensible loss in the $OASPL$, which measure all the energetic content of the signal, but the gain is strongly dependent on the polar angle $\theta$. Furthermore, the number of teeth seems to not affect the noise impact. The spectral analysis shows that both the broadband and tonal components were influenced by the serration. In particular, the reduction of the tonal component suggests that also the thrust generated may be reduced. The analysis on the PDF highlights a mitigation in the tales of the distribution that can give a physical interpretation to noise reduction.

As a further investigation, the dynamical characterization of the designed propellers will probe if acoustic gain is associated with a reduction in thrust generation (as spectra suggest). The purpose is to verify the usability of this technology on flying drones. In addition, further advanced analysis can be employed in order to understand the physical phenomena that stands behind the noise reduction and to keep more information about the noise generation mechanism for small-scale propellers.
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