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Research Paper

Artificial Intelligence–Assisted Aerodynamic Optimization of Toroidal Propellers for Enhanced Drone Performance

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Abstract

The rapid advancement of unmanned aerial vehicles (UAVs) has increased the demand for efficient, low-noise, and aerodynamically optimized propulsion systems. Toroidal propellers, characterized by their ring-shaped blade geometry, have emerged as a promising alternative to conventional propellers due to their potential for vortex reduction and noise suppression. This study integrates theoretical aerodynamic modeling with Artificial Intelligence (AI)-based optimization techniques to evaluate the performance and feasibility of toroidal propellers for drone applications. Mathematical thrust models for both traditional and toroidal propellers were developed and implemented using MATLAB simulations. Machine learning algorithms were applied to predict thrust performance across varying diameters and operating conditions. The AI-assisted analysis demonstrated improved thrust characteristics and reduced turbulence in toroidal designs. The results indicate that integrating AI with aerodynamic modeling enhances performance prediction accuracy and supports design optimization. This research highlights the transformative potential of toroidal propellers combined with computational intelligence for next-generation drone systems.

Keywords: Toroidal Propeller, Artificial Intelligence, Drone Aerodynamics, Machine Learning, Thrust Optimization, UAV Propulsion

1. Introduction

The increasing use of unmanned aerial vehicles (UAVs) in applications such as surveillance, delivery, and agriculture has created a demand for efficient and low-noise propulsion systems. Conventional propellers are simple and economical but suffer from efficiency losses and noise due to tip vortex formation [1]. Toroidal propellers, with their closed-loop blade geometry, reduce vortex formation and improve airflow, leading to better aerodynamic performance [2]. Studies also indicate that minimizing turbulence lowers acoustic emissions and enhances flight stability [3].

Modern engineering design increasingly employs Artificial Intelligence (AI) for analyzing complex systems and predicting performance. Machine learning models can

identify relationships between operating parameters and system output with high accuracy [4,5]. However, limited research integrates AI with toroidal propeller analysis for drone propulsion. Therefore, this study combines aerodynamic modeling and AI techniques to compare toroidal and conventional propellers, predict thrust performance, and evaluate their feasibility for drone applications considering performance, manufacturing complexity, and cost.

2. Methodology

2.1 Theoretical Aerodynamic Modeling

The thrust of a traditional propeller is given by:

$$T = C_T \rho \omega^2 D^4$$

where: C_T = thrust coefficient, ρ = air density, ω = angular velocity, D = diameter

For toroidal propellers, thrust is estimated using:

$$T = C \rho A (V_e^2 - V_0^2)$$

where: A = effective flow area, V_e = exit velocity, V_0 = inlet velocity.

MATLAB simulations were conducted to compare thrust variations across different diameters.

2.2 AI-Based Performance Prediction

A dataset was generated using thrust values calculated for varying diameters. Input features included:

- Diameter
- Angular velocity
- Air density
- Exit velocity
- Thrust coefficient

Machine learning models used:

- Artificial Neural Network (ANN)
- Regression-based Random Forest model

The AI system was trained to predict thrust output and efficiency trends. The predictive accuracy was validated using simulated datasets.

3. Results and Discussion

3.1 Thrust Comparison

Simulation results indicate that toroidal propellers produce comparable or higher thrust at similar diameters due to improved airflow confinement. The reduction in vortex formation enhances aerodynamic efficiency.

3.2 AI Prediction Accuracy

The AI model achieved high correlation between predicted and theoretical thrust values, confirming its capability to model nonlinear aerodynamic behavior.

3.3 Noise Reduction Mechanism

The toroidal geometry minimizes tip vortices, which are primary sources of propeller noise. Studies suggest significant reduction in high-frequency acoustic emissions [3]. This makes toroidal designs suitable for urban drone operations.

3.4 Manufacturing Feasibility

Additive manufacturing (SLA-based 3D printing using ABS-like resin) was identified as a viable fabrication method. However, increased geometric complexity leads to higher production cost compared to conventional propellers.

4. Applications

The AI-optimized toroidal propeller system is suitable for:

- Urban delivery drones
- Surveillance UAVs
- Agricultural drones (crop monitoring, pesticide spraying)
- Low-noise aerial photography

5. Advantages

- Higher aerodynamic efficiency
- Reduced tip vortex formation
- Lower acoustic signature
- Enhanced safety due to enclosed blade structure
- AI-enabled design optimization

6. Conclusion

This research integrates aerodynamic theory and Artificial Intelligence to evaluate toroidal propeller efficiency for drone applications. Mathematical modeling demonstrated improved airflow characteristics and potential thrust advantages. AI-based prediction enhanced performance evaluation accuracy and enabled optimization across varying operational parameters. Although manufacturing complexity remains a challenge, the aerodynamic and acoustic benefits make toroidal propellers promising candidates for next-

generation UAV propulsion systems. Future work should include experimental wind tunnel validation and real-time AI-based adaptive control systems.

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