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Design of an Experimental Device for Evaluating the Performance Characteristics of an Aircraft Propeller Propulsion System

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Abstract- Aircraft propeller propulsion systems are widely used in aviation and unmanned aerial vehicles. However, practical training and research on variable-pitch propellers remain limited due to the complexity and cost of full-scale systems. This paper presents the design of a laboratory-scale experimental platform for investigating aircraft propeller propulsion performance. The system integrates a BLDC motor, variable-pitch propeller mechanism, servo pitch control, thrust and torque sensors, rotational speed measurement, electrical power monitoring, and real-time data acquisition. The platform enables evaluation of thrust, power consumption, efficiency, aerodynamic loading, and reverse-thrust characteristics under various operating conditions.

Keywords: Variable-Pitch Propeller, Aircraft Propulsion System, Thrust Measurement, Torque Measurement, Real-Time Data Acquisition, Aerospace Engineering Education.

I. INTRODUCTION

Aircraft propeller propulsion systems play an important role in thrust generation and propulsion efficiency. Variable-pitch propellers enable adaptation to different operating conditions and are widely used in aviation applications. However, practical training and research are often limited by the cost, complexity, and safety requirements of full-scale propulsion systems. This paper presents the design of a laboratory-scale experimental device that enables real-time blade pitch adjustment, propulsion parameter measurement, and performance evaluation. The proposed platform supports education, research, and characterization of aircraft propeller propulsion systems.

II. RESEARCH OBJECTIVES

The objective of this study is to develop a laboratory-scale experimental device that can simulate the operating principles of an aircraft propeller propulsion system and support practical exercises for aerospace engineering education.

The device is designed to allow real-time blade pitch adjustment, direct observation of thrust variation and reverse thrust, measurement of thrust force, torque, rotational speed, voltage, current, and power, and construction of standard characteristic curves for evaluating propeller and motor loading behavior.

III. SYSTEM DESIGN

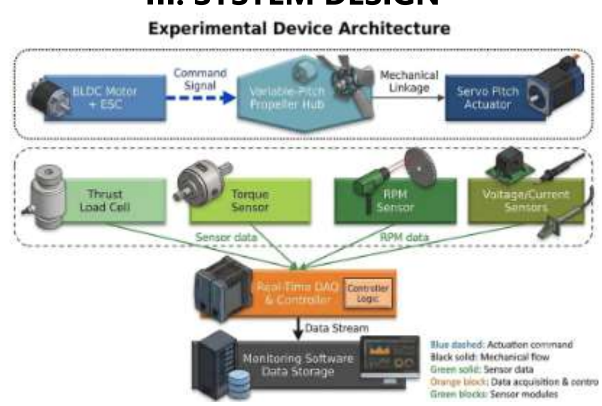

Figure 1: Overall architecture of the experimental system.

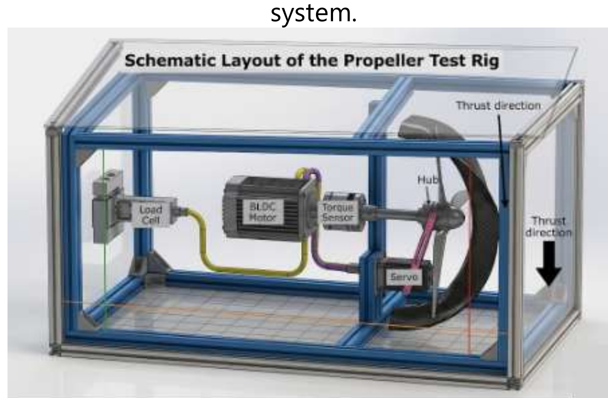

Figure 2: Schematic layout of the propeller test rig.

Propulsion Subsystem
The propulsion subsystem consists of a brushless DC motor, an electronic speed controller, and a power supply. The BLDC motor provides controllable rotational power, while the ESC regulates speed according to the test program.

The selected configuration is appropriate for laboratory experiments because it provides clean operation, precise speed control, compact installation, and lower operational risk than combustion-engine test systems.

Variable-Pitch Propeller Subsystem
A key feature of the device is the variable-pitch propeller subsystem. The subsystem includes an aircraft propeller, a pitch-changing rotating hub, a servo actuator, and a mechanical linkage for transmitting the control motion to the blade pitch mechanism.

The servo actuator permits adjustment of blade pitch angle during operation. This capability allows experiments on positive thrust, low-thrust operation, high-load operation, and reverse-thrust operating modes.

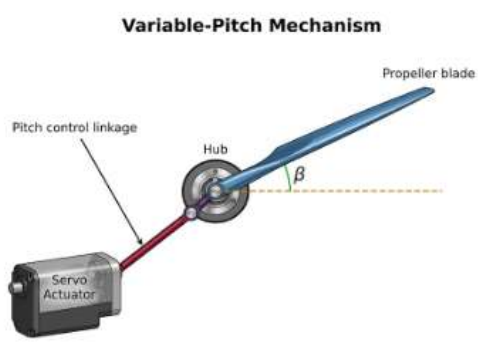

Figure 3: Schematic drawing of the variable-pitch mechanism.

Measurement and Data Acquisition Subsystem
The measurement subsystem integrates a thrust load cell, a rotary torque sensor, a rotational speed sensor, voltage and current sensors, and a blade pitch angle feedback signal. These sensors provide synchronized data for evaluating the propulsion system under different operating modes.

The real-time data acquisition system consists of a DAQ unit, signal conditioning circuits, a central controller, embedded software, communication interface, monitoring software, and an experimental workstation computer. The software displays real-time values, records test data, and exports data for performance analysis.

Mechanical Structure and Safety
The mechanical frame is designed to maintain stiffness and minimize vibration during high-speed operation. The motor, torque sensor, propeller hub, and thrust-measurement structure are arranged along the same axis to reduce measurement error.

The device includes a protective enclosure, emergency stop system, warning indicators, and operational procedures. These components are necessary because propeller testing involves high rotational energy and possible blade failure risks.

IV. MATHEMATICAL BASIS AND PERFORMANCE PARAMETERS

The experimental device calculates key propulsion performance parameters from measured thrust, torque, rotational speed, voltage, current, and pitch angle. Shaft power is determined from torque and rotational speed:

$P = 2\pi nQ$
$C\_T = T/(\rho\ n^2\ D^4)$
$C\_P = P/(\rho\ n^3\ D^5)$
$\eta = TV/P$
where P is shaft power, n is rotational speed in revolutions per second, Q is torque, T is thrust, rho is air density, D is propeller diameter, V is free-stream velocity, CT is thrust coefficient, CP is power coefficient, and eta is propeller efficiency.

V. EXPERIMENTAL CHARACTERISTICS AND ILLUSTRATIVE RESULTS

To demonstrate how the device can be used in training and research, representative characteristic curves are generated from sample experimental data. These curves illustrate the expected relationship between rotational speed, blade pitch angle, thrust, torque, shaft power, and reverse thrust. In actual operation, the same graph formats are generated from the measured data collected by the DAQ system.

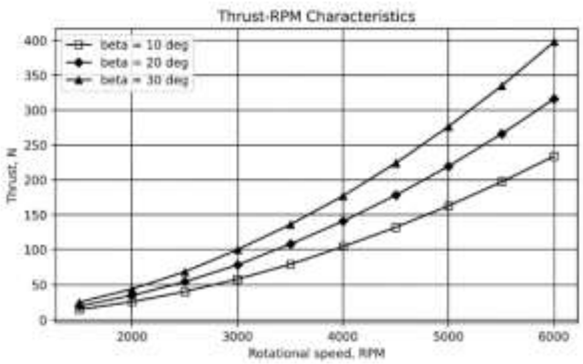

Figure 4: Thrust versus rotational speed characteristics for different blade pitch angles.

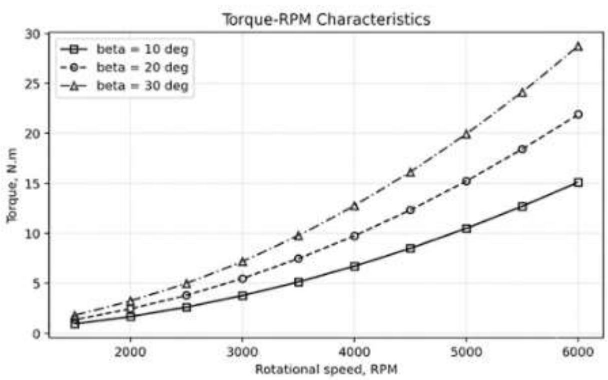

Figure 5: Torque versus rotational speed characteristics for different blade pitch angles.

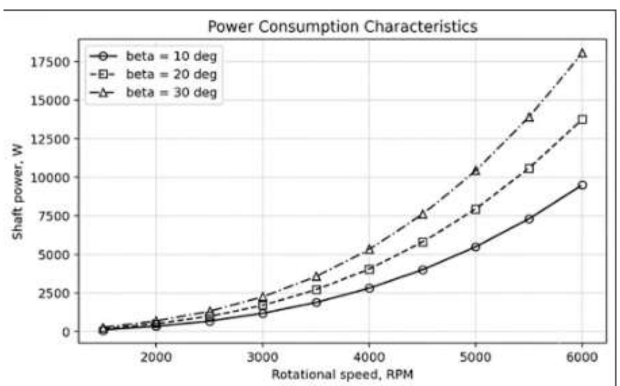

Figure 6: Shaft power versus rotational speed characteristics.

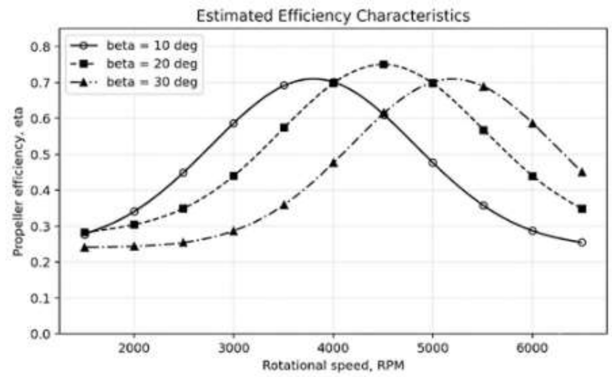

Figure 7: Estimated propeller efficiency characteristics.

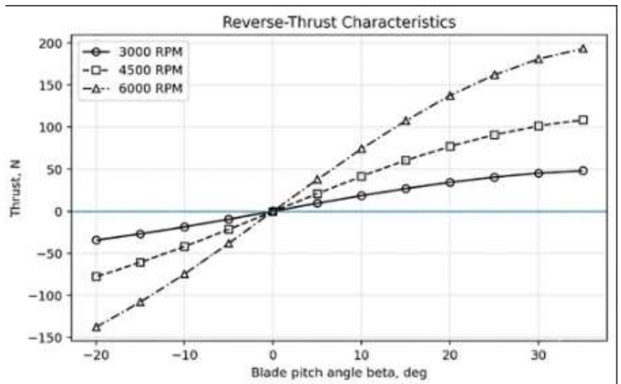

Figure 8: Reverse-thrust characteristics as a function of blade pitch angle.

Table 1: Main Specifications of the Proposed Experimental Device

Parameter	Specification	Purpose
Driving motor	BLDC motor, 22 kW, up to 8000 RPM	Speed-controlled propulsion drive
ESC	120 A electronic speed controller	Motor speed regulation
Propeller hub	Variable-pitch hub	Blade pitch adjustment
Pitch actuator	Servo motor and linkage	Real-time pitch control
Thrust sensor	Load cell, 0-1000 N	Axial thrust measurement
Torque sensor	0-50 N.m rotary transducer	Shaft torque measurement
RPM sensor	Optical or Hall sensor	Rotational speed feedback
DAQ system	Real-time DAQ and controller	Data acquisition and processing

Safety system	Protective enclosure and emergency stop	Operator protection

Table 2: Sample Data Structure for Experimental Testing

RPM	Pitch beta (deg)	Thrust (N)	Torque (N.m)	Voltage (V)	Current (A)	Power (W)
2000	10	26	1.7	48	9	432
3000	10	59	3.8	48	18	864
4000	20	145	8.5	48	39	1872
5000	20	226	13.4	48	63	3024
6000	30	421	25.8	48	116	5568

VI. DISCUSSION

The proposed experimental device provides a comprehensive platform for investigating the operating behavior of aircraft propeller propulsion systems. The variable-pitch mechanism enables students and researchers to observe how blade angle affects thrust generation, torque demand, and motor loading.

The thrust-RPM curves show that thrust increases strongly with rotational speed and that a larger blade pitch generally produces greater thrust under the same RPM. The torque and power curves indicate the corresponding increase in aerodynamic load and power requirement. These results help learners connect theoretical propeller equations with practical test data.

The reverse-thrust curve is especially useful for explaining the operating principle of propeller braking and reverse thrust. When the pitch angle changes into the negative operating region, the measured thrust can become negative, demonstrating thrust reversal in a safe laboratory-scale system.

VII. EXPECTED PRODUCTS OF THE PROJECT

One complete experimental device for aircraft propeller propulsion system characteristics.
One real-time monitoring, data acquisition, and processing software package.

One experimental database for propeller propulsion performance.

Five groups of standard characteristic curves: thrust, torque, power, efficiency, and reverse thrust.
Laboratory manuals and specialized practical exercises for aerospace engineering training.
Operating, maintenance, and safety procedures.

VIII. CONCLUSION

This paper presented the design of an experimental device for evaluating the performance characteristics of an aircraft propeller propulsion system. The device integrates a BLDC propulsion drive, variable-pitch propeller hub, servo pitch actuator, sensor system, real-time data acquisition unit, monitoring software, and safety enclosure.

The system enables measurement of thrust, torque, rotational speed, electrical power, and blade pitch angle, while supporting the construction of standard performance curves. The proposed platform is suitable for aerospace engineering education, laboratory training, and research on propeller propulsion systems. Future work will include fabrication, calibration, uncertainty analysis, and validation using measured experimental data.

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