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Preliminary design and performance analysis of eVTOL propellers using BEMT

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Abstract

Optimizing fixed-pitch propellers for a six-rotor aircraft poses a unique challenge, requiring a balance between high propulsive efficiency during cruise and maximum figure of merit during hover. A low-fidelity Blade Element Momentum Theory (BEMT) model was used to assess the performance of various propeller geometries. Design of Experiments (DOE) with Latin Hypercube Sampling generated 1,000 propeller designs by varying the twist angle while keeping the chord length fixed. The resulting database provides a robust foundation for refining the design through high-fidelity analysis, ensuring optimal performance across multiple flight conditions despite the fixed-pitch constraint.

Keywords: eVTOL propeller design; Aerodynamic efficiency; Noise reduction; BEMT; Low-Fidelity Propeller Design

1. Introduction

With increasing congestions faced by multiple cities around the globe, residents are forced to spend long unproductive hours stuck in traffic. The Southern California Association of Governments (SCAG), a Joint Powers Authority under California state law, reported that the average driver in the city of Los Angeles in California now spends over 100 hours every year, stuck in traffic [1]. Determined to address this issue, SCAG launched a series of initiatives, including ride sharing, first & last mile solution, public transport, and emerging technologies. One of the key emerging technologies that policy makers and investors believe will revolutionize the way people travel in the near future is the concept of urban air mobility (UAM) centered around the electric vertical take-off and landing aircraft (eVTOL). This concept enables point-to-point transport of people in a flexible, fast, safe and environmentally friendly manner [2]. Batteries, motors and propellers or rotors constitute the main components of an eVTOL propulsion system. In the last 3 years alone, researchers from different countries, including China, have set out to devise efficient design methodologies aimed at advancing the burgeoning field of eVTOLs propellers design and optimization [3-6].

Furthermore, noise plays a crucial role in determining whether eVTOLs will be adopted on a larger scale. The closer these aircraft can get to quiet, the more likely they are to be accepted in noise-sensitive urban areas. The design of the propellers directly influences noise levels, and engineers need to carefully consider blade geometry, rotation speed, and other design elements to minimize noise output. In short, propeller design has a direct impact not only on the aircraft's technical performance but also on its usability in everyday life. Optimizing propeller design for efficiency and noise reduction is absolutely critical to the success of eVTOL aircraft.

Efficiency directly affects the flight range, operational cost, and overall feasibility of the aircraft [7-9]. With limited battery capacity, maximizing energy use is essential, and the propeller plays a central role in determining how much of that energy is converted into useful thrust. A well-optimized propeller design reduces power consumption, allowing eVTOLs to fly longer distances, carry more payload, and operate more sustainably [3]. Without this optimization, the aircraft may face limitations that could restrict its practical applications, particularly in dense urban environments where flight range is crucial.

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In addition to efficiency, noise reduction is another vital factor that propeller optimization addresses. One of the biggest concerns with urban air mobility is the noise pollution that eVTOLs could introduce to already noisy cities [10-13]. Traditional propellers can generate significant amounts of noise, especially during hovering and takeoff. To make eVTOLs viable in city centers, noise levels need to be kept to a minimum to avoid disturbing both residents and wildlife. Optimized propeller designs can incorporate advanced blade shapes, reduced tip speeds, and specific rotational configurations that not only improve aerodynamic efficiency but also drastically reduce noise output.

In their work, Tao Zhang et al. [14] introduce a process for designing and analyzing propellers with multiple levels of fidelity, which they demonstrate through the preliminary design of a heavy-lift eVTOL vehicle, the Skybus, proposed by GKN Aerospace. This multi-fidelity approach incorporates tools and results of varying levels of fidelity. Initially, a robust exploration of the design space was conducted at a low-fidelity level. The output from this stage was transformed into 3D shapes and grids using an automatic meshing tool, which then facilitated high-fidelity CFD simulations and gradient-based optimization to further refine the designs. The methodology was initially validated using a benchmark multi-modal test function before being applied to the propeller design for the Skybus vehicle. Initial rectangular blade designs with linear twist were derived using the Blade Element Momentum Theory and served as the input for the low-fidelity stage [15]. The low-fidelity stage was able to improve upon the baseline design, reducing power by 3%, and further optimization at the high-fidelity stage resulted in an additional power reduction of 2.2% while maintaining equal thrust. This study also introduces a tool for mapping propeller pitch-RPM performance, which has proven valuable in supporting the development of the Skybus by quickly predicting performance and determining operating conditions [16]. For propellers that regulate both pitch and RPM, the performance map provides a clear correlation between various performance scopes to aid in optimization [17]. The construction of the performance map using a multi-fidelity approach and examples of its application are also discussed.

The aim of this paper is to contribute to the advancement of knowledge in the field of eVTOL propeller design and optimization. We do so by introducing a method to a) obtain the preliminary sizing of eVTOL propellers based on mission requirements, b) to estimate the performance of the preliminary design at a low computational cost.

2. Design Target and Methodology

The main objective of this research is to design and optimize the propellers and rotors of an 850 kg eVTOL aircraft, capable of flying at a cruise speed of 60 m/s and a cruise altitude of 600 m. For the scope of this paper, we will limit ourselves to the low fidelity section of the frameowrk.

2.1. Design Target

The aircraft design features six rotors and propellers, as illustrated in Figure 1. Two of these propellers are mounted on the wingtips, while two others are positioned behind the wings, all of which are fixed and responsible solely for generating vertical thrust. The remaining two propellers are located in front of the wings and are designed to produce both forward thrust and vertical lift, depending on the operational phase.

A key design challenge arises from the requirement that all propellers must be fixed-pitch, to allow for the use of a lightweight and simplified motor. This constraint makes the design of the forward propellers particularly complex. As fixed-pitch propellers, they must achieve both high propulsive efficiency during cruise and a high figure of merit during take-off and hover, all while maintaining a consistent twist angle.

In an ideal scenario, controllable-pitch propellers would adapt by having a relatively higher twist angle during cruise, which results in a lower angle of attack and reduces the thrust required for that flight phase. During take-off and hover, a higher thrust output is necessary, which would typically be achieved through a lower twist angle and a higher angle of attack.

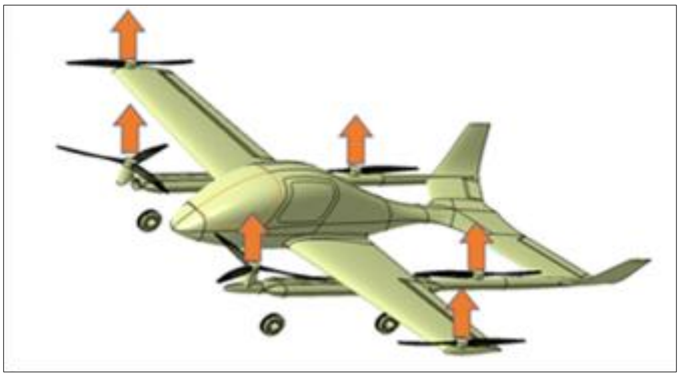

Figure 1 Propellers and rotors configuration

Meeting these two conflicting performance requirements with a fixed-pitch propeller presents a significant design challenge, as shown in Figure 2. Balancing the propeller's performance across multiple flight conditions without the ability to adjust the pitch complicates the optimization of the system.

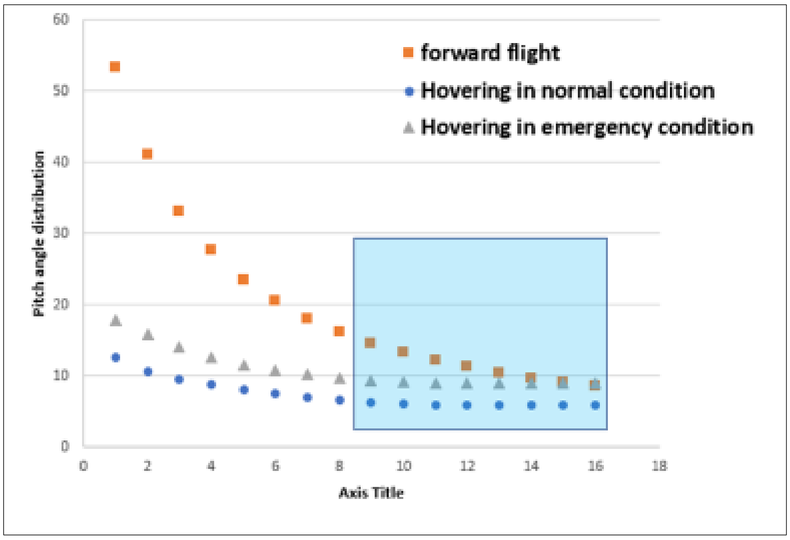

Figure 2 Hover, cruise and emergency conditions twist angle distribution

2.2. Design Methodology

The proposed framework, as depicted in Figure 3, integrates both aerodynamic and aeroelastic considerations for propeller design, ensuring a robust approach to optimizing performance across different flight regimes. The framework operates through a multi-step process aimed at balancing the conflicting requirements of cruise and hover performance.

The first step involves identifying the optimal propeller designs for both the cruise and hover flight regimes. These designs serve as the upper and lower bounds within the design space, establishing the performance limits for the optimization. Following this, a series of design samples is generated using Design of Experiment (DOE) techniques to ensure a diverse exploration of the design space.

Each of these DOE samples is then evaluated using a low-fidelity solver, allowing for the rapid assessment of aerodynamic performance. The performance metrics from these evaluations are stored in a database for further analysis. From this dataset, a subset of designs that meet the dual performance requirements for both cruise and hover is selected for further refinement.

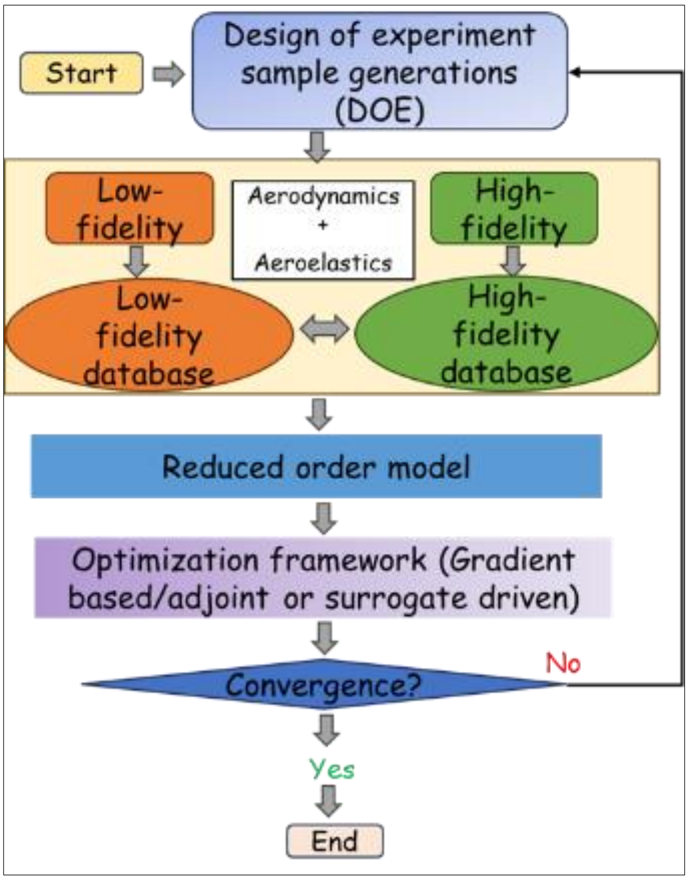

Figure 3 Proposed design and optimization flow chart

These selected designs are then evaluated using high-fidelity computational tools, which provide more accurate performance metrics. This high-fidelity data is used to construct a surrogate model that approximates the behavior of the propeller design, significantly reducing computational costs. Finally, an optimization framework is implemented, utilizing the surrogate model to efficiently evaluate a large number of design candidates. The process iterates until the most efficient design, balancing both cruise and hover requirements, is identified.

The aerodynamic aspect of the propeller design is refined through a methodical, multi-layered low-fidelity approach, which focuses on optimizing three critical aerodynamic parameters: twist angle distribution, sectional chord distribution, and sectional airfoil distribution, as depicted in Figure 4. Each of these parameters plays a vital role in enhancing the overall efficiency and performance of the propeller blade.

The twist angle distribution is essential in determining the angle of attack along the length of the blade. By optimizing this distribution, the blade can achieve an efficient lift-to-drag ratio across different flight conditions, particularly during transitions between hover and cruise. An ideal twist angle ensures that each section of the blade operates at its maximum aerodynamic efficiency, contributing to reduced drag and improved propulsive effectiveness.

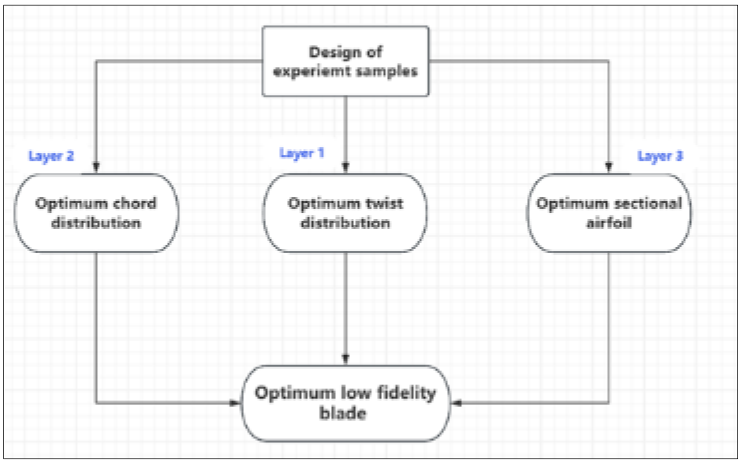

Figure 4 Low fidelity optimum 3-layered method

In conjunction with the twist angle, the sectional chord distribution directly affects the shape of the blade along its span. A well-optimized chord distribution ensures that lift is distributed efficiently across the entire blade, allowing for a balanced and effective generation of thrust. This optimization helps maintain stability and control while minimizing unnecessary drag.

The final layer in this approach involves optimizing the sectional airfoil distribution. Different airfoil shapes produce varying aerodynamic behaviours under distinct flight conditions. Selecting the right airfoil profile for each blade section is crucial for reducing drag and maximizing lift, further boosting the overall aerodynamic performance of the propeller.

Through careful optimization of these three parameters—twist angle, sectional chord, and sectional airfoil—the blade design is fine-tuned to ensure maximum efficiency in both hover and cruise flight modes. This structured approach allows for a systematic refinement of the blade's aerodynamic characteristics, leading to superior performance in the eVTOL propeller design.

3. Results and Discussions

Before setting out to build the low fidelity propeller database, both the ideal propeller for hover and the ideal propeller for cruise had to be derived. A computational framework that is not attached here has been deployed to estimate both platforms. Before the results are presented, a validation case was conducted to ensure that the framework deployed indeed captures the propeller performance with great accuracy.

3.1. Low-fidelity Ideal Hover Propeller Performance

Figure 5 illustrates the performance characteristics of the ideal hover propeller, focusing on three key metrics: static thrust, figure of merit, and torque, as functions of the propeller's rotational speed (RPM).

In the first graph on the left, static thrust per 5-bladed propeller with a diameter of 1.3 meters is plotted against RPM. The graph shows a steep rise in thrust as RPM increases, reflecting the typical behavior of a propeller. Notably, the minimum required thrust per propeller is marked at 1300 N, indicating that, for the propeller to meet the hover requirements, it must generate at least this amount of thrust. At around 2500 RPM, the thrust reaches approximately 1300 N, suggesting that this is the operational point needed to maintain hover.

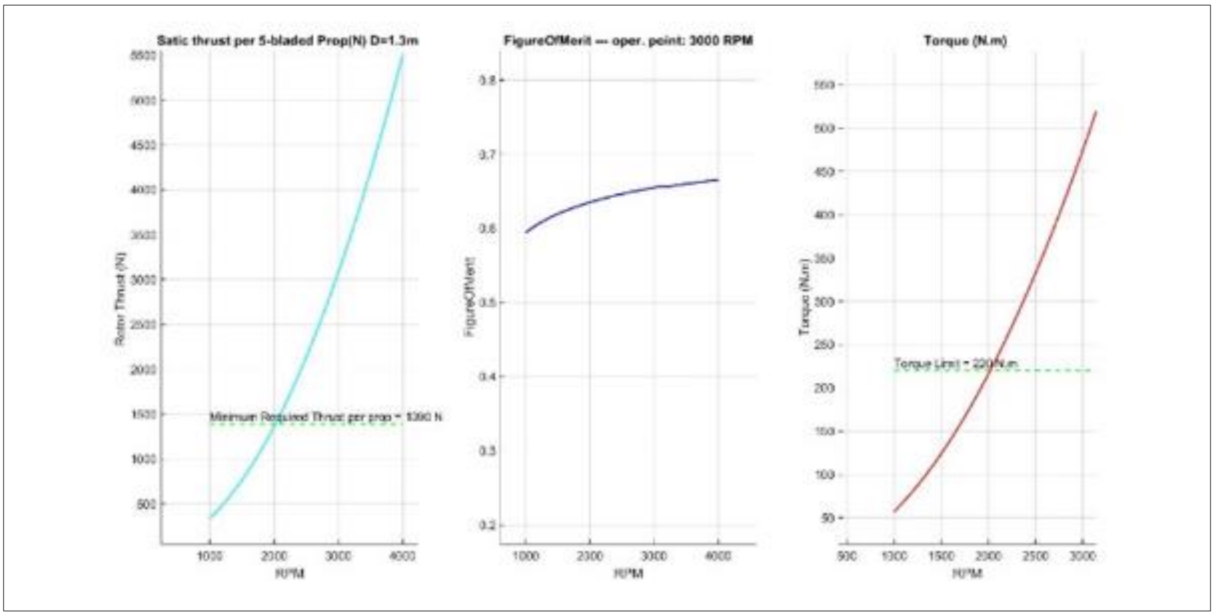

Figure 5 Ideal hover propeller performance

The center graph presents the figure of merit at an operational point of 3000 RPM, which reflects the efficiency of the propeller in hover. The figure of merit rises as the RPM increases, reaching a value of about 0.65. This demonstrates that the propeller is achieving a relatively high level of efficiency at this RPM. The figure of merit generally compares the actual power used by the rotor to the ideal power, so a value nearing 1 would be considered highly efficient.

The graph on the right illustrates the torque produced by the propeller as a function of RPM. The torque increases rapidly with RPM, and a torque limit of 220 Nm is shown with a green dashed line. At 3000 RPM, the torque reaches approximately 175 Nm, remaining well within the set limit. However, if the RPM continues to increase beyond this point, the torque would approach the limit, which may necessitate design adjustments to ensure the motor and other components can handle the load without damage.

Together, these plots offer a robust view of the hover propeller's performance. They show that the propeller meets the minimum thrust requirement at an RPM of around 2500, operates with a relatively high figure of merit at 3000 RPM, and generates torque that stays within safe operational limits.

3.2. Low-fidelity Ideal Cruise Propeller Performance

Figure 6 represents the performance characteristics of the ideal cruise propeller, highlighting three important metrics: cruise thrust, overall efficiency, and torque, all as functions of RPM.

The first plot on the left shows cruise thrust per 5-bladed propeller with a diameter of 1.3 meters. The curve shows a clear increase in thrust as RPM rises. The minimum required thrust per propeller is labeled as 420 N, and the plot indicates that this level of thrust is achieved at approximately 2300 RPM. This marks the lower operational threshold for the cruise phase. At around 3000 RPM, the thrust approaches 2500 N, significantly exceeding the required value, meaning that the propeller can provide more than sufficient lift for steady cruise flight. This could suggest that operating at lower RPMs during cruise might be possible, potentially saving energy without compromising thrust.

The second plot, in the center, tracks the overall efficiency of the propeller. At 3000 RPM, the efficiency approaches 80%, which aligns with the target efficiency marked by the dashed green line. The curve demonstrates how efficiency rises quickly with increasing RPM, peaking at just under 3000 RPM before tapering off slightly. This efficiency profile indicates that the propeller operates optimally at high RPMs, but there is a clear limit to how much efficiency can be gained. The high efficiency achieved here is crucial for eVTOLs, particularly during cruise, as it translates to lower energy consumption and extended flight ranges.

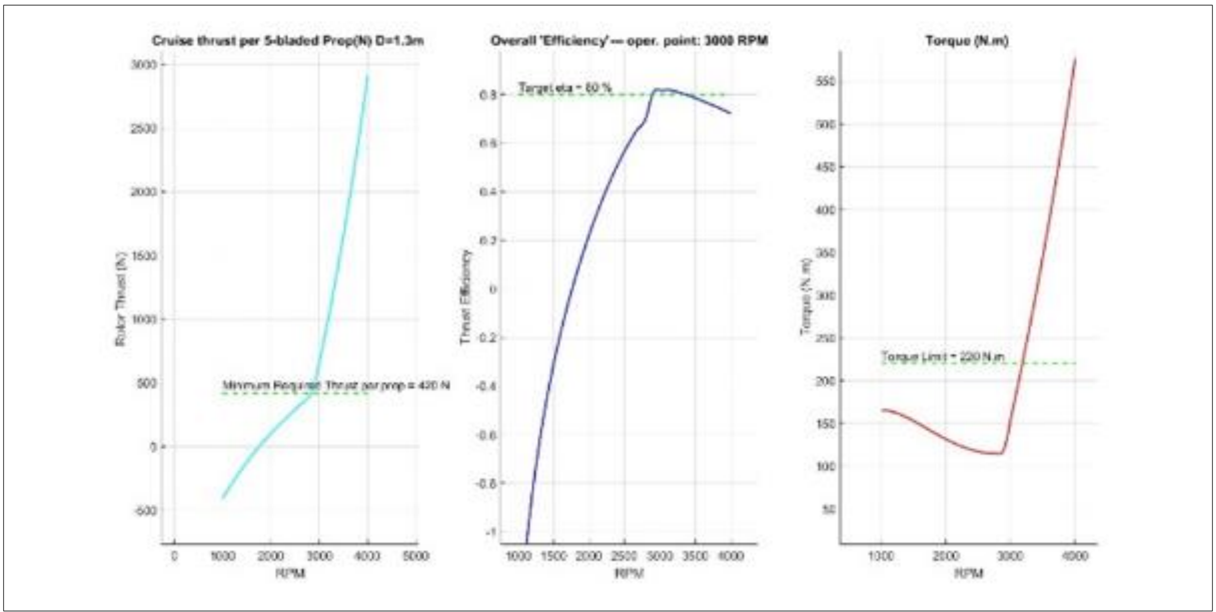

Figure 6 Ideal cruise propeller performance

The third plot on the right shows the torque curve as a function of RPM. Notably, the torque limit is again set at 220 Nm, similar to the hover propeller. However, this graph indicates that the torque briefly dips below the baseline value before rapidly increasing after 2500 RPM, exceeding the torque limit after 3000 RPM. This implies that the propeller may need to operate below 3000 RPM to avoid exceeding the torque capacity of the motor, which could otherwise lead to mechanical failure or motor damage. Careful attention must be paid to this limit, especially since high torque at elevated RPMs in cruise flight can stress the propulsion system.

In terms of implications, this figure reveals that while the cruise propeller can easily generate the necessary thrust and operate at near-optimal efficiency, managing torque will be critical in ensuring longevity and safety. Designers may need to make trade-offs between maximizing thrust and efficiency versus staying within safe operational torque limits. Moreover, the potential energy savings suggested by the ability to generate excess thrust at lower RPMs could significantly enhance the operational economics of eVTOLs, provided the torque remains within acceptable ranges.

3.3. Low-fidelity Database

To generate a robust database of propeller performance data, we employ a systematic Design of Experiments (DOE) approach using Latin Hypercube Sampling (LHS). The goal at this stage is to create a set of 1000 unique propeller designs, all of which will be analyzed using a low-fidelity Blade Element Momentum Theory (BEMT) tool. The low-fidelity tool is computationally efficient, making it ideal for conducting a batch analysis of such a large sample size without consuming excessive computational resources. This DOE-driven sampling strategy allows us to explore a broad range of geometries and performance metrics while retaining key geometric features from both the hover and cruise propellers.

For this phase of the study, the chord length remains fixed to maintain a consistent blade surface area across all samples. The twist angle is the sole variable allowed to change across the design space, as it is a key driver of aerodynamic performance. By focusing on this parameter, we can effectively capture the influence of twist angle on propeller efficiency, thrust generation, and torque.

The Latin Hypercube Sampling method is particularly suited for this scenario, as it ensures a diverse yet evenly distributed sample set across the design space. LHS requires upper and lower bounds for the design variable, which in this case is the twist angle. The twist angle distribution of the cruise propeller, which is characterized by a higher twist along the span, defines the upper bound, while the hover propeller, with its lower twist distribution, serves as the lower bound. This structured variation allows us to explore the trade-offs between high-twist and low-twist designs and their corresponding aerodynamic performance.

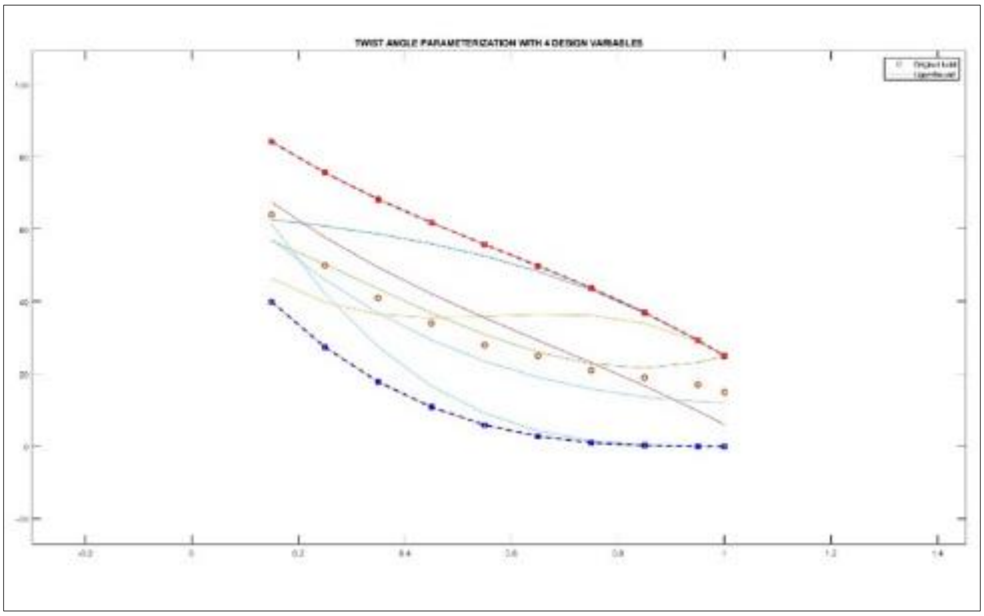

Figure 7 Design space with upper and lower bounds

The figure provided, Figure 7, illustrates the design space generated through this process. The plot displays the twist angle parameterization for different stations along the blade's radius (R). The x-axis represents the normalized station position, denoted as Stations/R, while the y-axis represents the twist angle distribution in degrees. The upper limit, indicated by the green dashed line, corresponds to the twist distribution of the cruise propeller. The lower bound, marked by the red dashed line, is the twist distribution for the hover propeller. The numerous lines in between, depicted in light blue, represent the 1000 unique samples generated through the Latin Hypercube Sampling method.

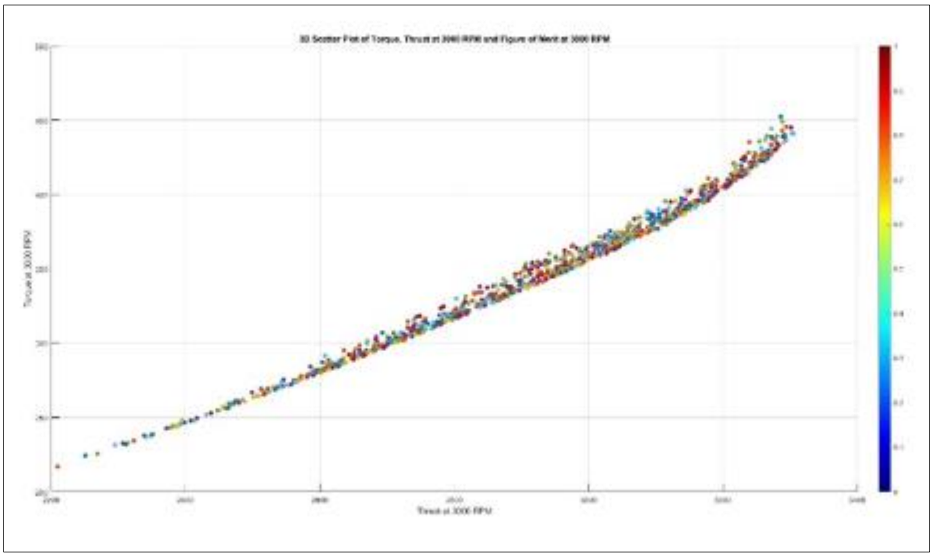

Figure 8 Performance map of samples in the design space

The trend in the figure highlights how twist angles decrease from the root of the blade toward the tip, a standard practice in propeller design to optimize aerodynamic efficiency. This gradual reduction in twist is critical to managing the angle of attack of each section of the blade relative to the incoming airflow. By allowing only the twist angle to vary, we maintain aerodynamic consistency across the blade, while still allowing for a diverse range of potential designs.

The importance of this step cannot be overstated. By sampling this design space efficiently, we are able to capture the performance characteristics of propellers ranging from hover-optimized designs to cruise-optimized configurations. This database will provide the foundation for subsequent analysis, where we will evaluate the aerodynamic performance of each sample and identify potential candidates for further high-fidelity optimization and testing. Figure 8 depicts the performance characteristics of the 1000 sample propellers.

4. Conclusion

The low-fidelity study focuses on solving the complex design challenge of fixed-pitch propellers in a multi-rotor aircraft, which must perform optimally in both cruise and hover conditions. As described, the six-rotor design includes fixed-pitch propellers that are required to achieve high propulsive efficiency during cruise and maintain a high figure of merit during take-off and hover. The key difficulty stems from the need to balance these competing requirements while keeping the propeller twist angle constant across different flight phases. To address this, a robust database of propeller designs was generated using Design of Experiments (DOE) and analyzed via a low-fidelity BEMT tool. By varying only, the twist angle and fixing the chord length, the study explored a wide range of potential geometries. The Latin Hypercube Sampling method, combined with twist angle bounds derived from hover and cruise propeller designs, provided a diverse and representative sample set. This low-fidelity database enables efficient performance evaluation across numerous configurations, offering information about the trade-offs between hover and cruise efficiency. Ultimately, this approach forms the foundation for further high-fidelity optimization, reducing the computational burden while ensuring a thorough exploration of the design space. It enables informed decision-making in later design stages.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed. This work received no external grant or funding.

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