# Multi-Objective Optimization of the Energy Efficiency and the Tonal Noise of the Propeller Blades of an Unmanned Aerial Systems Rotor.

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## 1 Introduction

Along with all the technological, operational and regulatory barriers, Unmanned Aerial System (UAS) noise radiation has been identified as a significant factor limiting the widespread adoption of UAS systems, particularly within densely populated regions. Understanding and mitigating the acoustic emissions from UAS while reducing their carbon footprint poses a significant challenge due to their unconventional vehicle layout with multiple propulsion units combined with their operation in reverberant urban environments at high thrust levels. An appropriate design of the propeller blades shape with an optimal number of blades allows, on one hand, to improve aerodynamic performance while reducing the energy dependence of the UAS, thus reducing CO2 emissions and on the other hand to have a quieter rotor. Recent advances in numerical simulation made the implementation of multidisciplinary optimization for complex shape propeller blade designs a feasible and affordable option. However, the numerical simulation linked to the optimization of complex systems such as the propeller blades is known as a task of considerable computational time and complexity. In addition, the cost associated with the required commercial software contribute to the increase in design costs. As a result, metamodel techniques using open source algorithms as a mean to explore and support the initial design concepts become standard practice to reduce the computational time required and decrease the total design cost.

This paper focusses on the reduction of the UAS rotor passage blade noise [1] which is one of the main sources of nuisance. A metamodel approach based on multi-objective optimization is proposed. Improved aerodynamic and aeroacoustics performances were demonstrated numerically for an optimized propeller blade configuration as compared to a baseline geometry configuration.

## 2 Materials

The reference geometry has not comprised the shrouded supports as used in the Karmal et al.'s works [2]. This geometry had $N = 3$ identical propeller blades with constant angular spacing of $360/N$ degrees mounted around a motor shaft of diameter $4.3\ in$ and length $10.5\ in$ with a parabolic shaped hub (Fig. 1.a). The blade was constructed using NACA 6412 type profiles. The propeller blade parameters such as the blade angle $\beta$, the chord and the thickness of each profile could be found on the page 14 of the ref. 3 The absence of the shrouded supports allowed to simplify the CFD model with only 1/n$^{th}$ of the UAS rotor (Fig.1a). To facilitate the setup, the geometry under study was placed in a cylinder of a diameter of $1.5D$, a length of $1.25D$ and sharing the same axis as the rotor. The volume of air thus defined was called the rotation volume (Fig. 1.b). The volume of rotation was also channelled in a cylindrical tunnel of diameter $4D$, length $12D$ and with the same axis. The rotation volume is located in the center of the channel (Fig 1.c).

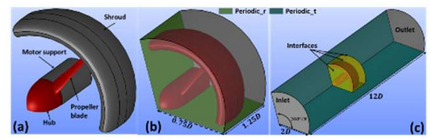

**Figure 1:** Baseline geometry: (a) $1/N$ th of the rotor, (b) $1/N$ th rotation volume and (c) CFD model

An incompressible solution using the OpenFoam RANS method was computed using air at $20^oC$ and 1 atm. For the modelling of the rotation, the multi-rotational frames (MRF) approach of the OpenFoam was chosen. For all CFD calculations, a velocity of $U_\infty = 30.226\ m/s$, was applied at the tunnel inlet while zero pressure was imposed at outlet. The adhesion boundary conditions was used on the walls.

## 3 Optimization problem

### 3.1 Design parameters

There are a variety of propeller blade design parameters that can influence both the aerodynamic and aeroacoustic performances of a UAS rotor. On the basis of a preliminary study and for reasons of computation time, four of these design parameters were retained for this study. Those parameters were: the number of propeller blades N, the blade angle $\beta_{75\%}$ at 75% of the rotor radius and the blade skew. The blade skew was defined in the plane perpendicular to the rotation axis of the rotor. It was characterized by the angular position $\theta_s$ with respect to the radial of the mid-chord point of the profile considered. For this study, the blade skew profile was a polynomial of degree 2 constructed using 3 given skew angles: $\theta_{s0} = 0^o$ at $0.3R$, $\theta_{s0}$ at $0.65R$ and $\theta_{s2}$ at blade tip. Once the blade angle $\beta_{75\%}$ is given a correction is made on other profile blade angles. Thus, the new blade angle $\beta$ becomes double the old blade angle $\beta_{old}$ for each profile minus $\beta_{75\%}$ ($\beta = 2\beta_{old} - \beta_{75\%}$).

Thus, the optimization variable vector was given by:

$$X = (N, \beta_{75\%}, \theta_{s1}, \theta_{s2}). \quad (1)$$

### 3.2 Objective functions

The main objective of this study was to optimize the shape of a propeller blade in terms of emitted sound pressure level of the tonal noise as compared to the baseline blade while

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increasing the UAS rotor aerodynamic performance. It is therefore necessary to define two objective functions, one for aerodynamic performance and one to quantify the total noise.

The aerodynamic performance is proportional to the total thrust (N propeller blades, hub, motor support and shrouded) and the engine torque and is defined by:

$$\eta = \frac{TU_\infty}{2\pi Q\Omega/60}, \quad (2)$$

with regard to the tonal noise, it is materialized in this study by the root-mean square pressure $p_{rms}$ of the acoustic pressure magnitude $|p|$of the first frequency. According to the Garrick et al.[3] work, the acoustic pressure magnitude for any harmonic $m$ is defined by the noise contribution due to the thrust of the propeller blades and that of the engine torque. The magnitude of the far-field sound pressure at a field point identified by (x, y, 0) emitted by a point moving force at (0, y1, z1), both (field point and force) in uniform motion with velocity $U_\infty$ along the x-direction is given by:

$$|p| = \frac{m\omega_1}{2\pi c S_0}\left| T\left(M + \frac{x}{S_0}\right)\frac{1}{\beta^2} - Q\frac{Nc}{\omega_1 R_e^2}\right| J_{mN}\left(\frac{kyR_e}{S_0}\right), \quad (3)$$

where $S_0 = \sqrt{x^2 - \beta^2 y^2}$, $\beta = \sqrt{1 - M^2}$, $M = U_\infty / c$, $c$ is the sound velocity, $\omega_1 = N\Omega$ is the fundamental frequency, $J_{mN}$ is the Bessel function of first kind, index $mN$, $\omega = mN\Omega = kc = m\omega_1$is *m-th* harmonic frequency and $R_e = R \text{ or } 0.8R$ is effective radius of propeller blades, with $R$ is propeller blades radius. The propeller blades total thrust and the engine torque are placed at the effective radius $R_e$.

From equation (2) the sound pressure root mean square at far-field is given by:

$$p_{rms} = \frac{1}{\sqrt{2}}|p| \quad (4)$$

### 3.3 Definition of the optimization problem

The optimization problem aims at finding the design parameters X (Eq. 1) to maximize the aerodynamic performance (Eq. 2) while minimizing the maximum of the magnitude root mean square of the sound pressure (Eq.4) of the UAS blade rotor first frequency of passage received at (x, 2D, 0). The problem to be solved is given by:

$$\begin{cases} \underset{X}{\text{maximize}}\, \eta(X) \text{ and} \\ \underset{X}{\text{minimize}}\left(\underset{x}{\max}(p_{rms}(X,x))\right) \\ J = 0.565,\ \Omega = 8000\,rpm,\ y = 2D, N = \{3,4,5\} \\ 17^o \leq \beta_{75\%} \leq 30^o \text{ and} -30^o \leq \theta_{s1}, \theta_{s1} \leq 30^o \end{cases} \quad (5)$$

## 4 Method

The solution of the optimization problem (Eq. 5) was carried out in 4 stages: (i) geometry space sampling; (ii) calculate the thrust and engine torque of each sample with the CFD model and deduce the objective functions (Eqs. 2 and 4); (iii) building the Kriging metamodel; (iv) determining the optimum metamodel by the Dakota's multi-Objective Genetic Algorithm; and finally, (v) once one or more optimum is found, a CFD calculation is performed to verify the accuracy of the metamodel. If the result is satisfactory, the process stops. Otherwise the optimization returns to step (i) by refining the discretization and / or by injecting into the sample the optimums found and repeating steps (ii) to (v). This process is iterated until one or several satisfactory optimums are found.

## 5 Results

A number of 123 Latin hypercube samples were needed to obtain the convergence of the Kriging metamodel. Three different solutions: 1, 2 and 3, have been found and are grouped in Table 1 and are represented in Fig. 2 as well as the baseline geometry (number 0). The predictions using the metamodel and the CFD calculation of the aerodynamic performance as well as the sound pressure level in dB are also grouped in the table. The relative error ($\left|f_{i_{CFD}} - f_{i_{model}}\right| / \left|f_{i_{CFD}}\right|$ with $f_1 = \eta$ and $f_2 = p_{rms}$) of each of the solutions is small and is average. Compared to the baseline geometry, a gain of approximately 3% in terms of aerodynamic performance was obtained for each of the 3 solutions. Regarding the amplitude of the first blade passage frequency, a decrease of about 59 dB in its level has been obtained.

**Table 1:** Optimum design parameter and the obtained results.

| Sol. | X | | | | Model | | CFD | |
|---|---|---|---|---|---|---|---|---|
| | $N$ | $\beta_{75\%}$ | $\theta_{s1}$ | $\theta_{s2}$ | $\eta(\%)$ | $p_{mrs}$ | $\eta(\%)$ | $p_{mrs}$ |
| 0 | 3 | 24 | 0 | 0 | | | 66.1 | 92.1 |
| 1 | 4 | 25 | −1.7 | −11.5 | 68.9 | 31.1 | 69.3 | 30.9 |
| 2 | 4 | 24.2 | 18.5 | −7.3 | 68.7 | 29.9 | 69 | 29.7 |
| 3 | 4 | 23.1 | −17.7 | 11.6 | 68.3 | 28.5 | 68.6 | 28.4 |

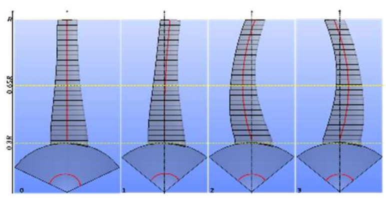

**Figure 2:** Propeller blade shape optimizer: (0) baseline geometry, (1) solution 1, solution 2 and (3) solution 3.

## 6 Conclusion

This study allowed the development of a highly multi-disciplinary optimization procedure using unexpensive open numerical tools. Three solutions quieter and better performing compared to the baseline geometry were presented. However, more design parameters and blade passage frequencies must be considered to further improve the emitted noise and efficiency of the UAS rotor.

## References


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