

ABSTRACT

Title of Dissertation: **PROPELLER-DRIVEN ROTOR
TWIRL PHENOMENON:
HOVER PERFORMANCE,
DYNAMICS, AND CONTROLS**

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Propeller-driven rotors use compact electric motors and propellers, mounted on the main rotor blade, to generate the mechanical torque needed to rotate the main rotor. The presented work details experiments and model developments in three major areas: hover performance, dynamics, and controls. The idea of a propeller-driven rotor has become attractive over the last several years due to the advances in electrification of aircraft, for several reasons. First, large mechanical transmissions and gears associated with single main rotor helicopter designs are replaced with efficient electric motors, simplifying the rotorcraft design, maintenance, and potentially reducing weight. Second, modulating the propeller speed can generate the control moments for the rotor, eliminating the need for a conventional swashplate. Third, an unmanned design can eliminate a conventional fixed frame fuselage and tail rotor – significantly reducing vehicle complexity and weight. Fourth, given these first three

advantages, the concept is essentially a “flying rotor design”.

Propeller-driven rotor performance and feasibility was investigated in a series of experiments with increasing complexity. First, high quality commercial-off-the-shelf electric motors and propellers were selected, and were characterized in axial flight in the Low Turbulence Wind Tunnel at the Naval Surface Warfare Center Carderock Division. Next, hover experiments using a 5.5 ft diameter 2-bladed composite rotor blade on a custom hover test stand identified performance trends and areas for improvement, such as reduction in power. During these experiments, several propellers suffered root failures. The next hover experiment focused on measuring propeller loads during propeller-driven rotor operation. The results indicated that a large, previously unmodeled, propeller pitching moment was present during propeller-driven rotor operation. Finally, propeller placement on the rotor blade was investigated. A 2.7 ft diameter test stand was built for this experiment, and showed that a propeller placed at the rotor blade mid-span location resulted in a 50% reduction in the electrical power coefficient compared to a tip mounted propeller.

While attempting additional propeller-driven rotor hover experiments, several propeller blades suffered root bending failures. This halted the hover test campaign, and prompted an investigation into the dynamics of spinning a fast propeller on a rotating rotor blade. The resulting failure has since been termed as the “propeller-driven rotor twirl phenomenon.” A rotor-propeller Coriolis interaction results in a large propeller pitching moment that bends the propeller. Additionally, this propeller pitching moment results in a rotor blade torsional load. The coupling of the propeller pitching moment with the rotor blade torsion mode is the suspected cause of the propeller failures during propeller-driven rotor operation.

The propeller-driven rotor dynamics were investigated in two vacuum chamber experiments, as vacuum chambers remove aerodynamic effects and allow for only rotor-propeller inertial interactions

to be studied. The first vacuum chamber experiment measured propeller flapping motion on an articulated propeller. The results indicated that a large, one per propeller rev, propeller flapping motion was present. A simplified physics model was derived, and showed the flapping was a result of the rotor-propeller Coriolis interaction. The second vacuum chamber experiment investigated the rotor and propeller loads, and showed that the propeller pitching moment resulted in a rotor blade torsional moment.

The findings of the various hover and vacuum chamber experiments highlighted the need to study the propeller-driven rotor concept using modern comprehensive rotorcraft analysis tools. A finite-element based propeller-driven rotor comprehensive model was created, and validated using the various datasets. Special attention was given to ensure proper modeling of the rotor-propeller Coriolis moment. The rotorcraft comprehensive analysis model showed good agreement with the test data. After validation, a systematic study of various propeller-driven rotor configurations was performed, such as: impact of propeller placement on performance, propeller loads during propeller-driven rotor operation, and propeller-driven rotor scaling.

The final section of this thesis explored a swashplateless control concept for a propeller-driven rotor. The propeller was mounted at a slight upward angle with respect to the rotor blade chord, which resulted in a portion of the propeller thrust to be in the vertical direction. The vertical portion of propeller thrust was controlled by varying the propeller speed around the rotor azimuth, resulting in a main rotor roll and pitch moment. The control concept was fabricated, characterized, and compared to a conventional rotor swashplate. The results indicated that, for certain propeller configurations, a 2.3% variation in propeller motor throttle resulted in the same control authority as 1 deg of swashplate excitation. Additionally, the propeller-driven rotor control scheme had excellent on-axis response, and little off-axis response.

This exploratory study observed several areas of future work. First, the suitable propeller design for propeller-driven rotor is still an open question. The propeller must have two properties: it has high propulsive efficiency, and it can withstand the significant inertial loads. Vacuum chamber and hover experiments are expected. The second area is forward flight investigations. Edgewise rotor flight brings about harmonic, or time varying, airflows on the propeller that are not seen in hover. Forward flight stability investigations are needed to identify new technical challenges related to propeller-driven rotors.

PROPELLER-DRIVEN ROTOR TWIRL PHENOMENON:
HOVER PERFORMANCE, DYNAMICS, AND CONTROLS

by

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Preface

Many propellers were harmed in the making of this work.

Dedication

To my loving wife, Leah, to whom I owe it all.

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I am grateful to the Naval Surface Warfare Center Carderock Division (NSWC Carderock) for employing me while I obtained this degree, and I look forward to giving back technical service to the United States of America. This research was made possible due to the Office of Naval Research (ONR), the Naval Innovative Science and Engineering (NISE) program, and the Defense Advanced Research Projects Agency (DARPA). I would like to give a special thanks to Dr. Krista Lossing, NSWC Carderock Director of Research, for her support. Additionally, I would like to thank the program officers that supported this work, who asked not to be named.

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Chapter 1: Introduction

1.1 Propeller-Driven Rotor Concept

A propeller-driven rotor, shown in Figure 1.1, uses compact, electric motors and propellers mounted on the rotor blade to generate the mechanical torque needed to rotate the main rotor. The objective of the current study is to systematically examine the historical concept of a tip-driven rotor system with modern high power density electric motors and comprehensive rotorcraft analysis techniques. As a starting point for this research, a generic rotor system was created to study the propeller-driven rotor concept using commercial-off-the-shelf components. The lessons learned from this initial research would lead to studies into propeller-driven rotor hover performance, dynamics, controls, and propeller placement impacts. The overall goal for this research was not to develop a highly optimized, high performance rotor system, but rather it was to demonstrate its feasibility and develop a refined methodology for analyzing the fundamental concept of a propeller-driven rotor system.

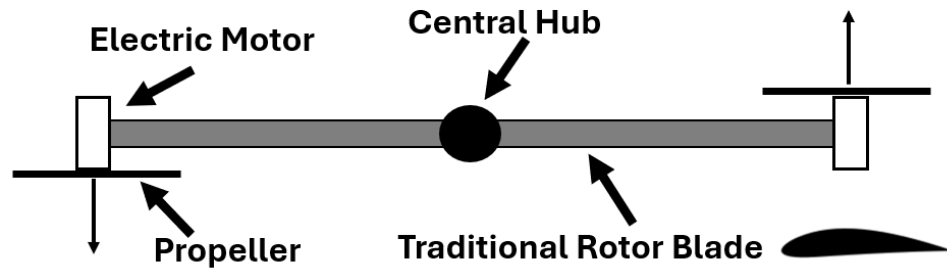


Figure 1.1: Propeller-driven rotor concept with a tip mounted propeller. Top down view.

The idea of a propeller-driven rotor has become attractive over the last several years due to the advances in electrification of aircraft, for several reasons. First, large mechanical transmissions and gears associated with single main rotor helicopter designs are replaced with efficient electric motors, simplifying the rotorcraft design, maintenance, and potentially reducing weight. Second, modulating the propeller speed can generate the control moments for the rotor, eliminating the need for a conventional swashplate. Third, an unmanned design can eliminate a conventional fixed frame fuselage and tail rotor – significantly reducing vehicle complexity and weight. Fourth, given these first three advantages, the concept is essentially a “flying rotor design”.

1.1.1 Historical Tip-Driven Rotors

Propeller-driven rotors are part of a larger field known as “tip-driven rotors”. These historical tip-driven rotors have been propelled by hot/cold gases or propellers. These gasses are exhausted out of the main rotor blade to provide the torque to spin the main rotor. Such designs pump the gasses from the fixed frame to the rotating frame using a pneumatic slipring.

The idea of a tip-driven rotor system dates back to one of the earliest attempts in vertical flight by the Brennan Helicopter, shown in Figure 1.2a. This helicopter was tested between 1916-1924, and it utilized propellers located at the tip of the rotor blade. The Brennan helicopter was the first helicopter to be tested in the United Kingdom, and made over 70 free flight tests.

After the 1950s, the tip-driven rotorcraft design largely focused on hot or cold gas driven jets located at the tip of the rotor blade. Arguably the most famous of these tip driven rotorcraft was the Fairey Rotordyne [1], shown in Figure 1.2b. The Rotordyne used tipjet engines to rotate the rotor in hover, and then flew as an autogyro with wings for high speed forward flight.



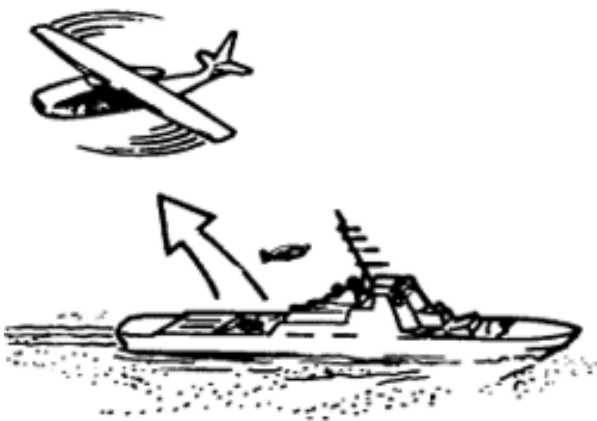
(a) Brennan helicopter (1910s).



(b) Fairey Rotordyne (1960s).

Figure 1.2: Early examples of tip-driven rotorcraft.

In the 1990s, the US Navy researched the application of tipjet engines on an unmanned aerial vehicle concept, as shown in Figure 1.3. The Naval Surface Warfare Center (NSWC) Carderock Division analyzed a 1200 lb, 9 ft radius tipjet-driven vertical takeoff and landing unmanned aerial vehicle for naval operations [2]. This configuration was designed for high speed flight, and featured a stoppable rotor with circulation control airfoils. A 37% scale model was evaluated at NSWC Carderock's 8 ft by 10 ft Subsonic Wind Tunnel [3].



(a) Naval tipjet concept.



(b) Subsonic Wind Tunnel testing of tipjet concept.

Figure 1.3: Naval tipjet concept explored by NSWC Carderock in the early 1990s.

Also in the 1990s, Cal Poly's Da Vinci III human powered rotorcraft featured a blade-tip-propeller, due to its mechanical simplicity [4]. A small, 3 ft diameter, propeller was mounted at the tip of the 50 ft radius rotor. A series of elastic bands, pulleys, and gears in conjunction with a pedal driven bicycle arrangement transferred the forces from the human pilot through the blade skin to the tip propeller.



Figure 1.4: Cal Poly Da Vinci III human powered rotorcraft.

More recently, a series of papers have described an electrical vertical takeoff and landing configuration that utilized small electric motors and propellers [5, 6], called the F-Helix. These papers applied the propeller-driven rotor idea to a manned 1900 lb, 2 bladed main rotor, 14.8 ft main rotor radius electric helicopter. Unlike the tip-driven designs that placed the actuator directly on the main rotor blade, the F-Helix used a dedicated “power boom” to mount the electric motors and coaxial pro-

pellers. The authors estimated the required power and performed a control analysis of the configuration in forward flight. However, this research only included theoretical calculations.

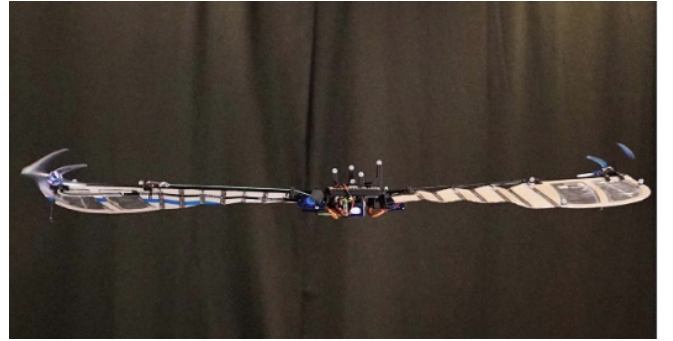
1.1.2 Swashplateless Micro Air Vehicle

Over the past 10 years, several efforts have investigated propeller-driven rotors, both analytically and experimentally. A literature review of similar propeller-driven swashplateless rotorcraft found three several examples. First, the 38 gram Samara II [7, 8], shown in Figure 1.5a, flight vehicle utilized a single rotor blade with a brushless motor and propeller attached at the blade tip, and a trailing edge flap. The brushless motor and propeller generated the torque to spin the rotor blade, and a cyclic variation was applied to the trailing edge flap for rotor control.

Singapore University’s Monocopter [9], shown in Figure 1.5b. The 29 in wingspan, Monocopter design was similar to the Samara II aircraft, with the addition that the motor command also varied with rotor blade rotation. In Ref. [10], the Monocopter completely eliminated the trailing edge flap and control of the aircraft was achieved solely through propeller RPM variations.



(a) University of Maryland’s *Samara II* [7].



(b) Singapore University’s *Monocopter* [9].

Figure 1.5: Small scale free flight rotors in literature.

The propeller-driven rotors micro air vehicles have even reached outside of academia, and have been explored in the hobby RC community. A former Alfred Gessow Rotorcraft Student, Nick Rehm,

has published a series of YouTube videos regarding a 3 ft diameter propeller-driven rotor [11]. His free-flying UAS used a clever arrangement of electric motors, servos, and control logic to enable the UAS to “reconfigure” in flight. Propellers located at around 75% span of the main rotor blade provided control for several flight modes: tricopter hover mode, propeller-driven rotor hover mode, and fixed wing mode in forward flight. This idea was later expanded to be a 15 ft diameter, 4 bladed UAS. The idea captured the public imagination, as the videos detailing the propeller-driven rotor development have millions of views online.

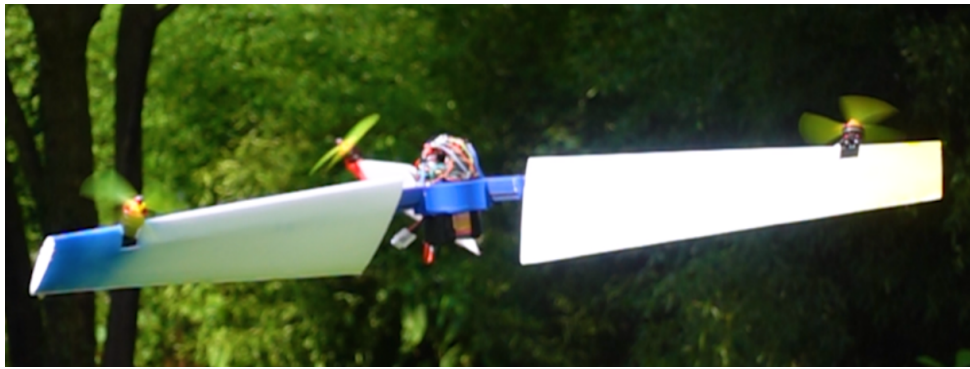


Figure 1.6: Propeller-driven rotor developed by Nick Rehm [11].

In addition to free-flight research projects, there have been several academic efforts to replace swashplate-based control for rotorcraft. In Refs. [12] and [13], a 5.6 ft diameter, 4-bladed rotor was modified with a trailing edge flap, located at 75%-89% of the rotor radius. A brushless DC motor, embedded in the rotor blade, actuated the trailing edge flap for roll and pitch control. Experiments demonstrated the feasibility of the trailing edge flap based control in both hover testing and wind tunnel testing up to a rotor advance ratio of 0.278. This work demonstrated the potential for high frequency brushless motors to augment rotorcraft control systems.

1.2 Timeline of Research Effort and Key Findings

For reader context, a brief overview of the various efforts for this work is summarized here. Figure 1.7 shows the timeline. More detailed descriptions are provided in the relevant sections of this manuscript. The following works were presented at the Vertical Flight Society's (VFS) Annual Forum or Transformative Vertical Flight (TVF) Conference.

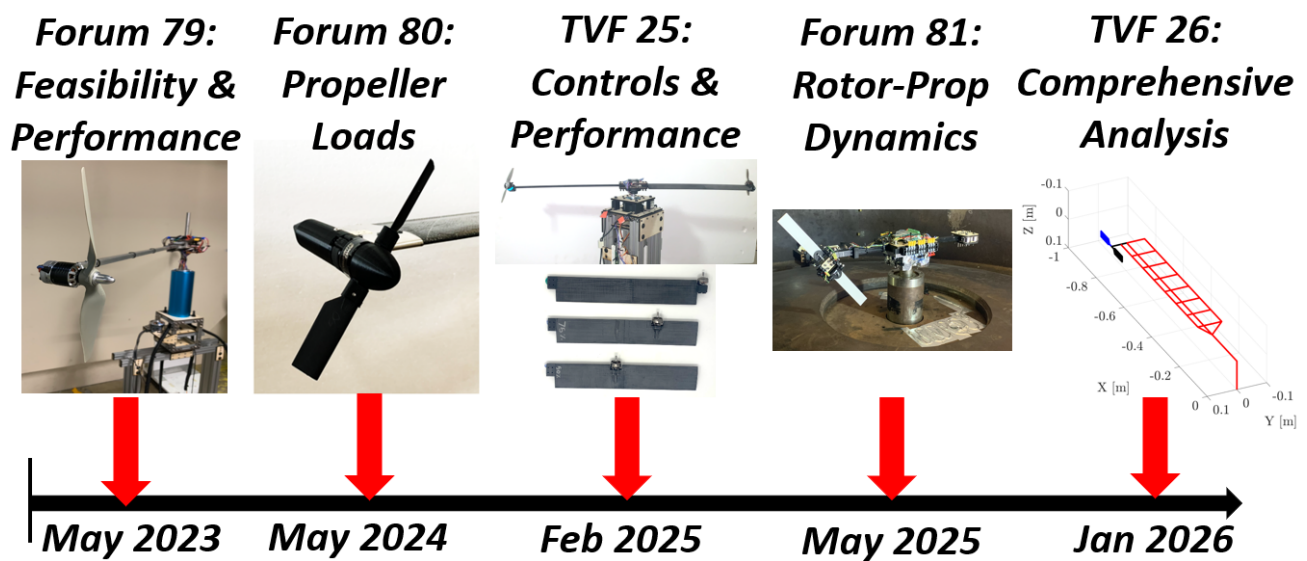


Figure 1.7: Timeline of propeller-driven rotor research.

Feasibility Study: May 2023, Forum 79

Initial work detailing the feasibility and performance of propeller-driven rotors was carried out for this paper. A simplified methodology was created to characterize and analyze isolated propeller performance, isolated rotor design, and propeller-driven rotor performance. A composite rotor blade was fabricated that featured a removable tip propeller assembly, enabling both propeller-driven rotor and shaft-driven rotor experiments to be conducted with the same rotor blade. A custom, 5.5 ft diameter test stand was fabricated. Propeller-driven rotor thrust and power was compared to an isolated,

shaft-driven rotor. During hover testing several propellers suffered a root bending failure, indicating that the loading environment for the propeller-driven rotor required further investigation.

Propeller-Rotor Hover Loads Measurement: May 2024, Forum 80

An experiment was conducted to measure propeller hub loads during propeller-driven rotor operation. A load cell was attached to a propeller at the tip of the composite rotor blade, and passed the signal wires through the main rotor blade composite shell. A checkout test on the tip propeller load cell was performed using a wind tunnel test on the isolated non-rotating composite rotor blade. The rotor blade acted as a wing for the wind tunnel test, and characterized nacelle drag impact and rotor blade lift and drag. After this, the composite rotor blade built for the Forum 79 was integrated into the University of Maryland's hover test stand, resulting in a 6 ft diameter rotor. During hover testing, propeller loads during propeller-driven rotor operation were recorded. Results showed a large propeller pitching moment that was several times larger than the propeller torque moment. This large, previously unknown, propeller pitching moment was the suspected failure cause of the Forum 79 propeller.

Swashplateless Primary Control and Propeller Placement: January 2025, TVF25

This work contained two novel investigations: a swashplateless propeller-driven rotor control experiment and a propeller placement experiment. This test utilized a custom 2.7 ft diameter test stand and, due to the smaller scale and large number of rotor blade designs, 3D printed rotor blades. First, a novel method of swashplateless control for a propeller-driven rotor was developed and compared to a conventional swashplate design. The scheme consisted of modulating the propeller rotational speed once per rotor azimuth. The results indicated that, for certain configurations, the novel method produced a similar amount of control authority to a conventional swashplate. Secondly, the propeller placement on the main rotor span was varied, and showed that a propeller mounted on the rotor blade midspan location resulted in a 50% reduction in the electrical power loading coefficient C_{Pe}/σ com-

pared to a tip mounted propeller.

Propeller Failure and Dynamics Investigation: May 25, Forum 81

Various propellers suffered root bending failures during a 6 ft diameter propeller-driven rotor hover test campaign. Several propeller designs were investigated but all failed. This halted the hover test campaign and prompted an investigation into the propeller loads during propeller-driven rotor performance. A vacuum chamber experiment was created to measure inertial loading effects on the propeller from the main rotor rotation. Encoders on the propeller blade hub measured the articulated propeller blade flapping motion. A large, one-per-propeller-revolution, sinusoidal propeller flapping was observed. A simple physics model was developed to explain the results, which was used to derive the propeller flapping equation of motion. Analyzing the propeller flapping equation of motion revealed that the propeller blade flapping motion resulted from a rotor-propeller Coriolis interaction.

Detailed Computational Analysis and Validation: February 2026, TVF26

After the Forum 81 work, it was clear that a computational model was needed to capture the coupled rotor-propeller dynamics and interactions in a systematic manner. A comprehensive model was created to model the propeller-driven rotor concept. The comprehensive model was validated using the Forum 80 hover experiment, the Forum 81 propeller flapping vacuum chamber experiment, and a new rotor-propeller loads vacuum chamber experiment. During this work, a description of the propeller-driven rotor swirl phenomenon was provided. After validating the comprehensive model, a study was performed on parametric variations of several propeller-driven rotor configurations.

Additionally, a report on propeller-driven rotor performance will be presented at Forum 82 in May 2026, and will include details on propeller design and spanwise placement impacts on propeller-driven rotor performance and propeller-driven rotor scaling. These results have been incorporated into this manuscript.

1.3 Hover Test Stands Developed

Three different hover test stands were developed over the course of the research program: a 5.5 ft, a 6 ft, and a 2.7 ft diameter test stand. Each test stand investigated unique areas of the propeller-driven rotor concept, and each stand could facilitate both conventional shaft-driven and propeller-driven tests. Figure 1.8 shows the three test stands.

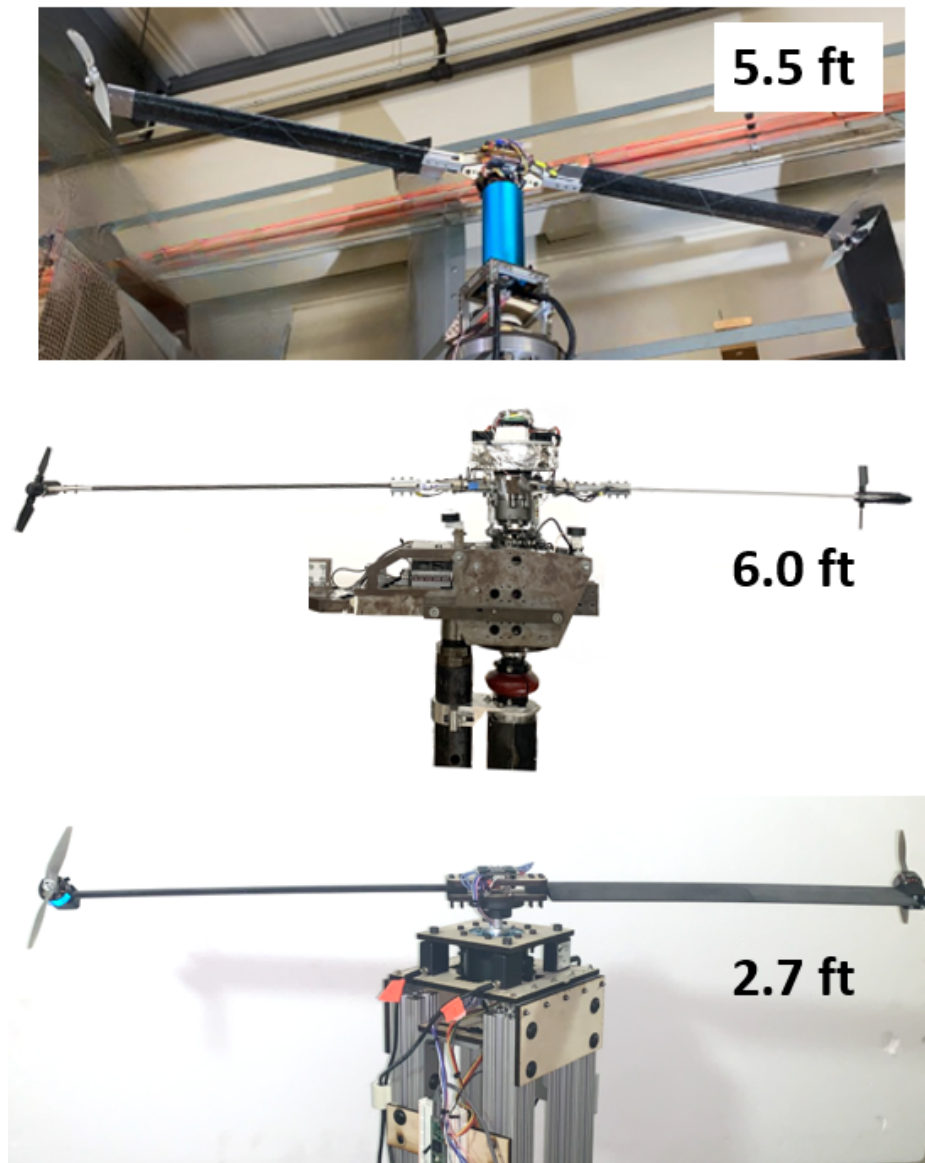


Figure 1.8: Hover test stands developed over the course of the program. Not to scale.

Each test stand will be described in the relevant section, but a brief overview is provided here. Table 1.1 details an overview of the experiments conducted for this research, and their relevant sections in this manuscript.

- **5.5 ft Diameter Test Stand** - The first test stand developed utilized commercial-off-the-shelf (COTS) components to assess propeller-driven rotor feasibility and performance. It featured a high powered slipring, a composite rotor blade, and a tip propeller. This test stand lacked a swashplate or collective change mechanism.
- **6 ft Diameter Test Stand** - After initial testing, the composite rotor blade and tip propeller assembly were integrated into the University of Maryland’s Hover Test Stand, resulting in a 6 ft diameter rotor. This second test featured a rotor swashplate for main rotor collective and cyclic control.
- **2.7 ft Diameter Test Stand** - This stand was easily modifiable, and used 3D printed rotor blades to facilitate two different experiments. The first experiment studied the impact on propeller placement on propeller-driven rotor performance, and the second experiment was on a novel swashplateless control concept for propeller-driven rotors. This test stand lacked a swashplate or collective change mechanism.

Table 1.1: Summary of key experiments and section details.

Experiment	Type	Test Stand	Rotor Blades	Propeller Set
Performance & Feasibility	Hover	5.5 ft, 3.2.1	Composite, 2.1.1	Forum 79, 2.3.4
Propeller Loads	Hover	6 ft, 3.3.1	Composite, 2.1.1	Forum 80, 2.3.5
Propeller Placement	Hover	2.7 ft, 3.4.1	3D Printed, 2.1.2	Forum 81, 2.3.6
Propeller Flapping	Vacuum	4.2.1	Rigid	Articulated
Propeller-Rotor Loads	Vacuum	4.3	Composite, 2.1.1	Forum 80, 2.3.5
Swashplateless Control	Hover	2.7 ft, 3.4.1	3D Printed, 2.1.2	TVF25

1.4 Propeller-Driven Rotor Comprehensive Analysis

Early concept exploration and experimentation utilized simple analytical models of the rotor and propeller. However as the project matured, it became critical to capture the propeller and rotor loads in this highly coupled dynamic system for a fundamental understanding of the propeller-driven rotor configuration. This need was highlighted after several propellers failed during the 6 ft diameter propeller-driven rotor hover tests. Although the comprehensive rotor model was developed late in the research timeline, a significant effort was spent on validating the comprehensive model with existing in-house experimental data sets.

Several comprehensive analysis codes were considered, and eventually selected the Elastic Rotorcraft Analysis (ERA) methodology due to its capability in detailed modeling a rotating system connected to another rotating system. ERA is a multi-body comprehensive analysis tool developed by U.S. Army Computational Aeromechanics Branch. It is fully integrated into the U.S. Army HELIOS framework. ERA's origin is UMARC-II (University of Maryland Advanced Rotorcraft Code-II [14]), with several key modifications. Both ERA and UMARC II were developed primarily to support tiltrotor stability and whirl flutter investigations.

Arbitrary topologies can be modeled in ERA using Euler-Bernoulli beams with bending in flap and lag directions, elastic torsion, and axial extension using a geometrically exact formulation and multi-body joints. As such, large blade deformations can be modeled. Beam elements are modeled using individual cross-section stiffness, inertial properties, and physical offsets. Joints can model devices such as hinges, bearings, springs, and dampers with the appropriate stiffness, damping, and can facilitate command inputs. Joints also include point/distributed mass and concentrated aerodynamic loads (such as from a rigid fuselage). Figure 1.9 shows a propeller-driven rotor system, with the

propeller located at the tip of the rotor blade.

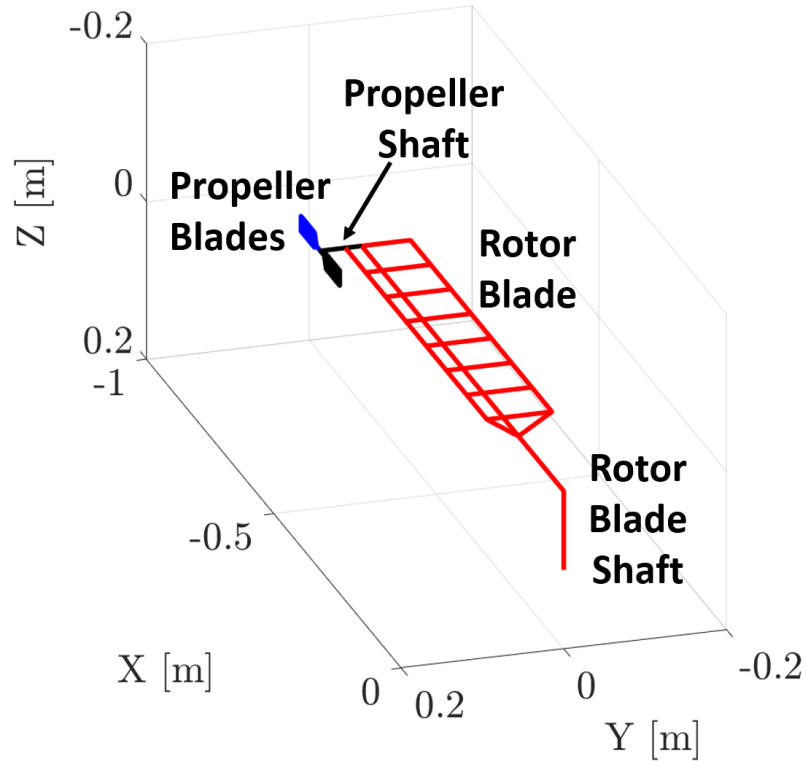


Figure 1.9: Propeller-driven rotor modeled in ERA.

ERA uses lifting line aerodynamic loads along with C81 look-up tables. Linear unsteady aerodynamic terms are included. No small term deflection assumptions are made. Main rotor induced inflow is incorporated using modified momentum theory or Maryland Freewake. As a standalone code, the rotor induced inflow is predicted using momentum theory, however wake models of varying fidelity are possible with straightforward HELIOS coupling. These models include reduced order models that uses actuator lines, freewake, and full RANS solutions. Loose coupling is used for periodic solution, and trim and tight coupling is used for maneuver solution.

Periodic solution is obtained using Finite Elements in Time or Harmonic Balance Approach. Maneuver solution is obtained using the Gen-Alpha time integration scheme, which encompasses

Hilber-Hughes-Taylor (HHT) and Newmark-Beta schemes. Equations of motions are solved by transforming Ordinary Differential Equations (ODEs) to algebraic equations using appropriate adapter routines. Trim equations are solved together with periodic solution algebraic equations (instead of an outer loop solution) to enable a more efficient and robust solution. System matrices are built using OpenMP which saves significant computation time. Rotor trim solution may be coupled to 3D CFD through the “delta airloads” coupling approach.

1.5 Outline of This Dissertation

Each Chapter in this thesis is self contained and independent. However, subsequent chapters build off the foundations of previous Chapters, which is critical to refine the methodology of this new concept. The organization of this dissertation is as follows:

Chapter 2: Isolated Component Design and Testing - This chapter documents the various subcomponents that were used in later experimental work. Details on rotor blade manufacturing, propeller testing procedure, and results are given.

Chapter 3: Hover Performance - Early experimentation focused on propeller-driven rotor feasibility and performance. Hover experiments compared propeller-driven rotor hover performance to a conventional, shaft-driven rotor. Propeller-driven rotor performance and loads were measured. Additionally, the propeller-driven rotor power was investigated - first at the tip and then for various rotor blade spanwise placements. This experimental work was followed up by comprehensive rotorcraft modeling of the propeller-driven rotor with various propeller placements. Next, a fundamental understanding of propeller-driven rotor power was derived. Finally, scaling effects were considered.

Chapter 4: Dynamics - During the performance investigation, several propellers suffered root failures. This chapter presents an explanation to these broken propellers, later termed as the “propeller-driven rotor twirl phenomenon.” Two vacuum chamber experiments were developed to systematically analyze rotor-propeller inertial couplings and their effect on propeller loads. Finally, propeller loads during propeller-driven rotor operation are compared to

Chapter 5: Controls - A novel method for primary control of a propeller-driven rotor is presented. The control scheme modulates the propeller RPM around the rotor azimuth. A vertical portion of the propeller thrust is used to generate control moments. The 2.7 ft diameter test stand and 3D printed blades were used. Later experiments compared the propeller-driven rotor control scheme to a conventional swashplate system.

Chapter 6: Conclusions and Future Work - A summary of the work is given, key results are reiterated, and future work is discussed.

Chapter 2: Isolated Component Design and Testing

The propeller-driven rotors research in this work featured a rotor blade, electric motors, and a variety of commercial off the shelf (COTS) and custom propellers. Prior to conducting propeller-driven rotor experiments, these components were designed, fabricated, and tested in-house. This chapter details the components, experimental setups, and characterization results.

2.1 Main Rotor Blades

There were two unique aspects for the rotor blade design for propeller-driven rotors. First, wires were embedded inside the rotor blade shell and transferred electrical power from the rotor blade hub to the propeller on the rotor blade. Secondly, the rotor blade was capable of mounting the propeller assembly. Early experiments utilized a conventional, composite rotor blade while later experiments used a 3D printed rotor blade for rapid iteration.

2.1.1 Composite Main Rotor Blades

The existing University of Maryland Alfred Gessow Rotorcraft Center method of blade fabrication [16, 17, 18] was modified to include three AWG16 power wires, four AWG22 signal wires, and a reinforced box-beam carbon fiber spar for mounting the blade tip motor and propeller. Approximately 10 prototype blades were manufactured before the correct combination of wire placement, spar

adhesive layering techniques, and leading edge weight sizing were achieved. Figure 2.1 shows the schematic for the rotor blade.

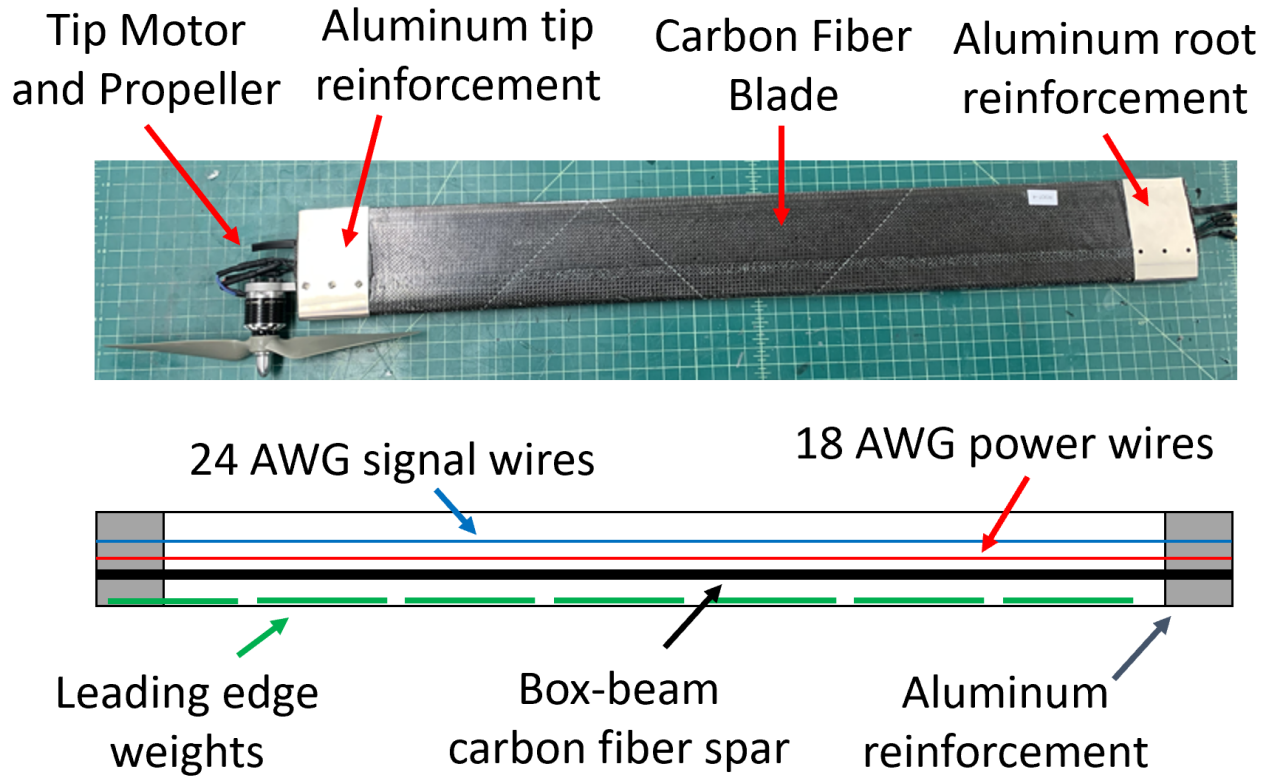


Figure 2.1: Tip propeller and composite rotor blade design.

The final blade, shown in Figure 2.1, had a length of 27 inch, a chord of 3.15 inch, and a NACA0012 airfoil. A single layer of ± 45 deg weave of carbon fiber skin was bonded to the blade to provide additional structural support. For manufacturing simplicity, the blade had no twist and no planform taper. The power and signal wires were located 0.5 and 1.5 inches behind the blade quarter chord location, respectively. To balance out this added rear weight, larger leading edge weights were used. Throughout the blade fabrication process, all weights were meticulously tracked to ensure the final blade weights and inertias were identical. Three blades were manufactured, with the best two blades selected for testing.

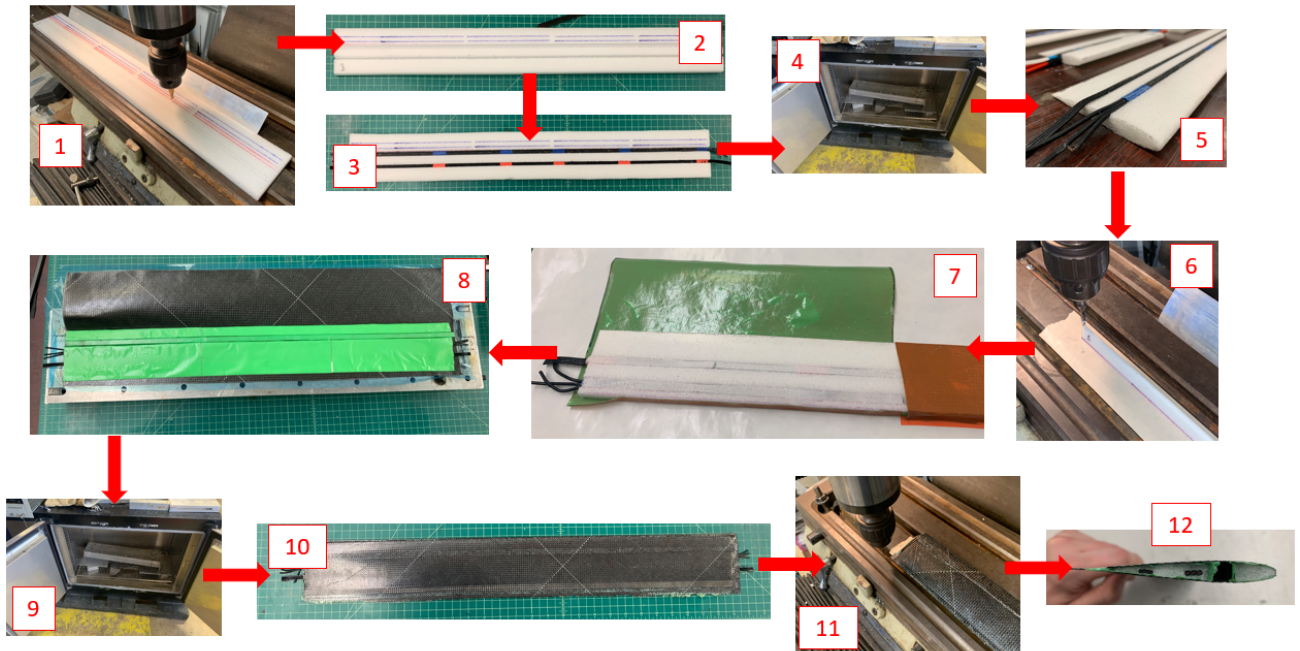


Figure 2.2: Blade fabrication steps for a blade-tip-propeller-driven rotor.

The final blade-tip-propeller fabrication method featured 12 steps, shown in Figure 2.2:

1. A rectangular piece of foam of 27 x 3.15 x 0.5 inches was cut out. Using a template, locations were marked on the foam for wire placement. A CNC mill was used to carve out the marked wire locations to depth of 0.275 inches.
2. Once the wire location areas were milled out, the power and sensor wires were placed into the rectangular foam specimen.
3. The wires were covered with a layer of compacted foam to ensure they remain along the center-line of the airfoil.
4. The foam section was placed into a NACA0012 blade mold, and the mold was placed into an oven at 175°C for 1.5 hours.
5. After the blade was removed from the mold, the resulting airfoil shape was inspected.

6. Next, a milling operation created space in the foam blade for the spar. This separated the blade into a leading and trailing edge sections.
7. In preparation for adding the carbon fiber skin, the leading edge section, spar, and trailing edge section were wrapped with a green adhesive layer. This ensures the the carbon fiber skin bonded to the airfoil. The leading edge weights were wrapped with the adhesive and placed in the leading edge section prior to the entire leading edge section being wrapped.
8. All parts of the blade were assembled inside the blade mold. A ± 45 deg weave of carbon fiber skin was cut into the required size. A layer of mold-release was placed between the carbon fiber skin and the mold. Next, all the constituent sections of the blade were laid into the mold.
9. A final oven process (175°C for 1.5 hours) ensured the blade assembly bonded together.
10. The blade was removed from the oven and inspected.
11. Next, the blade was post-processed. This involved sanding down the leading edge section, and excess carbon fiber skin was removed from the trailing edge.
12. The blade tips and root were reinforced with a thin (0.01 inch) sheet of aluminum. The final blades were inspected to ensure correct wire and center of mass locations.

After all the blades were fabricated, bending and torsional stiffness tests were performed to characterize the blade properties, shown in Figure 2.3. The blades were cantilevered at the blade root and forces were applied the blade tip, where an inclinometer recorded angular deflections. A standard Alfred Gessow Rotorcraft Center composite rotor blade was also characterized to serve as a reference.

Table 2.1 contains the structural properties of the composite rotor blades. There were two differences between the standard blade compared to a blade for the propeller-driven rotor. First, the

propeller-driven rotor blades (without the aluminum reinforcement) were approximately 35 grams heavier than the standard blade, due to the inclusion of the wires and larger leading edge weights. Secondly, the propeller blades were slightly stiffer in bending but more flexible in torsion compared to the standard blade. Overall, the structural results were comparable to the standard Alfred Gessow Rotorcraft Center composite rotor blade.

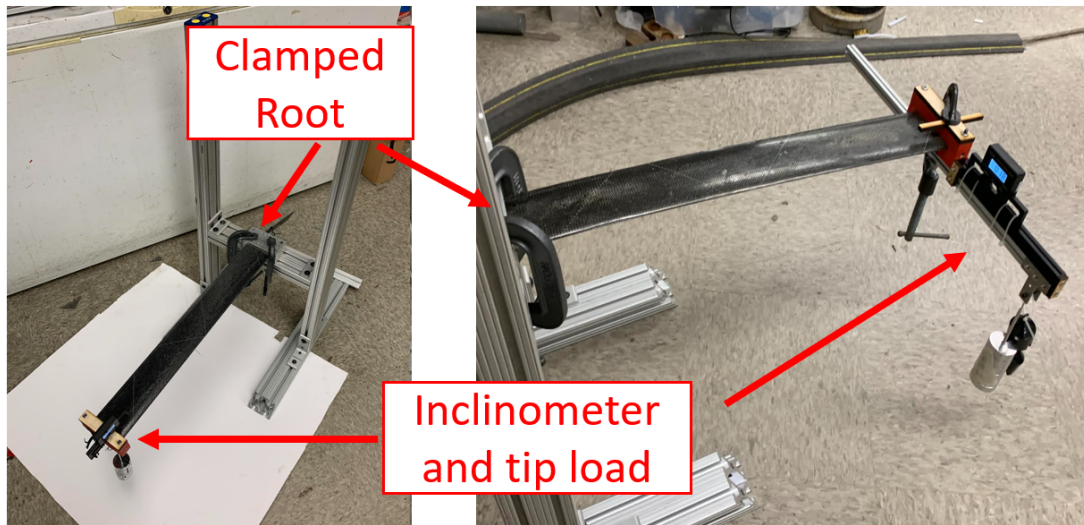


Figure 2.3: Left: Rotor blade bending stiffness (EI) measurements setup.
Right: Rotor blade torsion stiffness (GJ) measurements setup.

Table 2.1: Rotor blade structural properties without aluminum tip/root reinforcement.
Standard blade refers to a rotor blade that does not have any propeller-driven rotor modifications.

Blade	Mass [g]	EI [Nm ²]	GJ [Nm ²]
Blade 1	278.1	21.78	25.35
Blade 2	280.9	22.86	26.15
Blade 3	279.7	23.87	24.59
Standard Blade	246.1	21.48	32.64

2.1.2 3D Printed Main Rotor Blades

The early feasibility, performance, and propeller loads research utilized a 27 inch span composite rotor blade. After this work, the swashplateless control and impact of propeller placement were investigated. Due to the large number of designs, 3D printing the blades was preferable instead of using composite rotor blade designs (making CNC molds for each design, etc.) and resulted in significant time savings. Using 3D printers allowed the blade design to be systematically varied in a quick and efficient manner. The blade tip nacelle configuration and propeller placement along the blade span were altered. Figure 2.4 shows the blade, tip motor, and tip propeller. 3D printed rotors were used for the propeller spanwise placement investigation detailed in Section 3.4 and the swashplateless controls research in Chapter 5.



Figure 2.4: The 14 inch span, 3D printed propeller-driven rotor blade.

Three printers were investigated for 3D printing rotor blades: the Bambu Labs X1 Carbon, the Prusa MK4, and the Flashforge Creator 3 Pro. A small rotor blade section was printed on each printer. After comparing the surface quality, print times, and print options of all three printers, the Bambu Labs X1 Carbon printer was selected as it resulted in the highest quality rotor blade section.

The 3D printed rotor blades were printed in two sections per blade and reinforced with a 4 mm diameter solid carbon fiber beam as a spar. The blades were made of PLA and had a 1 mm thickness.

Spin tests revealed that the 3D printed blades were able to spin at over 1500 RPM, with a tip speed of 65 m/s or 212 ft/s.

A second objective of the 3D printed rotor blade was to evaluate the propeller-driven rotor performance with the propeller placed at various locations on the main rotor span. The design of the 3D printed rotor blade was modified to have the propeller placed at the 1/2 span, 3/4 span, and at the tip of the rotor blade. Figure 2.5 shows the 3D printed rotor blades. All blades utilized the same propeller and had the rotor collective θ_0 fixed at 8 deg.

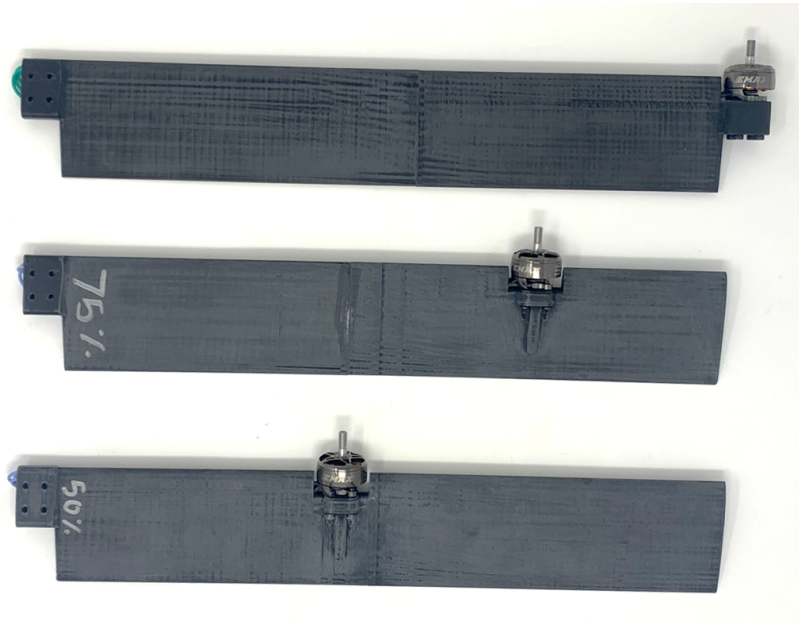


Figure 2.5: 3D printed 2.7 ft diameter main rotor blades showing the propeller at the 1/2 span, 3/4 span, and tip locations on the rotor blade.

2.1.3 Propeller Assembly

The propeller assembly consists of the electric motor, propeller hub, propeller, and physical mounting hardware between the motor and the rotor blade. Figure 2.6 shows the electric motor and propeller assembly used in the early feasibility and performance research. A key concern for this design was to minimize the tip weight as much as possible. The motor was attached to an aluminum

adapter that bolted directly inside the blade's box beam spar. A thin (0.01 inch) piece of aluminum was added to structurally reinforce these bolt hole locations, and enabled the tip loads to be more uniformly transferred to the blade. For the Figure 2.6 design, the propeller assembly had a mass of 55 grams (35 grams for the motor, 10 grams for the aluminum adapter, and 10 grams for the propeller).

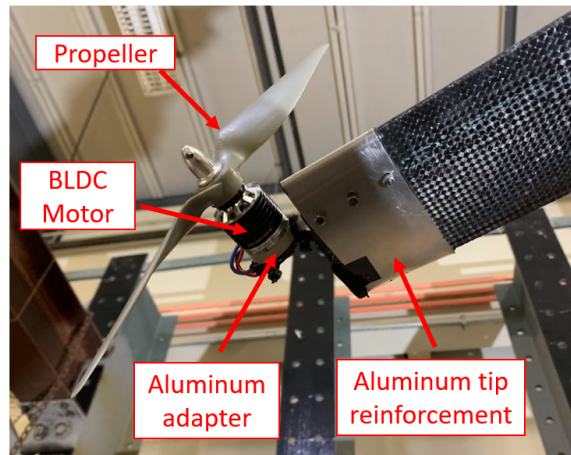


Figure 2.6: Tip propeller assembly for early feasibility testing.

2.2 Brushless Motor Characterization

It was important to have an understanding of electric motor performance as the electric motor was mounted on the spinning rotor blade. Power was passed through the rotor blades, so picking the optimal electric motor for the task was critical to reduce weight and power. This was a problem as the small, low-cost electric motors used in this lacked manufacturer supplied data sheets of sufficient quality for engineering design and analysis.

To address this, a motor characterization stand, shown in Figure 2.7, was developed to determine the performance of various electric motors. These tests were used to inform propeller assembly design and experiment operating conditions. From these tests, an informed decision on electric motor selection was made. The design of this motor characterization stand closely resembles one from previous

work, detailed in Ref. [15]. This motor stand measured the motor torque, motor RPM, DC power, and motor controller throttle setting over a range of test conditions. This data was used to estimate motor and motor controller performance parameters.

The dynamometer consisted of a DC power supply, DC current and voltage sensors, a torque load cell, a motor being tested, an AC generator, an RPM sensor, and a variable electric load. The electric motor connected to the AC generator, and a high powered potentiometer was connected to the output lines of the AC generator. Increasing the potentiometer resistance would impede the rotation of the AC generator, and would result in a decrease in motor speed and increase in torque. These tests were repeated at different motor controller (electronic speed controller, or ESC) throttle settings, and are shown in Figure 2.8.

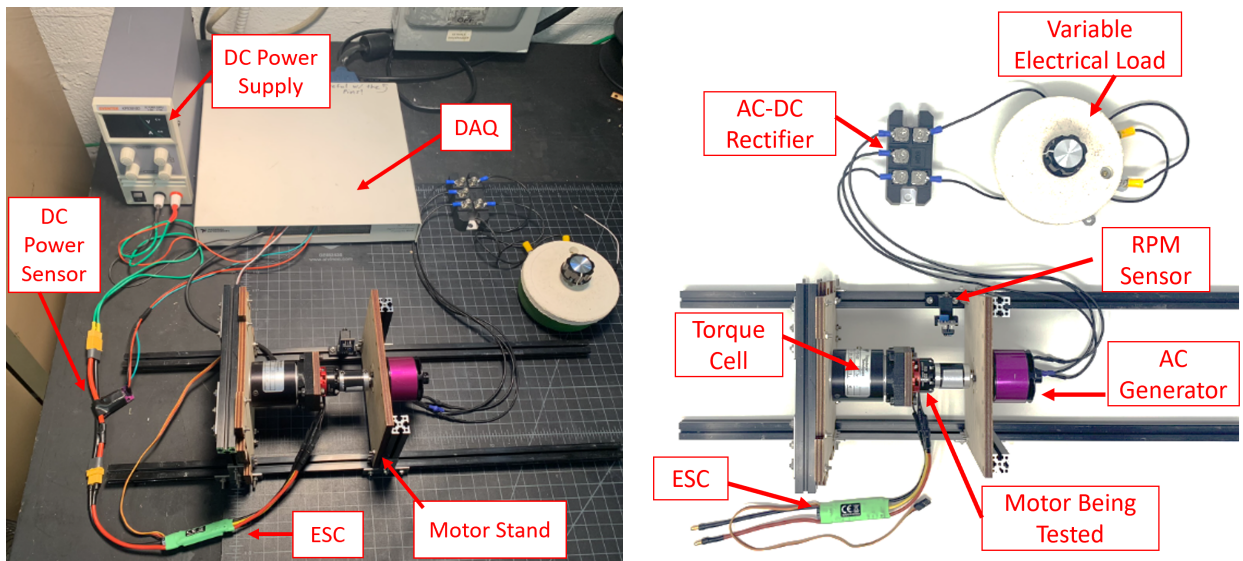


Figure 2.7: Electric motor characterization test stand.

A simplified, low-order equivalent system, methodology was developed [15] to describe the electric motor and motor controller performance over a range of test conditions. This model was developed after testing numerous brushless motors and motor controllers over a wide range of power settings. Figure 2.9 represents a brushless DC motor using an equivalent circuit diagram. The result-

ing brushless DC motor performance equations closely resemble the brushed DC motor performance equations.

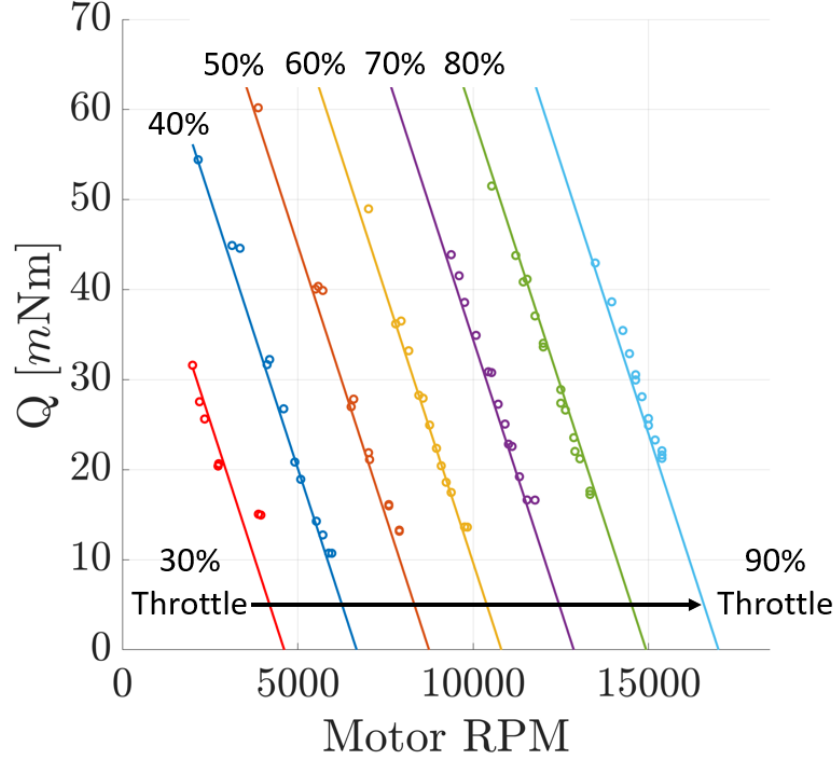


Figure 2.8: Torque versus motor RPM at various throttle settings for the EMAX 1500Kv motor. Dots represent experimental data and the lines represent the fitted model.

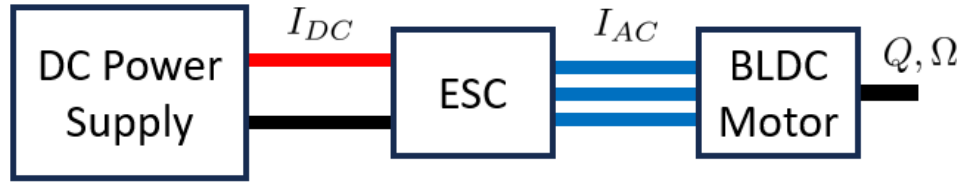


Figure 2.9: Equivalent brushless motor model representation.

The key findings of the model are summarized here, and full details can be found in Ref. [15].

The output torque of the brushless motor is described as:

$$Q_m = K_T(I_{AC} - I_o)$$

where K_T , K_E , I_{AC} , and I_o are the motor torque constant, the motor voltage constant, the AC current entering the motor, and the motor no-load current, respectively. The voltage acting across the brushless motor is:

$$\frac{3}{\sqrt{2\pi}}V_{DC}u = I_{AC}R_m + K_E\Omega$$

where V_{DC} is the DC voltage from the power supply, u is the motor throttle setting (normalized between 0-1), I_{AC} is the AC current applied to the motor, R_m is the motor resistance, and Ω is the motor RPM. Finally, the motor controller acts as a power transformer, that converts the DC power from the DC power supply into the AC power needed to run the brushless motor. This power conversion can be described using:

$$\frac{I_{AC}}{I_{DC}} = C_0u + C_1$$

where C_0 and C_1 represent physical constants related to the transistors used on the electric motor controller.

A simple least squares approach was used to estimate the brushless motor (K_T , K_e , I_o , R) and motor controller (C_0 , C_1) parameters from the test stand data. Three motors were tested with a KDE 35A ESC: an EMAX 1500 KV motor, an EMAX 1900 KV motor, and a Ready2sky 2300 KV motor, and the results are shown in Table 2.2. These results were combined with the isolated propeller testing results to estimate the required electrical power usage for the motor at the blade tip.

Table 2.2: Motor characterization results.

	1500 Kv	1900 Kv	2300 Kv
Manufacturer	EMAX	EMAX	Ready2Sky
K_T [mNm/A]	99	58	54
K_e [mV/(rad/s)]	35	29	27
R_m [Ω]	0.3	0.2	0.2
I_0 [A]	1.9	1.7	3.0
C_0 [-]	1.2	0.93	0.72
C_1 [-]	-0.07	0.005	0.005

2.3 Isolated Propeller Testing

A considerable amount of effort was devoted to characterizing the isolated propeller performance prior to propeller-driven rotor testing. Early experiments employed commercial-off-the-shelf components and wind tunnel testing. The propeller design and characterization methods advanced as the research effort progressed. Later experiments used custom fabricated propellers and utilized both propeller hover and wind tunnel testing. Three separate isolated propeller tests were conducted with various methods and components:

1. **Forum 79 Set, 2023:** These commercial-off-the-shelf components were used in early feasibility studies and for developing early propeller-driven rotor analytical performance models.
2. **Forum 80 Set, 2024:** The propeller design was a commercial-off-the-shelf propeller blade and a custom propeller hub. The propeller was a small scale remote control helicopter tail rotor that was cut to size. The propeller hub design featured an adjustable root pitch angle that could be modified in between experiments. The propeller was used for propeller-driven rotor loads hover experiment.
3. **Forum 81 Set, 2025:** Fully custom 3D printed propellers that failed during propeller-driven

rotor experiments. 3D printing enabled the propeller design, planform, airfoils, twist, and other properties of the propeller to be systematically adjusted. Despite reinforcing the propeller spar with carbon fiber, and later steel, the propellers continued to fail during propeller-driven rotor operation.

2.3.1 Propeller Aerodynamic Model

Early experiments utilized a simple analytical aerodynamic model while later tested utilized the comprehensive analysis. The simple propeller aerodynamic model is described here, and is based off Ref. [19]. The model examines a 2D sectional load on the propeller blade, and then integrates these loads over the propeller blade span. To start, consider section of the blade at some distance r_p from the center of rotation, shown in Figure 2.10.

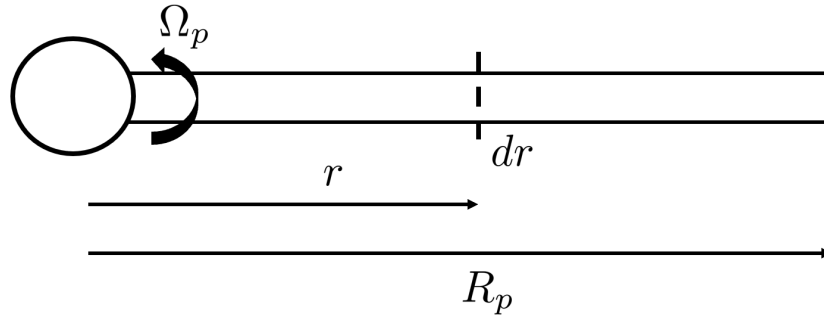


Figure 2.10: Propeller blade diagram.

Figure 2.11 shows the cross sectional view of this segment. The forces at this section are determined, and then integrated over the entire blade. The propeller operates at very large pitch angles over a range of inflow conditions. As a result, to properly capture the performance in these conditions, the traditional small angle assumptions were not made.

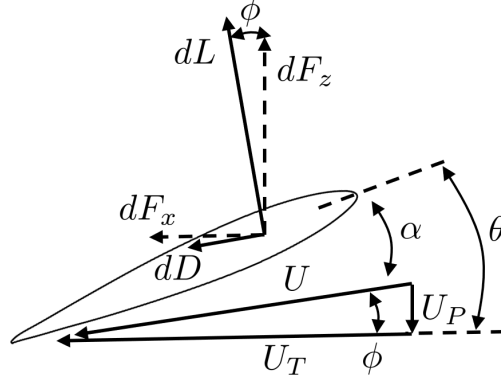


Figure 2.11: Blade element diagram. Angles exaggerated for clarity.

The velocities at these blade segments are calculated radially at a distance r_p from the propeller hub root, and are defined as:

$$U_T = \Omega_p r_p \quad (2.1)$$

$$U_P = \lambda_p \Omega_p R_p \quad (2.2)$$

where λ_p is the total propeller inflow, which will be described in detail later this section. Thus the total airspeed at this section is:

$$U = \sqrt{U_T^2 + U_P^2} \quad (2.3)$$

From Figure 2.11 and the airspeed definitions, the aerodynamic angles are defined as:

$$\phi = \tan^{-1} \frac{U_P}{U_T} \quad (2.4)$$

$$\alpha = \theta - \phi \quad (2.5)$$

where ϕ , α , and θ represent the propeller inflow angle, angle of attack, and pitch angle, respectively.

The lift and drag coefficients are defined in terms of look-up tables ($C_l(\alpha)$, and $C_d(\alpha)$). Following

from this, the 2D sectional lift dL and drag dD are:

$$dL = \frac{1}{2}\rho U^2 C_l(\alpha) c_p dr \quad (2.6)$$

$$dD = \frac{1}{2}\rho U^2 C_d(\alpha) c_p dr \quad (2.7)$$

The lift and drag are transformed into the vertical force F_z and horizontal force F_x by an angle ϕ :

$$dF_z = dL \cos \phi - dD \sin \phi \quad (2.8)$$

$$dF_x = dL \sin \phi + dD \cos \phi \quad (2.9)$$

Finally, the propeller thrust T_p , torque Q_p , and power P_p can be calculated from:

$$T_p = N_{bp} \int_0^{R_p} dF_z \quad (2.10)$$

$$Q_p = N_{bp} \int_0^{R_p} r dF_x \quad (2.11)$$

$$P_p = Q_p \Omega_p \quad (2.12)$$

where N_{bp} is the number of propeller blades per propeller. The nondimensional parameters are:

$$C_{T_p} = \frac{T_p}{\rho A_p (\Omega_p R_p)^2} \quad (2.13)$$

$$C_{Q_p} = \frac{Q_p}{\rho A_p (\Omega_p R_p)^2 R_p} \quad (2.14)$$

$$C_{P_p} = \frac{P_p}{\rho A_p (\Omega_p R_p)^3} \quad (2.15)$$

where A_p is the propeller disc area.

Returning now to the propeller inflow λ_p from equation 2.2. The total propeller inflow is the sum of the propeller induced inflow λ_{i_p} and the propeller climb inflow λ_{c_p} :

$$\lambda_p = \lambda_{i_p} + \lambda_{c_p} \quad (2.16)$$

The propeller climb λ_{c_p} inflow is set by the propeller climb speed v_c :

$$\lambda_{c_p} = \frac{\text{Propeller climb speed}}{\text{Propeller tip speed}} = \frac{v_c}{\Omega_p R_p} \quad (2.17)$$

The induced inflow is set by the thrust performance of the propeller. From momentum theory [19], the induced inflow can be calculated from:

$$\frac{\lambda_{i_p}}{\lambda_{h_p}} = -\frac{\lambda_{c_p}}{2\lambda_{h_p}} + \sqrt{\left(\frac{\lambda_{c_p}}{2\lambda_{h_p}}\right)^2 + 1} \quad (2.18)$$

where λ_{h_p} is the propeller induced inflow in hover:

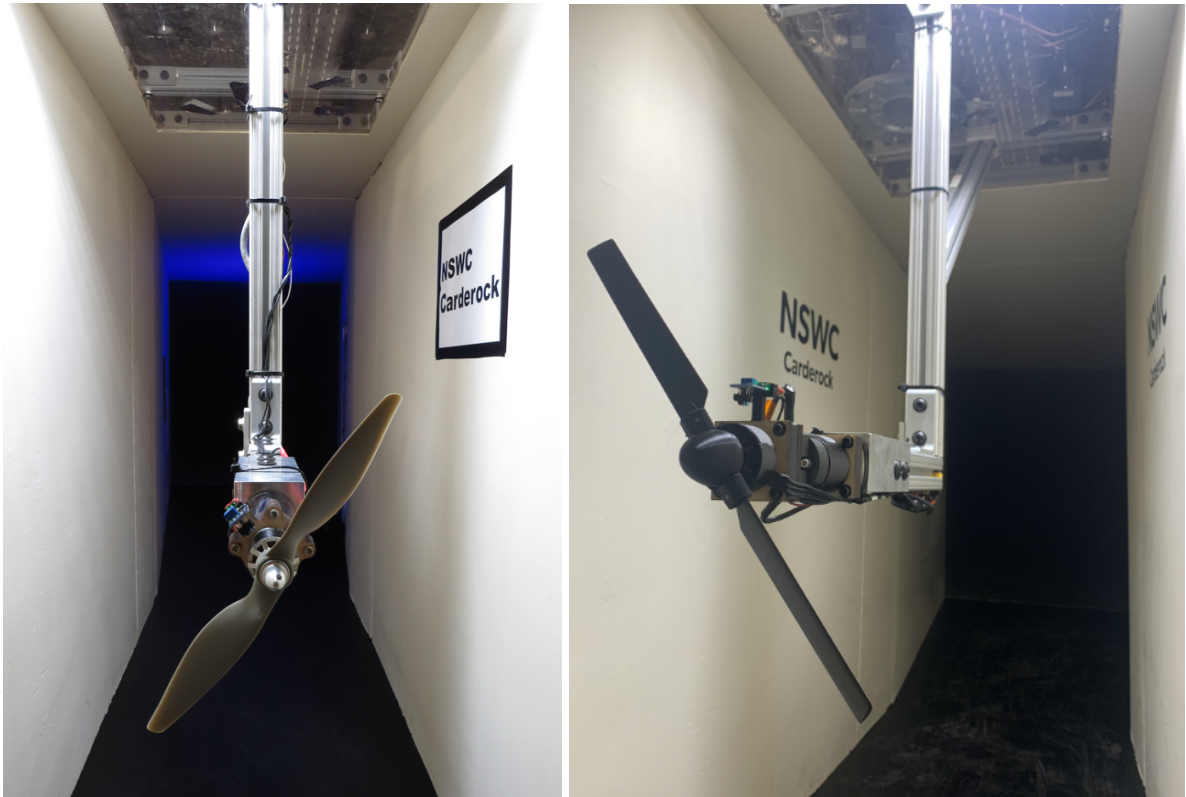
$$\lambda_{h_p} = \sqrt{\frac{C_{T_p}}{2}} \quad (2.19)$$

From these expressions, the total thrust is a function of the total inflow, which includes the induced inflow, that is a function of the total thrust. As a result, a simple loop iteration scheme is employed to resolve this, which converged within a few iterations. This model was used to validate

various propeller axial flight experiments conducted in the Low Turbulence Wind Tunnel.

2.3.2 Low Turbulence Wind Tunnel Facility

Prior to propeller-driven rotor testing, isolated propellers were tested in the 2 ft by 4 ft Low Turbulence Wind Tunnel, shown in Figure 2.12, located at NSWC Carderock Division. Three separate propeller sets and one non-rotating rotor blade (wing) configuration were tested. The open circuit tunnel features a 150 hp AC induction motor powered by a 460 V AC, 3-phase, variable frequency speed controller — enabling the tunnel to reach a maximum speed of 40 m/s (78 knots). Figure 2.13 shows a schematic of the tunnel. The isolated propellers were tested at tunnel speeds, v_∞ , up to 25 m/s (82 ft/s) and propeller tip speeds, $\Omega_p R_p$, up to 100 m/s (328 ft/s).



(a) Forum 79 propeller.

(b) Forum 80 propeller.

Figure 2.12: Isolated propeller testing in the Low Turbulence Wind Tunnel at NSWC Carderock.

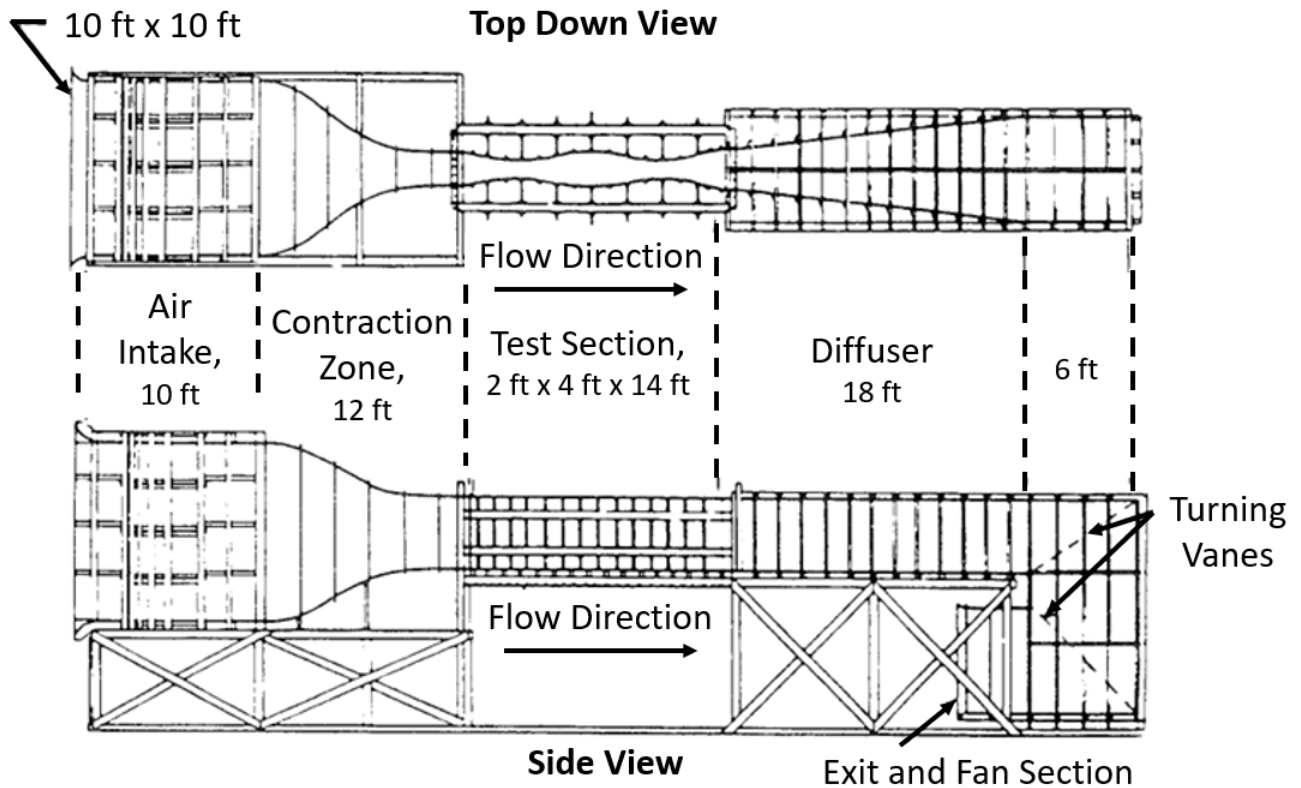


Figure 2.13: NSWC Carderock's 2 ft by 4 ft Low Turbulence Wind Tunnel.

2.3.3 Experiment Setup

The isolated propellers were mounted on an 80/20 sting in the center of the tunnel. The sensor suite was comprised of a Chroma 40V-120A power supply, a DC power analyzer, a Mensor pressure transducer, load cells, and a RPM sensor. Early experiments utilized an AMTI 6DOF FS6 Load Cell, which featured a wide measurement range. Later experiments utilized Transducer Techniques thrust/torque sensors, with a measurement range better suited to the small propellers. A PID controller was implemented to regulate the propeller RPM to achieve specific propeller climb ratios. All data acquisition, PID control, and data logging was controlled by a single LabView DAQ. A tunnel placement diagram of key equipment is shown in Figure 2.14.

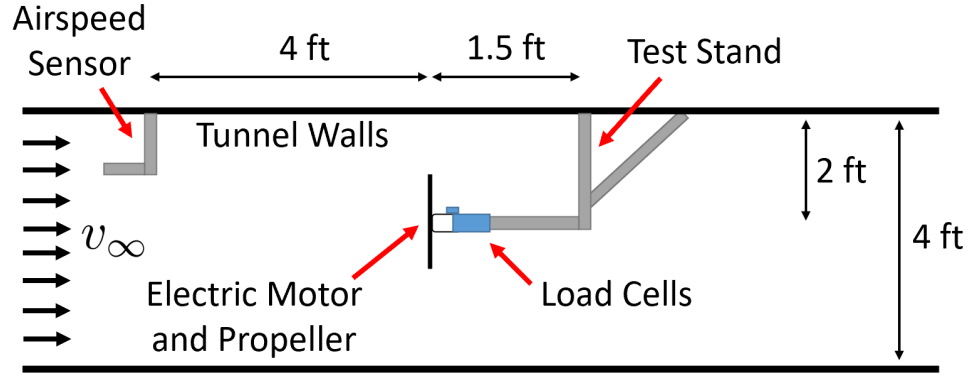


Figure 2.14: Sensor layout for isolated propeller axial climb testing.

After wind tunnel testing, the propeller performance was non-dimensionalized using the following definitions for propeller climb ratio λ_{c_p} , propeller thrust coefficient C_{T_p} , propeller power coefficient C_{P_p} , and propulsive efficiency η_p :

$$\lambda_{c_p} = \frac{v_\infty}{\Omega_p R_p} \quad (2.20)$$

$$C_{T_p} = \frac{T_p}{\rho A_p (\Omega_p R_p)^2} \quad (2.21)$$

$$C_{P_p} = C_{Q_p} = \frac{Q_p}{\rho A_p (\Omega_p R_p)^2 R_p} \quad (2.22)$$

$$\eta_p = \frac{C_{T_p} \lambda_{c_p}}{C_{P_p}} \quad (2.23)$$

Now that a description of the facility and aerodynamic model have been given, the next sections will provide details on the various isolated propeller data sets.

2.3.4 Forum 79 Propellers: Description and Results

The focus of the first propeller-driven rotor experiments was on feasibility and performance. As such, high quality commercial-of-the-shelf components were selected and combined in a logical

manner. The purpose was to see trends in propeller-driven rotor operation, and identify areas for future improvement. Later tests would seek to refine the propeller design.

A KDE 965Kv brushless DC motor and a KDE 35A ESC were selected due to their manufacturer provided thrust and power specifications, which assisted in the early stages of sizing the blade-tip-propeller-driven rotor system. Two commercial-off-the-shelf propellers were used: a 2 bladed-9 inch (9x6.0) propeller with a higher pitch angle distribution, and a 2 bladed-10 inch propeller (10x4.5) with a more moderate pitch angle distribution. These propellers, detailed in Table 2.3, were selected to gain insight on how propeller twist and size impacted the overall blade-tip-propeller rotor system performance. The motor, motor-controller, and propellers are shown in Figure 2.15.

Table 2.3: Propeller characteristics.

Propeller	Diameter	Number of Blades	Solidity
9x6.0	9 in	2	9.5%
10x4.5	10 in	2	9.7%

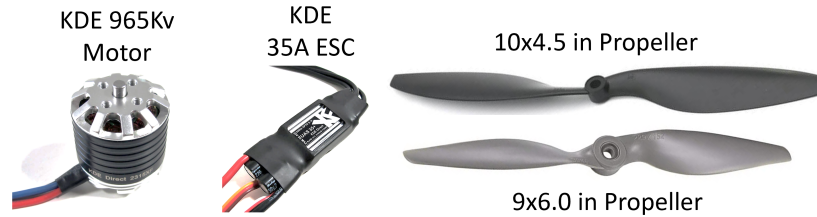


Figure 2.15: Electric motor, ESC, and propellers evaluated in propeller wind tunnel tests.

After selecting the components, they were tested in axial flight in a wind tunnel. Next, a laser-scanner was used to extract the blade pitch, chord, and airfoil distributions of the commercial-off-the-shelf propellers. Finally, the blade-element-momentum theory analysis described in Section 2.3.1 was compared to the experimental data.

2.3.4.1 Propeller Planform Extraction via a Laser Scan

The presence of non-uniform twist and taper distributions for the commercial-off-the-shelf propellers complicated the blade-element-momentum theory analysis. A laser-scanner was used to obtain a 3D point cloud of the propeller surface. An algorithm was developed to extract the resulting propeller chord, pitch, and airfoil distribution from the dense 3D point cloud. The propeller geometry information was then used to estimate the propeller's aerodynamic performance.

A Hexagon Romer Absolute Arm laser-scanner, shown in Figure 2.16, was used to obtain a point cloud of the propeller. The Romer arm is a 7 degree of freedom robotic arm, with encoders along each joint to accurately measure the orientation of the arm as it moved around the object. The laser-scanner was attached to the head of the arm and it produced a large, XYZ point cloud of the propeller surface.

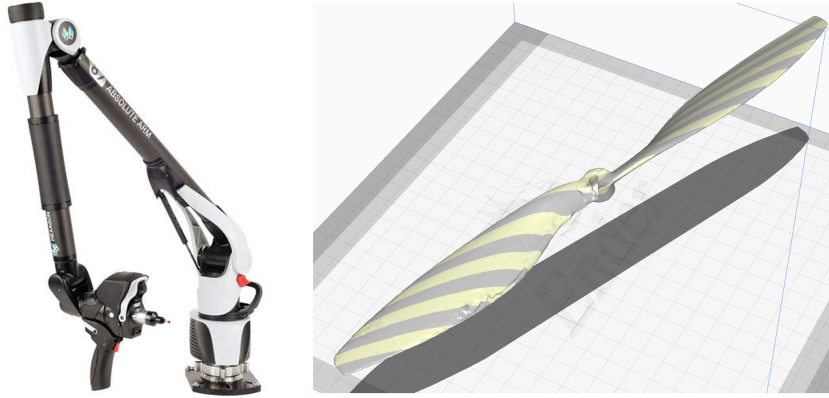


Figure 2.16: Left: Hexagon Romer Absolute Arm laser-scanner. Right: Raw point cloud produced from the laser-scan of the 10x4.5 propeller.

After the scan, the point cloud was imported into Matlab, shown in Figure 2.17. An algorithm was developed to search along the blade span, identify the 2D airfoil geometry, and estimate the airfoil pitch and chord values. The airfoil shape and orientation at a specific location along the propeller blade span r_p , was determined by acquiring all XYZ points in the point cloud within $r_p \pm 2.5\%$. Once the 2D

section of airfoil points are obtained, the airfoil's chord and pitch angle were estimated.

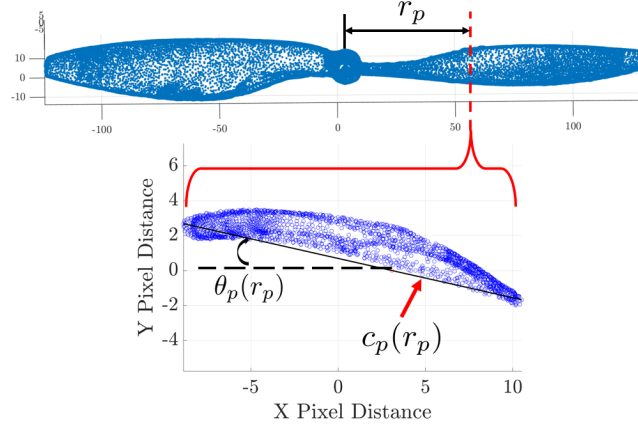


Figure 2.17: Process for extracting blade pitch θ_p and chord c_p information from the laser-scan point cloud.

The planform extraction process was repeated over all 20 radial locations of interest. The resulting propeller pitch and chord distributions for each propeller are shown in Figure 2.18. It was clear that the 9x6.0 propeller had a higher pitch angle distribution than the 10x4.5 propeller over the entire span. Both propellers have roughly the same solidity (around 9.5%), but the 10x4.5 propeller has a thicker tip whereas the 9x6.0 propeller has a thicker root. The resulting airfoils at the 75% radius location for both propellers are shown in Figure 2.19. The following section uses the laser-scanned planform information in a blade-element-momentum theory analysis.

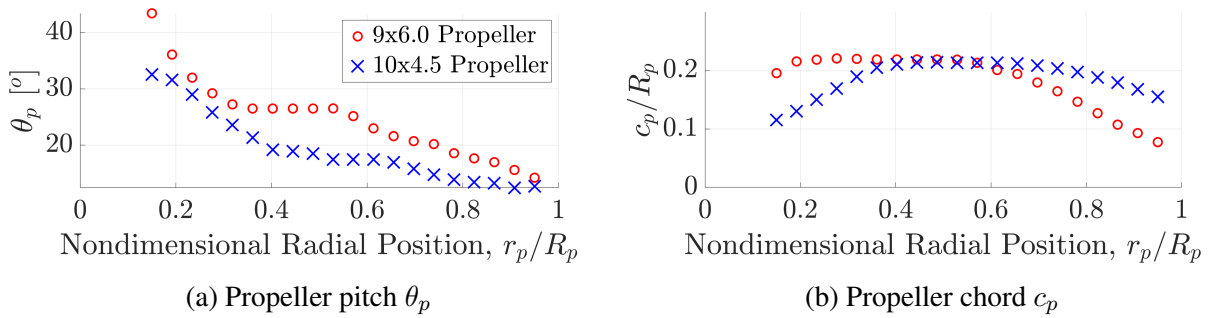


Figure 2.18: Propeller planform estimated from the laser-scan.

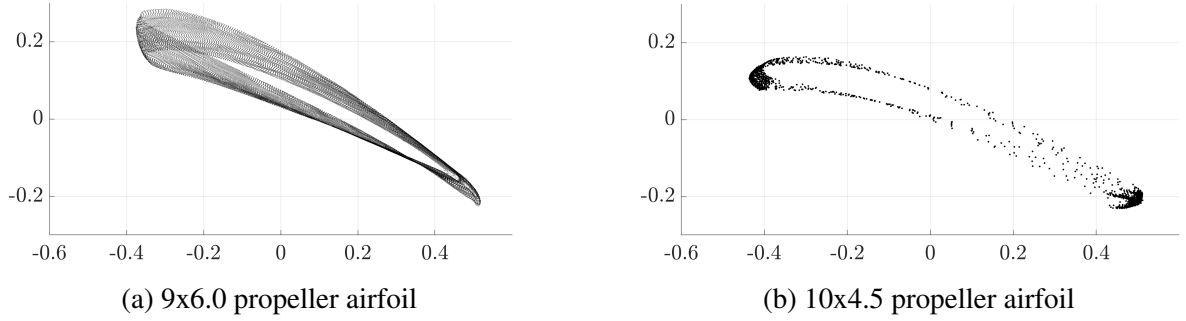


Figure 2.19: Propeller airfoils at the 75% radius location.

2.3.4.2 Propeller BEMT Analysis

After reviewing all the airfoils along the propeller, it was determined that they were similar enough to be approximated by the thin, cambered airfoil at the 75% radial location for the blade-element-momentum theory analysis. This motivated the following 2D airfoil approximation to be used for the blade-element-momentum-theory estimation:

$$C_l = C_{l,\alpha}\alpha + C_{l,0} \quad (2.24)$$

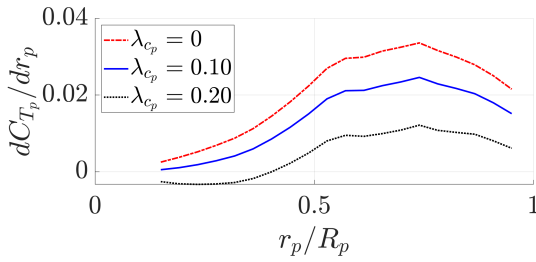
$$C_d = C_{d,0} + C_{d,1}\alpha + C_{d,2}\alpha^2 \quad (2.25)$$

This approach enabled the angle of attack distribution and other propeller performance indicators to be estimated. A numerical optimization scheme was utilized to determine the 2D airfoil coefficients that best match the experimental performance data. The estimated 2D airfoil coefficients are shown in Table 2.4. Suggested future work would be to utilize computational-fluid-dynamics to directly estimate the airfoil sectional lift and drag properties from the laser-scanned airfoil.

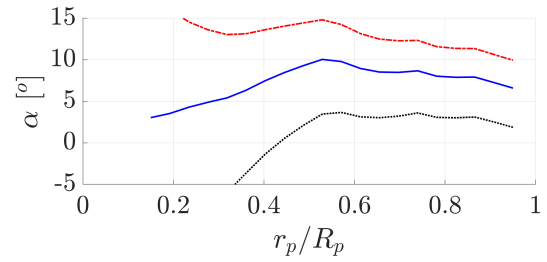
Table 2.4: Estimated propeller airfoil information.

Item	9x6.0 Propeller	10x4.5 Propeller
$C_{l,\alpha}$	4.95	5.72
$C_{l,0}$	0.12	0.051
$C_{d,0}$	0.12	0.063
$C_{d,1}$	0.76	0.96
$C_{d,2}$	0.96	0.15

Figures 2.20 and 2.21 show the blade-element-momentum theory performance estimates for both propellers at various propeller climb ratios λ_{c_p} . Due to the 10x4.5 propeller's lower sectional pitch angles θ_p compared to the 9x6.0 propeller, the 10x4.5 propeller experienced lower angles of attack across the entire span. As expected, the majority of the propeller blade's thrust generation occurs near the 75% radius location.

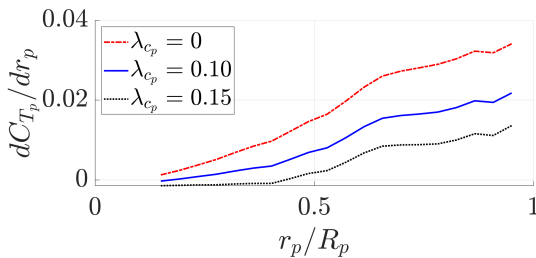


(a) 9x6.0 propeller thrust prediction.

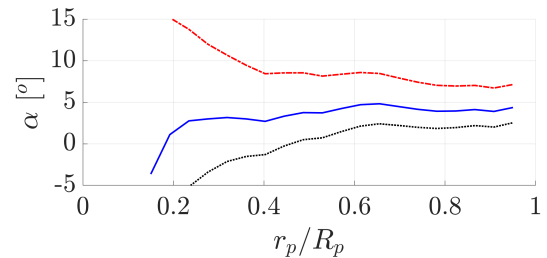


(b) 9x6.0 propeller angle-of-attack prediction.

Figure 2.20: 9x6.0 blade-element-momentum theory expected propeller performance.



(a) 10x4.5 propeller thrust prediction.



(b) 10x4.5 propeller angle-of-attack prediction.

Figure 2.21: 10x4.5 blade-element-momentum theory expected propeller performance.

2.3.4.3 Propeller Wind Tunnel Characterization

During the later propeller-driven rotor feasibility experiments, the untwisted rotor blade was operated at collective angles θ_0 of 0 and 8 degrees. As the blade-tip-propeller propellers were rigidly attached to the blade tip, any change in rotor collective angle resulted in a change in the propeller thrust vector with respect to the free stream air, as shown in Figure 2.22. Due to this change in blade root/tip angle, the isolated propeller testing was conducted with 0 and 8 degrees tilt.

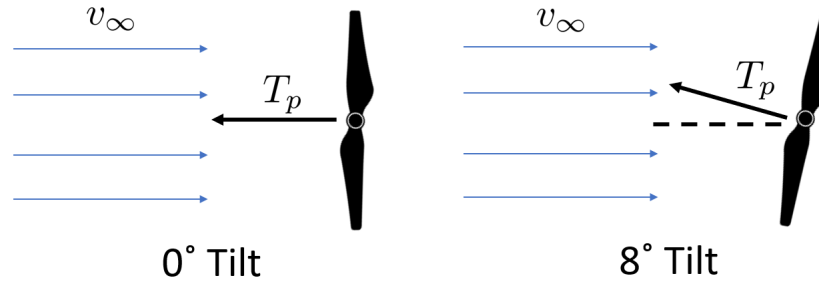
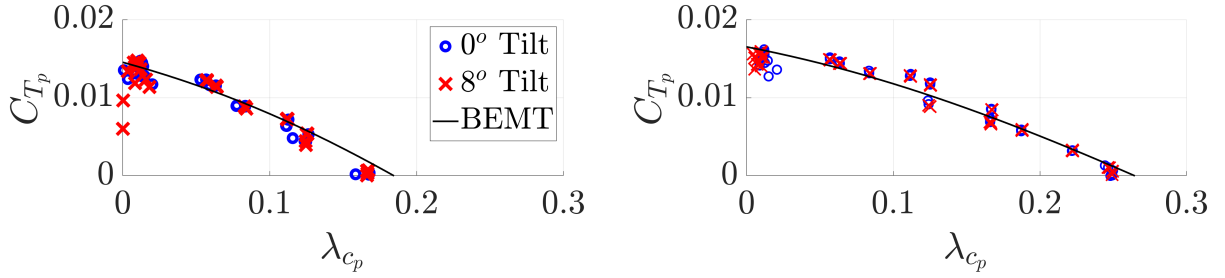


Figure 2.22: 0 and 8 degree tilt relative to the free stream velocity expected from changes in rotor collective θ_0 .

The experimental and predicted results are compared in Figures 2.23-2.25. The simplified 2D airfoil approach resulted in a slight over-prediction for propeller thrust coefficient for both the 10x4.5 and the 9x6.0 propellers at all climb ratios. The second order polynomial for drag in equation 2.25 resulted in a satisfactory estimate for the propeller power coefficient. Both of these results combined to create an optimistic prediction for propulsive efficiency. This blade-element-momentum theory result can be improved by using computational-fluid-dynamics to estimate the 2D lift and drag coefficients for the laser-scanned airfoils. This approach would need to be done for each unique airfoil, and would be subject to laser-scanning noise and could be the subject of future research.

The 9x6.0 propeller had a slightly higher propulsive efficiency and maximum climb ratio com-

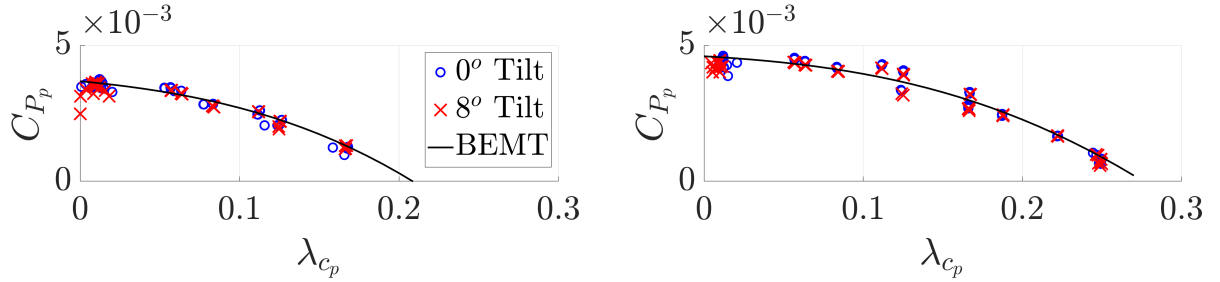
pared to the 10x4.5 propeller. Additionally, the small changes in tilt (0 and 8 degrees) had a negligible impact on the final isolated propeller results. The Forum 79 propellers were used in the propeller-driven rotor hover experiments detailed in Section 3.2. The next propeller set would expand on the propeller design and test procedures.



(a) 10x4.5 propeller.

(b) 9x6.0 propeller.

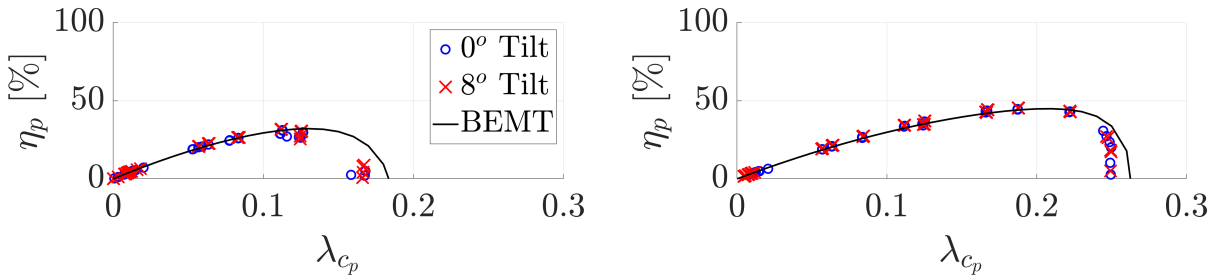
Figure 2.23: Propeller thrust coefficient vs propeller climb ratio.



(a) 10x4.5 propeller.

(b) 9x6.0 propeller.

Figure 2.24: Propeller power coefficient vs propeller climb ratio.



(a) 10x4.5 propeller.

(b) 9x6.0 propeller.

Figure 2.25: Propeller efficiency vs propeller climb ratio.

2.3.5 Forum 80 Propellers: Description and Results

After the initial feasibility and performance studies, there were two clear lessons learned regarding propeller design. First, the propeller design should be simplified to eliminate the need for laser-scanning the propellers for planform. Uniform propeller blade twist, pitch, mass, and other properties were desired. Secondly, the plastic 10x4.5 propeller failed during propeller-driven rotor operation. This indicated that stronger materials, such as carbon composite, should be utilized for propeller design.

Given these findings, the objective for the Forum 80 set of propellers was to simplify the propeller design and examine propeller loads. Instead of using commercial-off-the-shelf propellers, a 150mm carbon composite tail rotor blade of a small scale remote controller helicopter was used as a propeller blade. Additionally, the Forum 80 propeller featured a 3D printed propeller hub that could adjust propeller pitch angle $\theta_{0,p}$. These 3D printed blade grips, shown in Figure 2.26, enabled the same propeller blade to be tested at different collective angles $\theta_{0,p}$. Details on the propeller are found in Table 2.5.

Table 2.5: Propeller details.

$\theta_{0,p}$	5, 10, 15, 20, 25, 35, 45°
R_p	3 in
c_p	3/4 in
σ_p	0.16
N_{bp}	2
θ_{tw}	0°

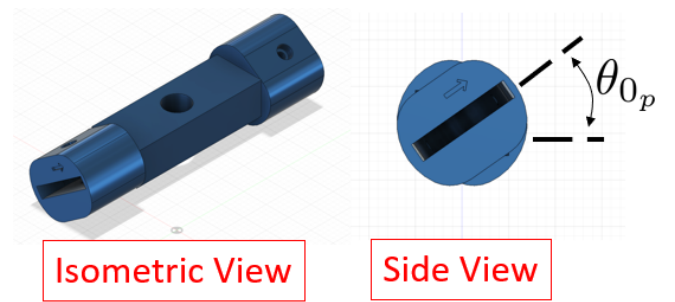


Figure 2.26: CAD of 3D printed adjustable pitch propeller hubs, $\theta_{0,p} = 35$ deg shown.

Due to the large angles of attack seen in axial flight from the Forum 79 propellers, it was decided to experimentally capture the stall performance of the propeller. A major improvement between the Forum 79 and Forum 80 propellers was the ability to adjust propeller pitch angle $\theta_{0,p}$. It was decided to also conduct hover testing of the propeller at high propeller collective angles $\theta_{0,p}$ to help validate the propeller aerodynamic model.

2.3.5.1 Propeller Hover Characterization

The propeller aerodynamic model was developed through hover stand testing, shown in Figure 2.27, and validated through wind tunnel testing in axial flow condition. The hover sweep enabled the stall performance of the propeller blade airfoil to be examined. The propeller collective $\theta_{0,p}$ was adjusted in between experiments, and propeller thrust and power were recorded.

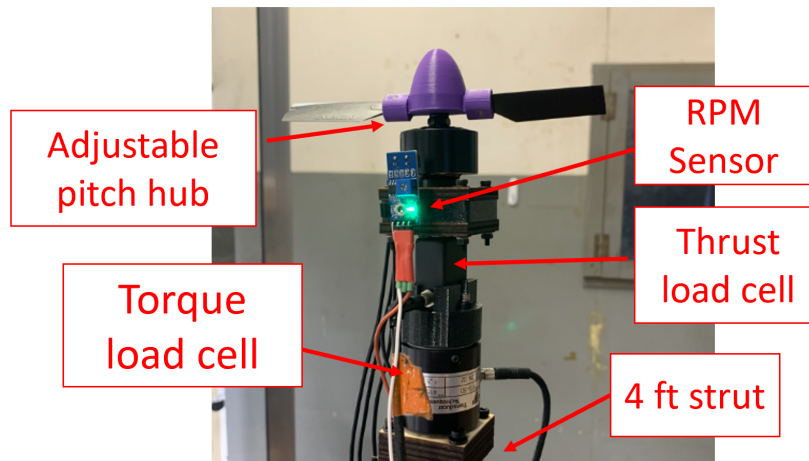


Figure 2.27: Hover test stand for the isolated propeller.

As this untwisted propeller was operating in a climb state during propeller-driven rotor operation, it was necessary to determine the propeller airfoil's lift and drag behavior at very high angles of attack. To accomplish this, propeller hover thrust and power were recorded over a range of propeller pitch

collective angles. The 3D printed propeller blade grips, shown earlier in Figure 2.26, were changed out in between tests for the desired pitch setting.

Figure 2.27 shows the hover stand that was constructed for the isolated propeller. It features a thrust load cell, a torque load cell, an RPM sensor, and an electric motor. All components were controlled via a LabView DAQ system. The results of the propeller hover tests are shown in Figure 2.28. These results were used to construct the propeller aerodynamic model. This aerodynamic model was validated through axial climb testing in the wind tunnel.

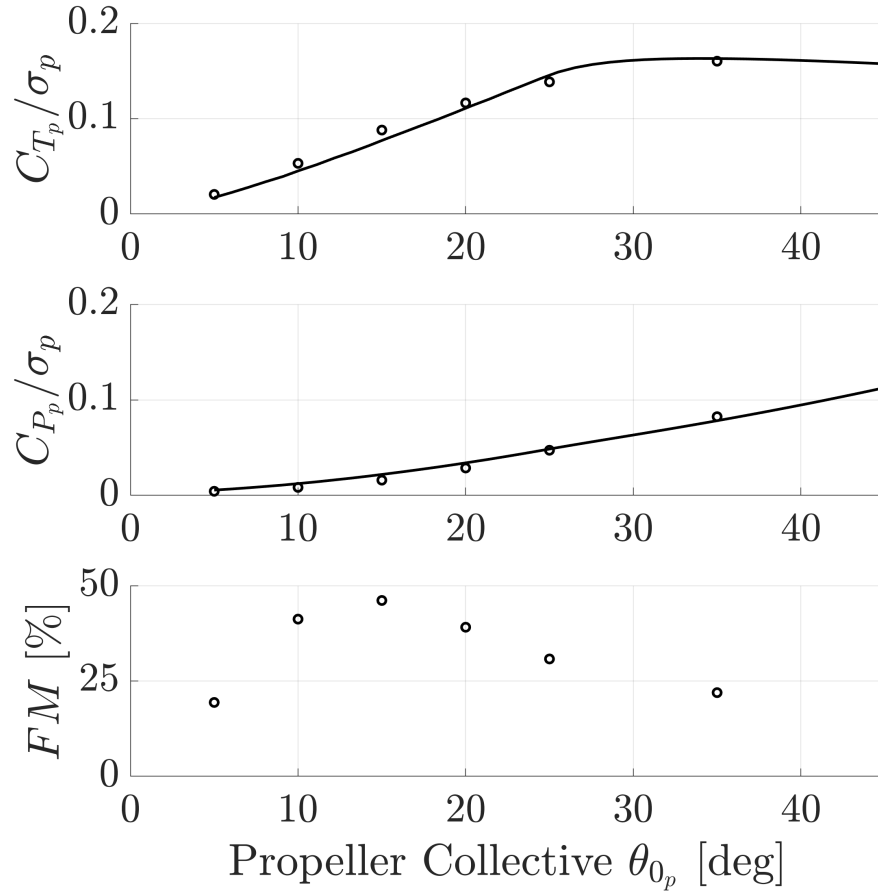


Figure 2.28: Propeller thrust (C_{T_p}/σ_p) coefficient, torque (C_{Q_p}/σ_p) coefficient, and figure of merit (FM) for different propeller pitch angles θ_{0_p} . Dots indicate experimental data whereas solid lines represent predictions.

2.3.5.2 2D Airfoil Performance

The propeller hover experimental results, shown in Figure 2.28, were used to estimate the 2D airfoil performance. A simple estimate of maximum lift along with drag divergence were needed to estimate stall performance. Using this data, an equivalent $C_l(\alpha)$ and $C_d(\alpha)$ were extracted and then the resulting propeller aerodynamic model was validated through axial flow testing in the wind tunnel.

From blade element theory, the average $\bar{C}_L$ of the rotor is:

$$\bar{C}_L = 6\left(\frac{C_{T_p}}{\sigma_p}\right) \quad (2.26)$$

This represents the average lift value of all blade sections for the propeller. Figure 2.29 shows the results of this equation applied to the propeller hover data.

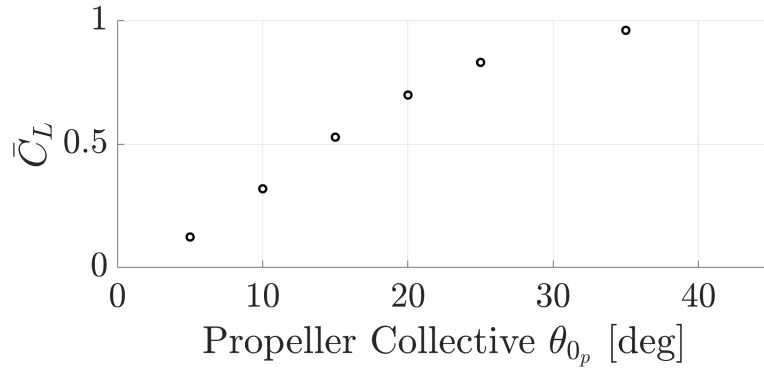


Figure 2.29: Average propeller lift $\bar{C}_L$ versus propeller collective pitch in hover experiments.

The results of Figure 2.29 indicate that the propeller in hover was able to operate at a high average lift coefficient. It also indicated that the stall of the propeller did not occur until above 25 degrees of propeller collective pitch θ_{0_p} . Based on these results, a simplified lift and drag model for the propeller airfoil were selected:

$$C_l = \max(C_{l\alpha}\alpha, C_{l,max}) \quad (2.27)$$

$$C_d = C_{d0} + C_{d1}\alpha + C_{d2}\alpha^2 \quad (2.28)$$

The propeller airfoil's lift curve is shown in Figure 2.30. The results of this propeller aerodynamic model are shown in Figure 2.28 with solid lines. The next section details the validation study that was performed by testing the propeller's aerodynamic model in axial climb over a range of airspeeds through wind tunnel testing.

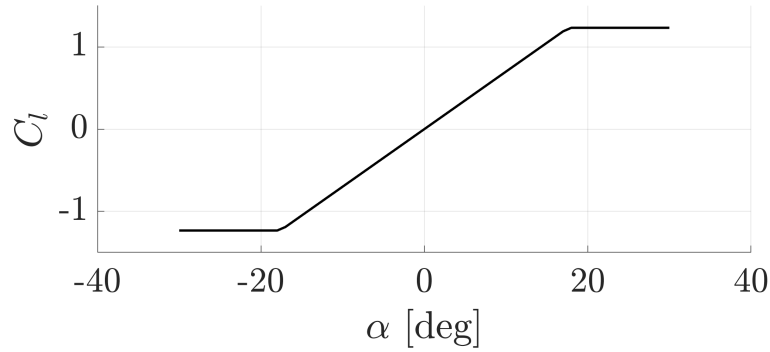


Figure 2.30: 2D Lift curve slope for the propeller airfoil.

2.3.5.3 Propeller Wind Tunnel Characterization

After propeller hover testing, the isolated propeller was tested in axial flight in the Low Turbulence Wind Tunnel at NSWC Carderock. The experimental and predicted results for the propeller wind tunnel test are shown in Figure 2.31. The aerodynamic model that was developed from the hover experimental data was applied in axial climb, and the results agreed well with the experimental data. The 25 degree and 35 degree pitch untwisted propellers have peak propulsive efficiencies of 37.5% and 45% respectively. From the predicted results, the angle of attack was determined. The angle of

attack of the 75% span location α_{75} was determined, and is shown in Figure 2.32. This reinforced why it was necessary to perform such a large propeller collective sweep θ_{0_p} during the propeller hover experiment.

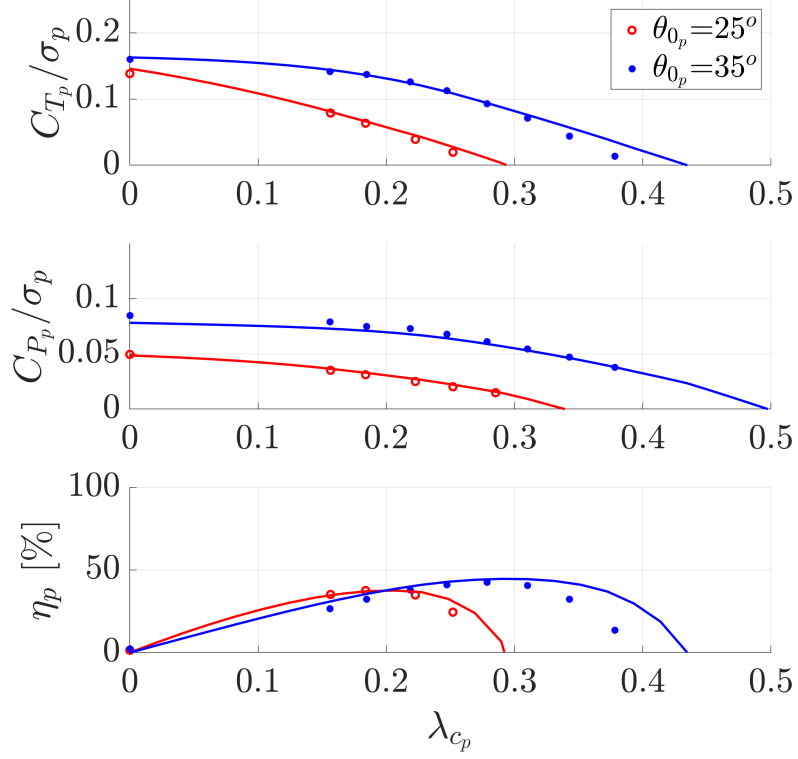


Figure 2.31: Propeller performance in axial climb. Dots indicate the experimental data, whereas lines represent the predictions using the propeller aerodynamic model.

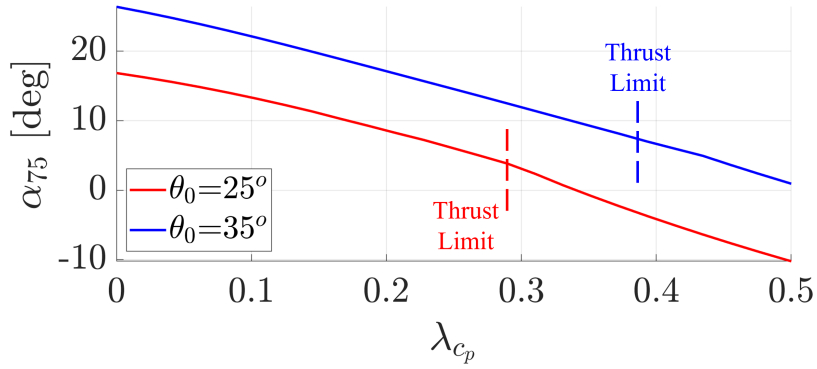


Figure 2.32: Propeller performance in axial climb.

2.3.6 Forum 81 Propellers: Description and Results

Building off the success of the adjustable propeller collective $\theta_{0,p}$ from the Forum 80 propellers, the primary objective of the Forum 81 propellers was a fully customizable propeller design for the propeller-driven rotor. Based off key findings from the Forum 79 and Forum 80 results, the intention was to create a high performance propeller that could minimize propeller-driven rotor power - that is the airfoil decks, propeller planform, twist, and other key parameters would be selected based off the propeller-driven rotor operating condition. While conducting this work, the Forum 81 propellers were used to identify the propeller-driven rotor swirl phenomenon. After this, the focus of the Forum 81 research shifted to investigating rotor-propeller dynamics.

A custom 3D printed propeller was designed for propeller-driven rotor testing, shown in Figure 2.33. 3D printing was selected as it enabled key features of the propeller design (such as root collective, twist rate, planform and airfoil) to be systematically and quickly adjusted. A spar hole was left in the 3D print at the propeller 1/4 chord location, and either a carbon fiber (CF) or steel (ST) rod was used as a spar. The spar size varied between 1.5 mm, 2.0 mm, 2.5 mm, and 3.0 mm.

The remainder of this section details the Forum 81 propeller development and experimentation. Similar to the previous Forum 80 propellers, the Forum 81 propellers were first tested in hover and then in axial flight in a wind tunnel. Through systematic hover and wind tunnel testing, an aerodynamic model was developed that could later be used to design an optimized propeller for propeller-driven rotor testing. After isolated propeller characterization, the propellers were used in propeller-driven rotor hover testing.

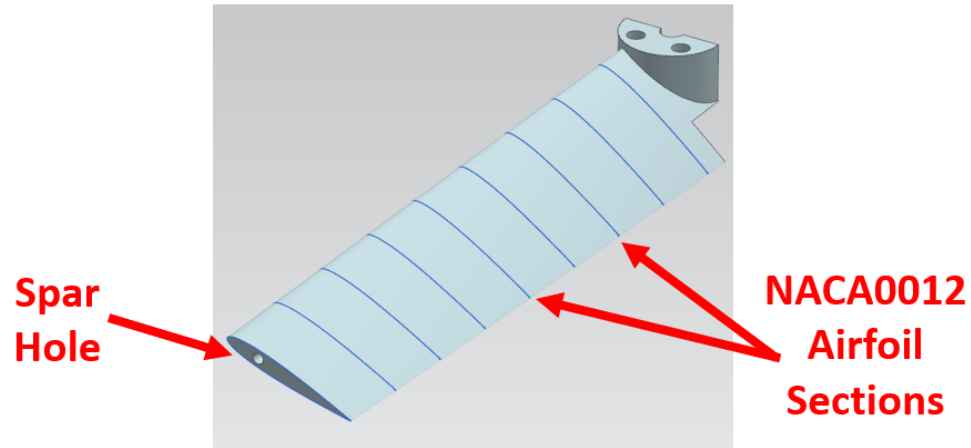


Figure 2.33: CAD design of 10 in diameter 3D printed propeller that was used in propeller-driven rotor testing.

2.3.6.1 Propeller Hover Characterization

A hover test stand, similar to the one used in Forum 80 hover experiments, was constructed to test the propellers in hover. Two datasets were collected on the propeller hover test stand. First, the untwisted propeller's root collective was adjusted $\theta_{0,p}$. Second, the propeller root collective was held constant at $\theta_{0,p} = 35^\circ$ and the propeller twist $\theta_{tw,p}$ was adjusted. Figure 2.35 and 2.36 show the results of the two experiments.

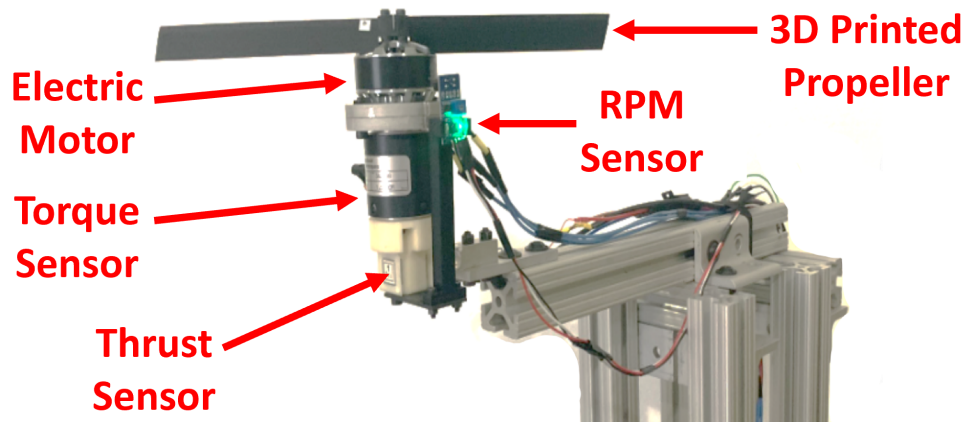


Figure 2.34: Propeller hover test stand.

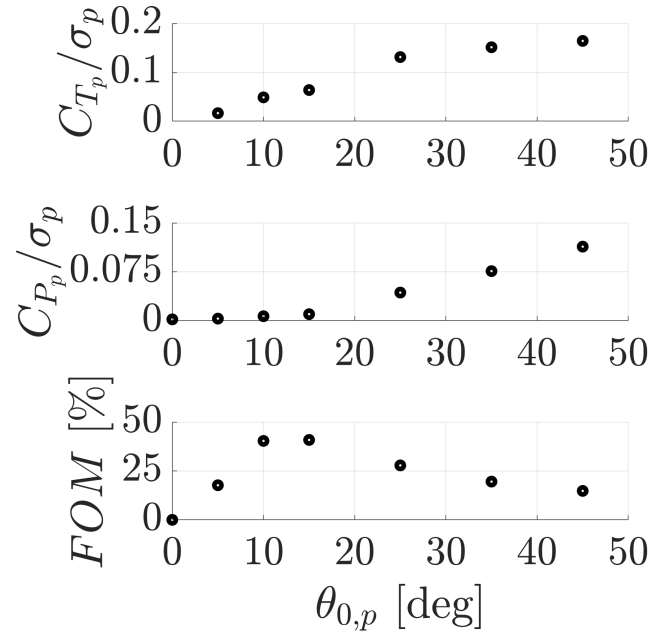


Figure 2.35: Propeller thrust C_{T_p}/σ_p , power C_{P_p}/σ_p , and Figure of Merit (FOM) hover test results with various propeller root collectives $\theta_{0,p}$ and no propeller twist $\theta_{tw,p}$.

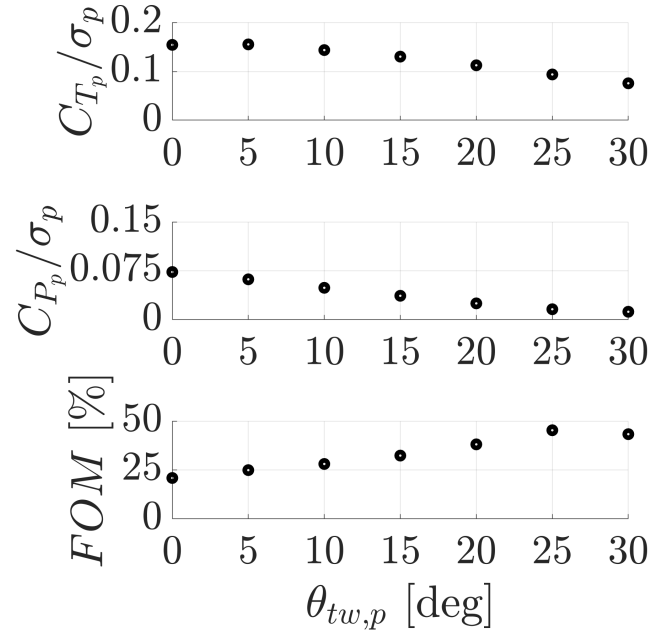


Figure 2.36: Propeller thrust C_{T_p}/σ_p , power C_{P_p}/σ_p , and Figure of Merit (FOM) hover test results with various propeller twist $\theta_{tw,p}$ and a fixed propeller root collective $\theta_{0,p} = 35^\circ$.

2.3.6.2 Propeller Wind Tunnel Characterization

After propeller hover testing, the 3D printed propeller was tested in the 2 ft by 4 ft Low Turbulence Wind Tunnel at NSWC Carderock. The propeller thrust, power, and efficiency were obtained over a range of axial flight speeds. Two different NACA0012 propellers were tested: one twisted and another untwisted. Both propellers had a root collective $\theta_{0,p} = 35^\circ$, and the twisted propeller had a $\theta_{tw,p} = 15^\circ$ twist. Figure 2.37 shows the experimental results of the propeller in axial climb.

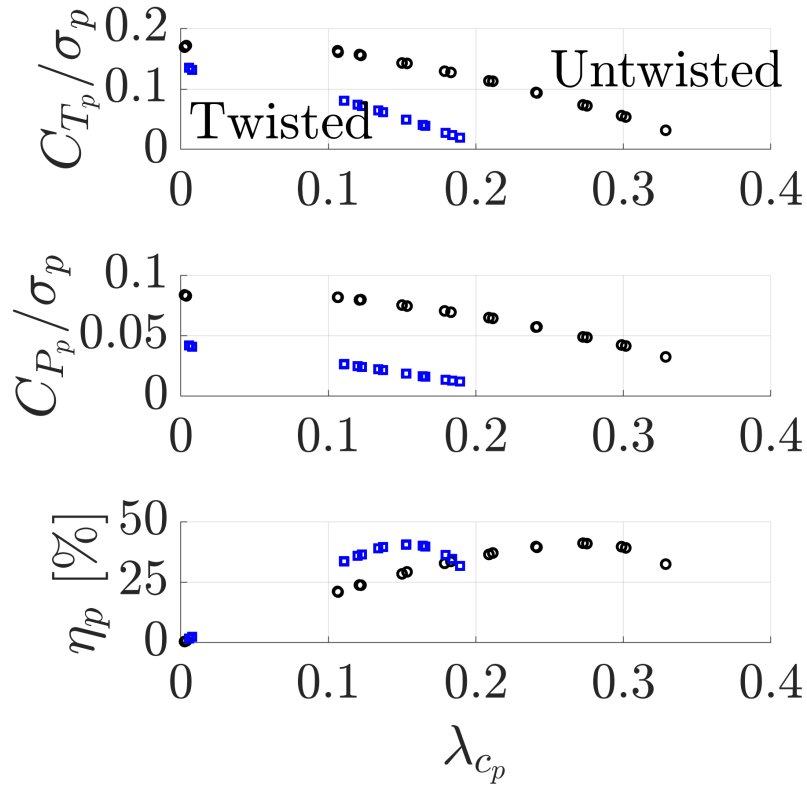


Figure 2.37: Axial flight test results versus propeller climb ratio λ_{c_p} . Both propellers had a $\theta_{0,p} = 35^\circ$, with either $\theta_{tw,p} = 0$ (circle) or $\theta_{tw,p} = 15^\circ$ (square).

The propellers were tested in axial climb speeds up to 11 m/s at a fixed propeller tip speed of 33.2 m/s. Figure 2.37 shows the non-dimensionalized propeller thrust C_{T_p} , power C_{P_p} , and propulsive

efficiency η_p experimental results versus axial climb ratio λ_{cp} . Propeller thrust C_{T_p} and power C_{P_p} are divided by their propeller solidity σ_p , which was 10%. It is clear that the twisted propeller had a reduced maximum axial speed compared to the untwisted propeller. This was due to the reduction in the propeller pitch, as higher propeller pitch is required for high speed flight. Also, the maximum propulsive efficiency η_p occurred at a lower propeller climb ratio λ_{cp} for the twisted rotor. Figure 2.38 shows the propeller thrust as a function of propeller power. From this it can be seen that for a given propeller thrust, the twisted propeller required less power.

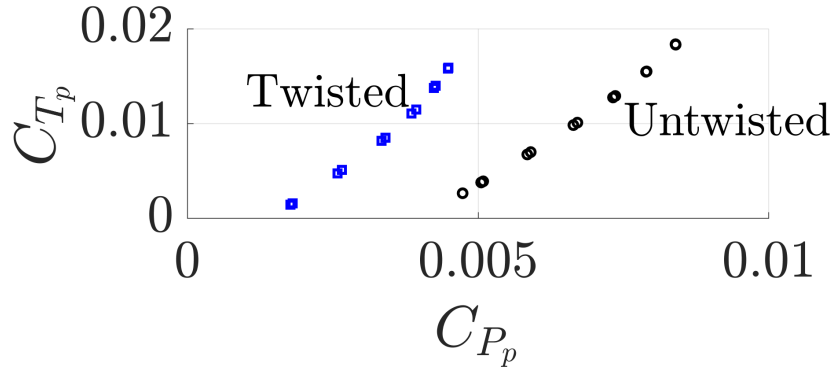


Figure 2.38: Axial flight test results for propeller thrust versus power.

After the Forum 81 propellers were tested, they were used in propeller-driven rotor testing where they failed. The failure of these propellers halted the propeller-driven rotor hover test campaign, and eventually lead to the discovery of the propeller-driven rotor twirl phenomenon. Additional details on the experimentation can be found at the start of Chapter ??.

2.4 Wing and Propeller Characterization

The final sub component system that was tested was the non-rotating rotor blade (wing) and tip mounted propeller. Later propeller-driven rotor hover testing would utilize a tip mounted load cell to

measure propeller loads, more details can be found in Section 3.3. Prior to this hover testing, the tip mounted load cell and non-rotating wing were tested in the Low Turbulence Wind Tunnel. This test served as a critical checkout test to ensure the tip load cell was operating properly. Additionally, the comprehensive analysis would later use the wing lift and drag properties to model the propeller-driven rotor configuration. In this context, the rotor blade is stationary and will thus be referred to as a wing. The wing and propeller were tested in the Low Turbulence Wind Tunnel at airspeeds of 15 and 20 m/s.

More specifically, the experiment sought to determine the nacelle drag and the influence of propeller rotation on the wing lift. The propeller at the tip of the blade has the potential to influence the wingtip vortex and could either add or reduce the wingtip vortex strength depending on the propeller speed and direction. Figure 2.39 shows this potential interaction.

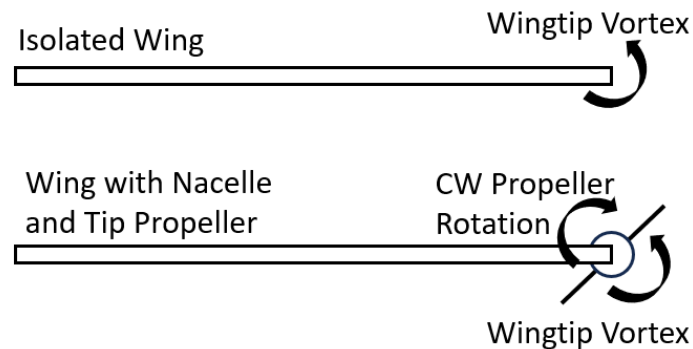


Figure 2.39: Potential influence of wingtip interaction with the tip propeller.
View is from the wing trailing edge.

Figure 2.40 shows the wing and propeller configurations that were tested. First, the isolated wing was tested. Next, the tip nacelle was installed on the wing, without the propeller. Finally, the tip propeller was installed and allowed to rotate in either the clockwise (CW) or counterclockwise (CCW) direction. Figure 2.41 shows the tip mounted propeller on a wing in the test section of the NSWC Carderock's Low Turbulence Wind Tunnel.

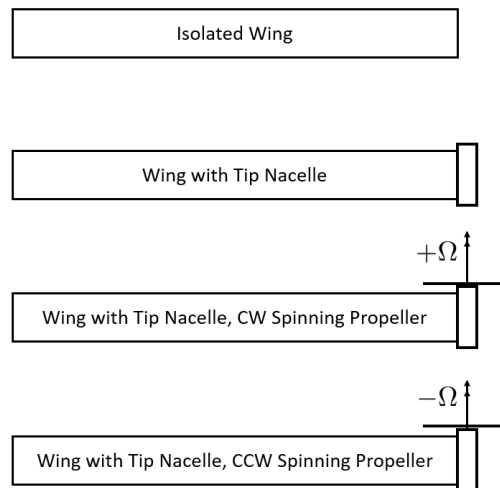


Figure 2.40: Configurations tested in the wind tunnel.



Figure 2.41: Wing and tip propeller inside the Low Turbulence Wind Tunnel.

2.4.1 Experiment Setup

A test stand was fabricated that allowed for simultaneously testing of a wing and propeller at various airspeeds and wing angles of attack. This stand featured a Newport URS50BCC motorized rotary table to adjust the wing's angle of attack, an AMTI FS6 6-DOF load cell to measure the wing loads, and an ATI Nano17 6-DOF load cell to measure the propeller loads. Figure 2.42 shows an overview of the test setup and Figure 2.43 shows the hardware mounted around the tunnel test section.

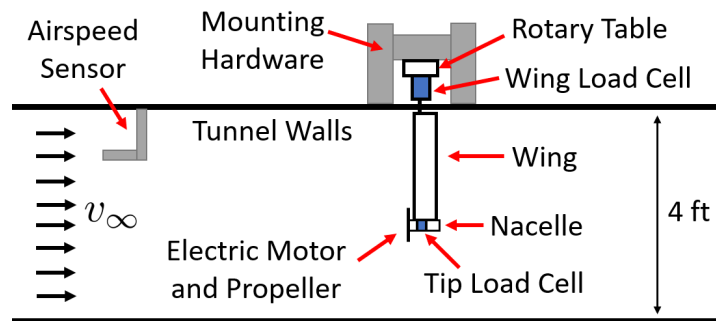


Figure 2.42: Overview of test setup for wind and propeller characterization.

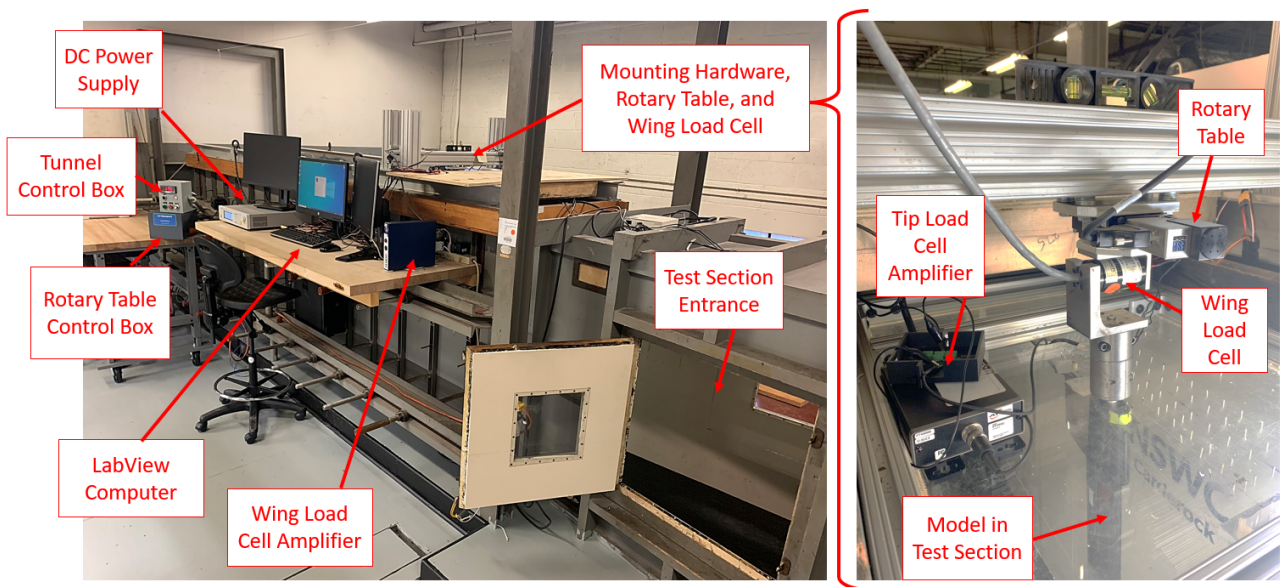


Figure 2.43: Test equipment at the Low Turbulence Wind Tunnel for the wing and propeller characterization.

An 80/20 mounting structure was installed above the tunnel. This structure holds the rotary table, the wing load cell, and the attachment mechanism to hold the wing inside the tunnel. Numerous parts were machined in order to ensure that the structure was as rigid as possible. The wing root bolted into a streamlined fairing that allowed a shaft to connect it to the load cell.

For the experiment, the wing angle of attack α_w was varied between 0 and 12 degrees at airspeeds of 15 and 20 m/s for each configuration. For the configurations with a propeller, the propeller was rotated at 5000 RPM and 6500 RPM for the 15 and 20 m/s airspeeds, respectively. The higher airspeed required a higher propeller RPM to produce positive propeller thrust.

As the wing load cell was mounted to the root of the wing, it rotated with the wing angle of attack α_w . Thus, the wing load cell was measuring the forces along the chord of the wing F_c , and normal to the wing F_n . This setup is shown in Figure 2.44.

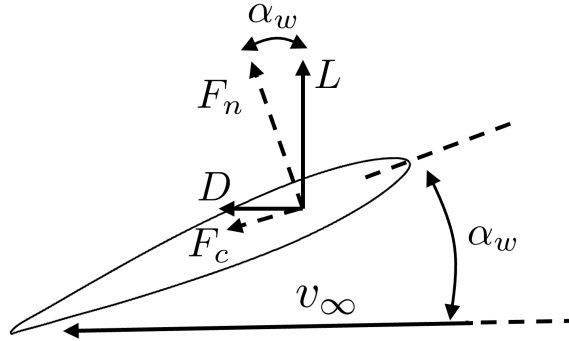


Figure 2.44: Load cell measurements versus wing lift and drag.

Wing drag is defined parallel to the free stream airspeed v_∞ , and the wing lift is defined normal to drag. The load cell forces are rotated to wing lift and drag by:

$$L = F_n \cos \alpha_w - F_c \sin \alpha_w \quad (2.29)$$

$$D = F_n \sin \alpha_w + F_c \cos \alpha_w \quad (2.30)$$

During propeller operation, the thrust of the propeller acted in the opposite direction of F_c . The propeller thrust value from the load cell was subtracted out of this F_c reading to calculate the wing lift and drag.

2.4.2 Experimental Results

First, the isolated wing was tested at airspeeds of 15 and 20 m/s, followed by adding the nacelle (without propeller blades). For both cases, the lift coefficient of the wing stalled around 10 degrees. The isolated wing and the wing with the tip nacelle results are shown in Figure 2.45.

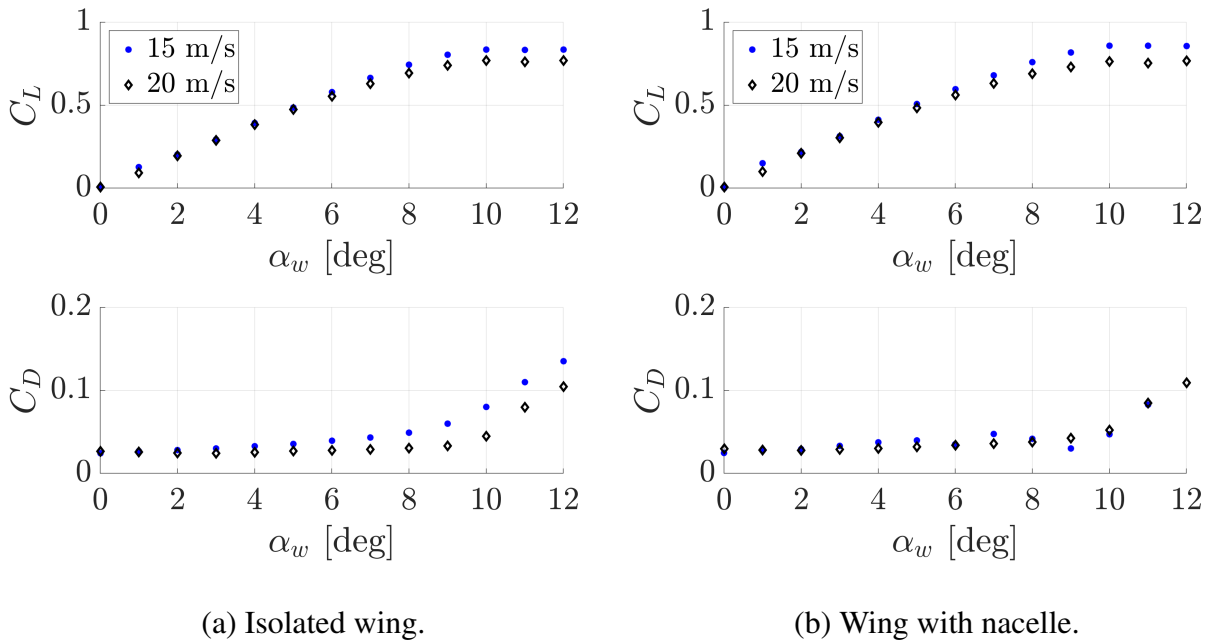


Figure 2.45: Wind tunnel results for isolated wing and wing with nacelle.

Next, the propeller was attached and rotated at different rotational speeds and directions. For the 15 m/s case the propeller rotational speed was 5000 RPM. For the 20 m/s case, the propeller rotational speed was increased to 6500 RPM in order to ensure it still produced positive thrust at this high speed.

Figure 2.46 shows the propeller thrust for the different airspeeds. It was observed that the propeller thrust remained relatively constant for all wing angles of attack, and with both rotational directions. The results for the spinning tip propeller are shown in Figure 2.47.

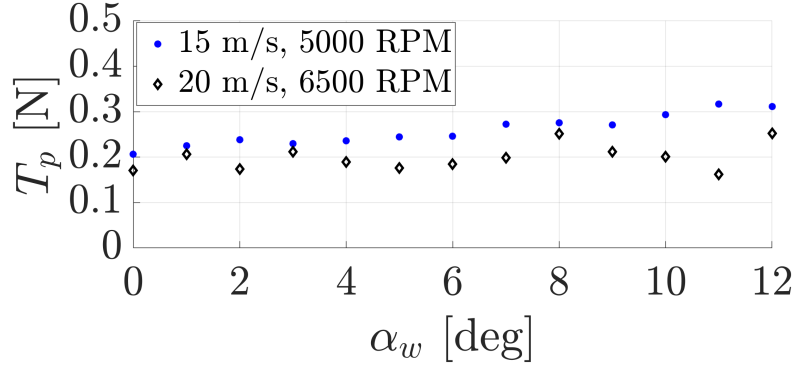


Figure 2.46: Propeller thrust for the tip propeller during the wing wind tunnel testing.

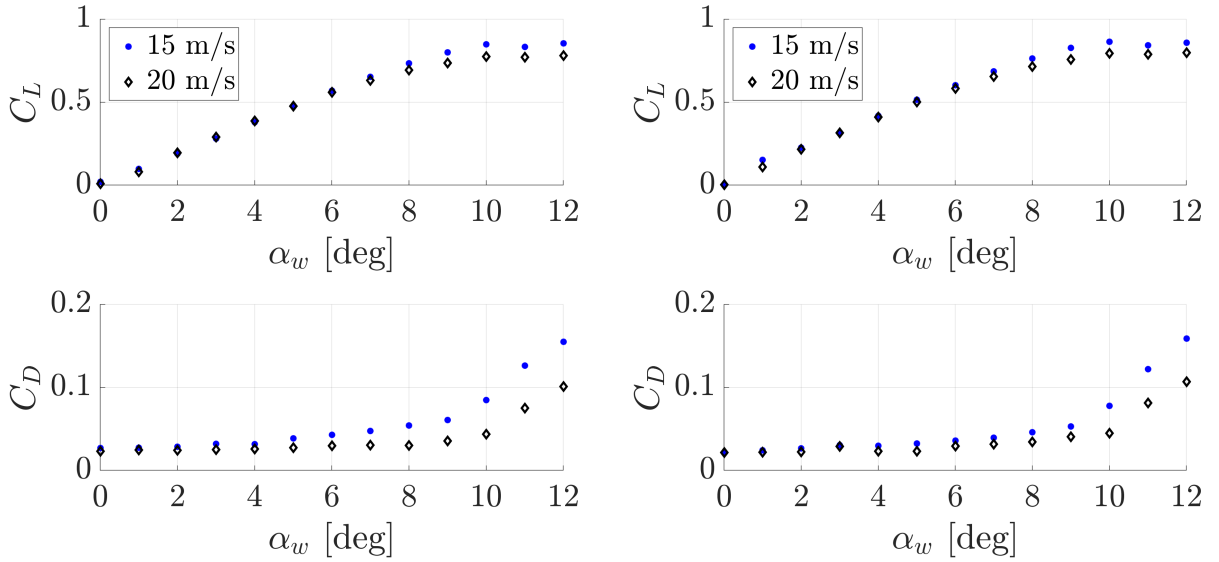


Figure 2.47: Wing, nacelle, and spinning propeller results.

2.4.3 Performance Comparison

The four cases are compared in Figure 2.48 at 20 m/s airspeed. A 20 m/s airspeed is important because the later rotor hover tests were conducted at a rotor tip speed of 20 m/s. From these results it is clear that the various configurations tested had a negligible impact on wing lift and a modest effect on wing drag. The profile drag coefficient C_{D0} was determined for each configuration, and the results are shown in Table 2.6.

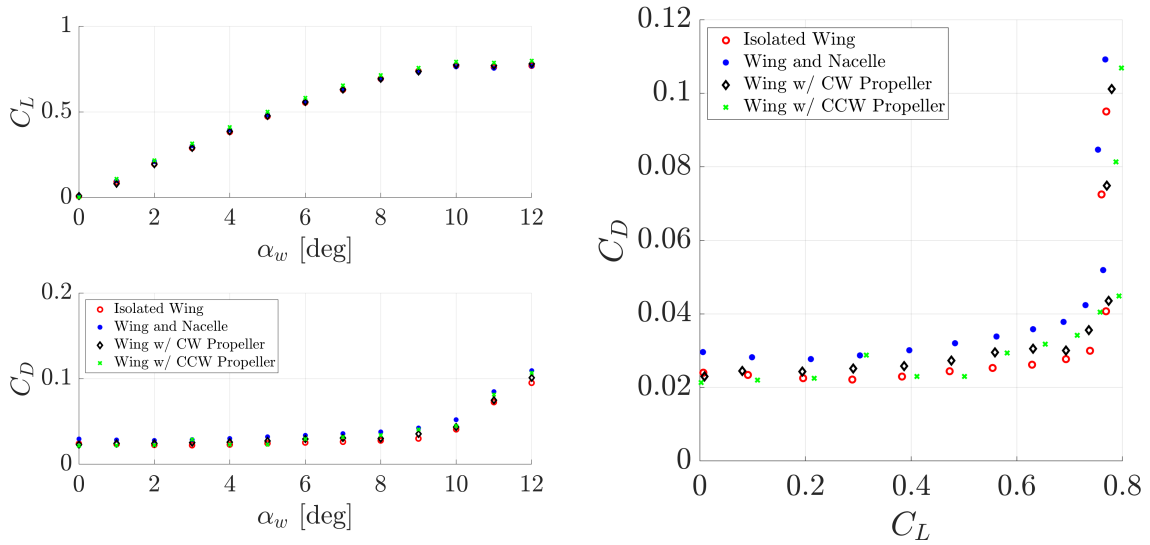


Figure 2.48: Wing performance for all configurations at 20 m/s airspeed.

Table 2.6: Drag coefficient comparison at 20 m/s airspeed.

Configuration	C_{D0}	% Change
Isolated Wing	0.0240	-
Wing and Nacelle	0.0296	+23%
Wing w/ CW Propeller	0.0230	-4%
Wing w/ CCW Propeller	0.0214	-10%

An increase in drag coefficient of 23% was observed between the isolated wing and the wing with the tip nacelle. Additionally, a modest drag reduction was observed for the wing with the tip

propeller. Little change in wing lift versus angle of attack was observed between the different cases. The wing stalled around $\alpha_w = 10^\circ$, and had a maximum lift value of only 0.8. Additionally, a relatively low 2D lift curve slope of $C_{l\alpha} = 4.3$ was observed. These low lift and high drag numbers are typical of low Reynolds numbers testing. These basic performance numbers obtained in this wing-propeller characterization study were later used in the comprehensive analysis.

Chapter 3: Hover Performance

This chapter documents the investigations on propeller-driven rotor feasibility and hover performance. Feasibility refers to comparing the required hover power and thrust between a propeller-driven rotor system and a conventional, shaft-driven rotor system. Early experiments focused on propeller-driven rotor feasibility, while later experiments focused on propeller loads and performance. Although the comprehensive analysis was developed after several experiments, the results shown in this chapter will be compared to the comprehensive model to help explain the experimental results.

This chapter has the following outline. First, an analytical performance model for a tip mounted propeller is presented. Second, the initial propeller-driven rotor feasibility experiments using commercial-off-the-shelf components are detailed. Third, propeller loads during propeller-driven rotor operation are investigated in the rotor-propeller hover loads experiment. Fourth, the variable propeller placement on the main rotor span was explored. Next, comprehensive rotorcraft modeling results for a variable propeller placement are shown. These results lead to a fundamental understanding of propeller-driven power. The chapter ends by examining scaling effects, and with a brief summary and conclusions.

Before starting, a brief note on nomenclature. The rotor refers to the main rotor. The isolated rotor refers to the rotor alone, that is without any propeller-driven rotor modifications. The rotor with the tip nacelle refers to the rotor with the tip nacelle assembly attached, but with no tip mounted propeller. Shaft-driven indicates that the power required to spin the rotor system was supplied by a

motor in the fixed frame. Propeller-driven implies that the main rotor is free to rotate about the rotor shaft, and is propelled only by the propeller mounted on the rotor blade.

3.1 Analytical Model for Tip Propeller Performance

This simplified physics model of the propeller-driven rotor with a tip propeller was developed in conjunction with the experimental results in Section 3.2 using the Forum 79 propellers. A tip propeller was the logical first location to place the propeller on the rotor blade as it maximized the moment arm to the rotor shaft. The tip propeller was modeled as a rotor in an axial climb state, shown in Figure 3.1. The model sets the rotor drag torque equal to the moment produced by the propeller at some distance. Next, the propeller thrust can be solved for. From this required propeller thrust, the propeller operating conditions are determined, resulting in a propeller power estimate. This approach was found to agree well with the experimental results.

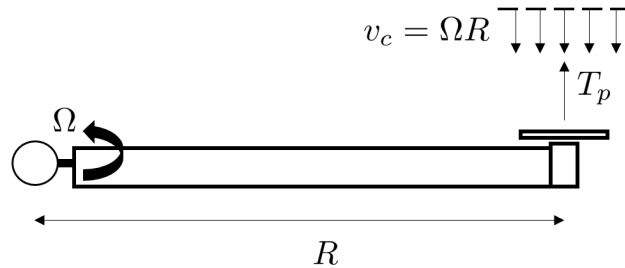


Figure 3.1: Tip propeller modeled as rotor in axial climb, with the climb speed equal to the rotor tip speed.

From blade element theory, the rotor has the following performance equations:

$$C_T = \frac{1}{2} \sigma C_{l,\alpha} \left[\frac{\theta_0}{3} - \frac{1}{2} \sqrt{\frac{C_T}{2}} \right] \quad (3.1)$$

$$C_P = C_Q = k_h \frac{C_T^{3/2}}{\sqrt{2}} + \frac{1}{8} \sigma C_{d0} + C_{PN} \quad (3.2)$$

where C_{PN} is the power to overcome the nacelle drag. To spin the rotor for a given rotational rate, the required torque Q is:

$$Q = C_Q \rho A (\Omega R)^2 R \quad (3.3)$$

From Figure 3.1, the rotational torque generated by a propeller located at the tip of the blade is simply:

$$Q = N_B T_p R \quad (3.4)$$

The torque required to spin the rotor must be equal to the torque produced by the tip propellers, meaning equations 3.3 and 3.4 are equal to one another:

$$N_B T_p R = C_Q \rho A (\Omega R)^2 R$$

As such, the required propeller thrust can be determined as:

$$T_p = \frac{C_Q \rho A (\Omega R)^2}{N_B} \quad (3.5)$$

Which can be written in non-dimensional terms as:

$$C_{T_p} = \frac{T_p}{\rho A_p (\Omega_p R_p)^2} \quad (3.6)$$

Combining the previous results yields:

$$C_{T_p} = \frac{C_Q \rho A (\Omega R)^2}{N_B} \frac{1}{\rho A_p (\Omega_p R_p)^2}$$

$$C_{T_p} = \frac{C_Q A}{N_B A_p} \left(\frac{\Omega R}{\Omega_p R_p} \right)^2 \quad (3.7)$$

The isolated wind tunnel performance data can be utilized after considering the propeller climb ratio. Recall, a climb speed ratio is defined as:

$$\lambda_c = \frac{v_c}{v_{tip}}$$

where v_c is the climb velocity and v_{tip} is the reference tip speed. For the isolated propeller tested in the wind tunnel the climb speed v_c was equal to the tunnel speed v_∞ , and v_{tip} was the propeller tip speed $\Omega_p R_p$. For modeling of tip propeller, it was assumed that the propeller acts as a rotor in axial climb and had a climb speed equal to the rotor tip speed:

$$v_c = \Omega R \quad (3.8)$$

Now, a new propeller climb ratio can be defined as:

$$\lambda_{c_p} = \frac{\Omega R}{\Omega_p R_p} \quad (3.9)$$

Physically, the propeller climb ratio for a blade-tip-propeller system represents the ratio of rotor tip speed to the propeller tip speed. Equation 3.9 can be combined to equation 3.7 to yield:

$$C_{T_p} = \frac{C_Q A}{N_B A_p} \lambda_{c_p}^2$$

which rearranges to:

$$\frac{C_{T_p}}{\lambda_{c_p}^2} = \frac{C_Q A}{N_B A_p} \quad (3.10)$$

with:

$$\text{Isolated propeller performance} \rightarrow \frac{C_{T_p}}{\lambda_{c_p}^2}$$

$$\text{Propeller-driven rotor sizing} \rightarrow \frac{C_Q A}{N_B A_p}$$

Equation 3.10 is of significant importance for the tip propeller configuration, and will be examined in greater detail in the next section.

3.1.1 Tip Propeller Equilibrium

An understanding of the steady-state tip propeller performance can be obtained by examining equation 3.10, as it relates the isolated propeller performance curves from Section 2.3.4 to the sizing of the propeller-driven rotor configuration. The left hand side of equation 3.10 can be defined as the propeller performance ratio γ_p , and is a function of λ_{c_p} :

$$\gamma_p(\lambda_{c_p}) = \frac{C_{T_p}}{\lambda_{c_p}^2} \quad (3.11)$$

The isolated wind tunnel results for the Forum 79 propellers, shown earlier in Figure 2.23, are used to create the graph of γ_p for both the 9x6.0 and 10x4.5 propellers. Figure 3.2a shows the γ_p for both propellers.

The right hand side of equation 3.10 is related to the design choices of the combined blade-tip-

propeller configuration. This is defined as the blade-tip-propeller equilibrium ratio γ_p^* :

$$\gamma_p^* = \frac{C_Q A}{N_B A_p} \quad (3.12)$$

where the superscript (*) refers to an equilibrium point. For the blade-tip-propeller configuration, an equilibrium condition occurs when:

$$\frac{C_{T_p}}{\lambda_{c_p}^2} = \frac{C_Q A}{N_B A_p}$$

$$\gamma_p(\lambda_{c_p}^*) = \gamma_p^* \quad (3.13)$$

where $\lambda_{c_p}^*$ is defined as the equilibrium propeller climb ratio. The value of $\lambda_{c_p}^*$ can be found by examining the intersection of γ_p to $C_Q A/(N_B A_p)$. This process is shown visually in Figure 3.2b.

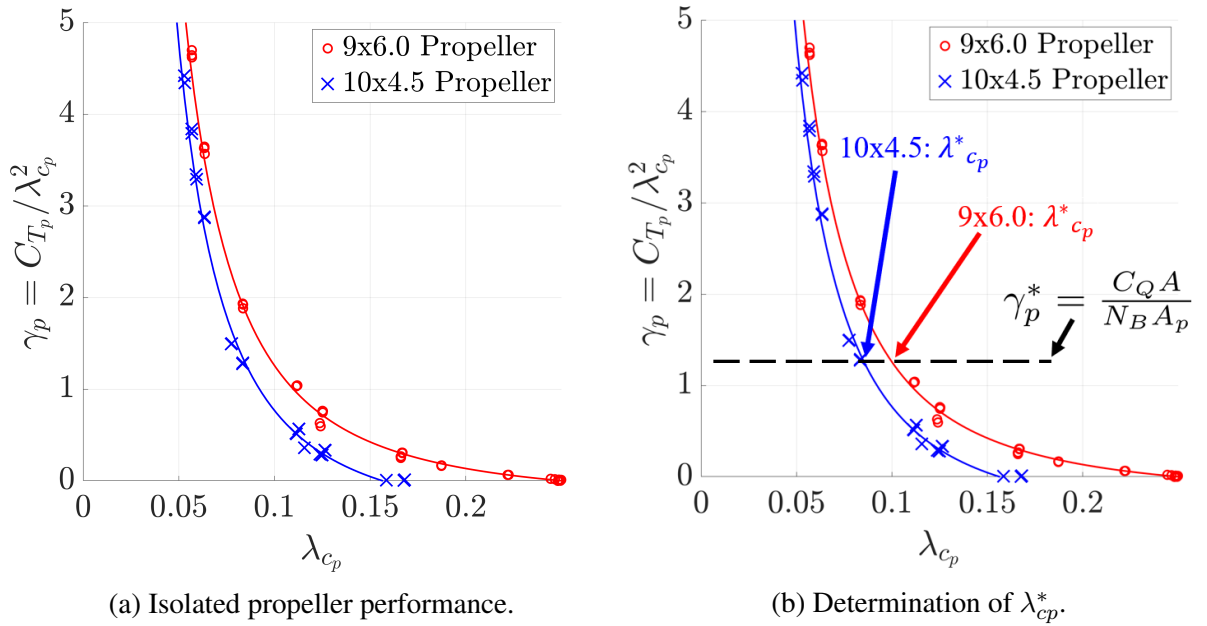


Figure 3.2: Intersection of the propeller performance ratio γ_p with the blade-tip propeller equilibrium ratio γ_p^* to find the equilibrium propeller climb ratio $\lambda_{c_p}^*$.

Once the equilibrium propeller climb ratio $\lambda_{c_p}^*$ has been identified, equation 3.9 can be utilized to determine the rotor tip speed for a given propeller tip speed:

$$\Omega R = \lambda_{c_p}^* \Omega_p R_p \quad (3.14)$$

The linear relationship between propeller RPM and rotor RPM can be written as:

$$\Omega = \lambda_{c_p}^* \frac{R_p}{R} \Omega_p \quad (3.15)$$

This prediction states that for some increase in propeller speed, there will be a proportional increase in rotor speed. For example, if $\lambda_{c_p}^* = 0.25$ and $R_p/R = 4.5/33$, then for every 30 RPM increase in propeller speed there will be a 1 RPM increase in rotor speed.

Using equation 3.14, the resulting rotor thrust can be written as:

$$\begin{aligned} T &= C_T \rho A (\Omega R)^2 \\ T &= C_T \rho A (\lambda_{c_p}^* \Omega_p R_p)^2 \end{aligned} \quad (3.16)$$

Physically, equation 3.10 represents an equilibrium balance between propeller thrust and rotor drag. Consider a rotor rotating with a tip speed of ΩR . An increase in propeller RPM results in a temporary reduction in the climb ratio $\Omega R / (\Omega_p R_p)$. This reduction in climb ratio results in an increase in propeller thrust. The increase in propeller thrust causes additional torque on the rotor, increasing rotor RPM and drag. With the increase in rotor tip speed, the climb velocity of the propeller increases and thus the climb ratio reduces back to its original $\lambda_{c_p}^*$ value before the propeller RPM increase.

3.1.2 Tip Propeller Inflow and Momentum Theory

According to momentum theory, the total inflow v_p of the propeller is a combination of the induced propeller velocity v_{i_p} and the climb velocity v_{c_p} :

$$v_p = v_{i_p} + v_{c_p}$$

The total inflow of the isolated propeller, for a given thrust level, can be written as [19]:

$$\frac{v_{i_p}}{v_{h_p}} = -\frac{v_{c_p}}{2v_{h_p}} + \sqrt{\left(\frac{v_{c_p}}{2v_{h_p}}\right)^2 + 1} \quad (3.17)$$

where the hover induced velocity is

$$v_{h_p} = \sqrt{\frac{T_p}{2\rho A_p}} \quad (3.18)$$

A key insight will be gained by examining the ratio of propeller climb velocity v_{c_p} to induced propeller hover velocity $2v_{h_p}$. For a propeller-driven rotor, the required propeller thrust varies as a function of the rotor speed, given in equation 3.5 (repeated here for convenience):

$$T_p = \frac{C_Q \rho A (\Omega R)^2}{N_B}$$

Inserting the expression for propeller thrust T_p , into equation 3.18 yields:

$$v_{h_p} = \sqrt{\frac{1}{2\rho A_p} \frac{C_Q \rho A (\Omega R)^2}{N_B}}$$

$$v_{h_p} = \Omega R \sqrt{\frac{C_Q A}{2 N_B A_p}} = \Omega R \sqrt{\frac{\gamma_p^*}{2}} \quad (3.19)$$

Returning now to the ratio of v_{c_p} to $2v_{h_p}$, the expression can now be written as:

$$\frac{v_{c_p}}{2v_{h_p}} = \frac{\Omega R}{2\Omega R \sqrt{\frac{\gamma_p^*}{2}}} = \frac{1}{2} \sqrt{\frac{2}{\gamma_p^*}} = \sqrt{\frac{1}{2\gamma_p^*}} \quad (3.20)$$

With this expression, one can now solve for the induced propeller velocity from equation 3.17:

$$\frac{v_{i_p}}{v_{h_p}} = \sqrt{\frac{1}{2\gamma_p^*} + 1} - \sqrt{\frac{1}{2\gamma_p^*}} \quad (3.21)$$

The values of γ_p are on the order of C_Q , which is around $1e-4$. This indicates that the values of $1/\gamma_p$ become quite large, so the square root can be approximated by:

$$\sqrt{\frac{1}{2\gamma_p^*} + 1} \approx \sqrt{\frac{1}{2\gamma_p^*}}$$

Indicating that the final ratio approximately equals:

$$\frac{v_{i_p}}{v_{h_p}} = \epsilon$$

where ϵ is some small number, between 0.05 - 0.10 for the tip propeller configurations considered in this research. This results indicates that the propeller induced velocity does not significantly contribute to the total propeller inflow for the tip propeller design.

3.1.3 Power Loading Comparison

The required power to spin the complete rotor system using the blade-tip-propeller design can now be estimated. According to Ref. [19], a rotor in climb has three primary contributions to power: the induced power P_{i_p} , the climb power P_{c_p} , and the profile power P_{0_p} . The power for a single propeller can be written as:

$$P_p = P_{i_p} + P_{c_p} + P_{0_p}$$

which can be expanded as:

$$P_p = k_p T_p v_{i_p} + T_p v_{c_p} + P_{0_p}$$

where k_p is some induced power factor for the propeller. Thus, the total power for the blade-tip-propeller system is the sum of the individual propeller power over all the blades:

$$P_{BTP} = N_B P_p \tag{3.22}$$

where BTP stands for blade-tip propeller. An interesting result can be obtained by comparing the required power loading of a traditional, shaft-driven rotor to a blade-tip-propeller-driven rotor configuration. Power loading is defined as:

$$PL = \frac{T}{P}$$

Using equation 3.2, the power of the shaft-driven rotor can be written as:

$$P_{Rotor} = C_P \rho A (\Omega R)^3$$

The ratio of power loading of an isolated rotor to a blade-tip-propeller design can be written as:

$$\frac{PL_{Rotor}}{PL_{BTP}} = \frac{T_{Rotor}}{P_{Rotor}} \frac{P_{BTP}}{T_{BTP}}$$

Assuming that the two configurations produce roughly the same thrust ($T_{BTP} \approx T_{Rotor}$), a simplification can be made:

$$\frac{PL_{Rotor}}{PL_{BTP}} = \frac{P_{BTP}}{P_{Rotor}} \quad (3.23)$$

Equation 3.22 can be inserted into equation 3.23 to yield:

$$\frac{PL_{Rotor}}{PL_{BTP}} = \frac{N_B(k_p T_p v_{i_p} + T_p v_{c_p} + P_{0_p})}{C_P \rho A (\Omega R)^3}$$

The expression for propeller thrust, equation 3.5, along with the fact that $v_{c_p} = \Omega R$ are used to simplify the expression:

$$\frac{PL_{Rotor}}{PL_{BTP}} = \underbrace{\frac{k_p v_{i_p}}{\Omega R}}_{Induced} + \underbrace{\frac{\Omega R}{\Omega R}}_{Climb} + \underbrace{\frac{N_B P_{0_p}}{C_P \rho A (\Omega R)^3}}_{Profile} \geq 1 \quad (3.24)$$

This result indicates that the power loading of a shaft-driven rotor system will always be higher than the blade-tip-propeller configuration. This is due to the fact that the ratio of climb power will always be equal to 1.0. Another way to understand this result is that this analysis predicts that the tip propeller configuration will always require more power than a shaft-driven rotor, for the same thrust level. Additionally, for the low climb ratios seen be fixed pitch propellers ($\lambda_{c_p} \leq 0.5$), both the induced and profile values are not negligible. With an understanding of the basic physics of a tip propeller-driven rotor system, the next sections will compare these predictions against experimental observations.

3.2 Initial Propeller-Driven Rotor Investigation - Basic Trends and Feasibility

The first set of experiments utilized the Forum 79 propellers and a custom hover test stand to compare propeller-driven rotor performance with an isolated, shaft-driven rotor. The goal was not to produce a highly optimized system, rather for the initial investigation it was to combine high quality commercial-off-the-shelf components in a logical manner to create first spin tests of a novel, propeller-driven rotor system. More specifically, the goal was to observe propeller performance, validate the simple performance model presented in Section 3.1, and identify areas of improvement.

Prior to using the propeller-driven rotor hover tests, a series of tests were conducted to assess the system with increasing levels of complexity. Early experiments characterized the propeller at the end of a rotating rigid bar and later experiments included both shaft-driven and propeller-driven testing. The use of a rigid bar was to help develop the early system without a rotor blade and to observe initial trends. The following experiments occurred:

1. First, the rigid bar was spun via a central shaft and the required torque was recorded. This torque estimate for the bar was used to find γ_p , and thus the propeller performance was estimated and compared to experimental results.
2. Second, the shaft-driven rotor blade was tested with and without the tip propeller assembly. This allowed the increase in rotor shaft torque due to the presence of the tip nacelle to be quantified.
3. Third, the propeller-driven rotor was spun and performance was compared to the shaft-driven rotor.

The initial set of experiments analyzed the relative performance of different rotor configurations to one another. Table 3.1 and Figures 3.3 detail the different design configurations that were tested.

Table 3.1: Rotor configurations tested for initial feasibility.

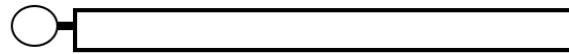
Configuration	Figure	Section	Drive Method	Tip Motor	Propeller
Rigid Bar	3.3a	3.2.5	Shaft	Yes	No
Rigid Bar	3.3b	3.2.5	Propeller	Yes	Yes
Isolated Rotor	3.3c	3.2.4	Shaft	No	No
Rotor w/ Tip-Motor	3.3d	3.2.4	Shaft	Yes	No
Tip Propeller-Driven Rotor	3.3e	3.2.5	Propeller	Yes	Yes



(a) Rigid bar configuration, shaft-driven.



(b) Rigid bar configuration, propeller-driven.



(c) Isolated rotor configuration, shaft-driven.



(d) Rotor with tip motor, shaft-driven.



(e) propeller-driven rotor with tip propeller.

Figure 3.3: Schematic of rotor configurations tested.

3.2.1 Custom Propeller-Driven Rotor Test Stand

Early propeller-driven rotor experiments were conducted using a custom hover test stand at the Hover Test Facility at the University of Maryland, College Park. This facility enabled different test stands to be mounted on top of a common test strut, which raised the rotor several radii from the ground

to avoid ground effect. This arrangement created a flexible testing environment for the facility, where custom test stands can be created to study different rotor systems. Figure 3.4 shows the tip propeller test stand in the Hover Test Facility.

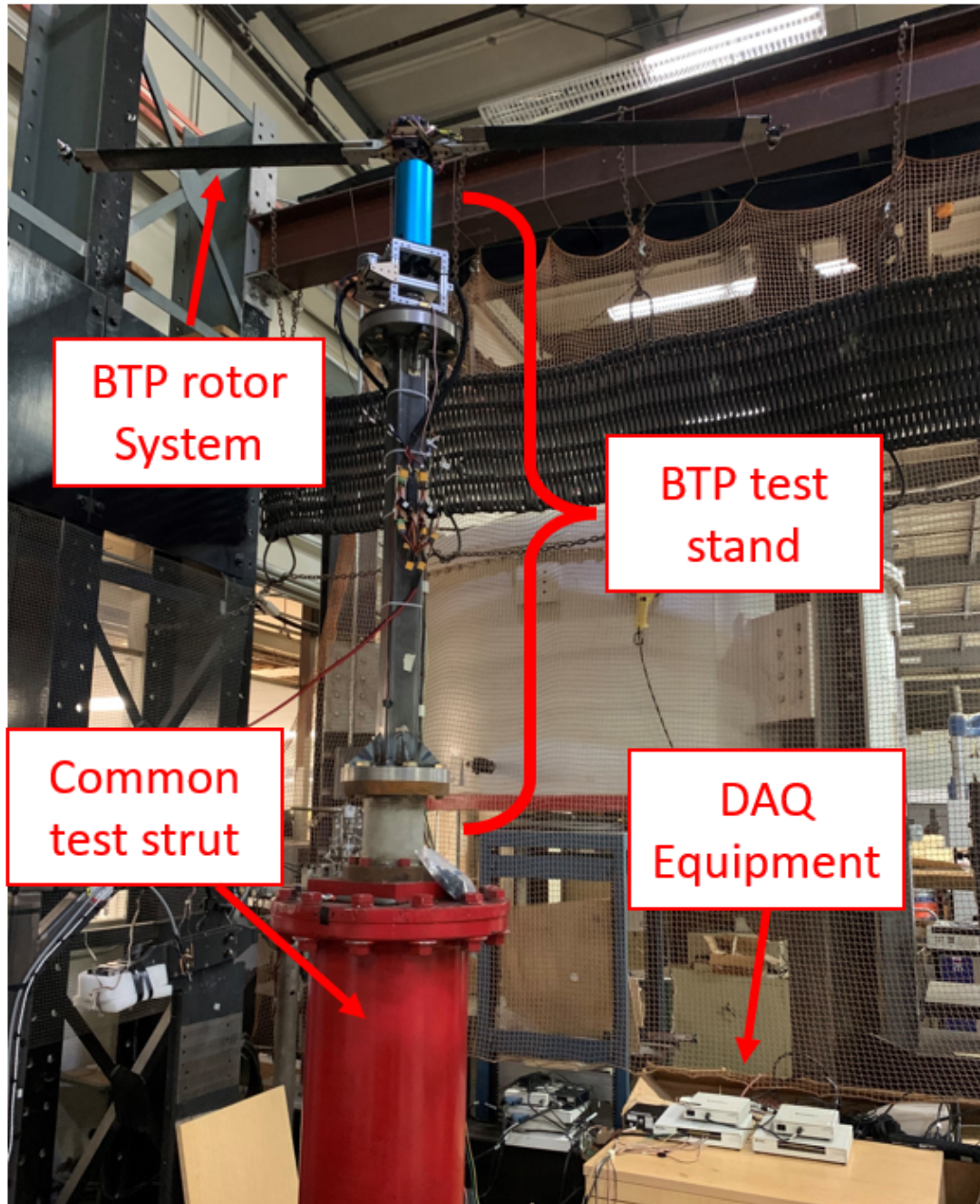


Figure 3.4: Blade-tip-propeller rotor testing in the Hover Test Facility at the University of Maryland.

The blade-tip-propeller test stand was capable of conducting both freely rotating (propeller-driven) and shaft-driven (isolated rotor) experiments. In addition, a high powered slip ring was required to provide power from the fixed frame to the motors located at the blade tip. Figure 3.5 shows the resulting propeller-driven rotor test stand. A changeable rotor blade grip allowed main rotor collectives of 0 and 8 degrees to be tested. The stand featured a high-powered slip ring, with 12 power channels (10A each) and 36 signal channels. A central drive motor, shaft belt, and pulley were used for shaft-driven test cases. For the blade-tip-propeller testing, when the shaft drive motor is not needed, the drive belt was simply disconnected, allowing the shaft to freely rotate.

The requirement to provide electrical power to the blade tips had an impact on the rotor hub design as well. Placing the ESCs in the rotating frame reduced the number of high powered channels for the slip ring. For simplicity, a power rail connected the slipring channels to the required electronics. The hub and blade grips resulted in the final rotor having a radius of 33 inches (0.84 meters).

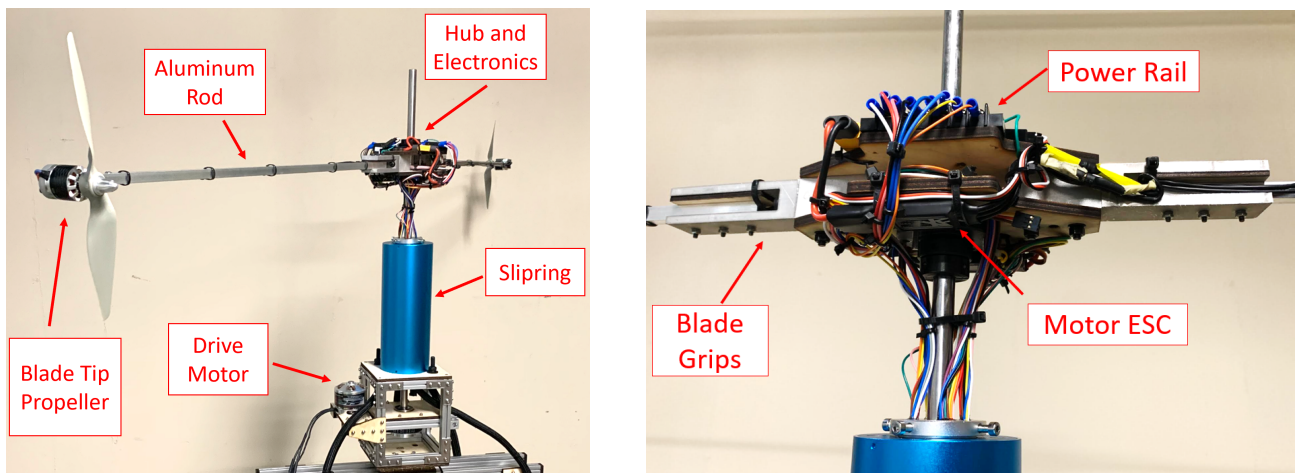


Figure 3.5: Test stand for blade-tip-propeller characterization and closeup of powered hub.

This custom rotor stand utilized an ATI Mini45 6DOF balance to measure rotor hub loads, along with RPM sensors and DC power measurements. The RPMs of the tip propellers were obtained by

measuring the line voltage between one of the motor leads and DC ground. This eliminated the need to place an RPM sensor at the blade tip, reducing tip weight and complexity. A common Labview DAQ interface was created to measure and record system performance.

3.2.2 Propeller Characterization on a Spinning Rigid Bar

Prior to using the tip propeller on a rotor blade, a series of tests were conducted with the blade tip propeller attached to a rigid bar. Figure 3.6 shows the hover test stand with the propeller-driven rigid bar (configuration 3.3b). This enabled the performance affects of the blade-tip-propeller system to be isolated, and to generate experimental data for the mathematical model. The required power to rotate a rigid bar using a shaft-driven method, configuration 3.3a, was compared to the propeller-driven method configuration 3.3b.

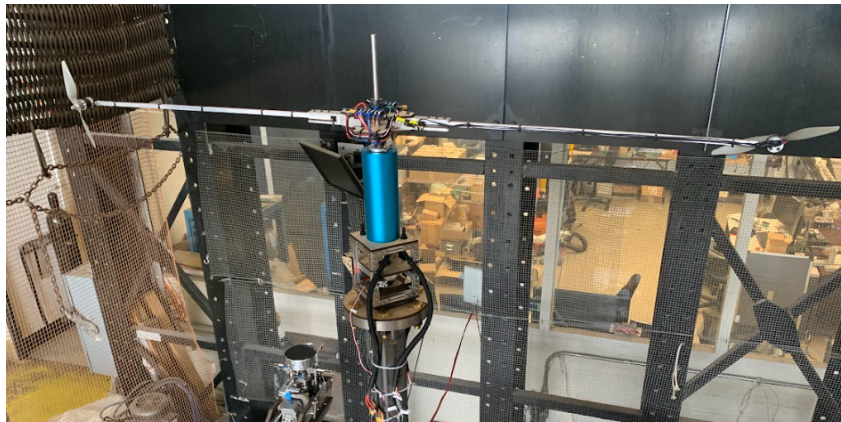


Figure 3.6: Configuration 3.3b, rigid bar driven with a tip propeller on the test stand.

First, the bar was spun using the central shaft drive motor, with the blade grips set at an angle of 0 and then to 8 degrees. Next, the central drive motor belt was disconnected so the hub could freely rotate, and the experiment was repeated using the tip propeller. It was observed that the rigid bar produced negligible thrust/lift at both 0 and 8 degrees. The required mechanical power to spin the

rigid bar was used to compare the two methods. For the shaft-driven case, Figure 3.7 shows the the resulting torque vs RPM curve, allowing a value of C_Q to be estimated.

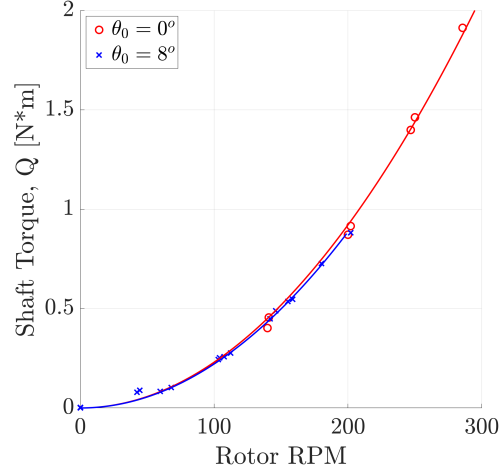


Figure 3.7: Shaft torque vs RPM for the rigid bar with the tip motor attached.

During tip propeller operation, the input to the system was the throttle setting to the tip motor ESC. Increasing the input throttle resulted in an increase in propeller speed, which resulted in an increase in shaft RPM. The corresponding propeller and shaft RPMs are recorded.

The estimated values for C_Q at 0 and 8 degrees were used to determine the value of γ_p for the propeller, and thus the predicted value of the propeller tip speed climb ratio $\lambda_{c_p}^*$ was found by referring to Figure 3.2. This value of $\lambda_{c_p}^*$ was used to predict the required propeller RPM based on RPM of the rigid bar. The resulting predictions are overlaid with the experimental results in Figure 3.8 and the final results are detailed in Table 3.2.

Table 3.2: Spinning Bar results with the 9x6.0 propeller, experiment vs prediction.

θ_0 [$^\circ$]	C_Q	γ_p^*	Exp. λ_{c_p}	Predicted λ_{c_p}
0	3.17e-4	0.0085	0.26	0.25
8	3.06e-4	0.0082	0.25	0.24

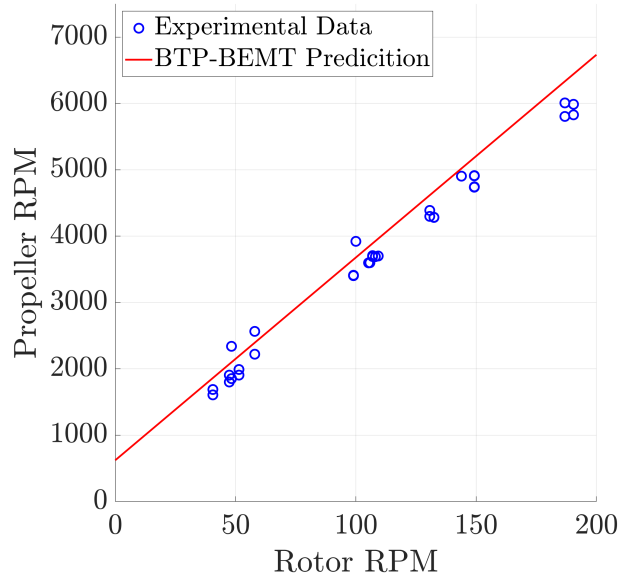


Figure 3.8:
Predicted and experimentally observed propeller RPMs vs shaft RPM for the rigid bar configuration with $\theta_0 = 8^\circ$ using the Forum 79 9x6.0 propeller.

The predicted rotor/propeller speeds closely followed the experimentally observed rotor/propeller RPMs. However, it is noted that there is some slight propeller offset at 0 RPM, Ω_{p0} , of the rigid bar, adjusting the predicted propeller RPM equation to:

$$\Omega_p = \frac{1}{\lambda_{c_p}^*} \frac{R}{R_p} \Omega + \Omega_{p_F}$$

This offset in propeller RPM Ω_{p_F} was due to the rotational friction of the test stand bearings and the slip ring. However, this friction did not appear to significantly impact the climb ratio results, as seen in Table 3.2.

Finally, Figure 3.9 compares the required power to spin the rigid bar for each configuration. The propeller power was inferred based on the isolated propeller Forum 79 isolated propeller characterization results from Section 2.3.4 and the analytical model from Section 3.1. These results indicated

that to spin the rigid bar, the tip propeller configuration required almost 10 times the power compared to the shaft-driven method, for this setup. However, the systematic design of the tip propeller allows for areas of improvement to be identified. The predicted and experimentally obtained propeller RPMs show good agreement, indicating that a later study can closely optimize the propeller and rotor to significantly reduce the required power.

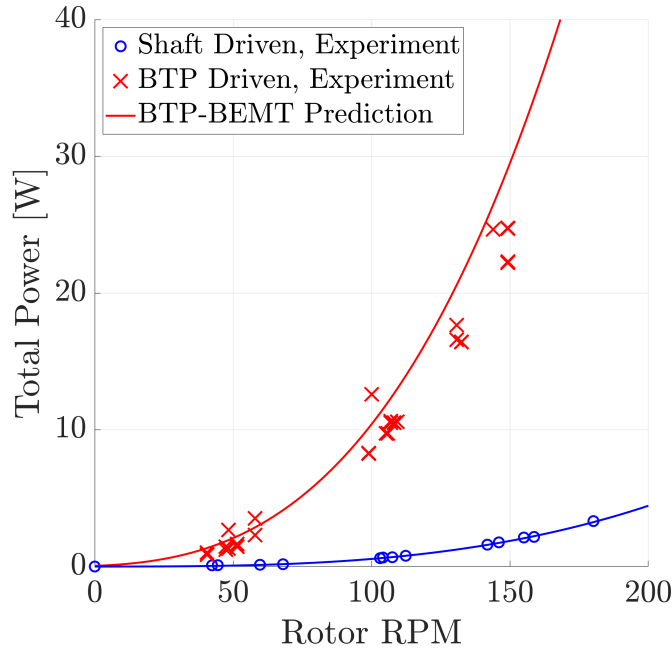


Figure 3.9: Power required to spin the rigid bar with $\theta_0 = 8^\circ$ vs shaft RPM for both shaft-driven and blade-tip-propeller-driven configurations ($\theta_0 = 8^\circ$).

3.2.3 Foreshadowing of the Propeller-Driven Rotor Twirl Phenomenon

Although two Forum 79 propellers were tested in axial flight in the Low Turbulence Wind Tunnel, only one completed propeller testing on the rigid bar. While testing the 10x4.5 propellers in the rigid bar tip propeller-driven configuration, Figure 3.3b, the 10x4.5 propellers repeatably broke at the propeller root. This occurred at relatively low shaft rotation speeds of only 100 RPM.

Figure 3.10 shows the broken 10x4.5 propeller. There were three suggested causes of the failure. First, a unique noise signature was observed throughout testing that indicating asymmetric loading of the propeller blade as it rotated around the propeller azimuth. This was assumed to be a result of the gyroscopic forces associated with spinning a tip propeller on a rotating rotor blade. Secondly, the 10x4.5 propeller was slightly larger than the 9x6.0 propeller (5 vs 4.5 inch radius), which correlates with larger root moments. Finally, the root area where the 10x4.5 propeller broke was significantly thinner than the root area on the 9x6.0 propeller. In any case, the 10x4.5 propellers were unable to be tested due to premature root failure.



Figure 3.10: Broken Forum 79 10x4.5 propeller that failed during propeller-driven rotor operation.

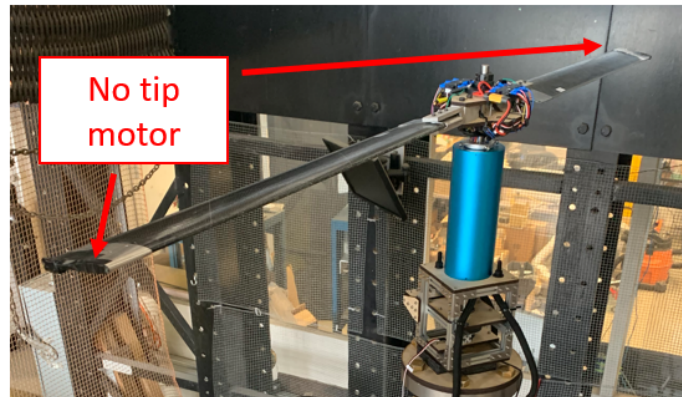
Although the 10x4.5 propeller failure was not investigated at the time, later experiments ran into a similar problem of propellers suffering root failures. Several investigations were undertaken to identify the issue, and are detailed in Chapter 4. The result would be categorized as the propeller-driven rotor swirl phenomenon.

3.2.4 Aerodynamic Impact of the Tip Motor on Rotor Performance

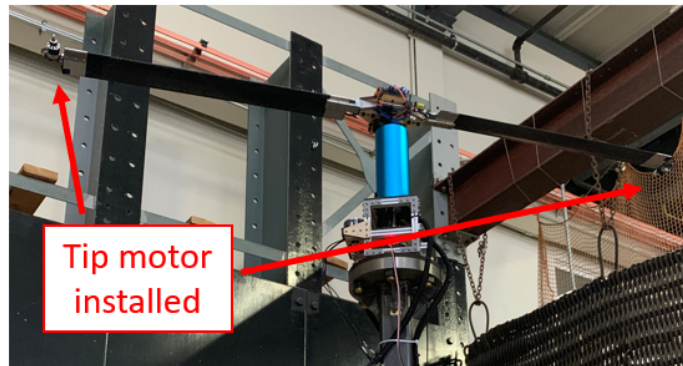
This section documents the aerodynamic impact of placing the exposed motor assembly at the blade tip. The placement of the motor had two primary impacts on the rotor performance: increased drag and reduced lift. First, adding a cylinder-like object to the blade increases the blade's wetted area

and thus an increase in drag was expected. Secondly, the bluff motor could possibly interact with the rotor blade tip vortex in some manner, thus altering the rotor blade's lift distribution.

The isolated rotor, configuration 3.3c, and rotor with tip motor, configuration 3.3d, for this section are shown on the test stand in Figure 3.11. The propellers are not placed on the tip motors for this section, allowing the impact of the motor placement to be isolated.



(a) Config. 3.3c: Isolated rotor, shaft-driven.



(b) Config. 3.3d: Rotor with tip motor, shaft-driven.

Figure 3.11: Configurations tested to quantify aerodynamic impact of tip motor placement.

The required shaft torque, rotor thrust, and resulting power loading were used to compare the two configurations. For the isolated rotor case (no tip motor), tape was used to secure the electrical wires in a streamlined manner to the blade tip. The required torque from the central motor, rotor thrust, and resulting power loading are presented in Figures 3.12, 3.13, and 3.14 respectively. Table 3.3 shows

the relative performance between the isolated rotor and rotor with tip motor configurations.

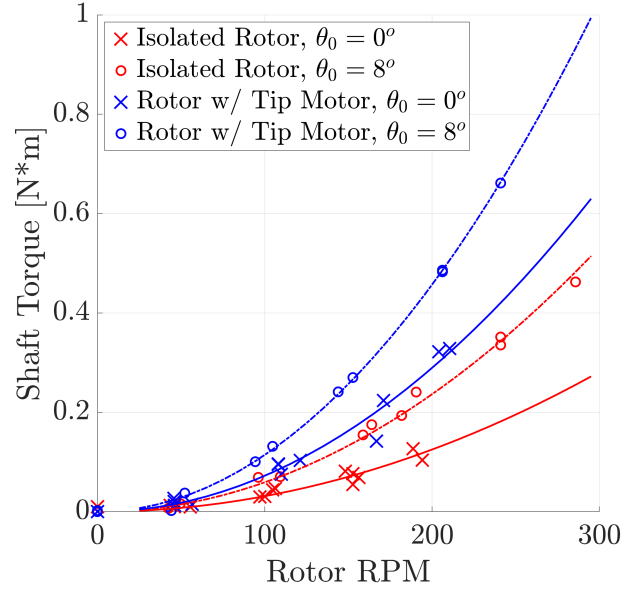


Figure 3.12: Required shaft torque vs rotor RPM. Dots indicate data points and lines represent trendlines.

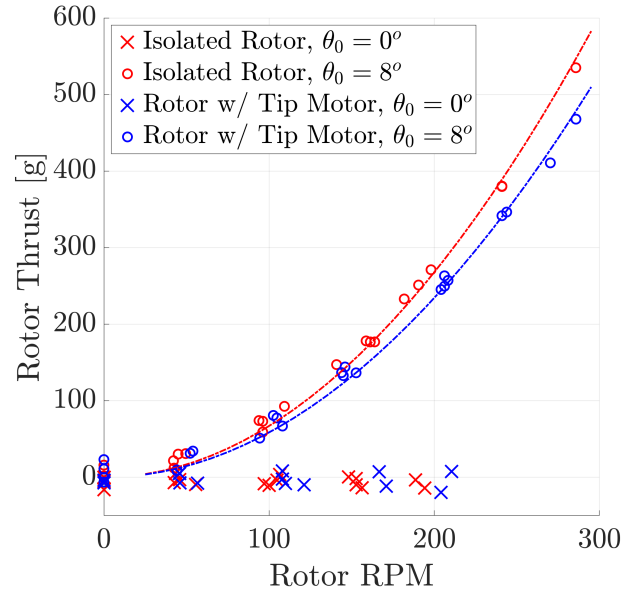


Figure 3.13: Rotor thrust vs rotor RPM. Dots indicate experimental data points and lines represent trendlines.

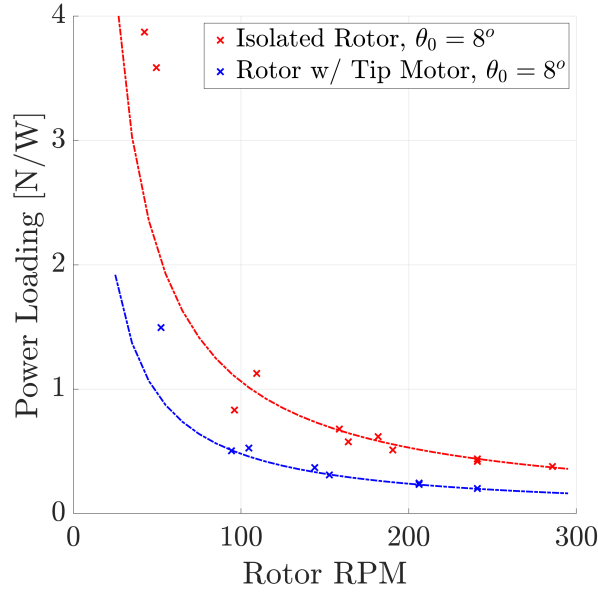


Figure 3.14: Power loading vs rotor RPM. Dots indicate experimental data points and lines represent predictions.

Table 3.3: Comparison of isolated rotor to rotor with tip motor.

Item	Isolated Rotor	Rotor with tip motor
$C_T(\theta_0 = 8^\circ)$	0.0032	0.0028
$C_Q(\theta_0 = 0^\circ)$	1.805e-4	4.138e-4
$C_Q(\theta_0 = 8^\circ)$	3.411e-4	6.532e-4
FOM	36.9%	15.6%
k_h	1.27	2.34
C_{d0}	0.0235	0.0545

The isolated rotor blade had a relatively low Figure of Merit of only 36.9%. This was due to the untwisted NACA0012 blade design and the presence of the aluminum reinforcement at the blade tip. Once the motor was attached to the rotor tip, the torque coefficient at 8 degrees nearly doubled from 3.411e-4 to 6.532e-4, and the thrust coefficient reduced 12.5% from 0.0032 to 0.0028. These results indicated that a more streamlined tip propulsor design is required for future testing, such as a nacelle or some other type of blended body design.

Both the impact of higher torque and lower thrust were evident in the lower power loading diagram. These results showed that the placing the exposed motor at the blade tip resulted in 2.2 times power increase compared to the isolated rotor design, for the same rotor thrust.

3.2.5 Tip Propeller-Driven Rotor Performance

The final set of feasibility experiments compared the power loadings between an isolated rotor (Figure 3.3c), a rotor with a tip motor (Figure 3.3d), and a blade-tip-propeller-driven rotor (Figure 3.3e) with the 9x6.0 propeller. Figure 3.15 shows the tip propeller-driven rotor, configuration 3.3e, on the hover stand.

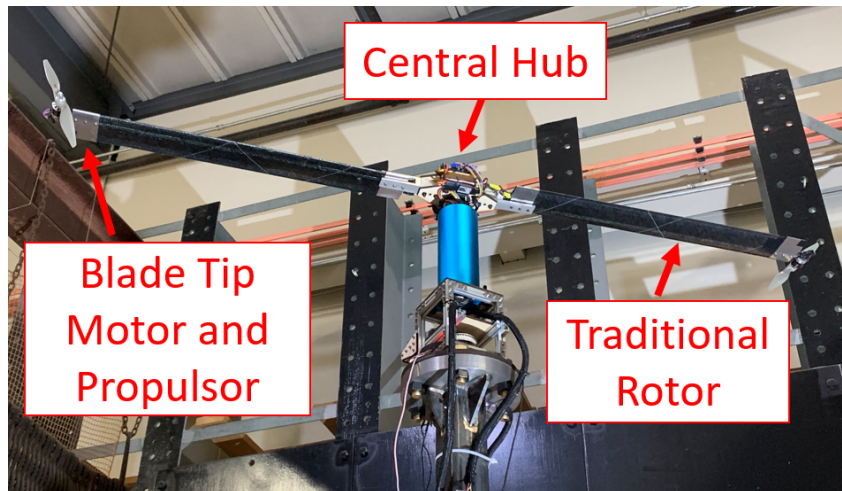


Figure 3.15: Propeller-driven rotor configuration.

As before with the rigid bar configurations from Section , the propeller RPM versus rotor RPM followed a straight line trend. Table 3.4 shows the experimental and predicted results for the blade-tip-propeller rotor configuration. Rotor thrust for the blade-tip-propeller configuration, shown in Figure 3.16, had a slightly higher thrust coefficient than the isolated rotor, 0.0033 vs 0.0032. Comparing the rotor and rotor and tip motor (no propeller) to the blade-tip-propeller (spinning propeller), the act of

spinning the tip propeller was found to increase C_T from 0.0028 to 0.0033. The propeller was rotated in an opposite manner of the tip vortex.

Table 3.4: Blade-tip-propeller results with the 9x6.0 propeller, experiment vs prediction.

θ_0 [°]	C_Q	γ_p^*	Exp. λ_{c_p}	Predicted λ_{c_p}
0	4.138e-4	0.0111	0.230	0.230
8	6.532e-4	0.0176	0.285	0.235

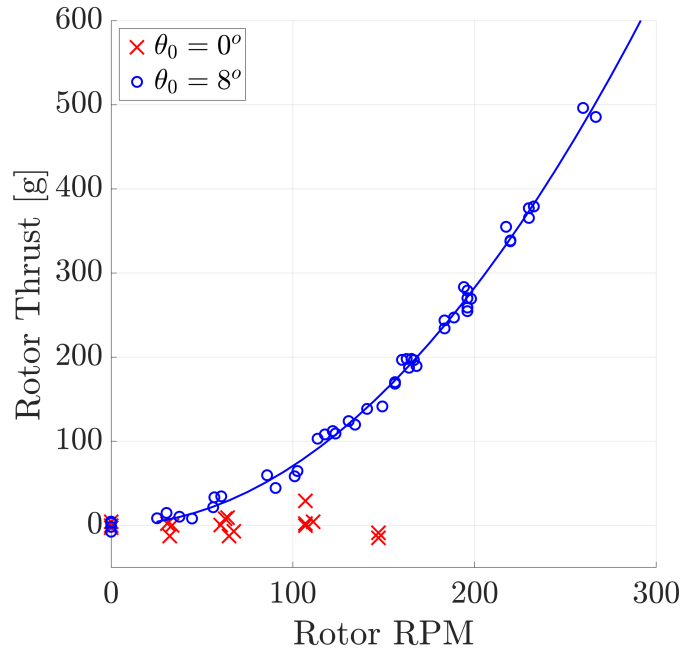


Figure 3.16: Rotor thrust vs rotor RPM for the blade-tip-propeller-driven rotor configuration.

For the 8 degree collective case, the predicted propeller RPM, shown in Figure 3.17, has a higher slope value than the experimentally obtained value. The experimentally obtained value of 0.28 is higher than the maximum climb ratio of 0.25 for the 9x6.0 propeller from Figure 2.23. This indicates that the resulting propeller-driven rotor had a lower C_Q for when the propeller was spinning compared to the non-spinning case.

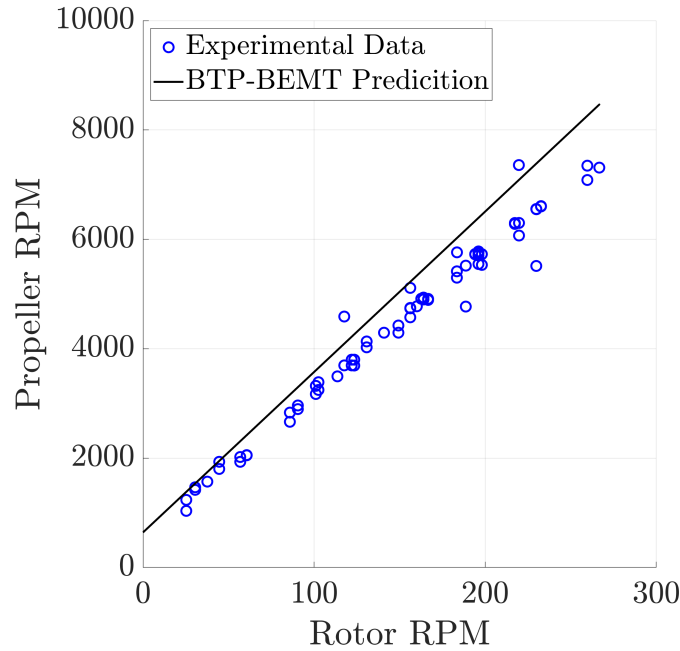


Figure 3.17: Experimental and predicted propeller RPM vs rotor RPM for the $\theta_0 = 8^\circ$ blade-tip-propeller configurations.

The power loadings between the propeller-driven rotor system, the isolated rotor, and the rotor with the tip motor attached are shown in Figures 3.18 and 3.19. The blade-tip-propeller configuration had the lowest power loading values between all the configurations tested. It required 6.38 and 2.67 times as much power to rotate compared to the isolated rotor and rotor with a tip motor configurations, respectively.

From these tests and the simple model, a large required power for the propeller-driven rotor was observed. This is due to two primary reasons. First, the nacelle drag of the tip propeller immediately doubled the profile drag of the main rotor. This is due to spinning a blunt cylindrical object at the location of the largest dynamic pressure. A streamlined nacelle is recommended for future tests. Secondly, based on Table 3.4 the propeller was operating in a region of low propulsive efficiency. This was due to the large inflow experienced by the propeller.

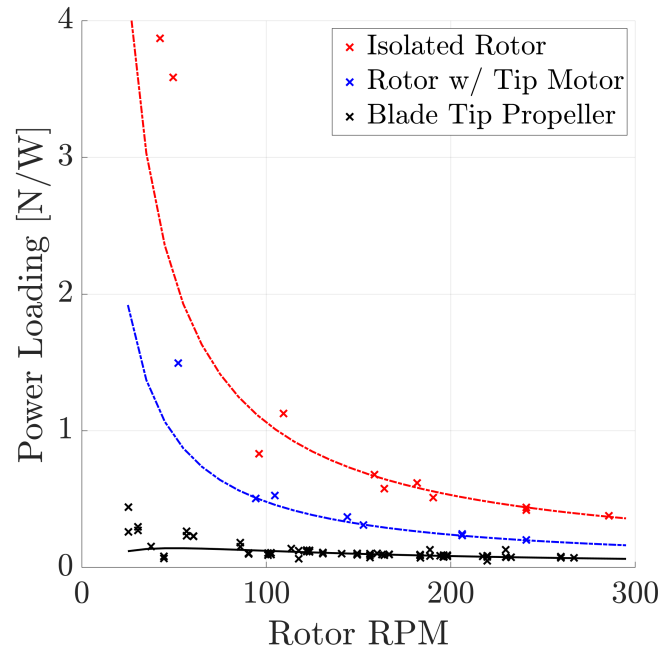


Figure 3.18: Power loading of blade-tip-propeller, isolated rotor, and rotor with tip motor configurations.

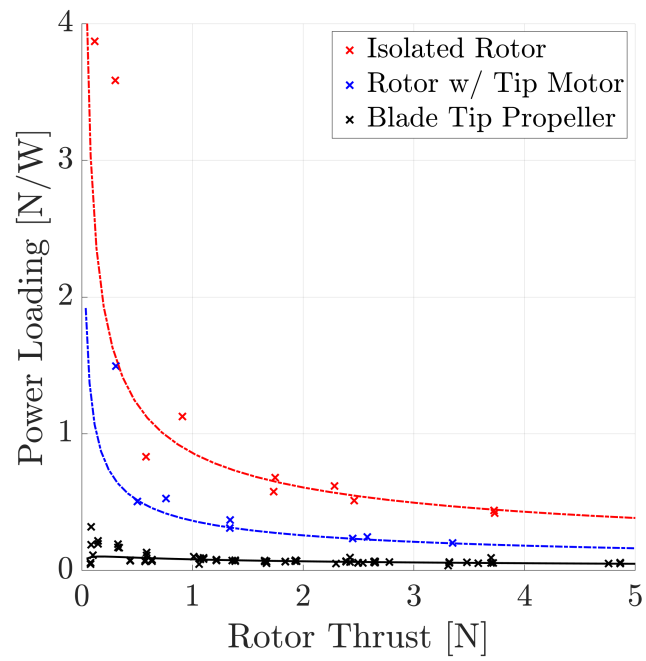


Figure 3.19: Power loading vs thrust comparison between the blade-tip-propeller, isolated rotor, and rotor with tip motor configurations.

3.3 Propeller-Driven Rotor Hover and Propeller Loads Test

After the initial feasibility work was completed, the next set of experiments sought to examine the propeller loads during propeller-driven rotor operation. Additionally, a wider set of rotor collectives were investigated. For these reasons, the propeller-driven rotor was integrated onto the University of Maryland's rotor test stand.

3.3.1 Test Stand

The rotor test stand, shown in Figure 3.20, featured a 50 hp hydraulic motor to drive the rotor, a swashplate, a 150 channel slipring, and a rotor hub balance to record fixed frame forces and moments. This capable test stand has been used for the past 50 years at the University of Maryland, and features a long lineage of both hover and edgewise flight tests in the Glenn L. Martin Wind Tunnel. The rotor test stand used the same Hover Test Facility at the University of Maryland as the custom rotor stand that was detailed in Section 3.2.1.

Three configurations were tested: a shaft-driven isolated rotor, a shaft-driven rotor with the tip nacelle, and the propeller-driven rotor. Figure 3.21 shows the configurations that were tested in hover. A rotor collective θ_0 sweep from 0 to 16 degrees was performed on all configurations. A high θ_0 of 16 deg was chosen to investigate the stall performance of the different configurations. From these experiments, the rotor C_T , C_P , figure of merit, and power loadings were recorded. These results were later compared to comprehensive analysis predictions.

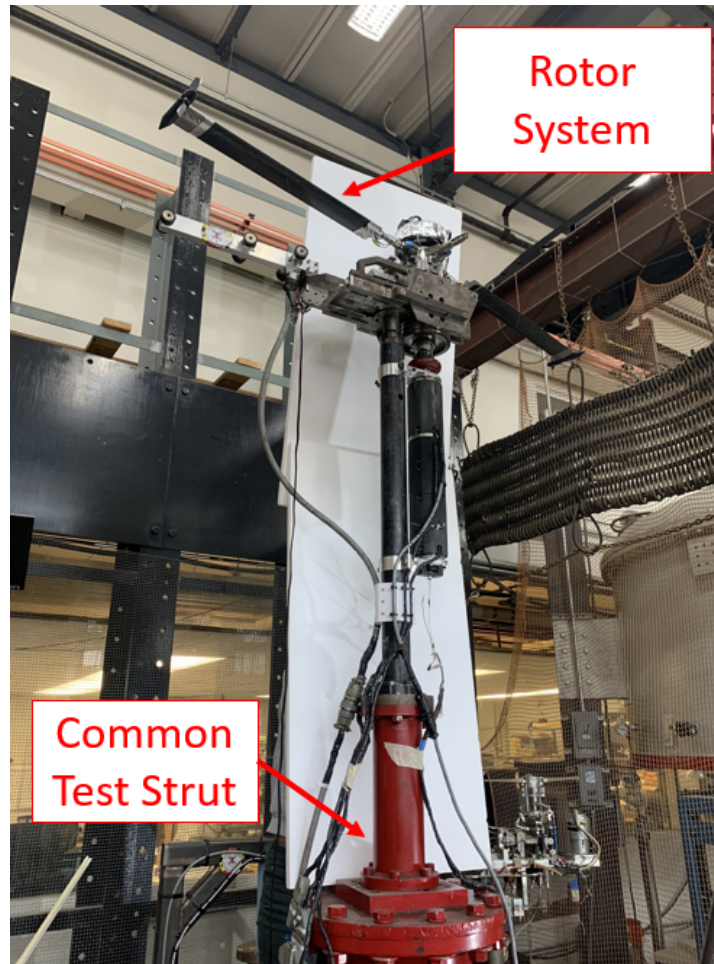


Figure 3.20: Propeller-driven rotor at the University of Maryland's hover testing facility.

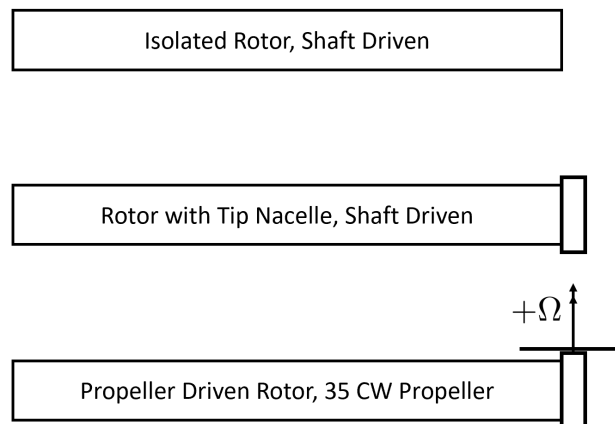


Figure 3.21: Rotor configurations tested on the hover stand.

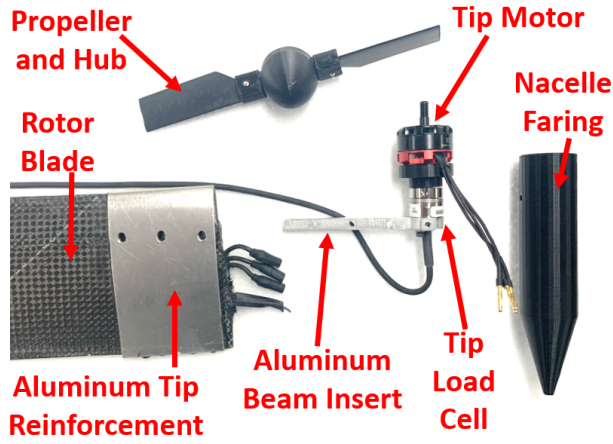
3.3.2 Tip Propeller Load Cell Description

In addition to the main rotor thrust and power measurements, the tip load cell measurements were also recorded. The composite rotor blade was modified to enable the tip load cell signal wire to pass cleanly through the main rotor blade shell. Figure 3.22 shows the rotor blade and tip propeller, with the load cell signal wires passed through the blade. Prior to hover testing, this setup was tested in the Low Turbulence Wind Tunnel, described in Section 2.4,

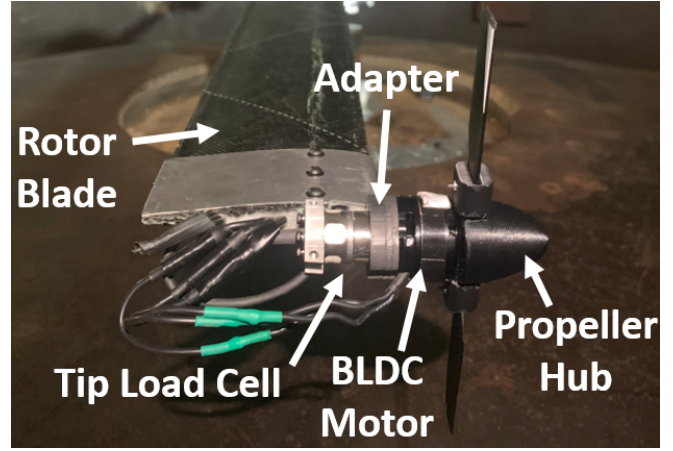


Figure 3.22: Composite rotor blade and tip propeller and load cell used in rotor-propeller hover loads experiment.

Figure 3.23 shows a closeup of the tip assembly. The tip assembly mounted the propeller to the rotor blade tip. The propeller and propeller hub were connected to the motor, which bolted to the propeller load cell. The propeller load cell attached to a beam insert that was bolted to the rotor blade tip. Figure 3.24 shows the reference frame for the tip load cell. The F_{xp} value is in the direction of the centrifugal load from the main rotor blade, F_{zp} is aligned with the propeller thrust, and F_{yp} completes the right hand system and so is oriented opposite of rotor thrust. All tip load cell forces and moments were found to be relatively invariant to main rotor collective θ_0 .



(a) Closeup of tip nacelle.



(b) Assembly mounted on rotor blade.

Figure 3.23: Propeller driven rotor tip load cell and assembly.

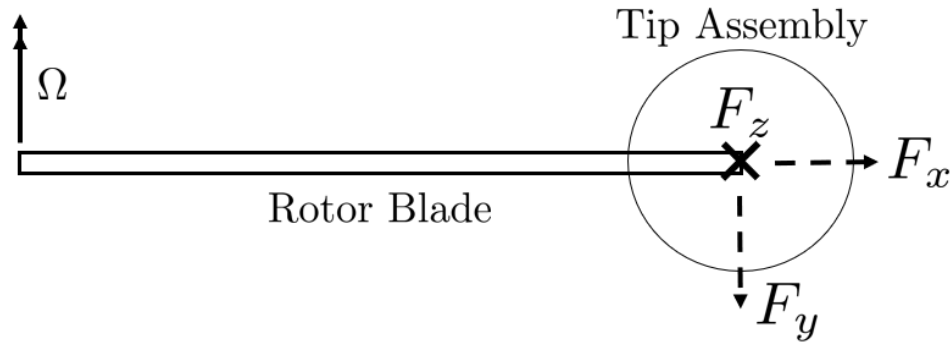


Figure 3.24: Tip load cell reference frame, view is from the rotor blade trailing edge.

An ATI Nano 17 6DOF load cell was used to measure propeller loads at the rotor blade tip. The source of the loads measured by the tip load cell for each propeller axis are as follows. Propeller F_{xp} is in the direction of the rotor blade span, and the rotor centrifugal forces. Propeller F_{yp} is in the gravity direction, so little load is expected once the balance has been tared. Propeller F_{zp} is in the propeller thrust direction. The propeller moment M_{xp} is the propeller-rotor Coriolis moment. Propeller M_{yp} comes from the mass offset ahead of the balance times the rotor centrifugal forces. Propeller M_{zp} is the propeller shaft torque, and is close to zero for the vacuum chamber experiment.

During hover testing, several inertial loads were measured by the tip propeller load cell. Figure 3.25 shows how a mass M offset from the load cell by some distance r creates propeller F_{xp} , F_{zp} , and M_{yp} loads. Propeller F_{xp} is in the rotor centrifugal force direction, so some large positive number is expected. Due to the forward offset of the assembly, an angle is created that projects some of the rotor centrifugal force in the forward propeller thrust direction. Thus, a small positive value is expected for F_{zp} even in the vacuum chamber. Finally, the M_{yp} load results from the forward offset of mass M has a centrifugal force that acts at a distance r from the load cell origin.

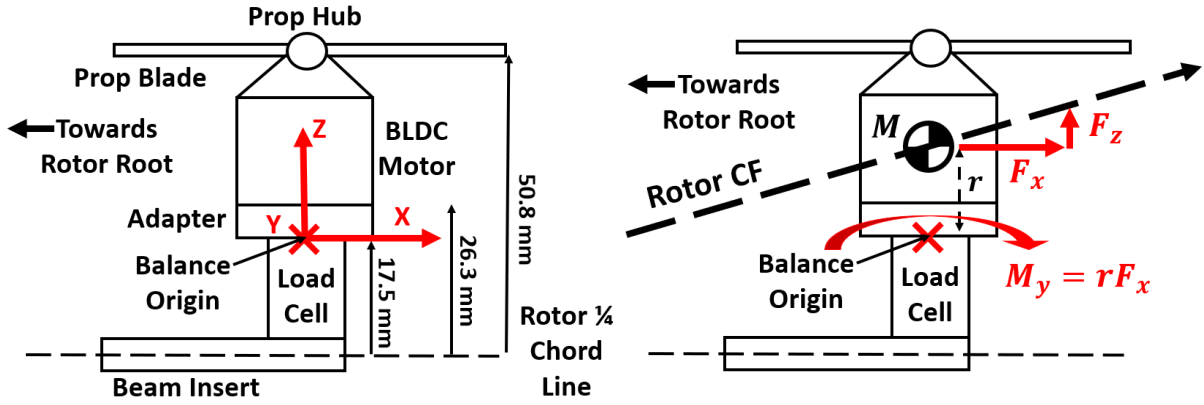


Figure 3.25: Tip assembly model, view is from above the rotor blade looking down. Mass M offset from distance r from load cell creates an F_{xp} , F_{zp} and M_{yp} load. Angle exaggerated for clarity.

3.3.3 Facility Modifications for Propeller-Driven Rotor Testing

Two major changes were required to facilitate propeller-driven rotor testing. First, the hydraulic motor that provided power to the shaft had to be removed, as the static friction of this motor prevented the shaft from freely spinning. Secondly, power needed to be transmitted from the fixed frame to the rotating frame and to the propellers at the blade tip.

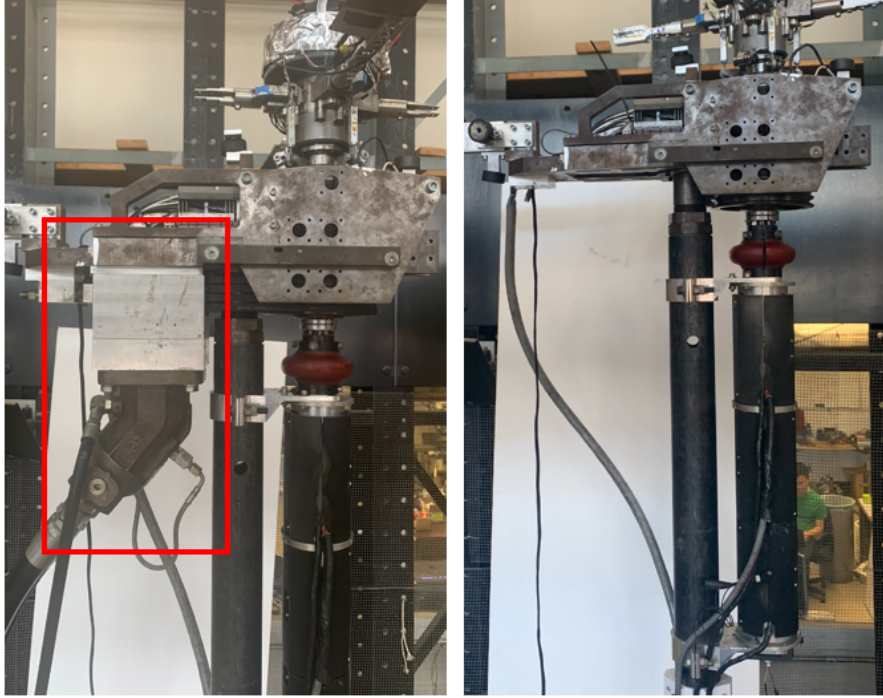


Figure 3.26: Left: Hydraulic motor (inside red box) attached to shaft. Right: Test stand without hydraulic motor.

Once the isolated rotor and the rotor with the tip nacelle testing was completed, the hydraulic motor was removed from the hover stand. Figure 3.26 shows the test stand with and without the hydraulic motor. This enabled the shaft to freely spin for propeller-driven rotor testing.

Power was supplied to the rotating frame using a Fabricast 150 channel slip ring, as shown in Figure 3.27. This slip ring featured 12 high powered channels capable of 60 V DC at 5A/channel current. These channels were wired in parallel to provide a total power of 30 A at 60 V DC, which was substantially more than the required power for the tip motors. To avoid line losses with long cables, the power was supplied from the 48 V DC power supply through the slip ring to the electronic components in the rotating frame. A DC-DC step down converter was mounted to the rotor hub to step the voltage from 48 V DC to 12 V DC for the electric motors.

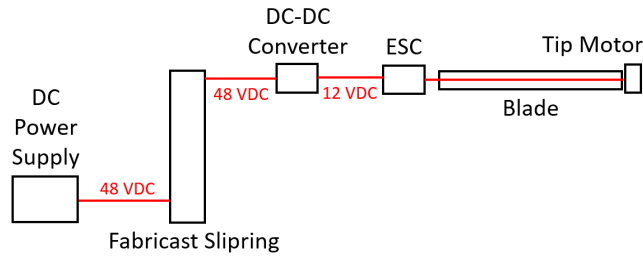


Figure 3.27: Power diagram for propeller-driven rotor operation.

In the rotating frame, a “powered hub assembly” was fabricated to convert the 48 V DC power into the required 12 V DC power to drive the tip motor and propeller. Figure 3.28 shows the powered hub. First, power was supplied to a DC-DC power converter that stepped the voltage down from 48 V DC to 12 V DC. Next, the 12 V DC was supplied to the motor controllers that spun the electric motors at the tip. The motor characterization testing performed earlier was critical for properly sizing all electronic components.

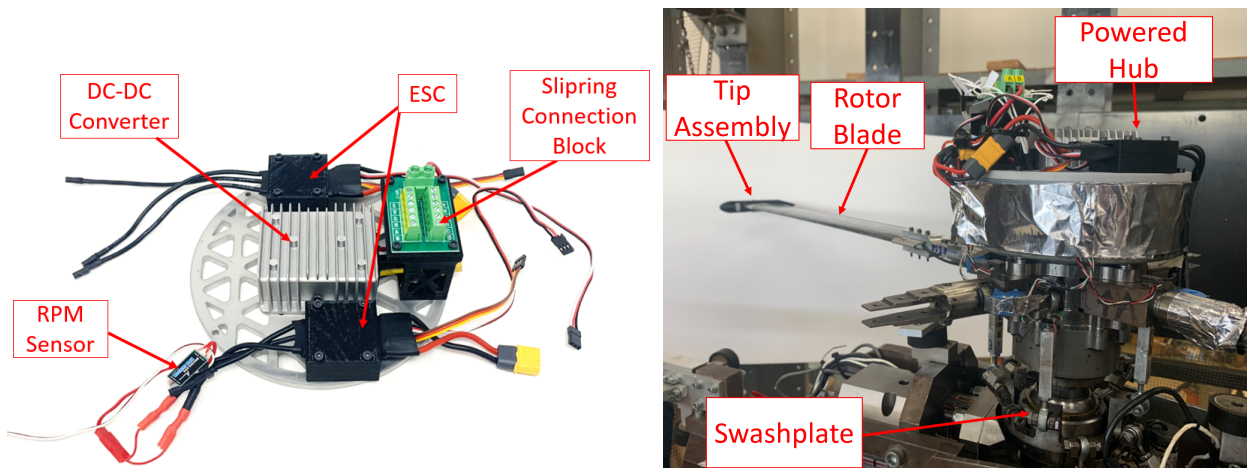


Figure 3.28: Powered hub on top of the rotor test stand with the shaft-driven rotor with tip nacelle configuration.

Power was routed to the tip motors via wires embedded inside the main rotor blade composite shell. There were several sensor measurements made in the rotating frame that were passed through

the slipping. These signals included the propeller load cell signal wires, the propeller RPM sensor, and motor commands.

3.3.4 Shaft-Driven Rotor Testing

First, the shaft-driven rotor was tested at 200, 300, and 400 RPM, and the results are shown in Figure 3.29a. It was observed that the rotor had similar performance at all rotational speeds tested. It had a highest C_T/σ of about 0.15, and stall was observed above $\theta_0 = 14$ deg. Next, the tip nacelle, motor, and propeller hub were attached to the tip of the rotor blade. A series of tests were performed to see how the tip load cell responded to the centrifugal loading. This established that 250 RPM was the maximum rotor speed for the load cell range of the tip load cell. All remaining rotor testing was conducted at 200 RPM. Figure 3.29b shows the results for the shaft-driven rotor with the tip nacelle at 200 RPM.

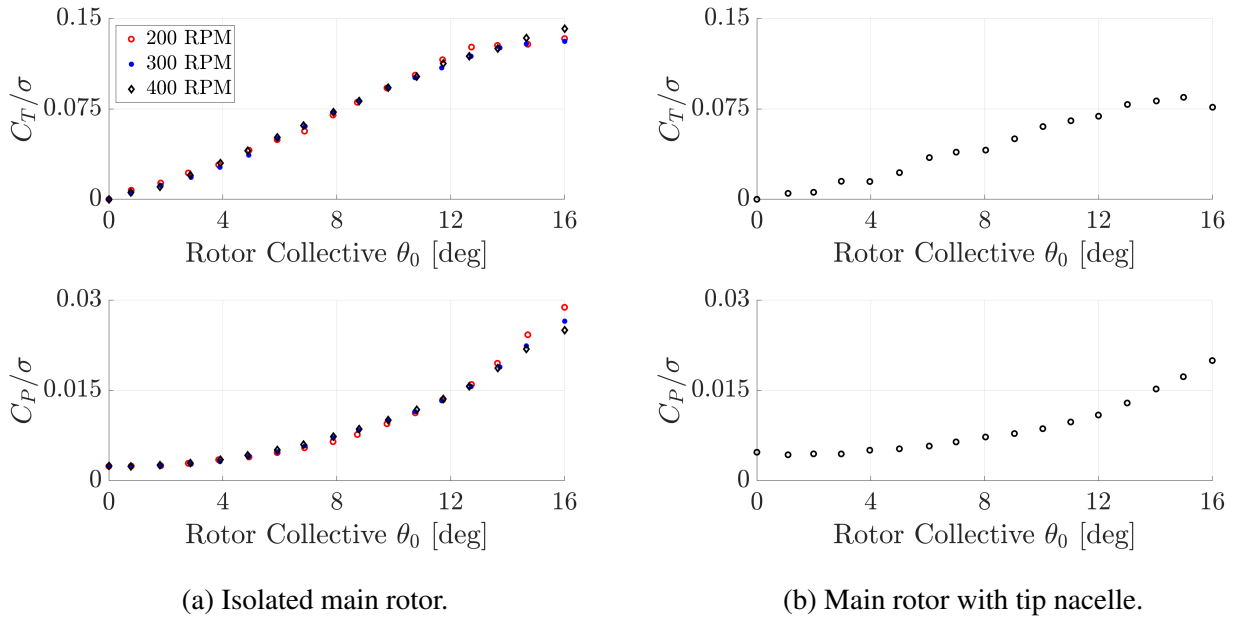


Figure 3.29: Results for the shaft-driven isolated rotor configuration, with and without tip nacelle.

The shaft-driven rotor had a reduced thrust coefficient and an increased power coefficient when compared to the shaft-driven isolated rotor. Maximum thrust coefficient reduced by nearly 50%. Additionally, the tip nacelle nearly doubled the profile drag of the rotor, increasing the C_P/σ from 0.0024 for the isolated shaft-driven rotor to 0.0047 for the shaft-driven rotor with the tip nacelle.

This increase in power was estimated from the profile drag wind tunnel results in Section 2.4. From Table 2.6, the equivalent flat plate nacelle area f_N was estimated by taking the difference in C_{D0} values between the isolated wing ($C_{D0} = 0.0240$) and the wing with tip nacelle ($C_{D0} = 0.0296$) configurations. The reference area was the wing area, and thus the equivalent flat plate nacelle area $f_N = 3.1\text{e-}4 \text{ m}^2$.

The power required to hover can be expressed as:

$$P = P_i + P_o + P_N$$

where P_i is the rotor induced power and P_o is the rotor profile power and P_N is the required power to overcome the tip nacelle drag. The power to overcome nacelle drag can be estimated from Figure 3.30.

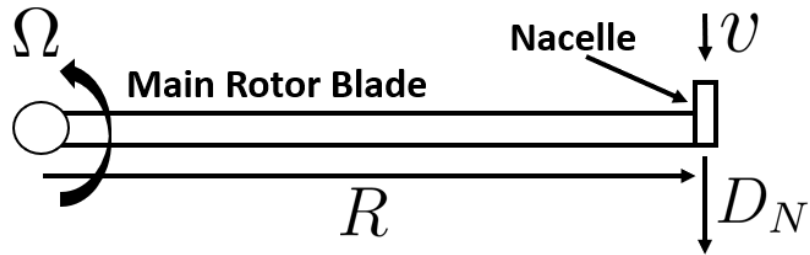


Figure 3.30: Nacelle drag D_N acts at a distance R and has incoming velocity $v = \Omega R$.

Nacelle power can be estimated using a drag build up method. The nacelle drag D_N , the airspeed

of the nacelle v , and the number of nacelles in the system (which is equal to the number of blades N_B):

$$P_N = N_B D_N v$$

The nacelle drag $D_N = \frac{1}{2} \rho f_N v^2$ where f_N is the nacelle flat plate area ($f_N = C_{D,N} A_N$). This expression can be used to find an expression for nacelle power P_N :

$$P_N = \left(\frac{N_B}{2} \rho f_N v^2 \right) v$$

$$P_N = \frac{N_B}{2} \rho f_N v^3$$

For a nacelle at the rotor blade tip, this airspeed v is equal to the rotor tip speed, ΩR . The nacelle power for a tip nacelle can be rewritten as:

$$P_N = \frac{N_B}{2} \rho f_N (\Omega R)^3$$

From this, the non-dimensional nacelle power coefficient C_{P_N} is:

$$C_{P_N} = \frac{P_N}{\rho A (\Omega R)^3} \quad (3.25)$$

$$C_{P_N} = \frac{N_B}{2} \frac{f_N}{A} \quad (3.26)$$

The value of f_N/A refers to the ratio of the nacelle flat plate area to the main rotor disk area, and has a value of:

$$\frac{f_N}{A} = 1.18e - 4 \quad (3.27)$$

Table 3.5 shows the results of this nacelle drag analysis applied to the experimental data. It can be seen that the predicted drag, using this simple estimate, shows good agreement with the experimentally observed value.

Table 3.5: Rotor drag comparison between the shaft-driven isolated rotor and the shaft-driven rotor with tip nacelle.

Configuration	Type	C_P/σ
Isolated Rotor	Measured	0.0024
Rotor and Nacelle	Measured	0.0047
Rotor and Nacelle	Predicted	0.0042

3.3.5 Propeller-Driven Rotor Hover Test

Next, the propeller-driven rotor with the tip load cell was tested. The hydraulic motor was disconnected from the rotor shaft and the 35 deg clockwise propeller was installed at the blade tip, as shown in Figure 3.31. The thrust performance of the propeller-driven rotor is shown in Figure 3.32.



Figure 3.31: Propeller-driven rotor configuration.

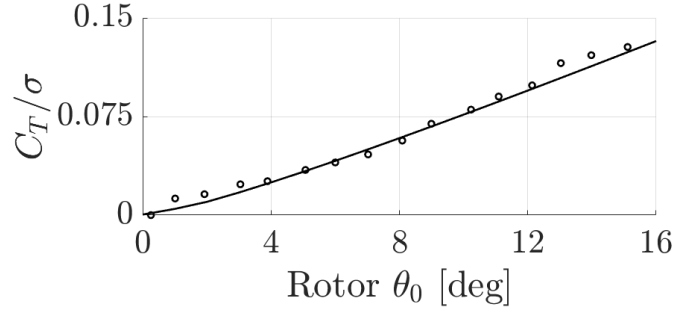


Figure 3.32: Rotor thrust during propeller-driven rotor operation at 200 RPM.

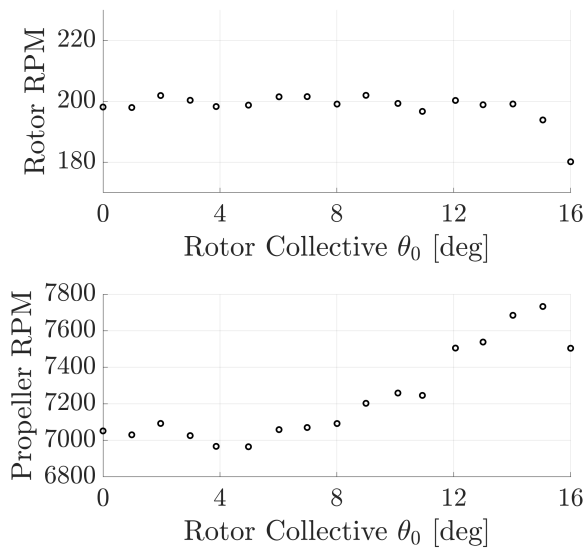
Figure 3.33 shows the experimental results during the propeller-driven rotor test. The throttle setting to the electric motor at the blade tip was manually adjusted to keep the rotor spinning at 200 RPM. Increasing the rotor collective increased the drag of the rotor, and an increase in propeller RPM was required to maintain the desired rotor RPM. Figure 3.33a shows the relationship between propeller RPM, rotor RPM, and rotor collective θ_0 . This strategy worked well until $\theta_0 = 16$ deg, when the motor approached its maximum electrical current limit. At this high angle, the rotor RPM was reduced to 180 RPM to prevent damaging the tip motor.

The propeller climb ratio for the tip propeller is the ratio of the rotor tip speed to the propeller tip speed:

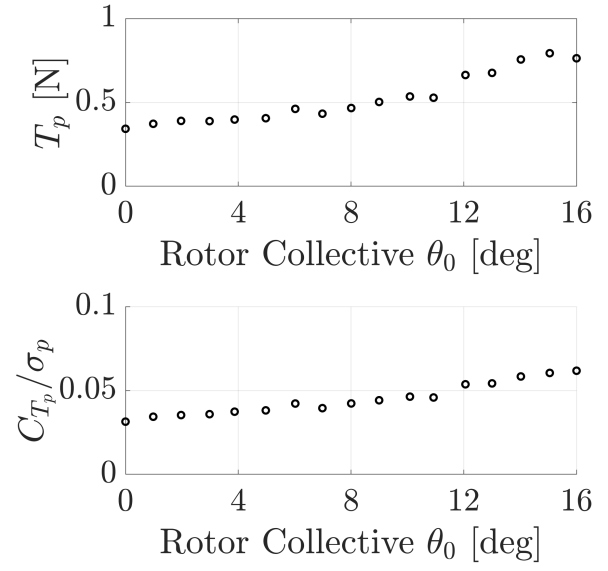
$$\lambda_{c_p} = \frac{\Omega R}{\Omega_p R_p}$$

Propeller propulsive efficiency measures the propeller's ability to produce a propulsive thrust (opposite to rotor drag). The propeller was rigidly mounted to the tip of the rotor blade, and rotated with the rotor collective θ_0 . To account for this, the propulsive efficiency metric was modified to:

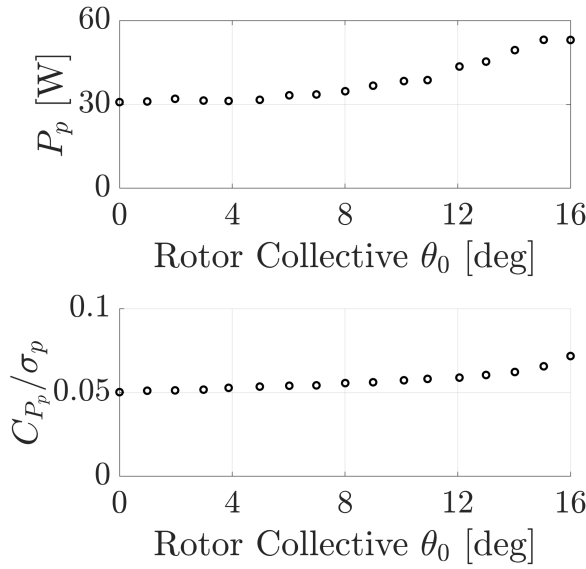
$$\eta_p = \frac{C_{T_p} \lambda_{c_p} \cos \theta_0}{C_{P_p}} \quad (3.28)$$



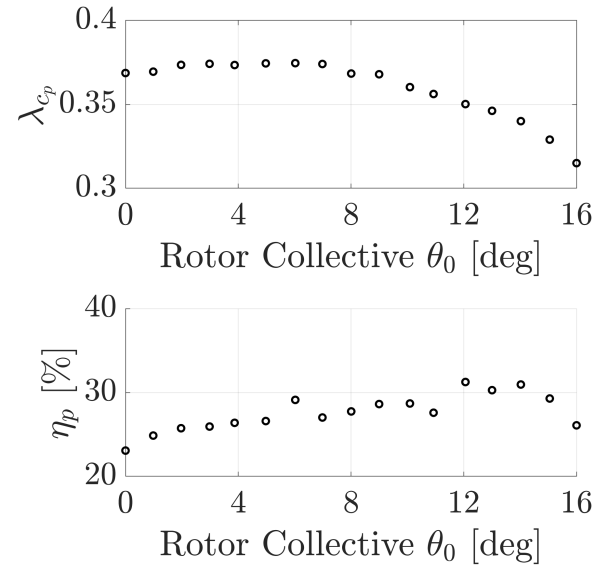
(a) Rotor and propeller rotational speeds.



(b) Tip propeller thrust.



(c) Tip propeller power.



(d) Tip propeller efficiency.

Figure 3.33: Performance metrics for the propeller driven rotor hover test.

The modified propulsive efficiency, equation 3.28, for the tip propeller is shown in Figure 3.33d. During isolated wind tunnel testing of the Forum 80 propellers, it was found that the tip propeller had a maximum efficiency of around 45% with a climb ratio λ_{c_p} between 0.3 and 0.4. The results from Figure 3.33d largely agree with this, but show the tip propeller operating at an efficiency of 25%-30%. Later vacuum chamber experiments would expand on this test.

3.3.6 Propeller Loads during Propeller-Driven Rotor Hover Test

A key objective of the hover test was measuring propeller loads during propeller driven rotor operation. The propeller tip assembly was detailed in Section 3.3.2. A comprehensive analysis model was created to predict propeller hub loads during propeller driven rotor hover testing. Figure 3.34 shows the comprehensive model that was created to model the tip propeller loads.

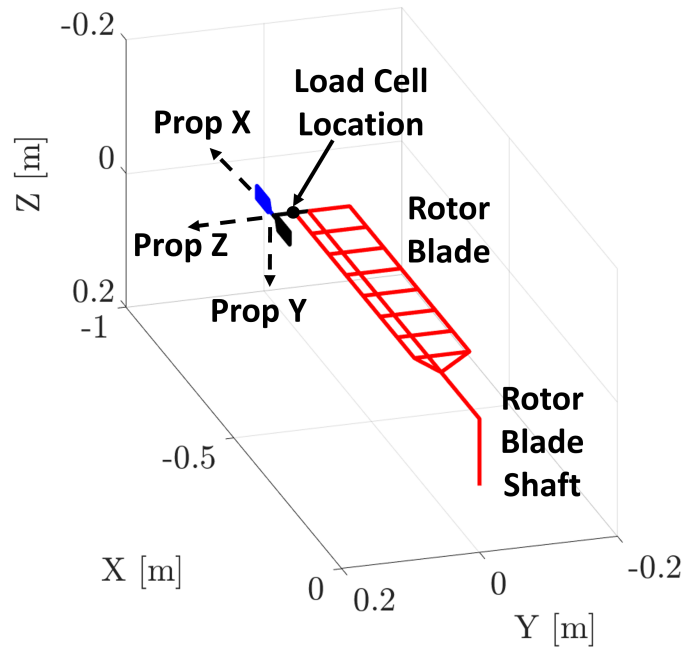


Figure 3.34: ERA model and propeller reference frame. Note that the load cell location has some physical offset from the propeller hub.

Figure 3.35 shows predicted and experimental results for the propeller tip load cell. The critical Coriolis moment M_{xp} and the propeller thrust F_{zp} are well captured. There appears to be a slight offset between the mass in the ERA model and the physical test stand. This is apparent as the measured propeller F_{xp} value is larger than predicted, as well as the M_{yp} value. Again, this indicates a minor mass discrepancy between the model and the physical test stand. Overall, the results are satisfactory.

The experiment and predictions both show a large propeller M_{xp} value. The propeller M_{xp} has a value close to 0.2 Nm whereas the propeller torque M_{zp} is close to 0.02 Nm. This is a difference of one order of magnitude. The explanation for this large propeller M_{xp} load is studied in Chapter 4.

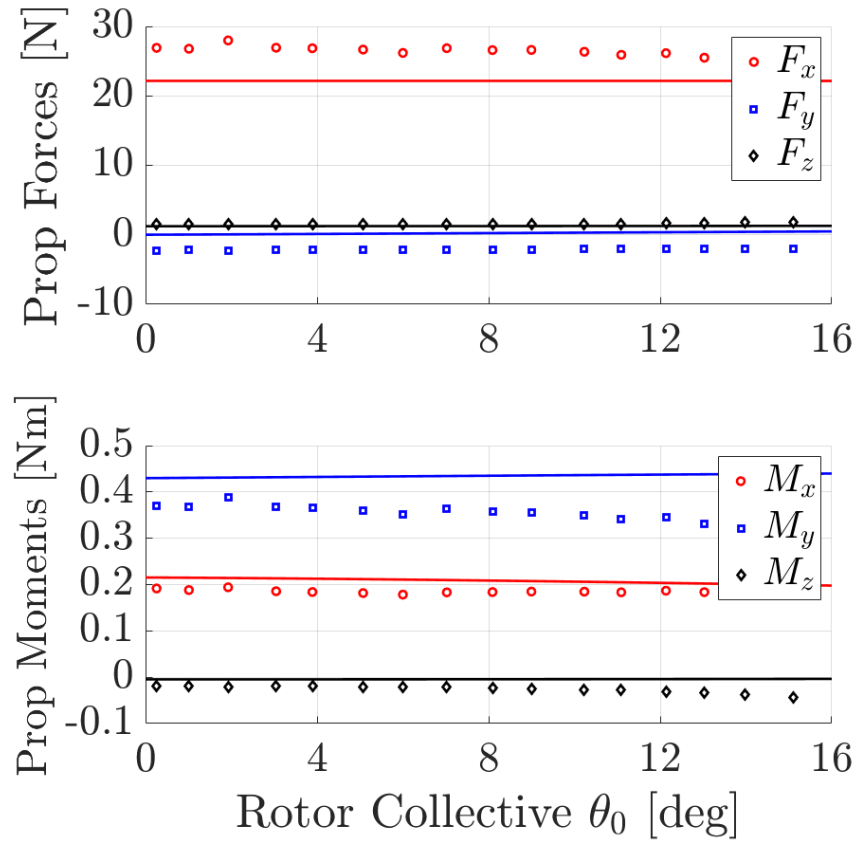


Figure 3.35: Propeller hub loads. Predicted (solid line) and experimental (dots) for propeller load cell forces at 200 rotor RPM and 7000-8000 propeller RPM.

3.3.7 Rotor Performance Comparison

Power loading and figure of merit are the key metrics of efficiency for a hovering rotor, and are shown in Figure 3.36. In addition, the thrust performance of all three rotors is shown in Figure 3.37. From Figure 3.36, it is clear that the power loading of the propeller-driven rotor system is the lowest out of all the configurations studied. There are two reasons for this. First, the addition of the tip nacelle adds twice the profile drag to the rotor. Secondly, the propeller rotor requires power to spin the tip propeller, and the propeller efficiency was found to be between 25-30%.

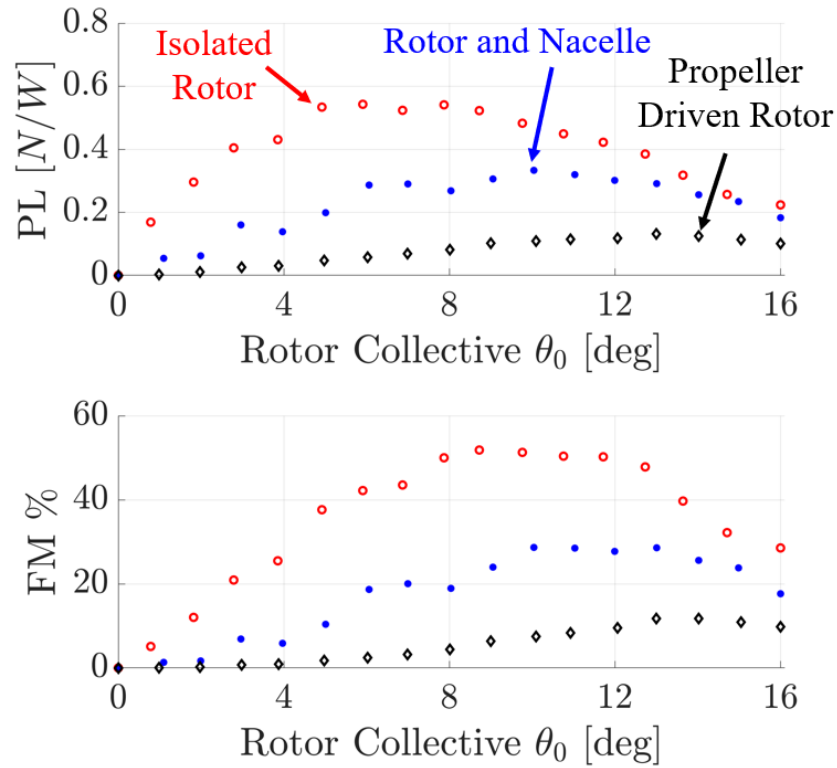


Figure 3.36: Power loading and figure of merit for the different configurations.

In regards to the thrust performance of the rotor, shown in Figure 3.37, the shaft-driven isolated rotor had the highest C_T/σ and the shaft-driven rotor with the tip nacelle had the lowest. Interestingly, the propeller-driven rotor configuration had similar performance to the rotor and tip nacelle configura-

tion, but did not have the same stall curve. This phenomena was not seen in the wing and tip propeller experiments from Section 2.4.

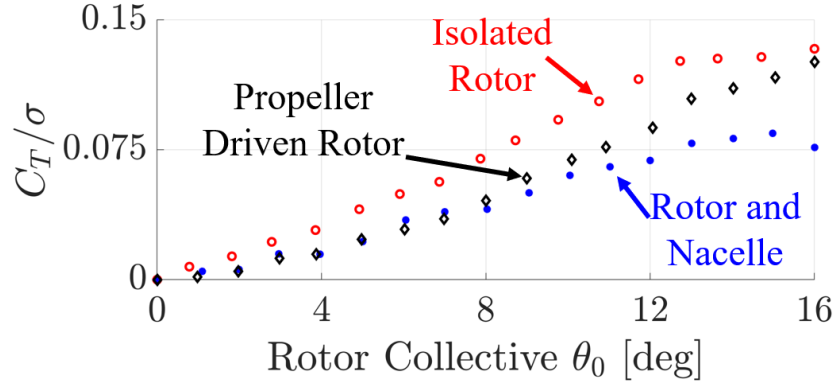


Figure 3.37: Thrust comparison between the different configurations.

While the propeller-driven rotor did have lower performance than the other configurations, the main focus of this work was *not* to optimize the propeller-driven rotor system, but to conduct parametric studies of key variables on a generic propeller-driven rotor system. Instead, this early research was focused on obtaining experimental results to develop the analytical models that describe propeller-driven rotor operation, not to create a highly efficient system. To improve propeller-driven rotor hover performance, the propeller placement on the main rotor span was investigated.

3.4 Impact of Propeller Placement on Main Rotor Blade Span

After conducting two separate propeller-driven rotor hover tests, it was clear that propeller efficiency had to be improved for the propeller-driven rotor concept to be a serious design concept. The simple model from Section 3.1 and the propeller-driven rotor hover results indicated that the propeller was operating at low propulsive efficiency η_p due to the fact that it was operating at high propeller climb ratios λ_{cp} . A small 2.7 ft diameter test stand using 3D printed rotor blades was fabricated to

examine the impact that the propeller placement on the main rotor blade span.

A rotor blade in hover has a change in velocity proportional to the distance from the hub, shown in Figure 3.38. A propeller mounted on the main rotor blade will experience this incoming velocity as a propeller climb velocity v_c .

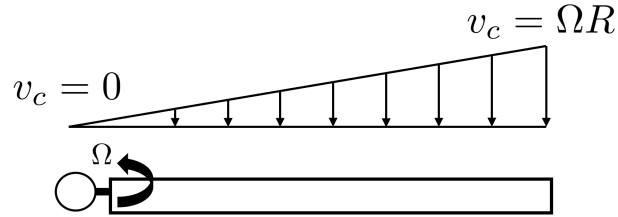


Figure 3.38: A main rotor blade in hover has a tangential velocity proportional to its distance from the hub.

The term x_p , shown in Figure 3.39, represents the non-dimensional location along the rotor span, relative to the hub, that the propeller was placed. An $x_p = 1/2$ represents placing the propeller at the half span location. Note that the propeller climb velocity v_c also increased with an increased x_p position, as $v_c = x_p(\Omega R)$. It was assumed that the propeller radius was small relative to the main rotor radius such that the climb velocity v_c was uniform across the propeller span. Figure 3.40 shows the change in propeller climb velocity for the different propeller placements. The 3D printed rotor blades described in Section 2.1.2 were used for this propeller placement investigation.

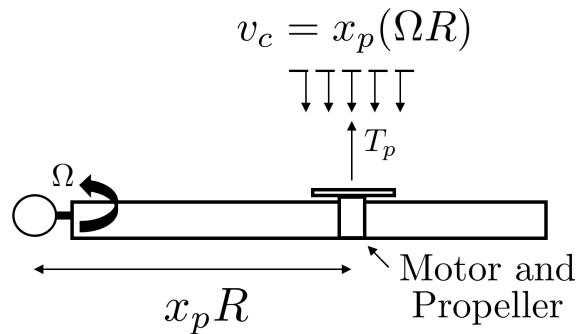


Figure 3.39: Definition of propeller location x_p .

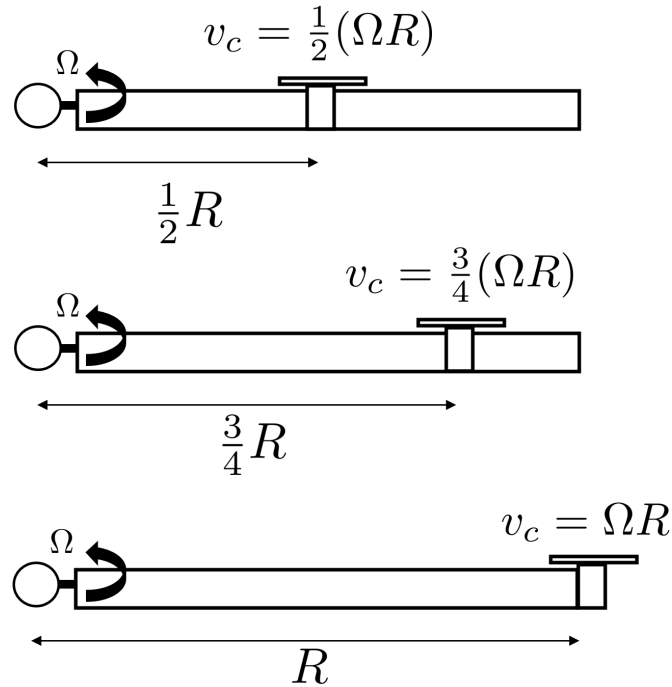


Figure 3.40: Propeller climb velocities for the 1/2 span, 3/4 span, and tip mounted propellers.

The rationale for placing the propeller at certain locations on the main rotor blade span was as follows:

- **Rotor Blade Tip** - The propeller is furthest from the rotor shaft and thus would produce the largest moment arm. However, placing the motor and propeller nacelle at the tip results in a high drag penalty. Previous studies found that this drag penalty can double the profile drag of the rotor.
- **Rotor 1/2 Span** - The incoming climb velocity v_c of the propeller is reduced, which could have impacts on the propeller performance. However, the moment arm is also reduced so propeller thrust and power could increase.
- **Rotor 3/4 Span** - This acts as an in-between case for the propeller placed at either the blade tip and half span locations.

3.4.1 2.7 ft Diameter Test Stand

A propeller-driven rotor test stand, shown in Figure 3.41, was fabricated to investigate: 1.) propeller placement performance impacts, and 2.) to develop a propeller-driven rotor swashplateless control strategy. This propeller-driven rotor test stand featured a high powered 12 channel slipring, four separate force loads cells, DC power measurements, a rotor azimuth magnetic encoder, and a microcontroller. A commercial-off-the-shelf 5x5 propeller, shown in Figure 3.42, was used for all propeller-driven rotor experiments. A microcontroller reads the rotor azimuth location and adjusts the motor commands accordingly. Additionally, the stand can be modified to enable shaft-driven rotor testing. Table 3.6 summarizes the details of the propeller-driven rotor test stand.

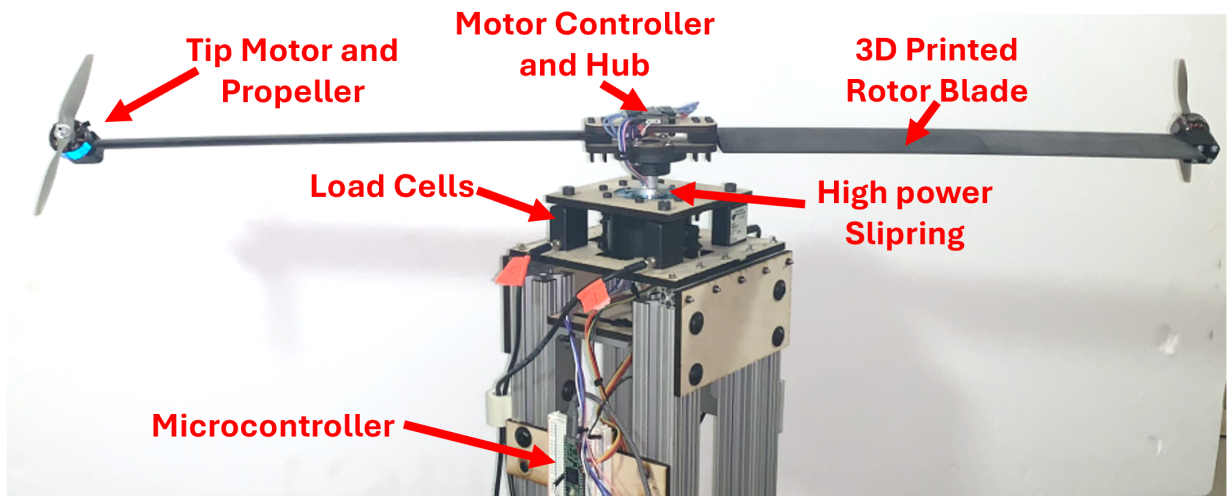


Figure 3.41: 2.7 ft diameter propeller-driven rotor test stand.



Figure 3.42: 5 inch diameter commercial-off-the-shelf 5x5 propeller that was used for all propeller-driven rotor experiments using the 2.7 ft diameter test stand.

Table 3.6: Rotor, propeller, and powertrain characteristics for the propeller-driven rotor test stand.

Rotor Radius R	16.2 in
Rotor Chord c	2.5 in
Rotor Aspect Ratio R/c	6.4
Number of Rotor Blades	2
Rotor Airfoil	NACA0012
Rotor Solidity σ	10%
Rotor Collective θ_0	8 deg
Rotor Twist	None
Propeller	5x5, shown in Figure 3.42
Propeller Radius	2.5 in
Propeller Chord	0.4 in
Number of Propeller Blades	2
Propeller Solidity	10%
Motor	EMAX Eco II 1700 Kv
Motor Controller	T-Motor Velox 50A

There were three test objectives with this 2.7 ft diameter propeller-driven rotor test stand. First, investigate reducing propeller-driven rotor performance with the propeller mounted at various locations along the main rotor blade span. Second, compare the propeller-driven rotor to the shaft-driven rotor performance for the various rotor configurations. Third, conduct experiments for the propeller-driven rotor control scheme outlined in Chapter 5. The first two objectives, related to performance, are detailed in this section and the final objective, related to control development, is detailed in Chapter 5.

Figure 3.43 shows the a schematic of the propeller-driven rotor test stand setup. A microcontroller read the rotor azimuth angle at a rate of over 1000 times per second. All sensors and the microcontroller were connected to a LabView DAQ and computer for real time data viewing and saving. The motor controller was placed on the hub in the rotating frame to reduce the number of channels that were required to transmit high powered current. The microcontroller connected to the motor controller in the rotating frame via signal wires that went through the slipring.

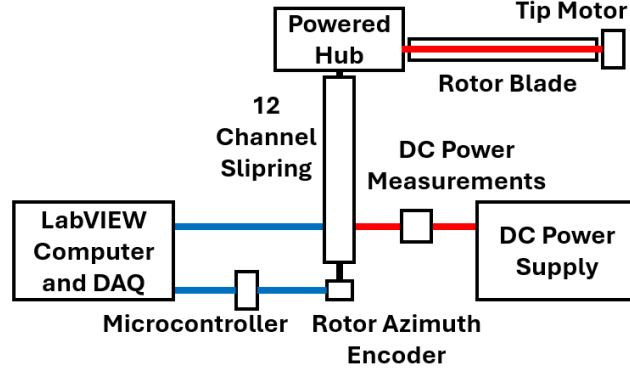


Figure 3.43: Wiring diagram for the 2.7 ft diameter propeller-driven rotor test stand.

3.4.2 Propeller Placement Experimental Results

The primary comparison metrics for the 2.7 ft diameter propeller-driven rotor tests are the thrust loading coefficient C_T/σ , electrical power loading coefficient C_{Pe}/σ , and the propeller/rotor RPM slope m . The thrust loading coefficient C_T/σ is defined as:

$$\frac{C_T}{\sigma} = \frac{1}{\sigma} \frac{T}{\rho A (\Omega R)^2}$$

The electrical power P_{DC} is defined as:

$$P_{DC} = V_{DC} I_{DC}$$

Due to the limited number of slipring channels, propeller mechanical power could not be measured. Instead, the DC electrical power to the slipring was measured in the fixed frame and will be used as a comparison metric, denoted as C_{Pe} .

$$P_{DC} = C_{Pe} \rho A (\Omega R)^3 + P_{DC,o} \quad (3.29)$$

where C_{Pe} is the electrical power coefficient that contributed to spinning the rotor whereas $P_{DC,o}$ is the power component to overcome the static drag of the rotor. The static drag comes from frictional forces in the bearings, slipping, and viscous rotor drag. From this relation, the static DC current I_o required to overcome this drag is defined as:

$$I_o = \frac{P_{DC,o}}{V_{DC}}$$

The propeller mechanical power P_p is related to the electrical power P_e through the powertrain efficiency η_{PT} , which includes the electric motor, motor controller, and wiring losses:

$$P_p = \frac{P_{DC}}{\eta_{PT}}$$

From the experimental test data, it can be seen that the main rotor RPM Ω and the propeller RPM Ω_p have a linear relationship, which can be written as:

$$\Omega_p = m\Omega + \Omega_{p,offset}$$

where m is the slope between rotor RPM and propeller RPM, called the propeller/rotor RPM slope. The propeller RPM offset $\Omega_{p,offset}$ is the required propeller RPM to overcome the static friction of the propeller-driven rotor test stand. Figure 3.44 shows a sketch of how $\Omega_{p,offset}$ and the propeller/rotor RPM slope m are defined. The terms $P_{DC,o}$, I_o , and $\Omega_{p,offset}$ were directly related to one another.

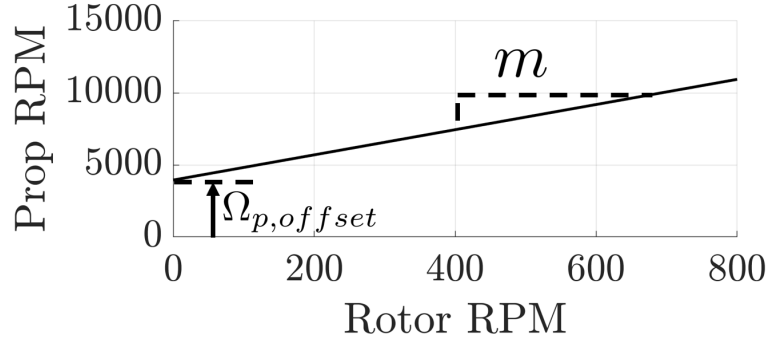


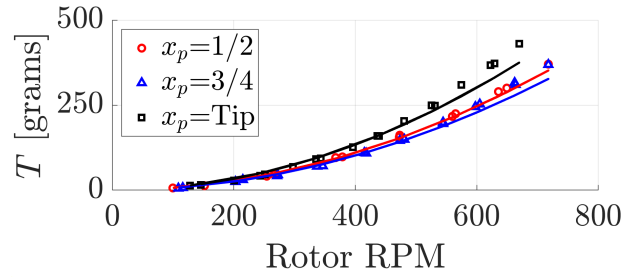
Figure 3.44: Definition of propeller offset $\Omega_{p,offset}$ and the slope m between rotor RPM and propeller RPM.

Table 3.7 shows the measured performance metrics for the test. Figure 3.45 shows the propeller-driven rotor's thrust, electrical power, and propeller RPM under x_p values of 1/2, 3/4, and 1. From these results, several deductions were made. Placing the propeller at the half span location required the propeller offset $\Omega_{p,offset}$ and the DC current offset I_o to nearly double due to the reduced moment arm when compared to placing the propeller at the blade tip. However, placing the propeller at the mid span location resulted in a 20% reduction in rotor thrust loading C_T/σ but a 50% reduction in rotor electrical power loading C_{Pe}/σ . This indicated an initial higher penalty for a mid span propeller placement, but a favorable C_{Pe} for moderate to higher rotor RPMs.

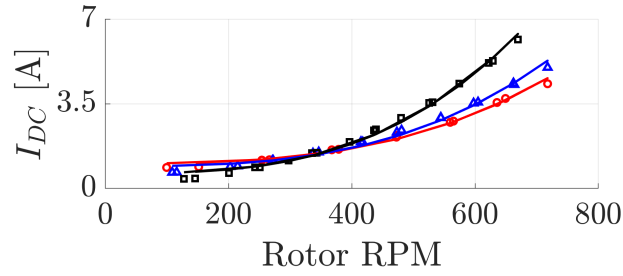
Additionally, the propeller/rotor RPM slope m that relates propeller RPM to rotor RPM was found to linearly vary from $x_p = 1/2$ to 1. The 1/2 span located propeller/rotor RPM slope m is nearly half the tip propeller/rotor RPM slope m value. Lastly, placing the propeller at the 3/4 span location resulted in the lowest C_T/σ value of any rotors, and had a higher C_{Pe}/σ value than the mid span propeller location. This implied that placing the bluff motor body at the rotor 3/4 span location significantly disrupted the rotor's ability to provide thrust, and was found to be the worst performing of any of the propeller locations.

Table 3.7: Propeller placement variation results.

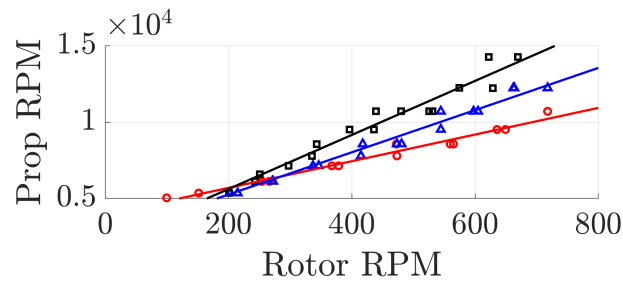
Propeller Position	$\frac{1}{2}R$	$\frac{3}{4}R$	Tip
C_T/σ	0.0573	0.0533	0.0701
C_{Pe}/σ	0.0224	0.0277	0.0450
$I_o[A]$	1.03	0.91	0.63
m [Propeller RPM/Rotor RPM]	8.74	13.8	17.2
$\Omega_{p,offset}$ [Propeller RPM]	3950	2490	2075



(a) Main rotor thrust vs main rotor RPM.



(b) Propeller DC Current vs main rotor RPM.



(c) Propeller RPM vs main rotor RPM.

Figure 3.45: Performance results for various spanwise propeller locations, for a main rotor collective of 8 deg. Dots represent experimental data while lines represent best fit.

Figures 3.46 to 3.49 plot the performance of the different propeller-driven rotors versus main rotor thrust. Figure 3.46 and Figure 3.47 show two distinct regions when comparing the propeller placements at the midspan and tip locations. For low thrust levels, the tip driven rotor required less electrical power to operate than the midspan located propeller. However, at higher thrust levels, the trend reversed and the midspan located propeller required less power to generate a certain thrust compared to the tip driven propeller. This crossover point occurs at around 125 grams of rotor thrust.

This observation can be explained by examining the values in Table 3.7. The 1/2 span located propeller had a higher propeller RPM offset of 3950 compared to the tip propeller's value of 2075. However, the electrical power loading coefficient C_{Pe}/σ for the midspan located propeller was 50% the value of the rotor with the tip propeller. This means that there was a higher initial electrical cost for the midspan located propeller but a lower required power once the rotor is spinning due to the lower C_{Pe}/σ .

As indicated in Figure 3.48, at lower rotor thrust levels the tip located propeller required less power than the 1/2 span located propeller. However, due to the 1/2 span located propeller's C_{Pe}/σ value, at higher rotor thrust levels the 1/2 span located propeller required less electrical power than the tip located propeller. The difference in electrical power increased with increasing rotor thrust. At 400 grams of main rotor thrust, the 1/2 span located propeller required 15% less electrical power compared to the tip located propeller. This crossover point was evident when considering the T/P_{DC} plot in Figure 3.47. These propeller placement results indicated that optimum propeller-driven rotor performance benefits can be achieved by properly sizing the propeller blade geometry, the propeller location, and the propeller-driven rotor configuration.

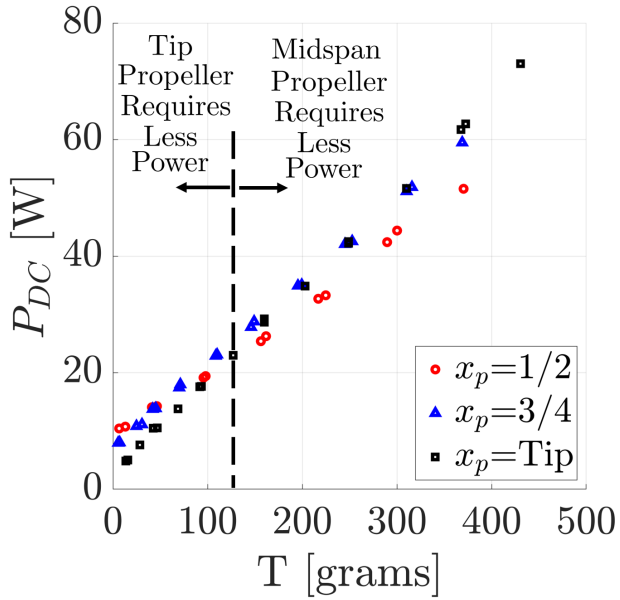


Figure 3.46: DC electrical power versus main rotor thrust.

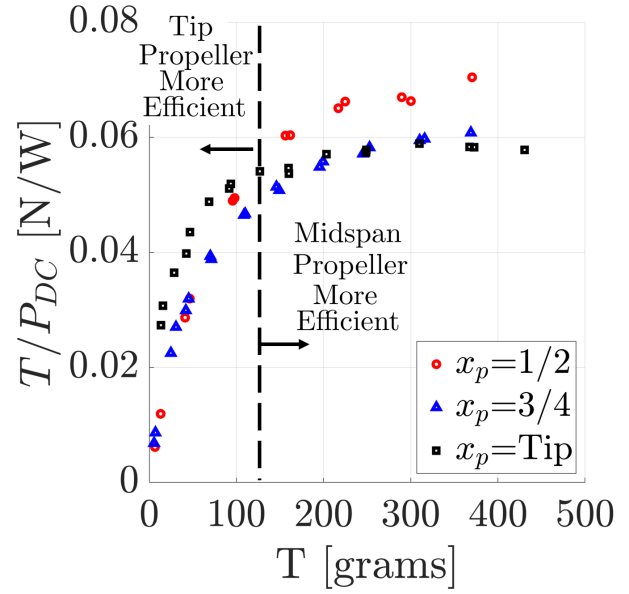


Figure 3.47: Electrical power loading versus main rotor thrust.

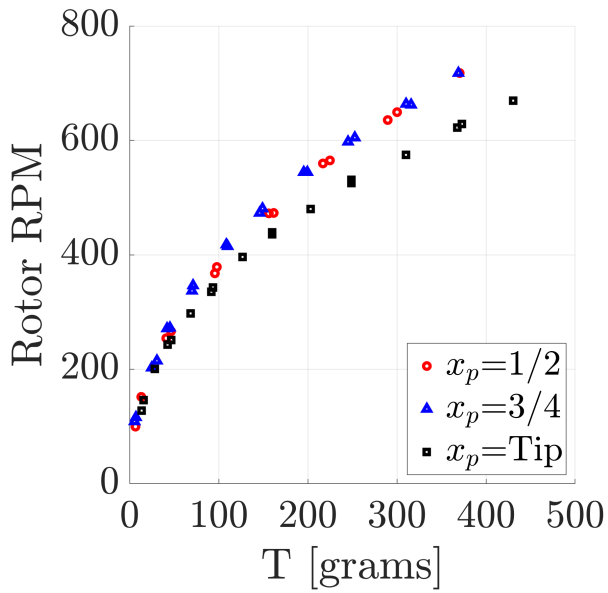


Figure 3.48: Main rotor RPM versus main rotor thrust.

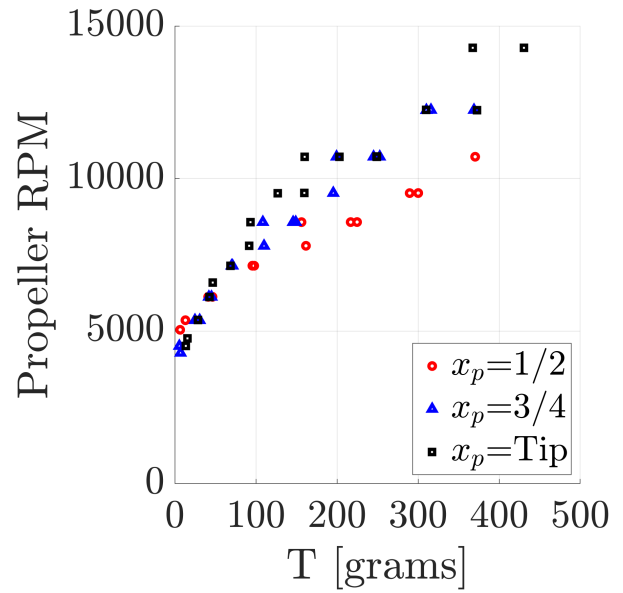


Figure 3.49: Propeller RPM versus main rotor thrust.

3.4.3 Propeller Placement Comparisons

The performance of the propeller-driven rotor was also compared by considering three cases: constant main rotor thrust, constant main rotor RPM, and constant propeller RPM. All results are for the same main rotor collective of 8 deg.

Case I: Constant Rotor Thrust

This case compares the required electrical power to generate a 300 grams of thrust from the main rotor. The intersection of the 300 gram thrust line and the corresponding electrical power points are shown in Figure 3.50. The dimensional results are shown in Table 3.8.

Table 3.8 shows that placing the propeller at the mid span location resulted in an 18% reduction in electrical power, an 11% increase in main rotor RPM, and a 20% reduction in prop RPM compared to placing the propeller at the tip location.

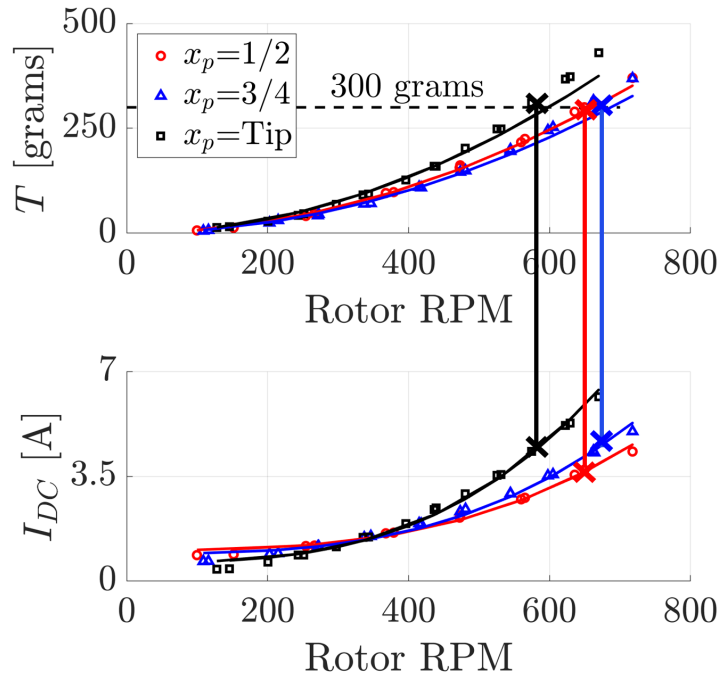


Figure 3.50: Intersection of 300 grams of thrust for the different propeller-driven rotors.

Table 3.8: Propeller-driven rotor performance at 300 grams of thrust.

Propeller Position	$\frac{1}{2}R$	$\frac{3}{4}R$	Tip
T [grams]	300	300	300
Rotor RPM	663	687	600
Propeller RPM	9,800	12,000	12,400
I_{DC} [A]	3.8	4.7	4.7
P_{DC} [W]	45.4	56.6	56.5
T/P_{DC} [N/W]	0.0648	0.0520	0.0521

Case II: Constant Main Rotor RPM of 500

Next, the propeller-driven rotor performance was compared at 500 RPM of the main rotor. Figure 3.51 shows the intersection of the rotor thrust and electrical power. Table 3.9 shows that placing the propeller at the mid span location results in an 18% reduction in thrust, a 26% reduction in electrical power, and a 22% reduction in propeller RPM compared to placing the propeller at the blade tip.

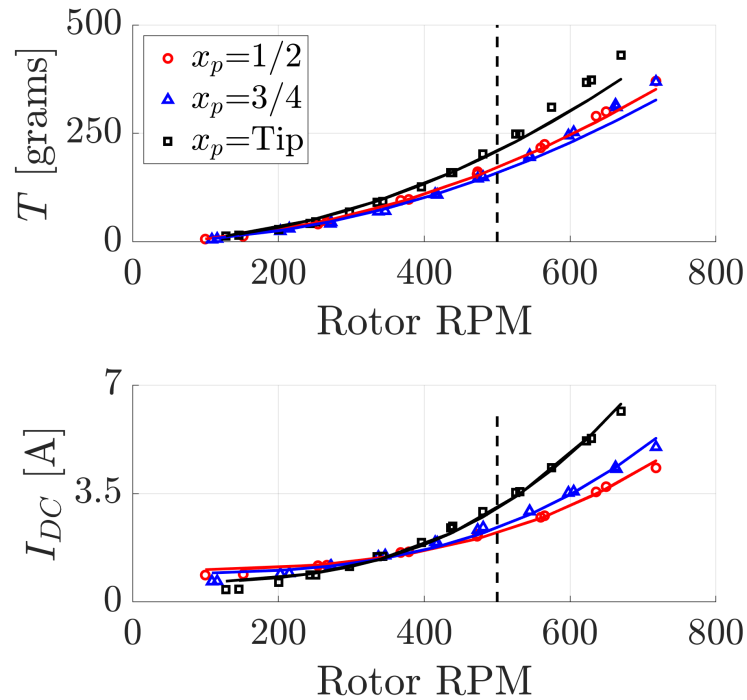


Figure 3.51: Intersection of 500 RPM of the main rotor for the different propeller-driven rotors.

Table 3.9: Propeller-driven rotor performance at 500 RPM of the main rotor.

Propeller Position	$\frac{1}{2}R$	$\frac{3}{4}R$	Tip
T [grams]	171	159	209
Rotor RPM	500	500	500
Propeller RPM	8,300	9,400	10,700
I_{DC} [A]	2.2	2.4	3.0
P_{DC} [W]	26.6	28.6	36.0
T/P_{DC} [N/W]	0.0630	0.0545	0.0569

Case III: Constant Propeller RPM of 10,000

Finally, the propeller-driven rotor performance is compared at 10,000 propeller RPM. Figure 3.52 shows the intersection of the propeller RPM lines with 10,000 propeller RPM and Table 3.10 shows the propeller-driven rotor performance results. Table 3.10 indicates that placing the propeller at the mid span location resulted in an 84% increase in thrust, a 68% increase in electrical power. This is due to the 50% increase in rotor RPM compared to the tip propeller placement.

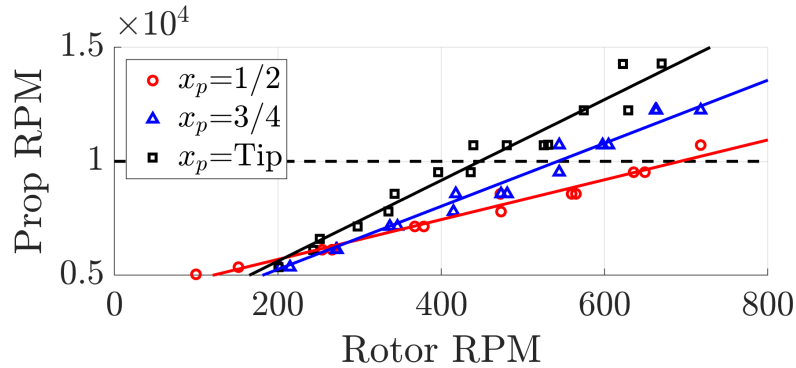


Figure 3.52: Intersection of 10,000 propeller RPM for the different propeller-driven rotors

Table 3.10: Propeller-driven rotor performance at 10,000 propeller RPM.

Propeller Position	$\frac{1}{2}R$	$\frac{3}{4}R$	Tip
T [grams]	327	188	177
Rotor RPM	692	545	460
Propeller RPM	10,000	10,000	10,000
I_{DC} [A]	4.2	2.8	2.5
P_{DC} [W]	50.0	33.6	29.8
T/P_{DC} [N/W]	0.0641	0.0549	0.0582

Next, the propeller-driven rotor test stand was modified for shaft-driven testing so that mechanical power of the different rotors could be measured.

3.4.4 Shaft-Driven Rotor Measurements

Mechanical power measurements were made by modifying the propeller-driven test stand to enable shaft-driven testing. The slinging was removed and replaced with an electrical drive motor and a torque cell. These modifications allowed for mechanical rotor power to be measured and compared between the different rotor configurations. The 3D printed hingeless rotors had a rotor collective θ_0 of 8 deg for all shaft-driven tests. Figure 3.53 shows the propeller-driven rotor test stand after it was modified for shaft-driven testing. The results were compared to an isolated rotor, that is a rotor that does not have a motor nacelle added to it.

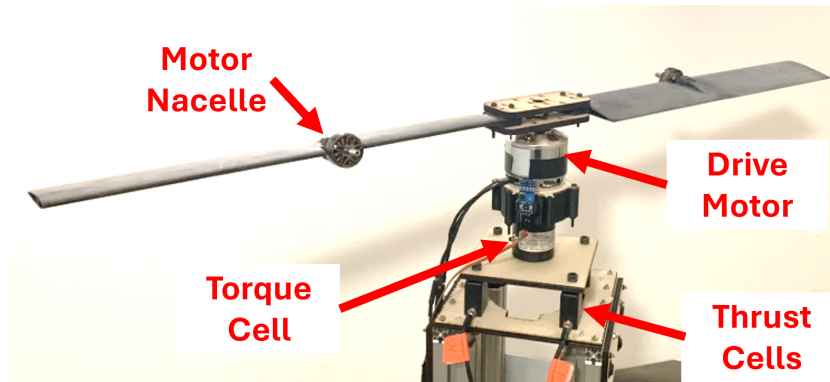


Figure 3.53: Propeller-driven rotor test stand modified for shaft-driven testing.

The rotor's mechanical power P was measured from the torque cell and RPM sensor as:

$$P = Q\Omega$$

where Q is the rotor's mechanical torque measured from the torque cell. The rotor's power loading

coefficient C_P/σ is defined as:

$$\frac{C_P}{\sigma} = \frac{1}{\sigma} \frac{P}{\rho A (\Omega R)^3}$$

From the measurement of mechanical power P , the rotor's figure of merit (FOM) is defined as:

$$FOM = \frac{C_T^{3/2} / \sqrt{2}}{C_P} \times 100\%$$

Table 3.11 shows the results of the shaft-driven rotor testing for the various rotor blades along with an isolated blade without a motor.

Table 3.11: Shaft-driven rotor results. Rotor collective θ_0 was fixed at 8 deg. The propeller tip angle δ was used in the control experiments, detailed in Chapter 5.

Propeller Position	δ [°]	C_T/σ	C_P/σ	FOM [%]
$\frac{1}{2}R$	0	0.0449	0.0077	27.3
$\frac{3}{4}R$	0	0.0408	0.0079	23.1
R	0	0.0416	0.0127	14.7
R	10	0.0421	0.0167	11.4
R	20	0.0400	0.0181	9.8
Isolated Rotor	-	0.0457	0.0076	28.3

As expected, the isolated rotor performed the best and had the highest figure of merit. Interestingly, placing the motor at mid span and tip locations resulted in a 1.3% and 67.1% increase in C_P/σ as compared to the isolated rotor. This indicated that placing the motor at the half span locations has significant performance benefits for the rotor and has a rotor figure of merit similar to an isolated rotor. Table 3.11 indicates that placing the motor further out created a bluff body was seen to reduce rotor thrust and increase rotor power. Additionally, placing the motor at the 3/4 span was also found to disrupt thrust and increase power, which was also seen during the propeller-driven rotor experiments.

3.5 Comprehensive Analysis for Spanwise Propeller Placement

In an effort to understand propeller placement impact, the comprehensive model was modified to enable variable propeller locations. Unfortunately, the propeller utilized in the small scale experiments was too small to make out the suitable details needed for engineering analysis. Instead, the 6 ft diameter rotor and Forum 80 propeller used in the propeller hover loads experiment, detailed in Section 3.3, were modeled. The only modification to the comprehensive model was that the nacelle drag was omitted, allowing only principal physics related to the effects of propeller placement to be captured. Additionally, no aerodynamic interference between the main rotor and propeller was modeled. Figure 3.54 shows variable propeller placement modeled in ERA.

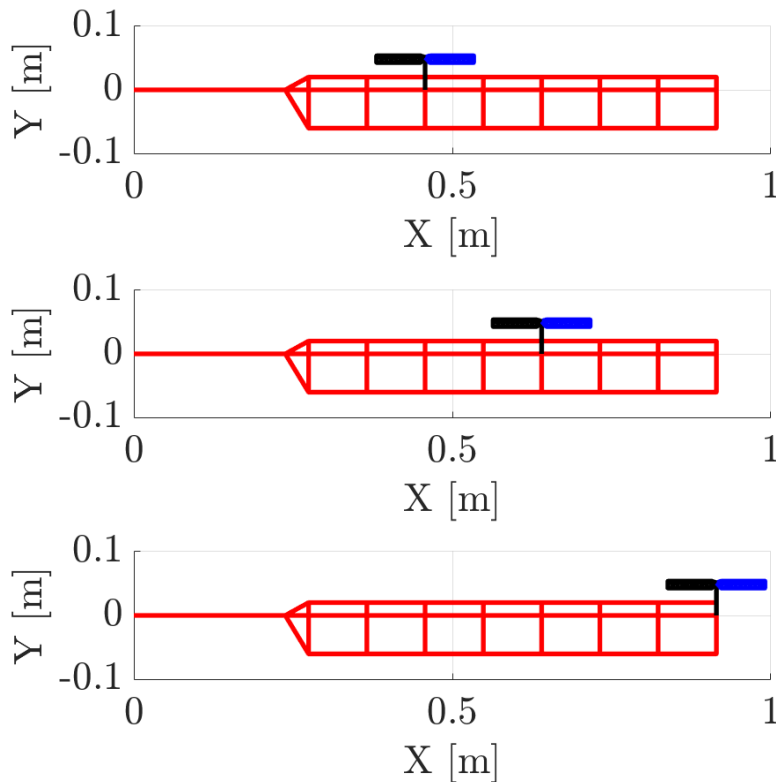


Figure 3.54: Propeller placed at 50%, 70%, and 100% rotor span in ERA.
View is above the rotor, looking down.

The analysis first begins by considering the physics of variable propeller placement. Next, the trim routine and results are described. Finally, the propeller loads for the different spanwise locations are computed.

3.5.1 Variable Propeller Placement Physics

Consider a rotor spinning at 200 rotor RPM and a propeller spinning at 4000, 5000, and 6000 propeller RPM. Each propeller produces a certain amount of thrust T_p for the given spanwise placement. The torque Q_p on the main rotor shaft generated by the propeller thrust T_p at location $x_p R$ is:

$$Q_p = T_p x_p R$$

In propeller-driven rotor hover trim, the torque produced by the propeller on the main rotor shaft Q_p must be equal to the main rotor aerodynamic drag Q_r . However, for any given propeller location x_p , rotor/propeller design, main rotor RPM Ω , and propeller RPM Ω_p the main rotor is likely not to be in equilibrium. In that case, there is a net torque Q_{net} on the rotor shaft:

$$Q_{net} = Q_r - Q_p \tag{3.30}$$

Figure 3.55 shows the net rotor shaft torque Q_{net} and propeller power for each configuration. Rotor hover trim is achieved when $Q_{net} = 0$. This occurs around $x_p = 1$ for the 6000 propeller RPM case, around $x_p = 0.8$ for the 5000 propeller RPM case, and around $x_p = 0.5$ for the 4000 propeller RPM case. To trim this specific rotor/propeller in hover, the 4000, 5000, and 6000 propeller RPM cases required 6.0 W, 8.3 W, and 13.1 W per rotor blade, respectively.

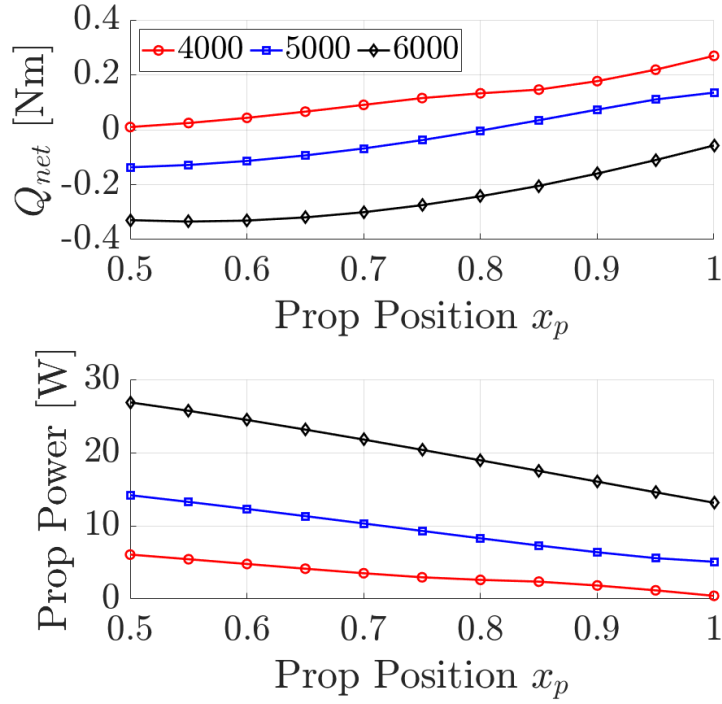


Figure 3.55: Impact of propeller RPM on rotor shaft torque for various spanwise propeller placements. Legend indicates propeller RPM.

3.5.2 Hover Trim Prediction Methodology

Newton's method was used to trim the propeller-driven rotor for any given propeller position x_p . The trim target to be minimized was the net rotor shaft torque Q_{net} , equation 3.30, and the trim variable was the propeller RPM Ω_p . Given a guess propeller RPM $\Omega_{p,n}$, the next propeller RPM $\Omega_{p,n+1}$ was calculated by:

$$\Omega_{p,n+1} = \Omega_{p,n} - \frac{Q_{net}}{Q'_{net}}$$

where Q'_{net} was calculated using numerical perturbation. This iteration continued until some tolerance was reached. Note that both Q_{net} and Q'_{net} were functions of propeller RPM Ω_p and the propeller position x_p .

3.5.3 Trim Propeller Placement Results

Figure 3.56 shows the hover trim solution results for 200 and 300 main rotor RPMs for an 8 deg rotor collective. For the 300 rotor RPM case, placing the propeller at the minimum power location, $x_p = 0.50$, reduced propeller power by 40% compared to the tip mounted propeller location. A similar trend was observed for the 200 rotor RPM case.

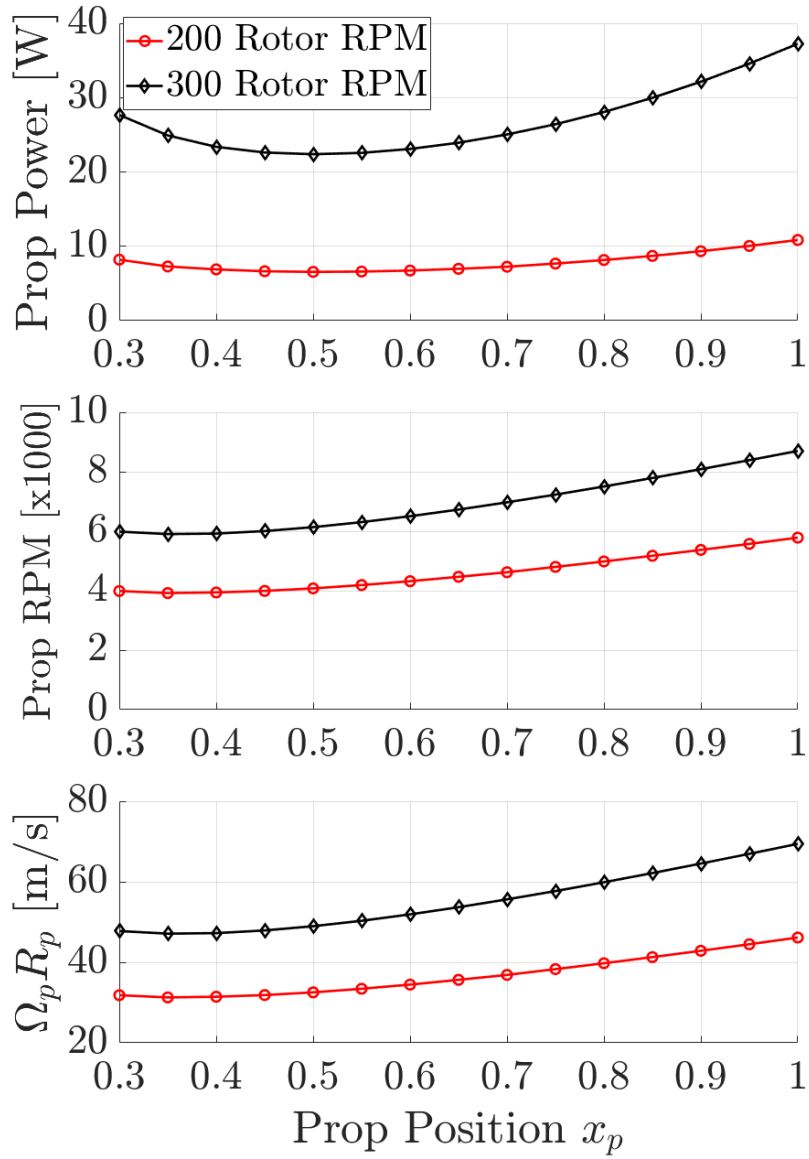


Figure 3.56: ERA predictions for variable propeller placement.

These ERA predictions agree with the experimental observations shown earlier using the 2.7 ft diameter test stand. Placing the propeller at the midspan location reduced power by 50% compared to the tip mounted propeller. Using the comprehensive rotorcraft analysis model, two additional quantities of interest can be computed: the propeller climb inflow λ_{cp} and the propeller hub loads.

3.5.4 Propeller Climb Inflow λ_{cp}

Propeller climb inflow λ_{cp} is defined as the ratio of the propeller climb velocity v_c to the propeller tip speed $\Omega_p R_p$. For a propeller-driven rotor in hover, the propeller climb velocity v_c is related to the spanwise location x_p and the rotor tip speed ΩR by $v_c = x_p(\Omega R)$. This yields:

$$\lambda_{cp} = \frac{v_c}{\Omega_p R_p} = \frac{x_p(\Omega R)}{\Omega_p R_p}$$

Figure 3.57 shows the propeller climb inflow at hover trim. Note that at $x_p = 0.50$, $\lambda_{cp} = 0.30$. This corresponds to the location of peak efficiency of the propeller, shown earlier in Figure 2.31. This can be seen in the required propeller power plot of Figure 3.56 why $x_p = 0.50$ corresponds to the minimum propeller power - it is the location of peak propulsive efficiency of the propeller.

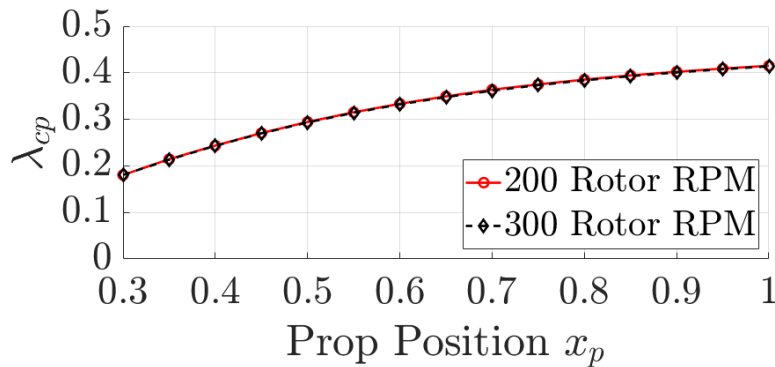


Figure 3.57: Propeller inflow at hover trim.

3.5.5 Propeller Loads vs Spanwise Propeller Location

Finally, the propeller hub loads are shown in Figure 3.58. As expected, placing the propeller further out on the rotor blade span reduced the required propeller thrust due to the larger moment arm. However, for all other loads, placing the propeller further out on the rotor blade span increased the magnitude the propeller loads. Additionally, the rotor-propeller Coriolis moment continues to have a large value, being several orders larger than the propeller torque.

Figures 3.56 to 3.58 strongly suggests not placing the propeller at the tip of the main rotor blade. Increasing the spanwise location of the propeller blade increases loads, required propeller power, and propeller tip speed. This, in turn, requires a stronger propeller and larger electric motor, further increasing propeller assembly mass and loads.

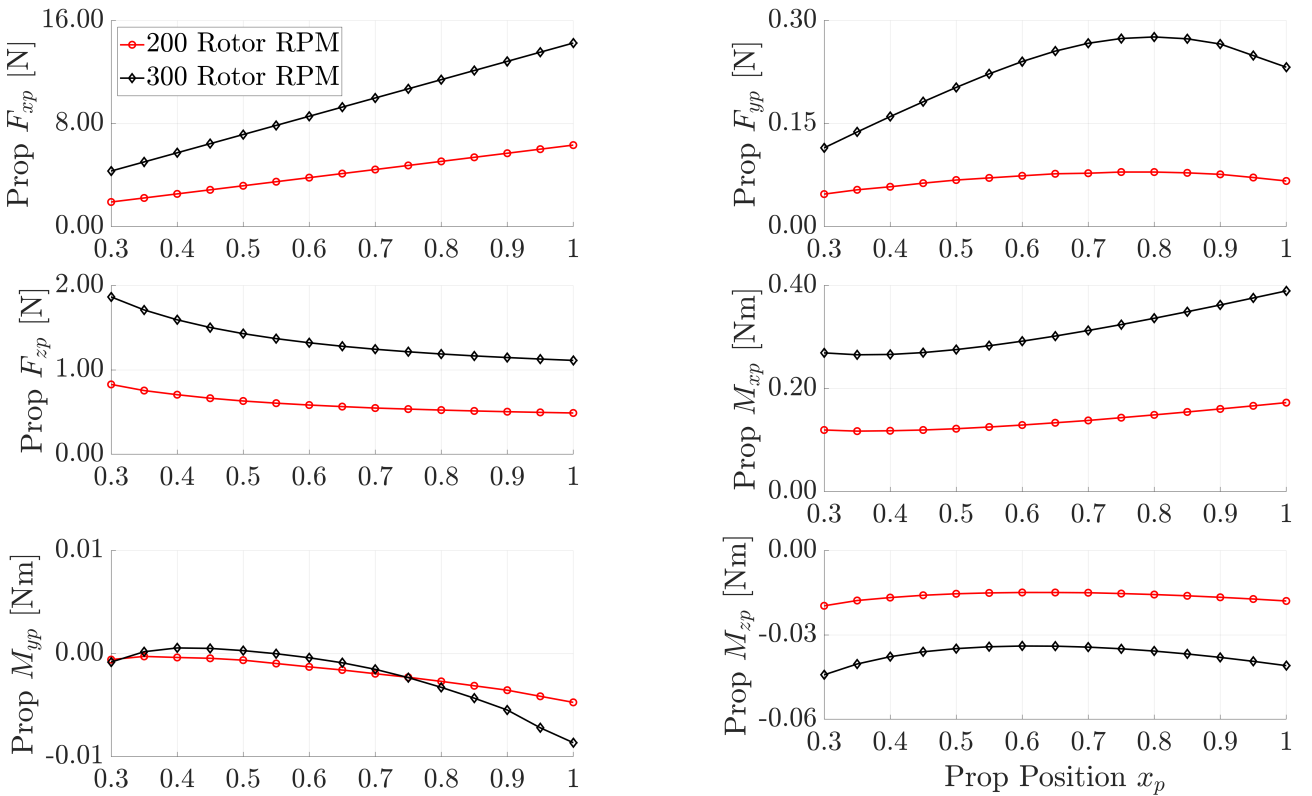


Figure 3.58: Propeller hub loads versus spanwise propeller location x_p on rotor blade.

3.6 Fundamental Understanding of Propeller-Driven Rotor Power

A deeper understanding of propeller design impact on propeller-driven rotor performance can be determined by creating a simple analytical performance model that incorporates propeller spanwise placement on the rotor blade. The spanwise propeller placement model uses a similar approach to the tip propeller performance model presented in Section 3.1. First, the equilibrium between propeller torque and rotor drag torque is studied to determine propeller thrust. Next, the isolated axial flight propeller performance is studied. Finally, a simple expression for propeller-driven rotor power is derived.

3.6.1 Torque Equilibrium

It was assumed that there is one propeller per rotor blade. From Figure 3.39, in hover equilibrium the propeller thrust T_p acting at a distance $x_p R$ from the rotor hub times the number of propellers N_B must be equal to the rotor drag:

$$Q_{PDR} = Q_{Rotor}$$

$$N_B T_p x_p R = C_Q \rho A (\Omega R)^2 R$$

This formula can be rearranged to:

$$C_{T_p} = \frac{1}{x_p} \frac{C_Q}{N_B} \left(\frac{R}{R_p} \right)^2 \left(\frac{\Omega R}{\Omega_p R_p} \right)^2 \quad (3.31)$$

For a tip mounted propeller $\lambda_{c_p} = \Omega R / (\Omega_p R_p)$, but for a propeller located at x_p on the rotor blade span, the propeller climb ratio λ_{c_p} is modified to use the propeller climb speed $v_c = x_p(\Omega R)$:

$$\lambda_{c_p} = \frac{x_p(\Omega R)}{\Omega_p R_p}$$

which can be re-arranged to:

$$\frac{\Omega R}{\Omega_p R_p} = \frac{\lambda_{c_p}}{x_p}$$

Inserting this expression back into equation 3.31 results in:

$$C_{T_p} = \frac{1}{x_p} \frac{C_Q}{N_B} \left(\frac{R}{R_p}\right)^2 \left(\frac{\lambda_{c_p}}{x_p}\right)^2$$

$$\frac{C_{T_p}}{\lambda_{c_p}^2} = \frac{1}{x_p^3} \frac{C_Q}{N_B} \left(\frac{R}{R_p}\right)^2 \quad (3.32)$$

with:

$$\text{Isolated propeller performance} \rightarrow \frac{C_{T_p}}{\lambda_{c_p}^2}$$

$$\text{Propeller placement on rotor blade} \rightarrow \frac{1}{x_p^3}$$

$$\text{Propeller-driven rotor sizing} \rightarrow \frac{C_Q A}{N_B} \left(\frac{R}{R_p}\right)^2$$

This is the propeller-driven rotor hover equilibrium equation. Note that if $x_p = 1$, corresponding to a tip mounted propeller, it is the same equation presented earlier in equation 3.10. Equation 3.32 has the same components as equation 3.10 with the addition of the propeller placement term. Much like with the tip propeller model from Section 3.1, propeller-rotor hover trim is achieved when the value of the left hand side of equation 3.32 equals the right hand side. That is, when the non-dimensional propeller

thrust equals the required thrust for the given propeller-driven rotor configuration. When these two lines meet, that is the propeller trim climb ratio $\lambda_{c_p}^*$.

The propeller-driven rotor hover trim equilibrium, equation 3.32 will be examined using the Forum 81 propellers. Figure 3.59 shows the performance plots for the Forum 81 propellers, from Section 2.3.6, with a trendline showing best fit. There are two propellers, both with a 35 deg root propeller collective, one is untwisted and the other has a -15 deg twist.

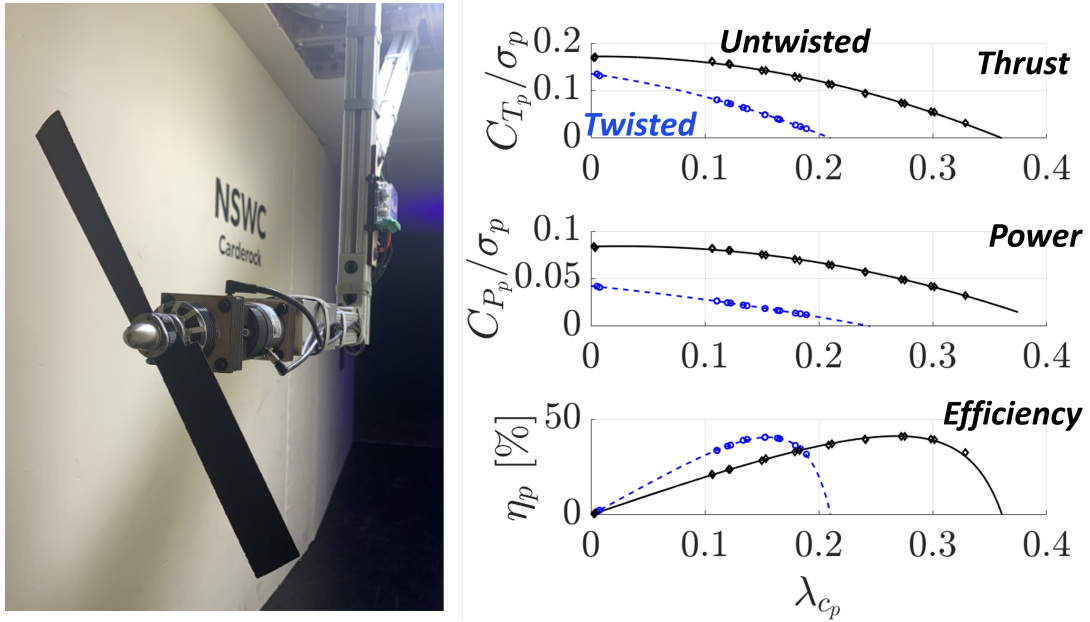


Figure 3.59: Isolated propeller characterization in axial flight using Forum 81 propellers. Solid lines indicate trendline and dots are experimental data.

The 6 ft diameter rotor parameters used for this example result in a value of $(C_Q/N_B)(R/R_p)^2 = 0.011$. Note that this value is fixed for all rotors, but as x_p changes it has a $1/x_p^3$ impact on the trim performance. The $1/x_p^3$ term acts as a multiplier, and shifts the value of the right hand side of equation 3.32 to a higher value. As such, a lower $\lambda_{c_p}^*$ value is required to trim the rotor. As the value of $\lambda_{c_p}^*$ changes, the propeller propulsive efficiency η_p changes as well. Figures 3.60 to 3.64 shows the how the hover trim $\lambda_{c_p}^*$ and propeller efficiency η_p change as propeller position x_p is varied.

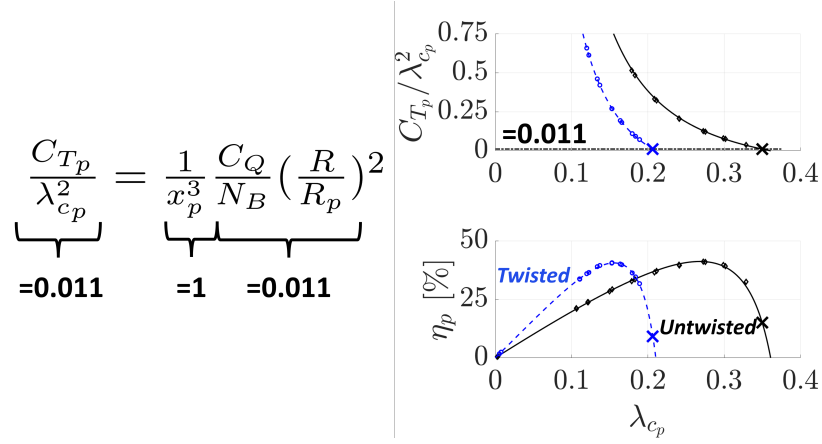


Figure 3.60: Trim for $x_p = 1$.

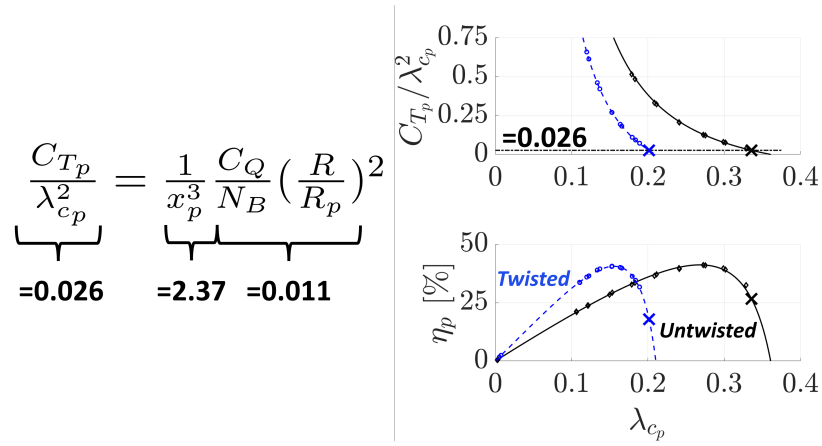


Figure 3.61: Trim for $x_p = 3/4$.

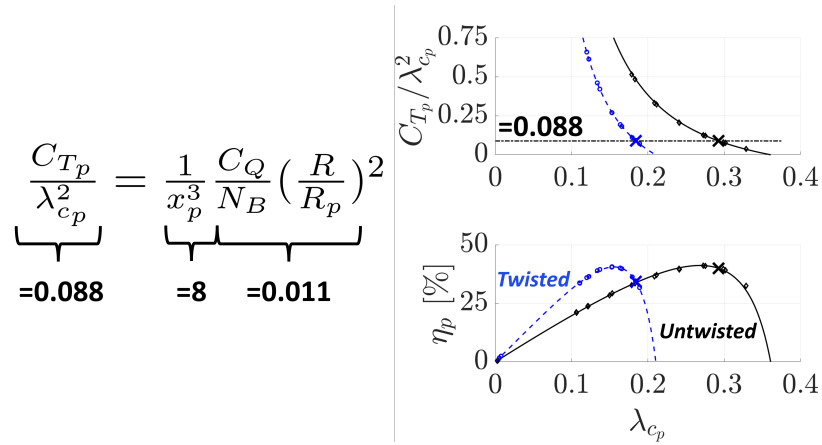


Figure 3.62: Trim for $x_p = 1/2$.

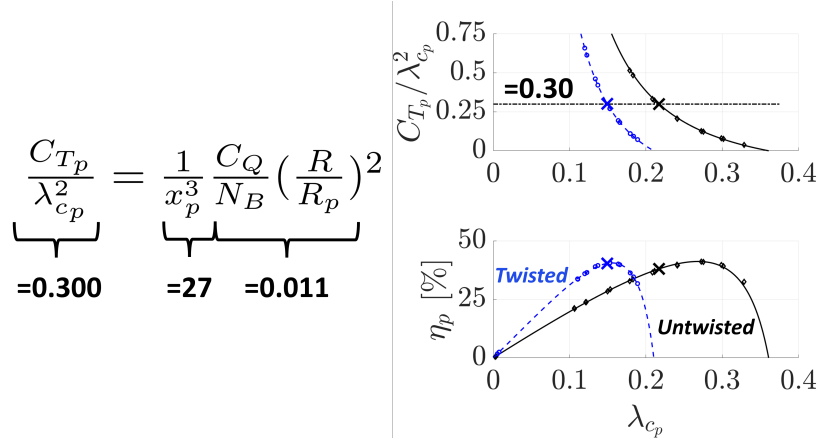


Figure 3.63: Trim for $x_p = 1/3$.

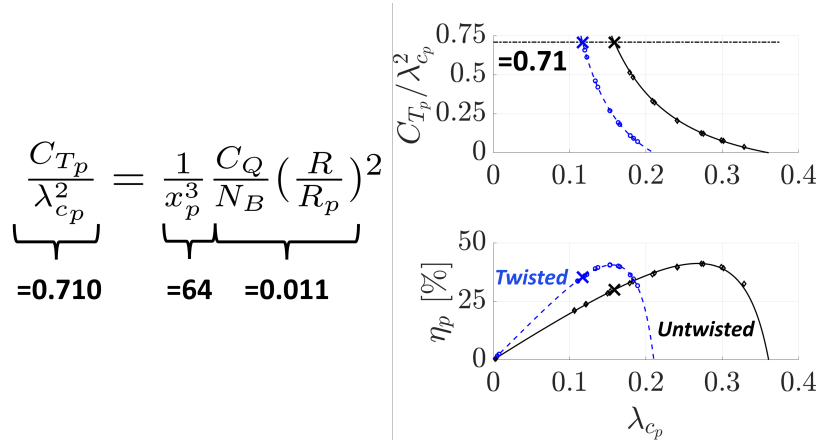


Figure 3.64: Trim for $x_p = 1/4$.

From Figures 3.60 to 3.64 it is clear that as the propeller position x_p is moved from the tip towards the root, the $1/x_p^3$ portion continues to increase, and results in additional thrust from the propeller. However, in doing so the propeller trim climb ratio $\lambda_{c_p}^*$ decreases and results in moving across the propulsive efficiency curve. Each propeller had its own thrust and efficiency curve, and therefore they have different optimal locations on the main rotor blade. Note that the untwisted propeller reached maximum propulsive efficiency near the $x_p = 1/2$ location and the twisted propeller around the $x_p = 1/3$ location, respectively shown in Figures 3.62 and 3.63.

Once the propeller trim climb ratio $\lambda_{c_p}^*$ has been determined, the resulting propeller thrust can be determined. Figure 3.65 shows the non-dimensional performance of the propeller. To find the propeller tip speed and propeller-driven rotor power, a rotor speed is needed.

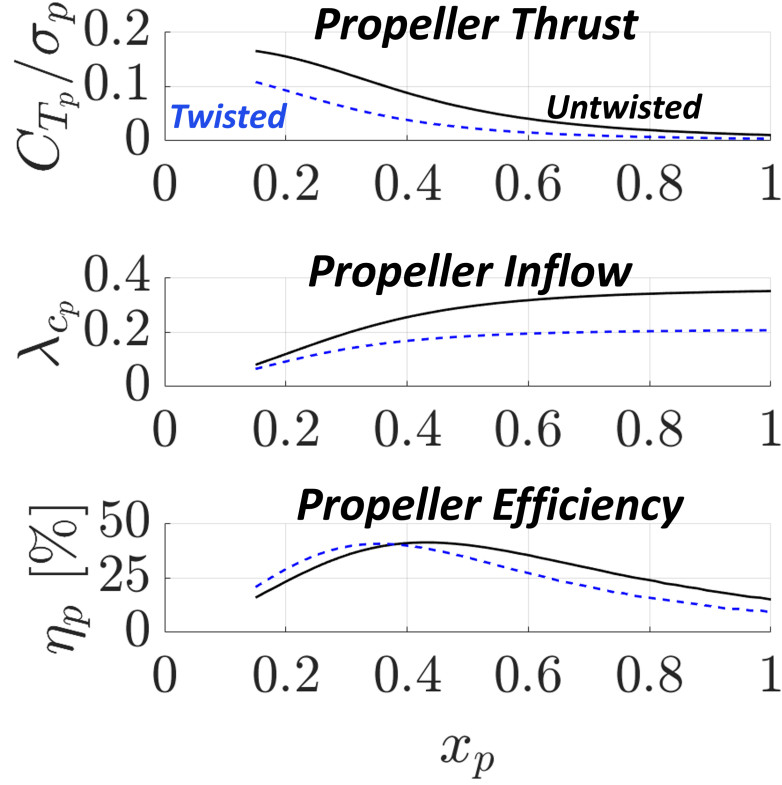


Figure 3.65: Trim performance for a propeller-driven rotor with varying propeller location x_p .

3.6.2 Propeller-Driven Rotor Power

This section examines the propeller-driven rotor power, and leads to a simple expression for power in terms of propeller efficiency, rotor drag, and rotor tip speed. Using the trim climb ratio $\lambda_{c_p}^*$, the propeller tip speed is simply:

$$\Omega_p R_p = \frac{x_p(\Omega R)}{\lambda_{c_p}^*}$$

where a value of 400 rotor RPM is used for this example. The propeller power can be written as:

$$P_p = C_{P_p} \rho A_p (\Omega_p R_p)^3$$

The propeller-driven rotor power is the propeller power P_p times the number of rotor blades N_B :

$$P_{PDR} = N_B P_p$$

Figure 3.66 shows the propeller tip speed $\Omega_p R_p$ and propeller-driven rotor power P_{PDR} as the propeller location x_p is varied for the two different propellers. Again, each propeller has its own performance curve, and thus different propeller tip speeds and powers are observed. The isolated, shaft-driven rotor power is also plotted as a comparison.

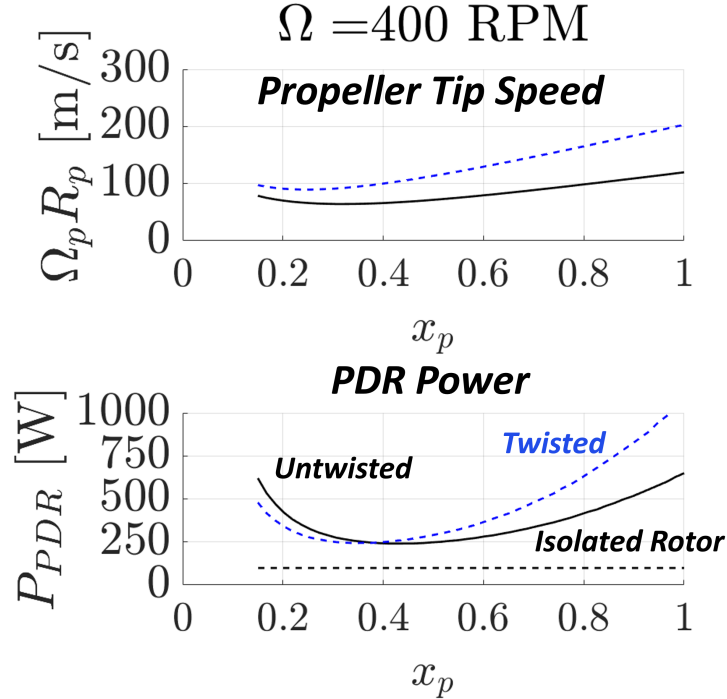


Figure 3.66: Propeller-driven rotor tip speed and power versus propeller location x_p at 400 main rotor RPM.

It can be seen that the minimum ratio of propeller-driven rotor power to isolated rotor power is around $1/0.41=2.44$ for this example. This is informative, as the maximum isolated propeller propulsive efficiency η_p , shown in Figure 3.59, is about 41% for both propellers. This interesting observation can be expressed mathematically, to arrive at an expression for propeller-driven rotor power.

To arrive at a propeller-driven rotor power P_{PDR} expression in simple terms of propeller performance, we begin by examining the propeller propulsive efficiency η_p definition:

$$\eta_p = \frac{C_{T_p} \lambda_{c_p}}{C_{P_p}}$$

which can be re-arranged to:

$$C_{P_p} = \frac{C_{T_p} \lambda_{c_p}}{\eta_p}$$

This can be expanded using the propeller thrust found earlier, repeated here for convenience:

$$C_{T_p} = \frac{1}{x_p^3} \frac{C_Q}{N_B} \left(\frac{R}{R_p}\right)^2 \lambda_{c_p}^2$$

plugging this back into the C_{P_p} expression yields:

$$C_{P_p} = \frac{\lambda_{c_p}}{\eta_p} \left(\frac{1}{x_p^3} \frac{C_Q}{N_B} \left(\frac{R}{R_p}\right)^2 \lambda_{c_p}^2 \right)$$

which results in an expression for the propeller power coefficient in terms of propeller-driven rotor parameters. This expression for C_{P_p} can be combined

$$P_p = \left[\frac{\lambda_{c_p}}{\eta_p} \left(\frac{1}{x_p^3} \frac{C_Q}{N_B} \left(\frac{R}{R_p}\right)^2 \lambda_{c_p}^2 \right) \right] \rho A_p (\Omega_p R_p)^3$$

$$P_p = \frac{C_Q}{N_B \eta_p x_p^3} \left(\frac{R}{R_p} \right)^2 \lambda_{c_p}^3 \rho (\pi R_p^2) (\Omega_p R_p)^3$$

$$P_p = \frac{C_Q}{N_B \eta_p x_p^3} \rho (\pi R^2) \lambda_{c_p}^3 (\Omega_p R_p)^3$$

using the climb expression:

$$\lambda_{c_p} = \frac{x_p(\Omega R)}{\Omega_p R_p}$$

$$P_p = \frac{C_Q}{N_B \eta_p x_p^3} \rho A \left(\frac{x_p(\Omega R)}{\Omega_p R_p} \right)^3 (\Omega_p R_p)^3$$

$$P_p = \frac{C_Q}{N_B \eta_p} \rho A (\Omega R)^3$$

Resulting in a simplified expression for propeller power P_p . Combining this with the fact that $P_{PDR} = N_B P_p$ results in a closed form expression for the propeller-driven rotor power with variable propeller placement:

$$P_{PDR} = \frac{C_Q}{\eta_p} \rho A (\Omega R)^3 \quad (3.33)$$

This equation relates isolated propeller performance η_p to propeller-driven rotor parameters.

$$C_{P,PDR} = \frac{C_{P,rotor} + C_{P,Nacelle}}{\eta_p}$$

If the nacelle is streamlined and/or close to the root of the main rotor blade then $C_{P,Nacelle} \approx 0$. Then comparing isolated rotor power to propeller-driven rotor power.

$$\frac{P_{rotor}}{P_{PDR}} = \frac{1}{\eta_p}$$

For an ideal configuration $\eta_p = 0.85$, then $1/0.85 = 1.176$. But if $\eta_p = 0.90$ then $1/0.90 = 1.111$. This is significant as tail rotor power in a single main rotor helicopter configuration can be 10-20% of main rotor power. Thus, the propeller-driven rotor configuration power is comparable to single main rotor helicopter configuration. The next section uses this simple performance model to evaluate propeller driven rotor scaling trends.

3.7 Scaling Considerations

The propeller driven rotor concept was further explored by investigating the scalability of a notional design, and comparing it to an isolated main rotor design. Three different sizes of aircraft were considered: a 20,000 lb, a 5,000 lb, and a 100 lb aircraft – corresponding to a UH-60-like helicopter, a notional e-VTOL platform, and a unmanned aerial system. Helicopters typically have rotor disk loadings between 2 and 10 lb/ft². For an initial analysis, a main rotor disk loading of 2 lb/ft² was selected. This study first describes the scaling methodology for an isolated rotor for a given aircraft weight and disk loading, and then determines the required power for a propeller-driven rotor of the same gross weight. The propeller design, placement on the main rotor span, and propeller size were considered. Later, a sensitivity study was conducted by re-examining the concept at a higher main rotor disk loading of 5 lb/ft².

3.7.1 Notional Main Rotor Design

It is worth noting that an isolated main rotor cannot fly itself, it typically is included in a single-main rotor design that also features a tail rotor. For a single main rotor, the need to “de-spin” the fuselage means that roughly 10-20% of the main rotor power is used by the tail rotor. A propeller-

driven rotor imparts no torque on the rotor shaft, and thus no de-spin power is required for the fuselage. This potential power saving needs to be considered.

Figure 3.67 shows the isolated rotor, propeller-driven rotor, and single main rotor helicopter configurations. A four bladed main rotor with a rotor blade aspect ratio of 18 was selected, resulting in a main rotor solidity of 7.07%. For the various designs, the propeller placement was varied along the main rotor blade span. A rotor $C_T/\sigma = 0.08$ was selected. The parameters in Table 3.12 were held constant for each configuration.

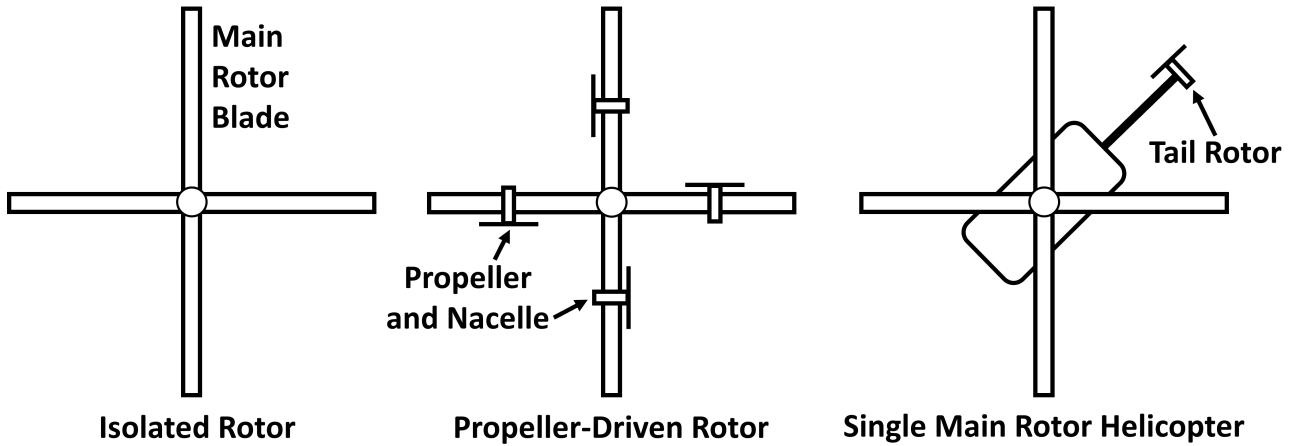


Figure 3.67: Rotor designs considered in scaling analysis.

Table 3.12: Main rotor design parameters held constant for scaling study.

Disk Loading, DL	2 lb/ft ²
c/R	1/18
N_b	4
σ	7.07%
C_T/σ	0.08
C_{d0}	0.010
k_h	1.15
Figure of Merit	70%
Density, ρ	1.23 kg/m ³
Nacelle Drag f_N/A	1.18e-4

The scaling study begins by first sizing the main rotor based off aircraft weight and disk loading. The main rotor disk loading is defined as:

$$DL = \frac{T}{A}$$

where T is the rotor thrust, and it is equal to the vehicle gross weight W , hence $T = W$. The rotor radius R can be found using:

$$R = \sqrt{\frac{W}{\pi DL}}$$

After this, the rotor area is simply $A = \pi R^2$. Next, the rotational speed of the main rotor Ω must be found. For a given rotor blade loading C_T/σ and main rotor solidity σ , the rotor thrust coefficient is:

$$C_T = \left(\frac{C_T}{\sigma}\right)\sigma$$

Finally, the rotational speed of the main rotor Ω can be found:

$$W = T = C_T \rho A (\Omega R)^2$$

$$\Omega = \sqrt{\frac{W}{C_T \rho A R^2}}$$

Note that for a constant disk loading W/A and rotor thrust coefficient C_T , the rotor tip speed ΩR is constant. The final step for the isolated rotor configuration is that the main rotor power P in hover. This is found from the rotor power coefficient C_P :

$$C_Q = C_P = k_h \frac{C_T^{3/2}}{\sqrt{2}} + \frac{\sigma C_{d0}}{8} \quad (3.34)$$

and the power P is:

$$P = C_P \rho A (\Omega R)^3$$

One additional step is required for the propeller driven rotor design. The nacelle, located at a distance of $x_p R$ on the main rotor blade, has an additional drag term that must be taken into account. A drag build up method, similar to the shown earlier in Figure 3.30, was used. Consider the nacelle drag shown in Figure 3.68.

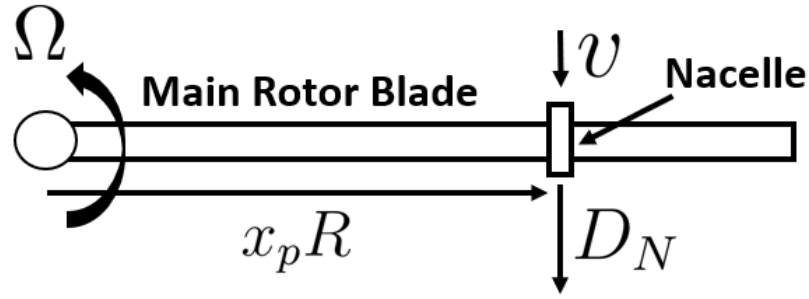


Figure 3.68: Nacelle drag D_N for propeller located at $x_p R$ on main rotor blade.

The torque Q_N from the nacelle drag D_N is:

$$Q_N = N_b (x_p R) D_N$$

where $D_N = \frac{1}{2} \rho v^2 f_N$, and the incoming velocity $v = x_p (\Omega R)$. This leads to:

$$Q_N = \frac{N_b}{2} \rho x_p^3 f_N (\Omega R)^2 R$$

$$C_{Q,N} = \frac{Q_N}{\rho A (\Omega R)^2 R}$$

$$C_{Q,N} = \frac{N_b}{2} x_p^3 \frac{f_N}{A} \quad (3.35)$$

where the ratio of f_N/A is considered a constant for this scaling analysis, and has a value of 1.18×10^{-4} from the equation 3.27 based of the propeller-rotor loads hover test from Section 3.3. Hence, the torque coefficient for the main rotor of the propeller driven rotor is:

$$C_{Q,PDR} = C_Q + C_{Q,N} \quad (3.36)$$

where C_Q is from the isolated rotor, equation 3.34, and $C_{Q,N}$ is from the propeller driven rotor nacelle drag, equation 3.35. Figure 3.69 shows the change in $C_{Q,PDR}$ as the propeller location x_p is varied. Note that at $x_p = 0.5$, the value of $C_{Q,PDR}$ is only 8% larger than the isolated rotor C_Q . The next section examines scaling impacts on the propeller.

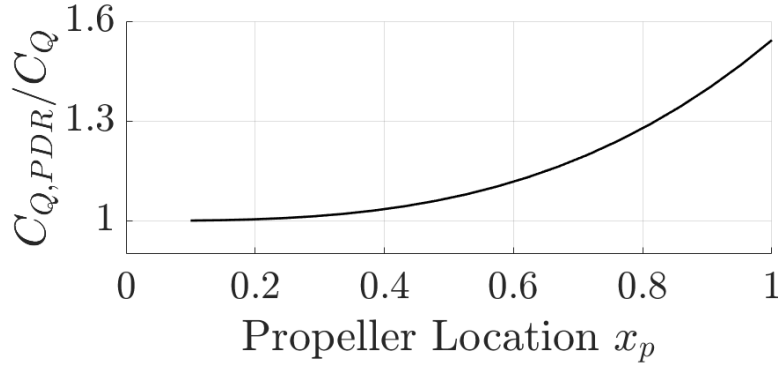


Figure 3.69: Increase in propeller-driven rotor $C_{Q,PDR}$ compared to isolated rotor C_Q as nacelle location varies.

3.7.2 Propeller Design and Reynolds Number Impact

An important factor to consider when discussing scaling is the Reynolds's number. For the various propellers that were used in this research, they all suffered low propulsive efficiencies due to low Reynolds numbers. For the Forum 79, 80, and 81 propellers, this was a Reynolds number around 50,000, which was evident in the low lift, high drag, and a propulsive efficiency of only 45%. Consider

the airfoil performance of a Clark-Y airfoils at Reynolds number of 50,000 and 1,000,000, shown in Figure 3.70. The difference in performance is quite clear, as the increase in lift and reduction in drag as Reynolds number increases. Note that the 50,000 Reynolds number case the airfoil has a maximum C_l/C_d of only 30, compared to a maximum C_l/C_d of 114 for the 1,000,000 Reynolds number case.

As such, this increase in propeller aerodynamic performance with scaling was taken into account. The Clark-Y airfoil with a Reynolds number of 1,000,000 was chosen. This was due to the increase in rotor/propeller speeds with scaling, and that the Clark-Y is a common airfoil found in fixed wing aviation propellers. Additionally, the Clark-Y has a high maximum C_l/C_d compared to the NACA0012 airfoil.

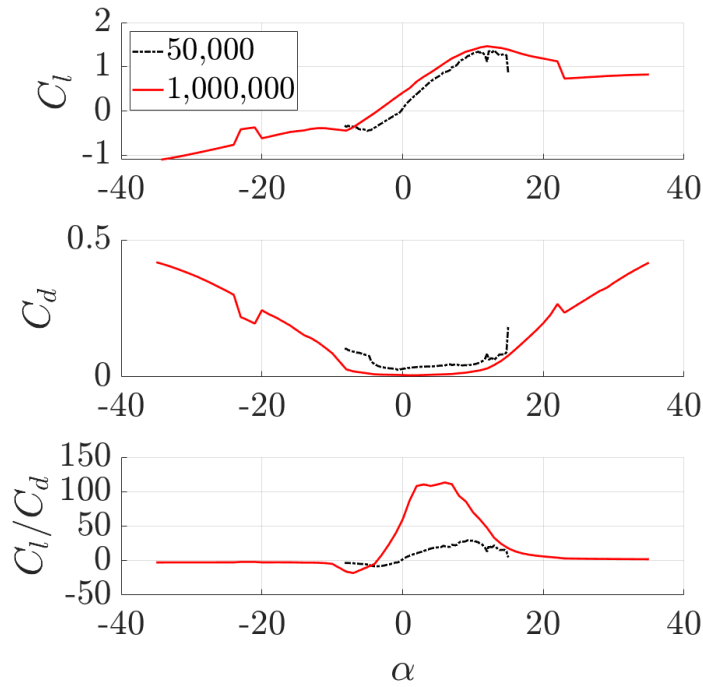


Figure 3.70: Variation in Clark-Y airfoil performance with Reynolds number of 50,000 and 1,000,000.

To understand the impact that propeller design has on propeller-driven rotor performance, two different propellers were designed: one optimized for lower speed axial flight and the other optimized

for higher speed axial flight. Each 3 bladed propeller had no taper, and a $c_p/R_p = 1/8$, which yielded a propeller solidity $\sigma_p = 11.9\%$. A 3 bladed propeller was chosen due to dynamic reasons that will be discussed later in Section 4.1.6.

The propeller pitch angle distribution was estimated using the optimum angle of attack α^* (corresponding to a maximum C_l/C_d) and a design axial climb ratio $\lambda_{cp,des}$. The low speed propeller has a $\lambda_{cp,des} = 0.15$, and the high speed propeller has a $\lambda_{cp,des} = 0.30$. For the Clark-Y propeller with a 1,000,000 Reynolds number, the optimum angle of attack α^* is 6 deg. The propeller pitch angle θ_p can be found using the propeller blade element theory model, shown earlier in Figure 2.11:

$$\alpha = \theta_p - \phi$$

$$\phi = \tan^{-1} \frac{U_P}{U_T} = \tan^{-1} \frac{(\lambda_{c_p} + \lambda_{i_p})\Omega_p R_p}{\Omega_p r_p}$$

for high speed axial flight, the value of λ_{c_p} is much larger than λ_{i_p} , implying $\lambda_{c_p} + \lambda_{i_p} \approx \lambda_{c_p}$. Using this assumption, the propeller pitch angle distribution θ_p can be found using:

$$\phi = \tan^{-1} \frac{\lambda_{c_p} \Omega_p R_p}{\Omega_p r_p}$$

$$\phi = \tan^{-1} \frac{\lambda_{c_p}}{r_p/R_p} \quad (3.37)$$

Thus, the propeller pitch angle distribution θ_p can be determined across the propeller blade span r_p/R_p using the design axial climb ratio $\lambda_{cp,des}$ and the optimum angle of attack α^* :

$$\theta_p = \alpha^* + \tan^{-1} \frac{\lambda_{cp,des}}{r_p/R_p} \quad (3.38)$$

Figure 3.71 shows the propeller pitch distribution for the low speed and high speed propellers. Equation 3.38 produces very large propeller pitch angles upwards of 75 deg towards the propeller root. To combat this, a maximum propeller pitch angle of 45 deg was imposed. Figure 3.73 shows the predicted isolated propeller performance for the two different propellers, and Table 3.72 has the propeller details.

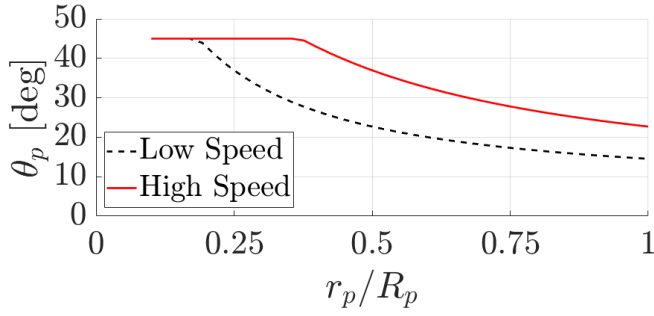


Figure 3.71: Propeller pitch angle θ_p as a function of propeller blade span r_p/R_p .

Figure 3.72: Propeller parameters held constant for scaling study.

Airfoil	Clark-Y
Reynolds Number	1,000,000
R_p/R	1/20, 1/10, 1/5
c_p/R_p	1/8
N_{bp}	3
σ_p	11.9%

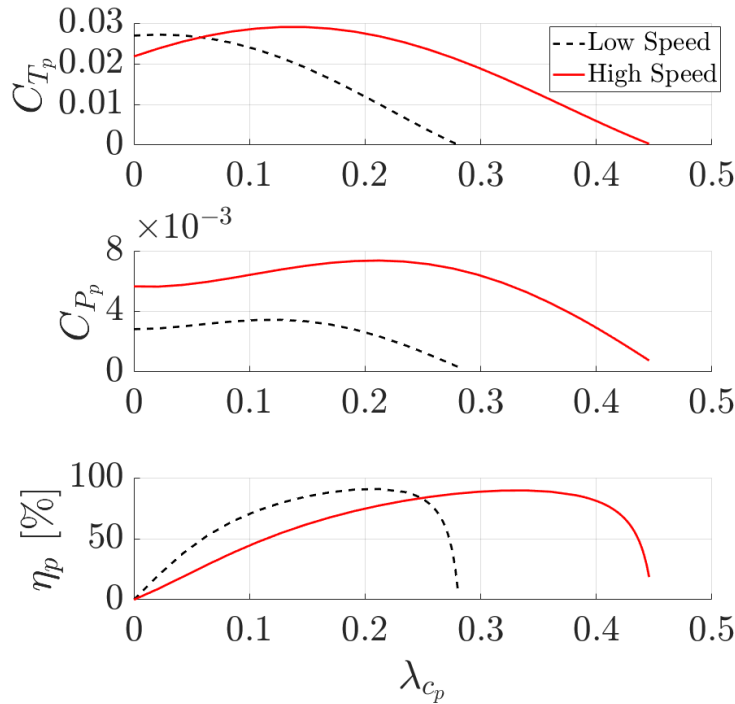


Figure 3.73: Predicted isolated propeller performance for propeller used in scaling study.

3.7.3 20,000 lb Aircraft

The first aircraft considered was the 20,000 lb aircraft, corresponding to a UH-60-like helicopter. Tables 3.13 and 3.14 contain details on the isolated rotor and propeller-driven rotor design. Figure 3.75 compares the hover power for the different configurations, and Figure 3.75 shows details on the propeller-driven rotor sizing.

Table 3.13: Main rotor results for 20,000 lb aircraft.

R [ft]	56.4
Ω [RPM]	65
ΩR [ft/s]	385
P [hp]	1075

Table 3.14: Propeller-driven rotor results for 20,000 lb aircraft with main rotor disk loading of 2 lb/ft².

Propeller Spec	Low Speed Propeller			High Speed Propeller		
R/R_p	20	10	5	20	10	5
R_p [ft]	2.82	5.64	11.28	2.82	5.64	11.28
x_p [%]	48	34	19	57	38	24
λ_{cp}	0.18	0.20	0.19	0.28	0.30	0.31
$\Omega_p R_p$ [ft/s]	1001	643	394	774	486	305
η_p [%]	90	91	90	87	89	89
P_{PDR} [hp]	1271	1206	1198	1353	1246	1217

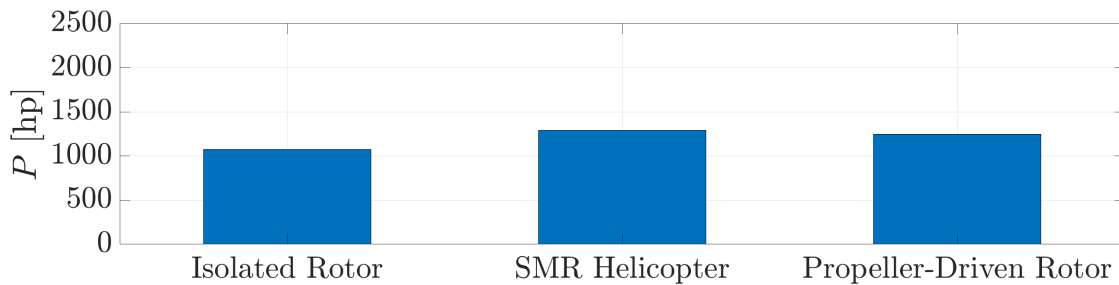
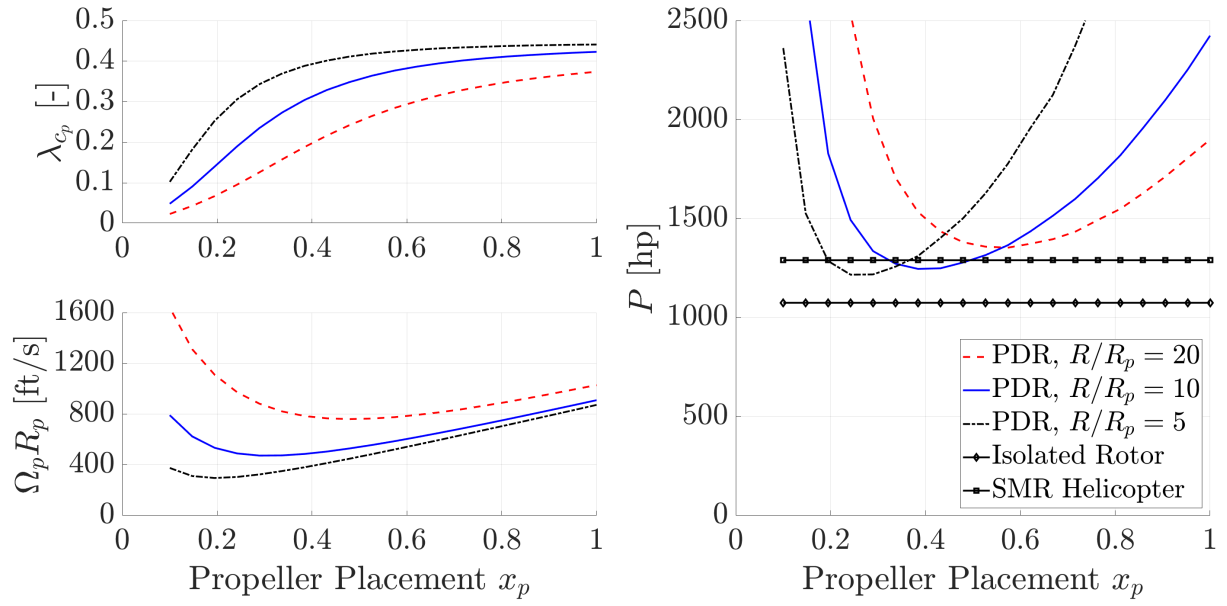
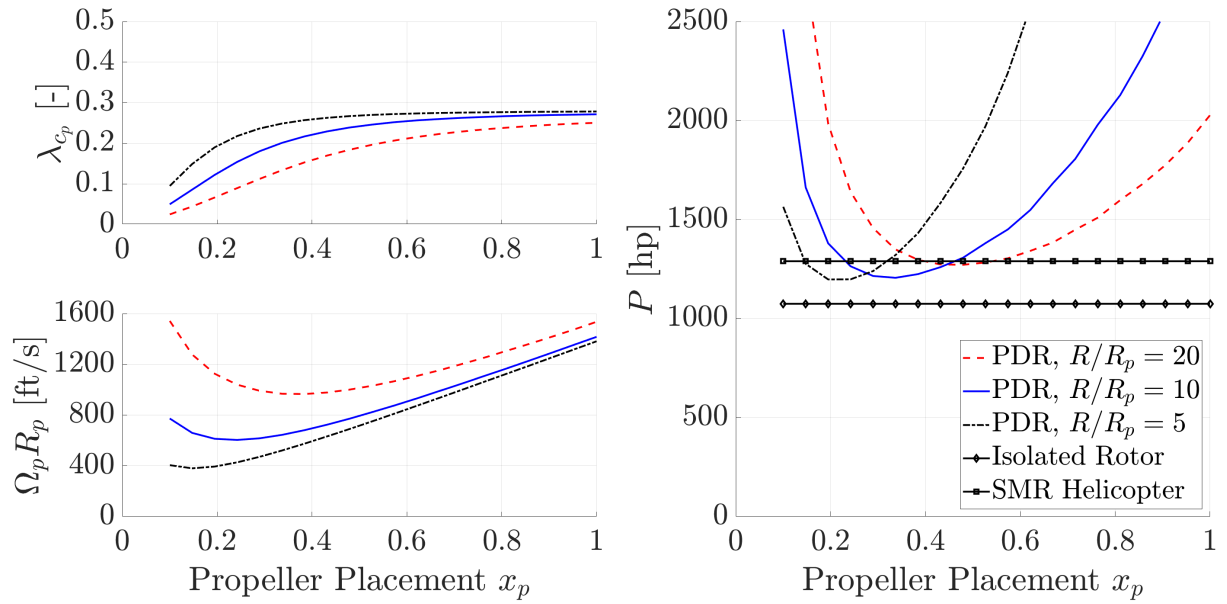


Figure 3.74: Hover power for various configurations at 2 lb/ft² for 20,000 lb aircraft. High-speed propeller with $R/R_p = 10$ shown for propeller-driven rotor configuration.



(a) High speed propeller.



(b) Low speed propeller.

Figure 3.75: Impact of propeller design and placement on propeller-driven rotor results for 20,000 lb aircraft with a main rotor disk loading of 2 lb/ft².

3.7.4 5,000 lb Aircraft

Next, the 5,000 lb aircraft was analyzed using the same methodology as the 20,000 lb aircraft. Tables 3.15 and 3.16 contain details on the isolated rotor and propeller-driven rotor design. Figure 3.76 compares the hover power for the different configurations, and Figure 3.77 shows details on the propeller-driven rotor sizing.

Table 3.15: Main rotor results for 5,000 lb aircraft.

R [ft]	28.2
Ω [RPM]	130
ΩR [ft/s]	385
P [hp]	268

Table 3.16: Propeller-driven rotor results for 5,000 lb aircraft with main rotor disk loading of 2 lb/ft².

Propeller Spec	Low Speed Propeller			High Speed Propeller		
R/R_p	20	10	5	20	10	5
R_p [ft]	1.41	2.82	5.64	1.41	2.82	5.64
x_p [%]	48	34	19	57	38	24
λ_{cp}	0.18	0.20	0.19	0.28	0.30	0.31
$\Omega_p R_p$ [ft/s]	1001	643	394	774	486	305
η_p [%]	90	91	90	87	89	89
P_{PDR} [hp]	318	301	299	338	311	304

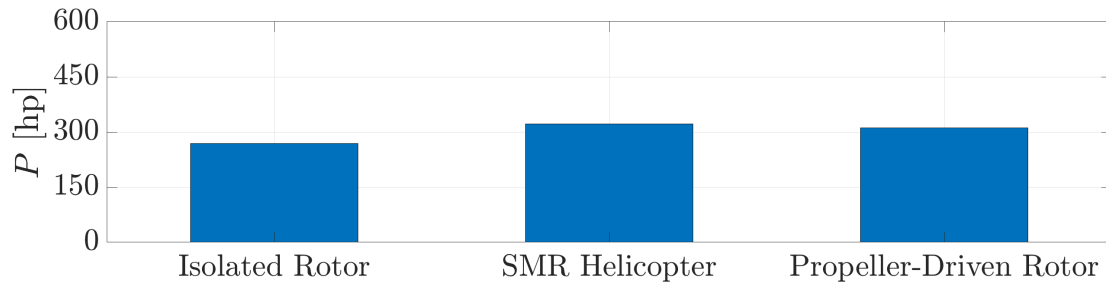
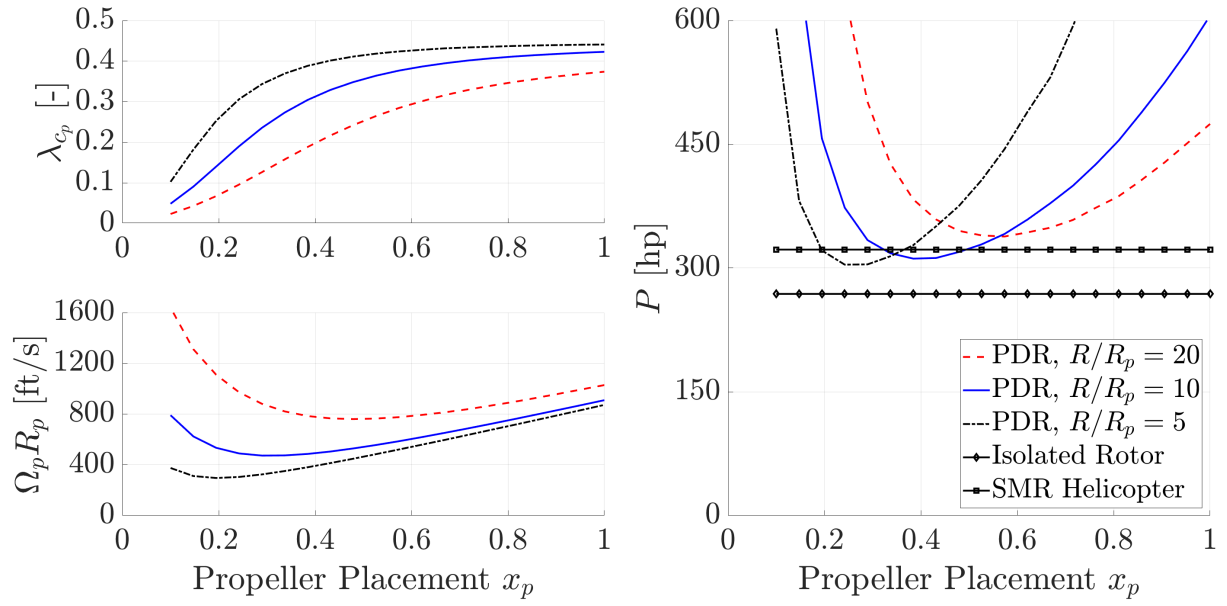
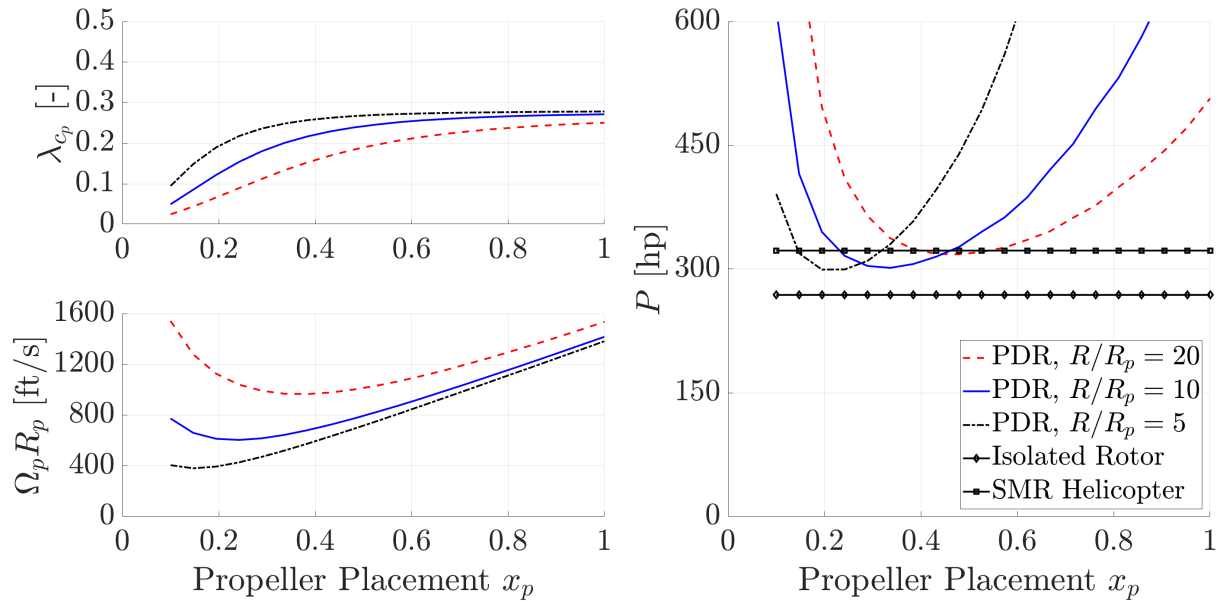


Figure 3.76: Hover power for various configurations at 2 lb/ft² for 5,000 lb aircraft. High-speed propeller with $R/R_p = 10$ shown for propeller-driven rotor configuration.



(a) High speed propeller.



(b) Low speed propeller.

Figure 3.77: Impact of propeller design and placement on propeller-driven rotor results for 5,000 lb aircraft with a main rotor disk loading of 2 lb/ft².

3.7.5 100 lb Aircraft

Finally, the 100 lb aircraft, representative of a notional unmanned system, was sized. Tables 3.15 and 3.16 contain details on the isolated rotor and propeller-driven rotor design. Figure 3.76 compares the hover power for the different configurations, and Figure 3.77 shows details on the propeller-driven rotor sizing.

Table 3.17: Main rotor results for 100 lb aircraft with a disk loading of 2 lb/ft².

R [ft]	4.0
Ω [RPM]	932
ΩR [ft/s]	385
P [hp]	5.4

Table 3.18: Propeller-driven rotor results for 100 lb aircraft with main rotor disk loading of 2 lb/ft².

Propeller Spec	Low Speed Propeller			High Speed Propeller		
R/R_p	20	10	5	20	10	5
R_p [ft]	0.20	0.40	0.80	0.20	0.40	0.80
x_p [%]	48	34	19	57	38	24
λ_{cp}	0.18	0.20	0.19	0.28	0.30	0.31
$\Omega_p R_p$ [ft/s]	1001	643	394	774	486	305
η_p [%]	90	91	90	87	89	89
P_{PDR} [hp]	6.36	6.03	5.99	6.76	6.23	6.08

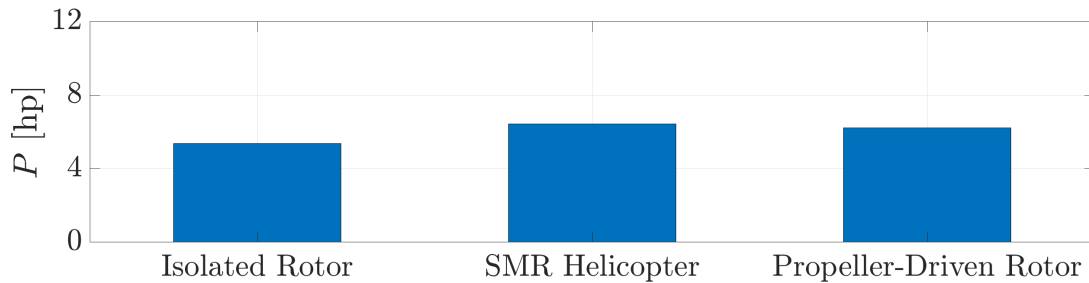
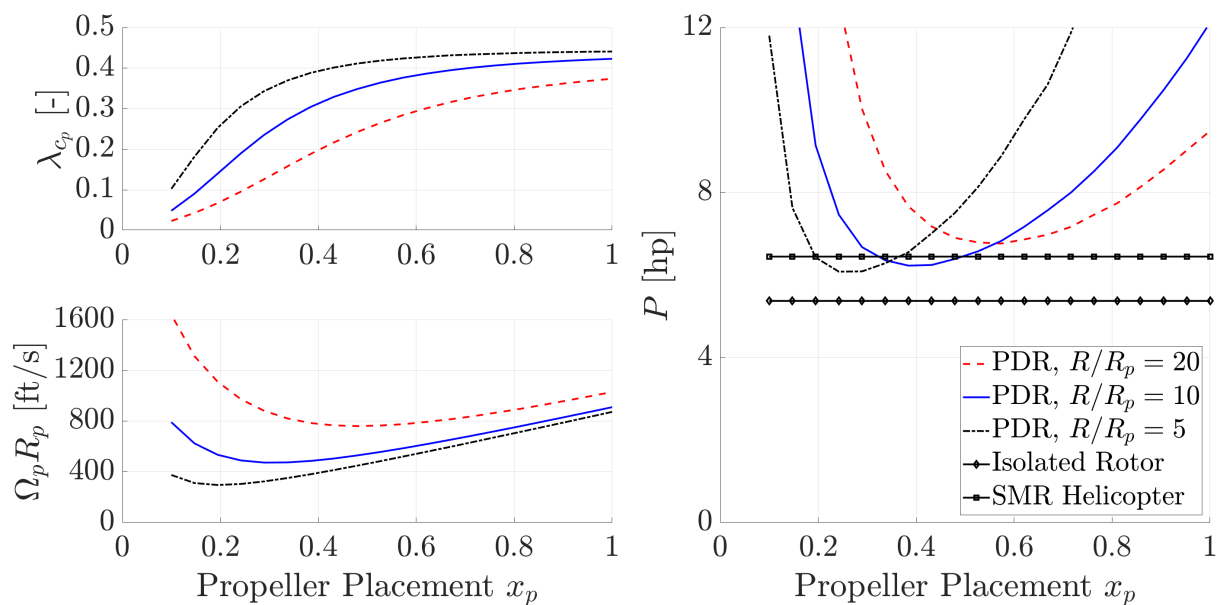
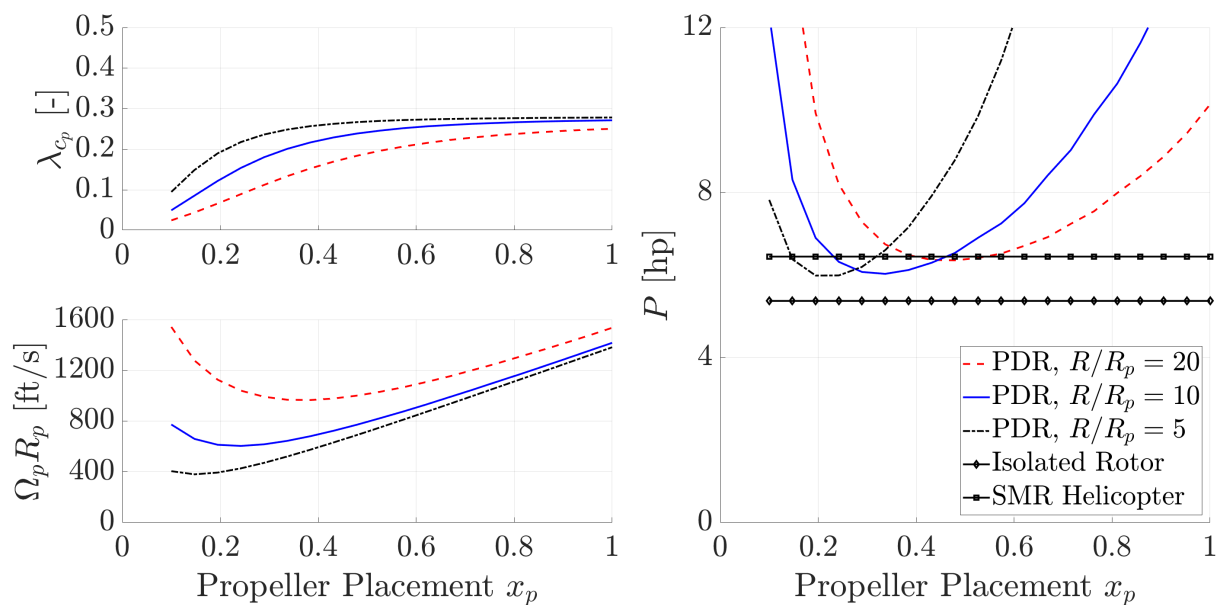


Figure 3.78: Hover power for various configurations at 2 lb/ft² for 100 lb aircraft. High-speed propeller with $R/R_p = 10$ shown for propeller-driven rotor configuration.



(a) High speed propeller.



(b) Low speed propeller.

Figure 3.79: Impact of propeller design and placement on propeller-driven rotor results for 100 lb aircraft with a main rotor disk loading of 2 lb/ft².

3.7.6 Sensitivity to Main Rotor Disk Loading

After completing the scaling results with a disk loading of 2 lb/ft^2 , a sensitivity study was performed to analyze the propeller-driven rotor configuration. The main concern was the rotor and propeller's tip speeds would approach or exceeding Mach 1. Approaching supersonic speeds results in unwanted compressibility effects, such as drag divergence. This concern is investigated in this section.

Figure 3.80 shows the isolated rotor scaling results for a 20,000 lb aircraft as the main rotor disk loading was varied. Note that as the disk loading increases, the main rotor tip speed ΩR increases to close to the speed of sound (roughly 1120 ft/s or 343 m/s at sea-level). A suitable propeller margin tip speed margin is required when considering the main rotor disk loading.

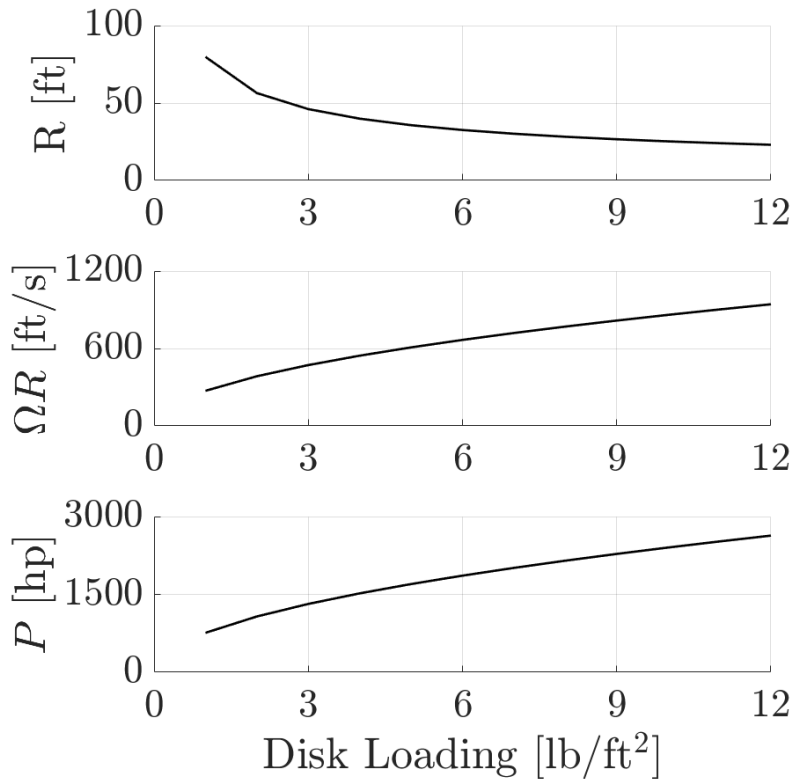


Figure 3.80: Isolated rotor scaling results for 20,000 lb aircraft.

For a feasible design, the propeller-driven rotor helical Mach number M_h should be subsonic. The propeller helical Mach number M_h is comprised of the rotor tip speed at the propeller location $x_p(\Omega R)$ and the propeller tip speed $\Omega_p R_p$, and can be written as:

$$M_h = \frac{\sqrt{(\Omega R)^2 + (x_p \Omega_p R_p)^2}}{a}$$

where a is the speed of sound (1,121 ft/s at sea-level).

A main rotor disk loading of 5 lb/ft² was selected to give the propeller-driven rotor design suitable tip speed margin. The remainder of this section recomputes the previous sizing results with a main rotor disk loading of 5 lb/ft². Table 3.19 shows the isolated main rotor scaling results. Tables 3.20, 3.21, and 3.22 detail the propeller-driven rotor results, Figures 3.81 to 3.83 compare hover power for the different configurations, and Figures 3.84 to 3.86 show the impact of propeller placement and design on propeller-driven rotor performance.

It can be seen that the low speed propeller consistently produced designs that had propeller tip speeds above 1600 ft/s, or at roughly Mach 1.4. The high speed propeller was more forgiving, and consistently produced feasible designs. This indicates that the propeller-driven rotor configuration is very sensitive to main rotor disk loading, and that a lower disk loading should be considered for practical use. Additionally, the single main rotor hover power was comparable to the propeller-driven rotor hover power.

Table 3.19: Main rotor results with a disk loading of 5 lb/ft².

	20,000 lb	5,000 lb	100 lb
R [ft]	35.6	17.8	2.5
Ω [RPM]	162	326	2300
ΩR [ft/s]	608	608	608
P [hp]	1700	425	8.5

Table 3.20: Propeller-driven rotor results for 20,000 lb aircraft with main rotor disk loading of 5 lb/ft².

Propeller Spec	Low Speed Propeller			High Speed Propeller		
R/R_p	20	10	5	20	10	5
R_p [ft]	1.78	3.57	7.14	1.78	3.57	7.14
x_p [%]	48	34	19	57	38	24
λ_{cp}	0.18	0.20	0.19	0.28	0.30	0.31
$\Omega_p R_p$ [ft/s]	1581	1017	623	1227	768	482
η_p [%]	90	91	90	87	89	89
P_{PDR} [hp]	2010	1907	1894	2139	1970	1924

Table 3.21: Propeller-driven rotor results for 5,000 lb aircraft with main rotor disk loading of 5 lb/ft².

Propeller Spec	Low Speed Propeller			High Speed Propeller		
R/R_p	20	10	5	20	10	5
R_p [ft]	0.89	1.78	3.57	0.89	1.78	3.57
x_p [%]	48	34	19	57	38	24
λ_{cp}	0.18	0.20	0.19	0.28	0.30	0.31
$\Omega_p R_p$ [ft/s]	1581	1017	623	1227	768	482
η_p [%]	90	91	90	87	89	89
P_{PDR} [hp]	503	477	473	535	492	481

Table 3.22: Propeller-driven rotor results for 100 lb aircraft with main rotor disk loading of 5 lb/ft².

Propeller Spec	Low Speed Propeller			High Speed Propeller		
R/R_p	20	10	5	20	10	5
R_p [ft]	0.13	0.25	0.50	0.13	0.25	0.50
x_p [%]	48	34	19	57	38	24
λ_{cp}	0.18	0.20	0.19	0.28	0.30	0.31
$\Omega_p R_p$ [ft/s]	1581	1017	623	1227	768	482
η_p [%]	90	91	90	87	89	89
P_{PDR} [hp]	10.05	9.53	9.47	10.70	9.85	9.62

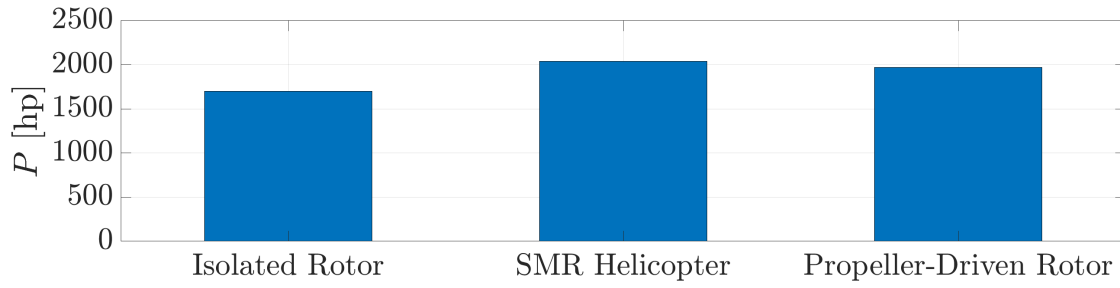


Figure 3.81: Hover power for various configurations at 5 lb/ft² for 20,000 lb aircraft. High-speed propeller with $R/R_p = 10$ shown for propeller-driven rotor configuration.

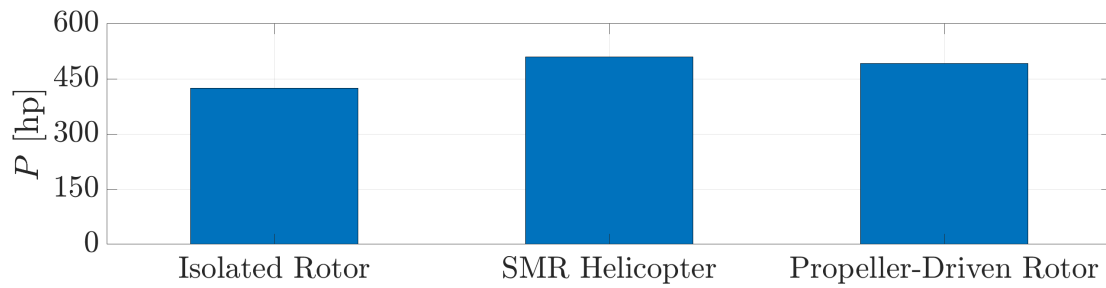


Figure 3.82: Hover power for various configurations at 5 lb/ft² for 5,000 lb aircraft. High-speed propeller with $R/R_p = 10$ shown for propeller-driven rotor configuration.

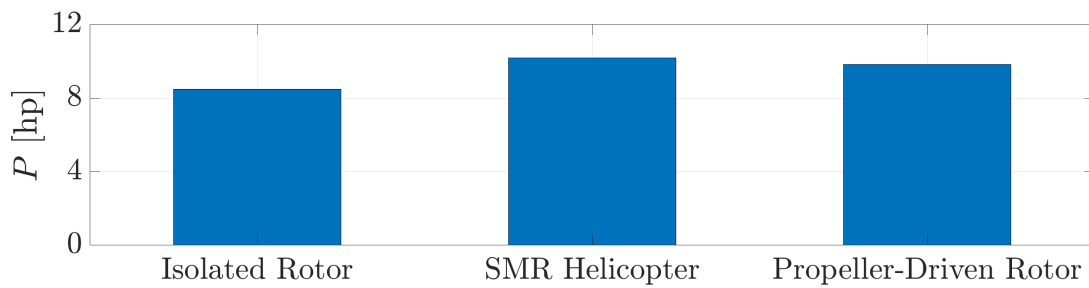
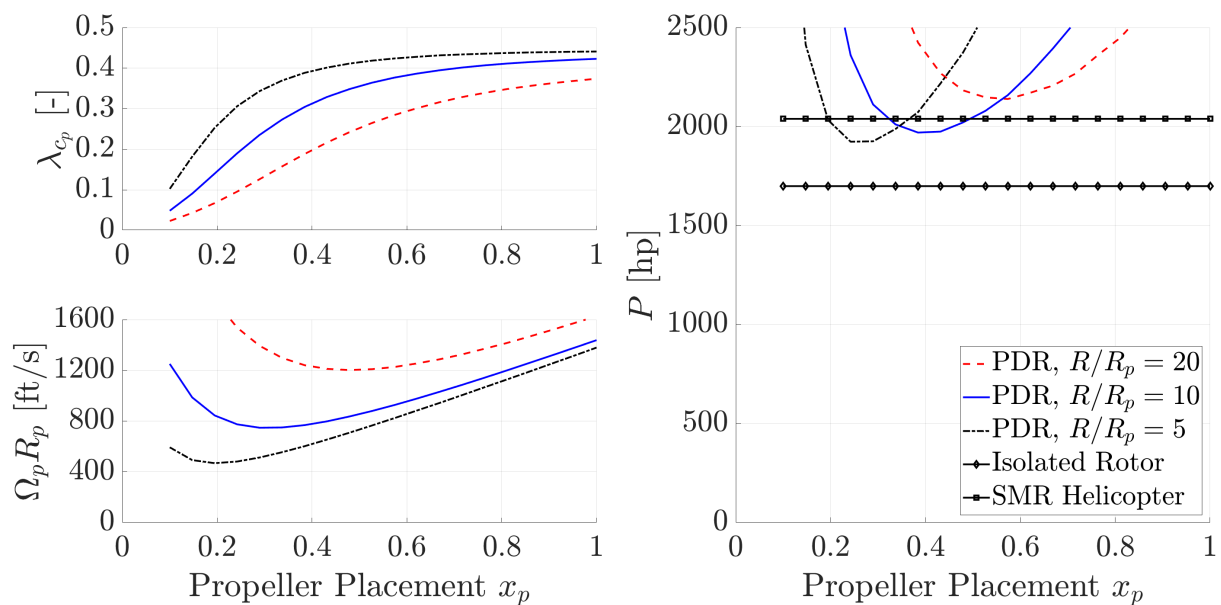
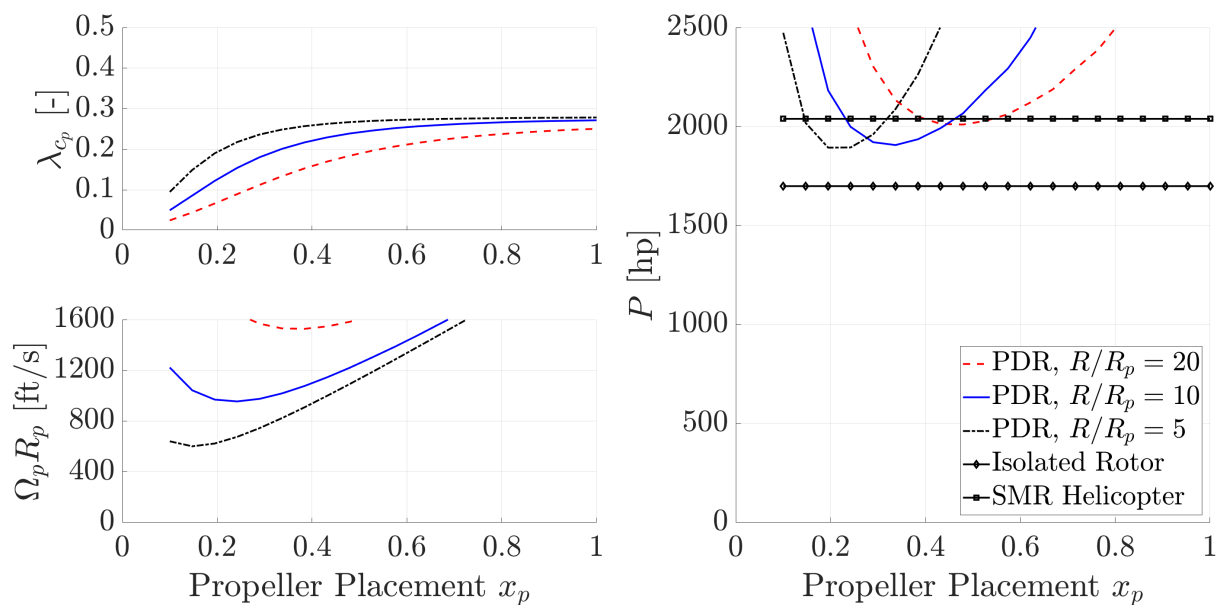


Figure 3.83: Hover power for various configurations at 5 lb/ft² for 100 lb aircraft. High-speed propeller with $R/R_p = 10$ shown for propeller-driven rotor configuration.

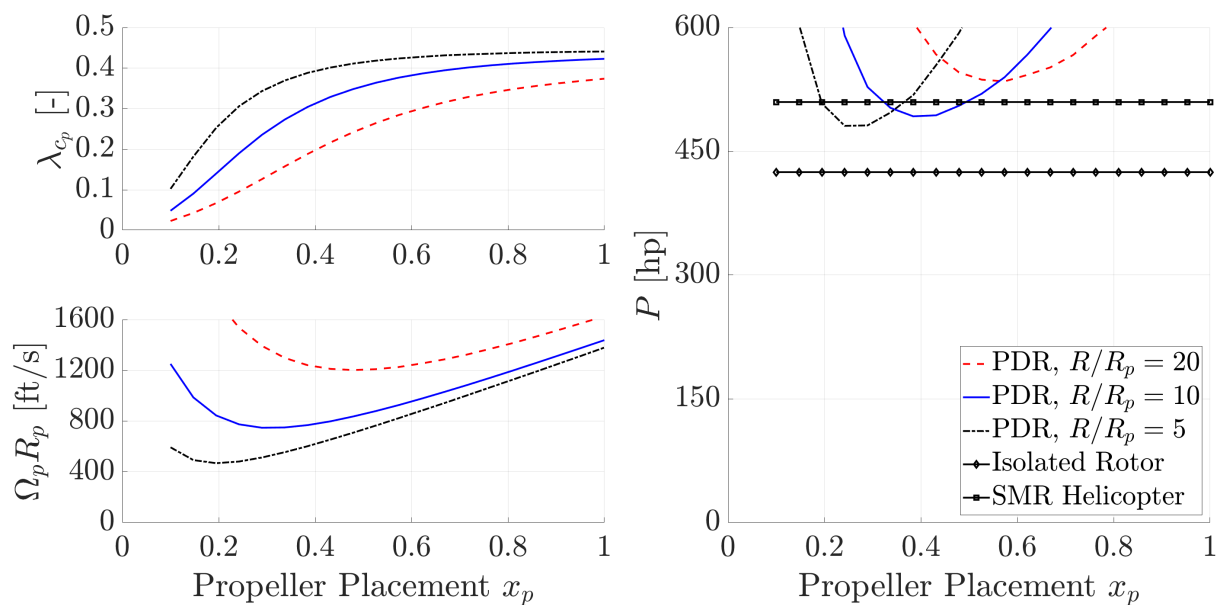


(a) High speed propeller.

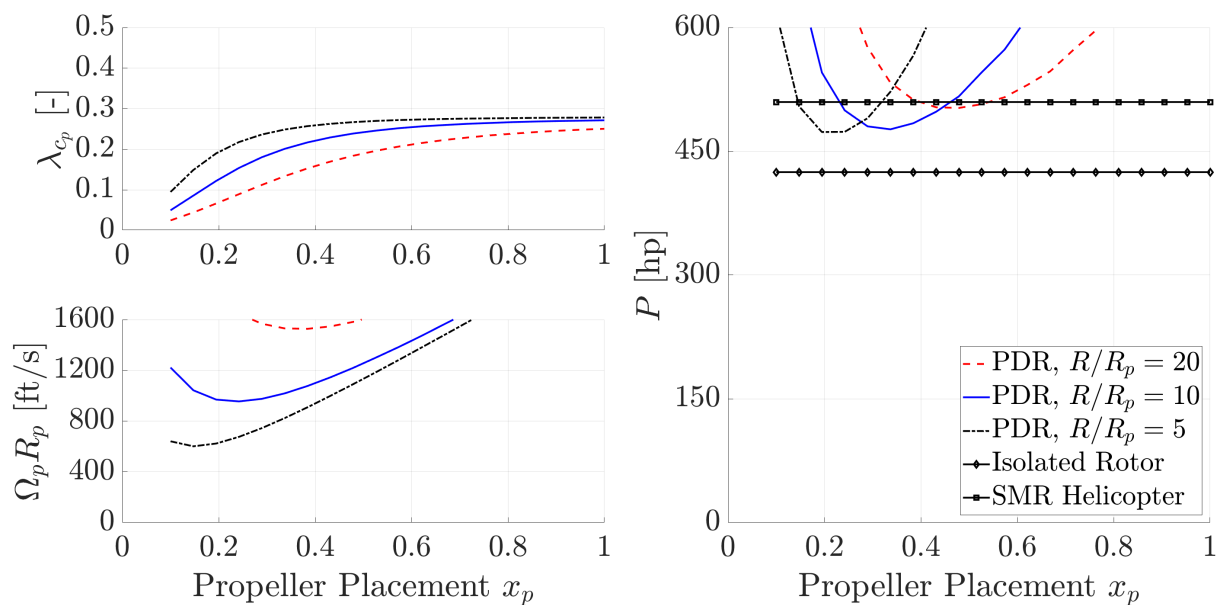


(b) Low speed propeller.

Figure 3.84: Impact of propeller design and placement on propeller-driven rotor results for 20,000 lb aircraft with a main rotor disk loading of 5 lb/ft².

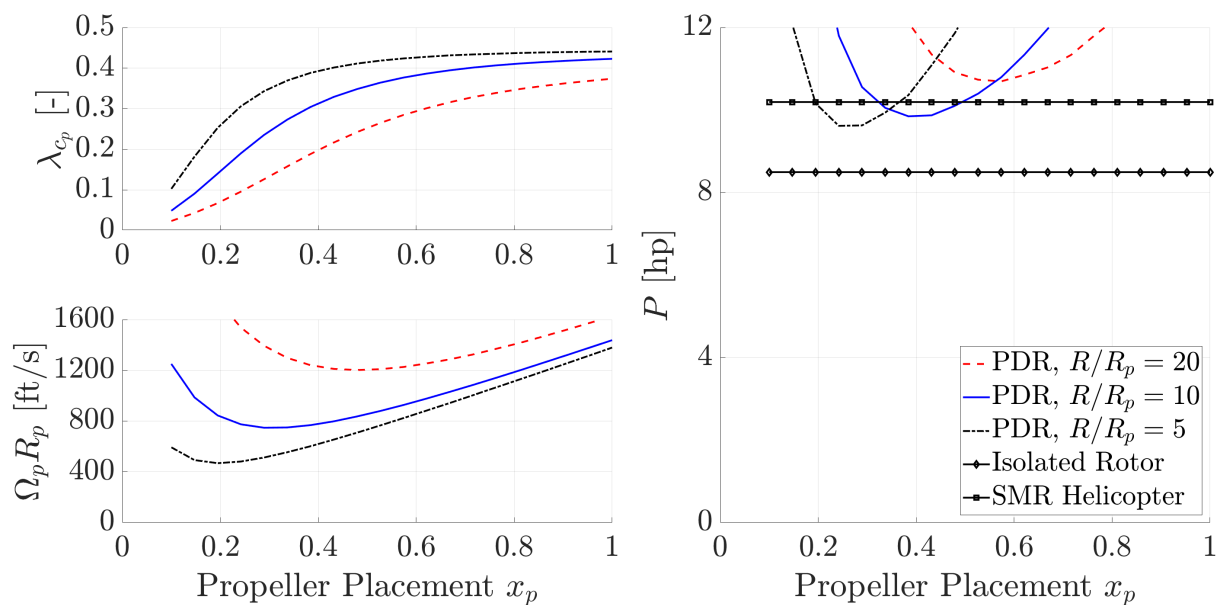


(a) High speed propeller.

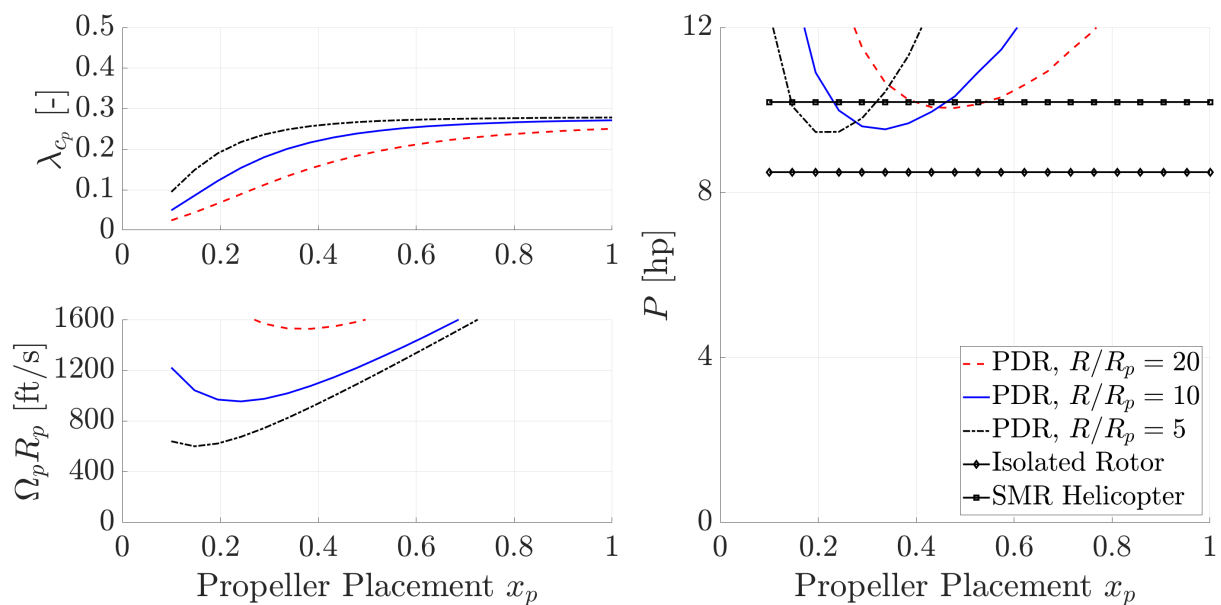


(b) Low speed propeller.

Figure 3.85: Impact of propeller design and placement on propeller-driven rotor results for 5,000 lb aircraft with a main rotor disk loading of 5 lb/ft².



(a) High speed propeller.



(b) Low speed propeller.

Figure 3.86: Impact of propeller design and placement on propeller-driven rotor results for 100 lb aircraft with a main rotor disk loading of 5 lb/ft².

3.7.7 Scaling Remarks

For all the scaling cases considered, a well designed propeller-driven rotor had comparable power to an isolated rotor and a single main rotor helicopter. Well designed refers to two features. First, that the isolated propeller had a high propulsive efficiency. Second, that the propeller was placed at an ideal location on the rotor blade.

Two additional items are present when reviewing the propeller-driven rotor scaling considerations. First, the propeller-driven rotor design was very sensitive to main rotor disk loading. For the 5 lb/ft², the main rotor had a high tip speed of roughly Mach 0.5. As a result, many designs had propeller tip speeds above Mach 1. Additionally, the higher disk loading had a faster main rotor tip speed. For a feasible design, the propeller-driven rotor helical Mach number M_h should be subsonic. As such, a low main rotor disk loading should be considered.

The final comment concerns the ratio of R/R_p , it is desirable to have this ratio as small as possible, corresponding to a larger propeller. From simple momentum theory, this makes intuitive sense. As the propeller disk area increases, the propeller disk loading decreases. Additionally, the larger propeller ($R/R_p = 5$) saw the lowest propeller tip speeds of any propeller sizes for all cases. However if the propeller is too large, the design could potentially become impracticable from a ground clearance and operations perspective. It should also be noted that as propeller size increased, the optimum propeller location shifted closer towards the main rotor root, shifting from 62% for $R/R_p = 20$ to 29% for $R/R_p = 5$.

3.8 Summary and Conclusions

This chapter considered the hover performance and feasibility of the propeller-driven rotor concept. Three hover test stands of various scales were used to investigate aspects of hover performance. The first hover test used the 5.5 ft diameter test stand to examine propeller-driven rotor feasibility by taking high quality commercial-off-the-shelf components and combining them in a logical manner. Basic performance trends were observed, and the propeller-driven rotor hover power was approximately 6.4 times the power of a shaft-driven rotor. Additionally, the first propeller failed during propeller-driven rotor testing due to the swirl phenomenon.

The second hover test, using the 6 ft diameter test stand, investigated tip propeller loads. A 6DOF load cell was attached to the propeller, and propeller loads were measured. The experimental results showed that the propeller experienced significant inertial loading, coming from the rotor centrifugal force and the rotor-propeller Coriolis moment. The comprehensive analysis methodology predicted the propeller hub loads, and had good agreement with the test data. Although a different propeller and nacelle design were used in this second test, propeller-driven rotor hover power was still 6 times larger than a shaft-driven rotor.

The third hover test focused on investigating rotor spanwise propeller placement on propeller-driven rotor performance using the 2.7 ft diameter test stand. Experimental results showed that the tip mounted propeller had twice the electrical power coefficient compared to a propeller located at the midspan. The comprehensive analysis methodology was employed to understand this result, and found similar findings.

A simple analytical model was created to understand the physics of propeller placement. The simple model showed that propeller placement changes the inflow on the propeller, and that the pro-

propeller should be placed at the rotor spanwise location that resulted in peak propeller propulsive efficiency. Each propeller has its own propeller performance curve, and will favor a different spanwise placement compared to another propeller. For the fixed pitch propellers used in this research, that generally occurred around the rotor midspan location. As spanwise propeller location increased, required propeller thrust decreased but all other loads increased significantly.

This simple model was expanded to investigate the scalability of the propeller-driven rotor concept. The change in propeller Reynolds number from 50,000 to 1,000,000 increased the maximum C_l/C_d from 20 to 120, and increased peak propulsive efficiency from 45% to 90%. Isolated rotor, propeller-driven rotor, and single-main rotor helicopter designs for main rotor disk loadings of 2 and 5 ft/lb² were computed. For a well designed propeller and suitable spanwise rotor blade location, the propeller-driven rotor power was similar to the isolated rotor and single-main rotor helicopter designs.

Chapter 4: Dynamics

While the initial focus of the research was on propeller-driven rotor feasibility and performance, it became clear after several broken propellers that propeller-driven rotor dynamics needed to be investigated. This prompted the author to suspend hover testing to investigate the dynamics of spinning a propeller on a spinning rotor blade. It was determined that the rotor-propeller Coriolis interaction resulted in a bending load on the propeller blade. Two separate vacuum chamber experiments were conducted to measure: 1.) the Coriolis impact on propeller flapping motion and, 2.) loads on the propeller hub and rotor blade. The vacuum chamber experiments removed aerodynamics from the experiments, so only inertial loads were present. Based on these findings, the resulting phenomenon has been termed as “propeller-driven rotor swirl phenomenon”.

This chapter focuses on the propeller-driven rotor swirl phenomenon description, and the two vacuum chamber experiments that were used to study it. The remainder of this chapter is as follows. First, the propeller-driven rotor swirl phenomenon is described. Second, a vacuum chamber experiment to measure propeller flapping motion was conducted, and a simplified model was derived. This simple model highlighted the need for a comprehensive rotorcraft model. Third, the impact of the rotor-propeller Coriolis load on rotor blade loads was measured and validated using comprehensive analysis. Next, predicted loads for a propeller during propeller driven rotor operation are compared to an isolated propeller in axial flight. Finally, a brief summary is given and conclusions are made.

4.1 Propeller-Driven Rotor Twirl Phenomenon

This is a general term to describe broken blades for propeller-driven rotors. The rotor-propeller Coriolis interaction plays a key role in this phenomenon, and is especially destructive due to the large rotor and propeller rotational speeds. The understanding of this phenomenon must be built up from first principles. An introduction to this phenomenon is examined using the one-way (i.e. propeller loads on rotor blade torsion) coupling. Further research is needed to investigate the two-way coupling between the rotor and propeller. While the explanation of the physics was developed after the two vacuum chamber experiments, it is presented first here for additional context for the reader.

4.1.1 Broken Propellers During Propeller-Driven Rotor Testing

After hover and wind tunnel testing of the Forum 81 propellers, detailed in Section 2.3.6, the propellers were tested with the propeller-driven rotor test stand shown in Figure 3.20. The purpose of the hover test campaign was to operate at a higher main rotor speed Ω of 400 RPM compared to the 200 RPM of previous tests. Several propellers failed during hover testing of the propeller-driven rotor, mostly around a main rotor speed of 225 RPM and a propeller speed of 4250 RPM. Close inspection of the propeller failure indicated that the propeller spar failed at the propeller root. This was the same observed failure as the Forum 79 propellers that failed during initial feasibility and performance testing, shown earlier in Figure 3.10.

After the initial failure of the 1.5 mm diameter carbon fiber spar for the Forum 81 propellers, the spar diameter was strengthened up to 3.0 mm. The spar diameter was increased to a larger size in an effort to try and quickly move through main rotor 225 RPM region, but without success. In a final effort, a 2.0 mm diameter steel spar was used but that also failed at the same operating region.

Figure 4.1 shows the propeller RPM versus main rotor RPM and the RPM of the main rotor where the propeller failed, and the various propeller designs that failed.

After breaking numerous propellers of various spar sizes and strengths, it was clear that a serious problem was present. The propellers operated at higher thrust values, rotational speeds, and axial flight speeds during isolated propeller characterization, but broke at relatively low speeds on the propeller-driven rotor. The failures prompted a re-examination of the loads acting on the propeller during propeller-driven rotor operation.

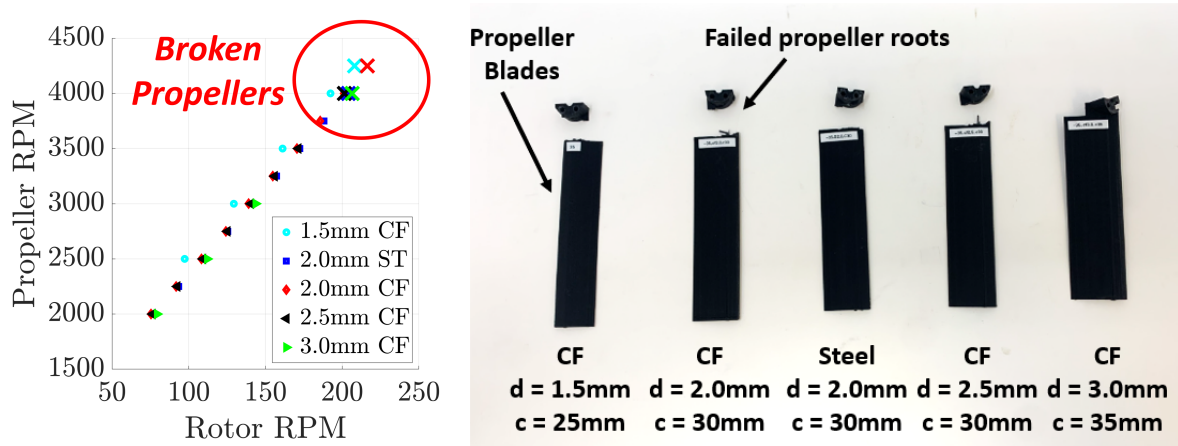


Figure 4.1: Propellers with various spar sizes, spar materials, and propeller chords that failed around 225 rotor RPM and 4250 propeller RPM during propeller-driven rotor testing. X's marks approximate failure location. (c: chord, d: spar diameter, CF: Carbon fiber).

4.1.2 Rotor-Propeller Coriolis Coupling

The Coriolis force (CorF) results from moving mass inwards/outwards in a radial direction during rotation. The classic example is the figure skater pulling their arms inward to spin faster. Consider a mass situated on a rotating disk shown in Figure 4.2a. If the mass moves radially towards the center of rotation, it reaches a location of lower angular momentum. Based on the conservation of angular momentum, the tangential velocity of the mass must increase. The Coriolis force causes the increase

in tangential velocity of the mass. The result is that as the mass moves radially towards the center of rotation, it speeds up in the tangential direction. In Figure 4.2b the situation is reversed - the mass moves outwards and is pushed in the opposite direction of rotation.

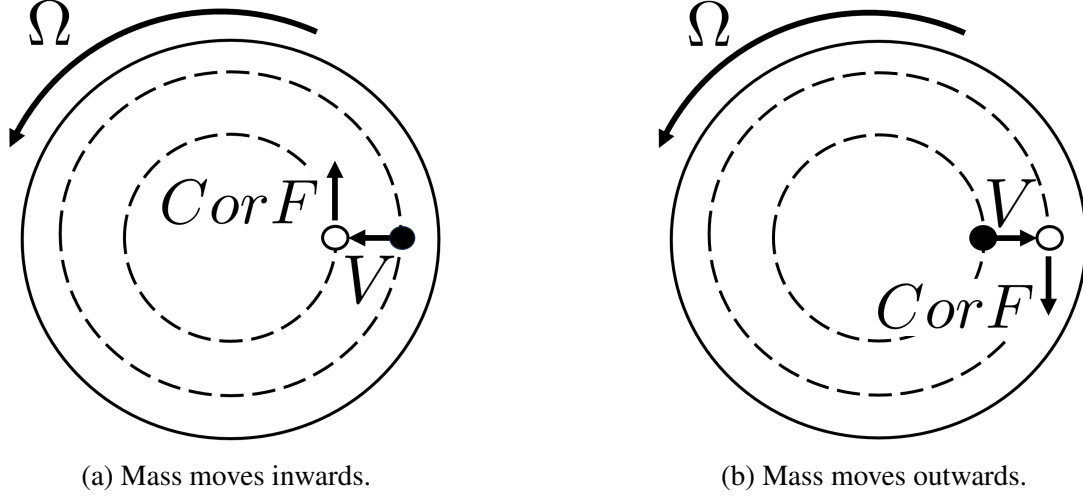


Figure 4.2: Coriolis force ($CorF$) pushes mass depending on radial movement direction.
Top down view.

Figure 4.2 has strong implication for propeller-driven rotor designs. As the propeller spins the propeller blade moves towards and away from the main rotor's center of rotation. This results in the Coriolis force on the propeller blade. Consider a radial point along the propeller r_p , it is moving at a speed $V = \Omega_p r_p$, where Ω_p is the propeller speed. A Coriolis force is generated on the elemental mass $m_p dr_p$ that has the magnitude:

$$CorF = -2m_p \underline{\Omega} \times \underline{V} dr_p \quad (4.1)$$

where m_p is the propeller mass per unit length, $\underline{\Omega}$ is the main rotor rotational speed, $\underline{V}$ is the propeller speed, and the underline denotes a vector.

The Coriolis force acts to bend the propeller, and arises from spinning a propeller on a spinning

rotor blade. Figure 4.3 show how the Coriolis force bends the propeller blade during propeller-driven rotor operation. The value of this Coriolis moment can be relatively large, and it was experimentally found to be 10 times larger than the propeller torque during propeller-driven rotor hover testing. Note that the Coriolis force does not appear during isolated testing, and is only present during propeller-driven rotor operation.

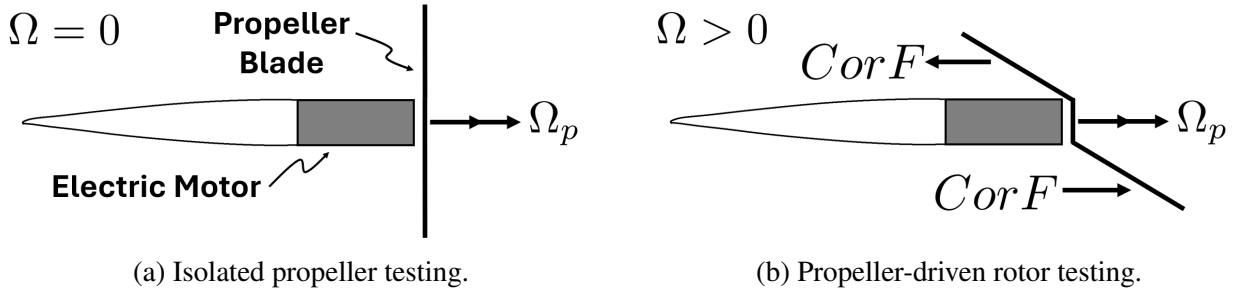


Figure 4.3: Coriolis force appears during propeller-driven rotor testing, and bends the propeller blades. View is from the rotor blade tip looking towards the rotor blade root.

4.1.3 Modeling Propeller Coriolis Moment

An understanding of the dangers of the propeller-driven rotor twirl phenomenon is shown using a simple one-way analytical model. Figure 4.4 shows a 2 bladed propeller spinning on a tip of a rotor blade. The Coriolis moment can be found by examining the $CorF$ acting at some distance $r_p \sin \psi_p$ from the rotor blade torsion axis.

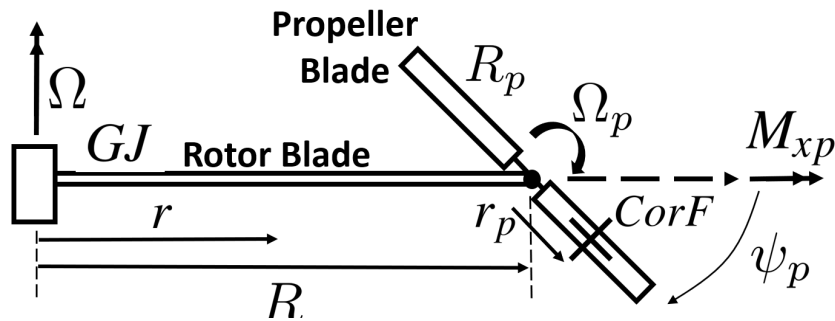


Figure 4.4: Schematic for rotor blade torsion dynamics coupled with a 2 bladed propeller.

Using Figure 4.4 and equation 4.1, one can solve for the propeller hub moment M_{xp} in terms of propeller azimuth angle ψ_p :

$$M_{xp}(\psi_p) = \int_0^{R_p} r_p \sin \psi_p \times Cor F dr_p$$

$$M_{xp}(\psi_p) = 2I_p \Omega \Omega_p \sin^2 \psi_p \quad (4.2)$$

where $I_p = (1/3)m_p R_p^3$ is the propeller flap inertia per propeller blade. Consider a two bladed propeller, the first propeller azimuth is $\psi_{p1} = \psi_p$ and the second propeller blade is located at $\psi_{p2} = \psi_p + \pi$. Summing both blades yields:

$$M_{xp}(\psi_p) = M_{xp,1}(\psi_{p1}) + M_{xp,2}(\psi_{p2})$$

$$M_{xp}(\psi_p) = 2I_p \Omega \Omega_p [\sin^2 \psi_p + \sin^2(\psi_p + \pi)]$$

$$M_{xp}(\psi_p) = 4I_p \Omega \Omega_p \sin^2 \psi_p \quad (4.3)$$

Note that the steady Coriolis moment M_{xp} can be found by integrating equation 4.3 over one propeller revolution:

$$M_{xp} = \frac{1}{2\pi} \int_0^{2\pi} 4I_p \Omega \Omega_p \sin^2 \psi_p d\psi_p$$

$$M_{xp} = 2I_p \Omega \Omega_p \quad (4.4)$$

which is a useful expression to determine the impact a spinning propeller has on the rotor blade torsion axis. Returning to equation 4.3, one can separate it using the trigonometric identity: $\sin^2 \psi_p =$

$(1/2)(1 - \cos 2\psi_p)$:

$$M_{xp}(\psi_p) = 4I_p\Omega\Omega_p\left(\frac{1 - \cos 2\psi_p}{2}\right)$$

$$M_{xp}(\psi_p) = 2I_p\Omega\Omega_p - 2I_p\Omega\Omega_p \cos 2\psi_p \quad (4.5)$$

which has a steady component and a propeller 2/rev component. In this example, the 2/rev originates from the fact that this specific propeller has 2 blades. This forcing can be combined with the rotor blade torsional dynamics.

4.1.4 Rotor Blade Torsion Dynamics

Now the one-way coupling with the rotor blade torsional dynamics are considered. For simplicity, assume that the blade is spinning at some rotor speed Ω in vacuum and has a uniform torsional stiffness GJ . Figure 4.4 shows the main rotor blade with a tip mounted propeller. The rotor blade torsional dynamics are written as:

$$I_\theta(\ddot{\theta} + \Omega^2\theta) - \frac{d}{dr}(GJ\frac{d\theta}{dr}) = M_\theta \quad (4.6)$$

where θ , I_θ , r , M_θ represent the main rotor blade's torsional angle, torsional inertia, radial coordinate, and sectional torsional load.

A direct analytical solution for equation 4.6 is not available. Instead, the main rotor blade torsion dynamics can be studied using approximate methods using the Rayleigh-Ritz energy method. Consider a one term shape function of:

$$\theta(r) = \left(\frac{r}{R} - \frac{1}{2}\left(\frac{r}{R}\right)^2\right)q \quad (4.7)$$

where q is the generalized torsional coordinate. For a cantilevered rotor blade $\theta(0) = d\theta(0)/dr = 0$, indicating that the shape function is permissible. Solving for the main rotor blade's kinetic and potential energies, and using the Euler-Lagrange equation yields:

$$\frac{2}{15}I_{\theta}R\ddot{q} + \left(\frac{1}{3}\frac{GJ}{R} + \frac{2}{15}I_{\theta}R\Omega^2\right)q = Q_{\theta} \quad (4.8)$$

where Q_{θ} is the generalized torsional load. Note that rotor torsional frequency ω_{θ} can be written as:

$$\omega_{\theta}^2 = \frac{15}{6} \frac{GJ}{I_{\theta}R^2} + \Omega^2 \quad (4.9)$$

From this, the non-rotating ($\Omega = 0$) torsional frequency can be found:

$$\omega_{\theta} = \sqrt{\frac{15}{6} \frac{GJ}{I_{\theta}R^2}}$$

The analytical expression for the 1st rotor blade torsional frequency ω_{θ} is:

$$\omega_{\theta} = \frac{\pi}{2} \sqrt{\frac{GJ}{I_{\theta}R^2}}$$

The values for $\sqrt{15/6} = 1.5811$ and $\pi/2 = 1.5708$, indicating that the proposed shape function, equation 4.7, is quite satisfactory.

The inclusion of the rotor-propeller Coriolis moment M_{xp} can be found by considering equation 4.8's generalized torsional load Q_{θ} . This virtual work is the propeller's moment M_{xp} applies to the rotor blade tip:

$$\delta W_{\theta} = Q_{\theta}\delta\theta = M_{xp}\delta\theta_{Tip}$$

using the fact that $\theta_{Tip} = \theta(R) = 1/2$ yields:

$$Q_\theta = \frac{1}{2}M_{xp}$$

Thus, the rotor blade's torsional equation of motion is:

$$\frac{2}{15}I_\theta R\ddot{q} + \left(\frac{1}{3}\frac{GJ}{R} + \frac{2}{15}I_\theta R\Omega^2\right)q = \frac{1}{2}M_{xp} \quad (4.10)$$

4.1.5 Coupling Rotor Torsion w/ Propeller Coriolis Forcing

The following considers the impact of propeller loads on the rotor torsion mode. Inserting the expression for $M_{xp}(\psi_p)$, equation 4.5, into the rotor blade's torsional equation of motion, equation 4.10, yields:

$$\frac{2}{15}I_\theta R\ddot{q} + \left(\frac{1}{3}\frac{GJ}{R} + \frac{2}{15}I_\theta R\Omega^2\right)q = I_p\Omega\Omega_p - I_p\Omega\Omega_p \cos 2\psi_p \quad (4.11)$$

Note that this equation has the form:

$$M\ddot{q} + Kq = F_0 + F \cos(\Omega_F t)$$

with:

$$M = \frac{2}{15}I_\theta R$$

$$K = \frac{1}{3}\frac{GJ}{R} + \frac{2}{15}I_\theta R\Omega^2$$

$$F_0 = I_p\Omega\Omega_p$$

$$F = -I_p \Omega \Omega_p \cos \Omega_F$$

$$\Omega_F = 2\Omega_p$$

which represents a forced harmonic oscillator, with:

$$\omega_\theta^2 = \frac{K}{M} = \frac{15}{6} \frac{GJ}{I_\theta R^2} + \Omega^2$$

which gives the same equation for ω_θ found earlier (equation 4.9). The solution $q(t)$ can be found as:

$$q(t) = \frac{F_0}{M\omega_\theta^2} + \frac{F/M}{1 - (\frac{\Omega_F}{\omega_\theta})^2} \cos \Omega_F t \quad (4.12)$$

$$q(t) = q_0 + q_F(t)$$

containing both a steady component q_0 and a time varying component $q_F(t)$. Figure 4.5 shows the magnitude of the amplitude of the time varying response. The resonance condition occurs at $\Omega_F = 2\Omega_p = \omega_\theta$, or simply:

$$\Omega_p = \frac{1}{2}\omega_\theta \quad (4.13)$$

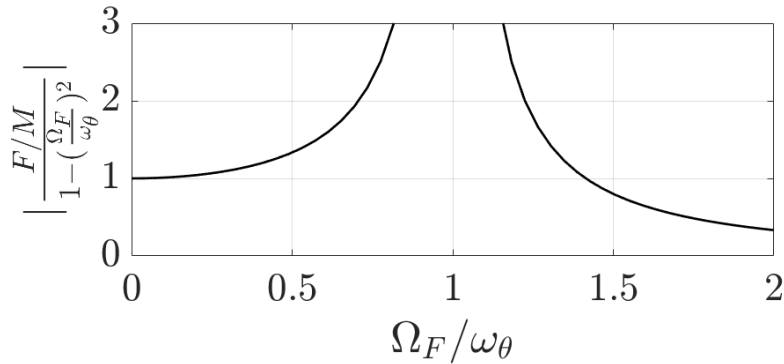


Figure 4.5: Magnitude of simple harmonic oscillator response with no damping.

4.1.6 Impact of Number of Propeller Blades N_{bp}

The previous analysis assumed a 2 bladed propeller. However, analytically varying the number of propeller blades leads to a well known result but interesting in the context of a propeller-driven rotor. When calculating the total moment about the main rotor blade torsional axis M_{xp} , it is the sum of all the individual moments $M_{xp,i}$ of each propeller blade:

$$M_{xp}(\psi_p) = \sum_{i=1}^{N_{bp}} M_{xp,i}$$

$$M_{xp}(\psi_p) = 2I_p\Omega\Omega_p \sum_{i=1}^{N_{bp}} \sin^2 \psi_{pi}$$

where N_{bp} is the number of propeller blades for each propeller. The propeller azimuth ψ_{pi} for each propeller blade is:

$$\psi_{pi} = \psi_p + \frac{2\pi(i-1)}{N_{bp}}$$

Using these observations, an interesting trend emerges when examining the variation in the number of blades, shown in Table 4.1.

Table 4.1: Impact of number of propeller blades N_{bp} .

N_{bp}	$\sum_{i=1}^{N_{bp}} \sin^2 \psi_{pi}$
1	$\sin^2 \psi_p$
2	$2 \sin^2 \psi_p$
3	$3/2$
4	2
5	$5/2$
N_{bp}	$N_{bp}/2$

This is significant for $N_{bp} > 2$ as now there is no harmonic oscillating component to M_{xp} . This

eliminates the main rotor blade torsion resonance as there are no oscillatory propeller hub loads for more than 2 bladed propellers. However, increasing the number of propellers N_{bp} increases the total propeller inertia $N_{bp}I_p$ and thus increases the total steady propeller load M_{xp} to:

$$M_{xp} = N_{bp}I_p\Omega\Omega_p \quad (4.14)$$

This indicates that spinning the rotor, propeller, or increasing the number of propeller blades can result in a steady torsional load that can exceed the rotor blade's torsional strength.

4.1.7 Propeller-Driven Rotor Twirl Failure Modes

This simple one-way, analysis has presented two failure modes for a propeller-driven rotor, one static and the other dynamic:

- **Rotor blade torsional static failure** - Much like any static beam, a rotor blade can break statically if the applied load exceeds its torsional strength. Here, M_{xp} increases with the number of propeller blades N_{bp} , the propeller/rotor speeds, or from a reduction in rotor blade torsional strength.
- **Rotor blade torsional resonance** - For a 2 bladed propeller, operating at $2\Omega_p = \omega_\theta$ resulting in forcing the system at the rotor blade torsion resonance condition. Increasing the number of propeller blades above 2 removes this dynamic failure.

In addition to the main rotor blade static and dynamic failure modes from propeller loads, the rotor motion effects on propeller loads (known as two-way coupling) must also be studied. The presented one-way analysis indicated that the main rotor blade could fail, which is unlikely. During the

hover tests, the propeller blades failed. The modeling of such a case requires two way coupling. In this case, the torsional motion of the main rotor blade acts as forcing motion of the propeller hub. Increasing oscillatory motion of the propeller hub results in increased propeller loads. This is the suspected failure mode of the propellers in Figures 3.10 and 4.1. The rotor motion-propeller loads failure modes requires further analysis and will be the subject of future work.

Finally, the role of aerodynamics have not been investigated in this analysis. The twirl phenomenon was studied in a vacuum chamber where a motor spins the main rotor, hence no aerodynamics. Aerodynamics can act to dampen oscillatory motion (such as rotor hover flap damping). However, aerodynamics can also add energy to the system (such as flutter). Further work is needed to address this issue. Now that these rotor-propeller interactions have been discussed, the next sections will present the two vacuum chamber experiments and comprehensive modeling efforts.

4.2 Vacuum Chamber Experiment #1: Propeller Flapping Characterization

This vacuum chamber experiment was carried out to shed light on the effects of the Coriolis moment on propeller motion. There were two objectives for this vacuum chamber experiment. First, to experimentally measure the Coriolis bending on the propeller blade. Second, to generate experimental data that was used to validate a simple analytical model of the propeller motion.

The University of Maryland's 10 ft diameter vacuum chamber, shown in Figure 4.6, can pump out air from inside the tank and hold it at 1% atmosphere pressure for an extended period of time. This chamber is often used to investigate structural dynamic properties of rotor blades without aerodynamic forces. For this experiment, removing the air from the tank allows the inertial loads to be isolated. Inside the vacuum chamber, any motion or bending of the propeller blades arises solely from the

inertial couplings of the rotor-propeller system.



Figure 4.6: University of Maryland's 10 ft diameter vacuum chamber.

Figure 4.7 shows a schematic of the experimental setup inside the vacuum chamber. The setup was designed to rotate a propeller at the end of a rotor and record the resulting propeller blade motion. In the vacuum chamber, both the rotor and the propeller were driven by separate motors, allowing the rotor speed Ω and propeller speed Ω_p to be adjusted independently.

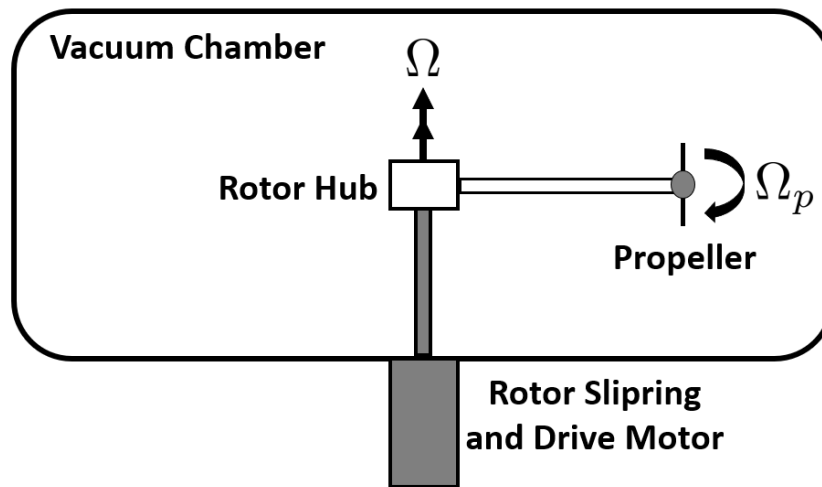


Figure 4.7: Vacuum chamber experiment setup.

4.2.1 Experiment Description

The propeller flapping experiment was designed to measure the propeller flapping β_p as a function of the propeller azimuth ψ_p . Figure 4.8 shows the definition of propeller flapping β_p and the propeller azimuth ψ_p . The propeller blades were attached to an articulated propeller hub. Encoders on the propeller hub measured the propeller flapping angle.

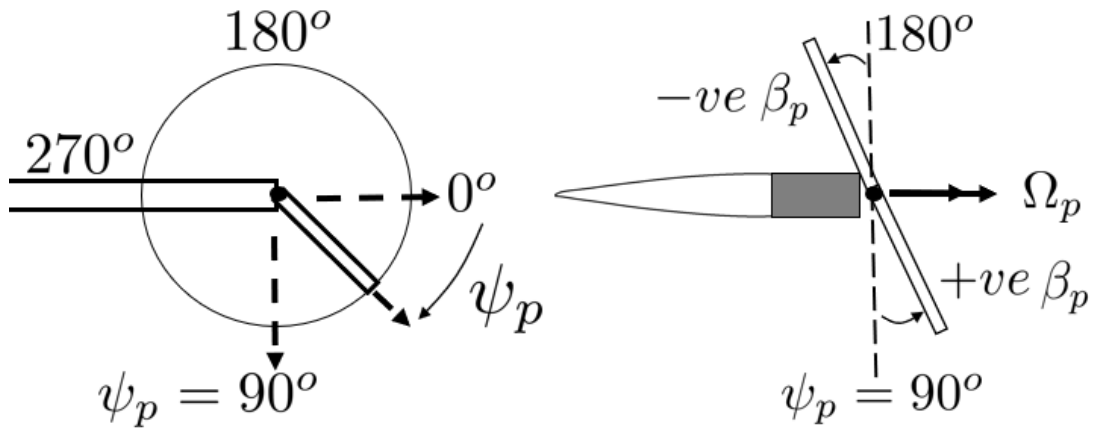


Figure 4.8: Definition of propeller flapping β_p and propeller azimuth ψ_p .

Figures 4.9 and 4.10 show the experimental test stand that was fabricated to study the propeller flapping motion inside the vacuum chamber. Figure 4.11 shows the experimental test stand mounted on the rotor hub inside the vacuum chamber. Table 4.2 presents the physical parameters of the setup.

Magnetic encoders on the propeller blades measure the angle that the propeller experiences relative to the propeller hub. A propeller slipring passed the propeller flap encoder signals from the rotating propeller hub to the rotor. A second slipring connects all signals from the rotor hub to the fixed frame outside the vacuum chamber. The “rotor blade” for this setup was a rigid extruded aluminum beam that allowed for easy mounting of the propeller assembly.

A motor controller was mounted to the rotor hub and controlled the propeller drive motor. The ODrive Pro motor controller was used as it enabled accurate low speed control of the motor. The propeller motor was aligned with the rotor blade and connected to the propeller shaft via a set of right angle bevel gears. A propeller azimuth encoder recorded the rotation of the propeller shaft, and thus the propeller azimuthal location ψ_p .

Table 4.2: Parameters for the propeller flapping experiment.

Rotor Radius, R	11.5 in
Propeller Radius from flap hinge, R_p	5.157 in
Propeller flap offset, e_p	0.866 in
Propeller forward offset, h	3 in
Propeller blade mass, mR_p	8.5 grams
Propeller hinge stiffness, K_p	0.0866 Nm/rad
Rotor RPM, Ω	75, 100 RPM
Propeller RPM, Ω_p	160-240 RPM

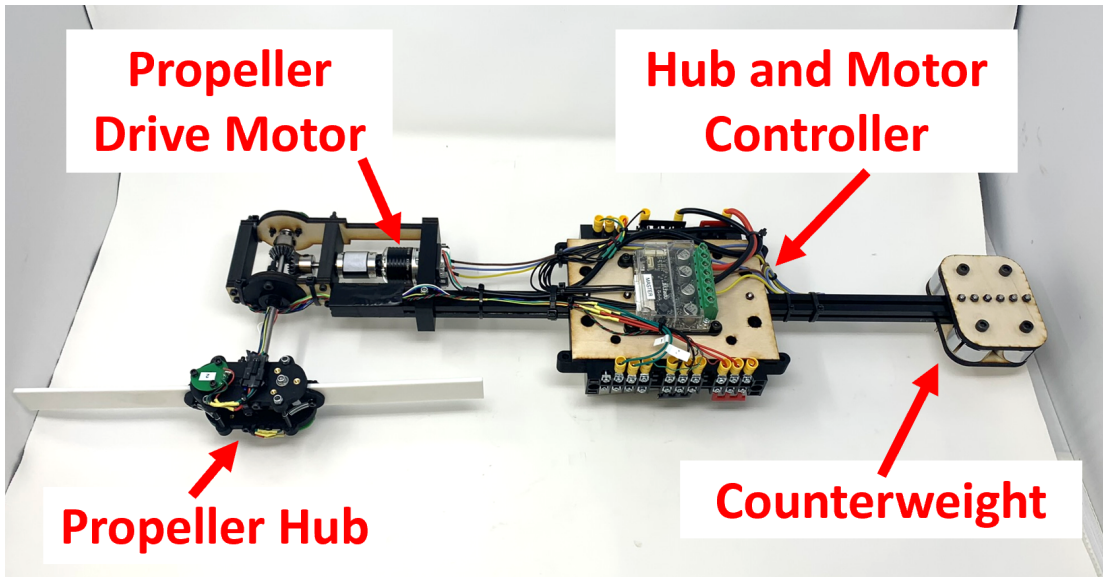


Figure 4.9: Propeller flapping experiment.

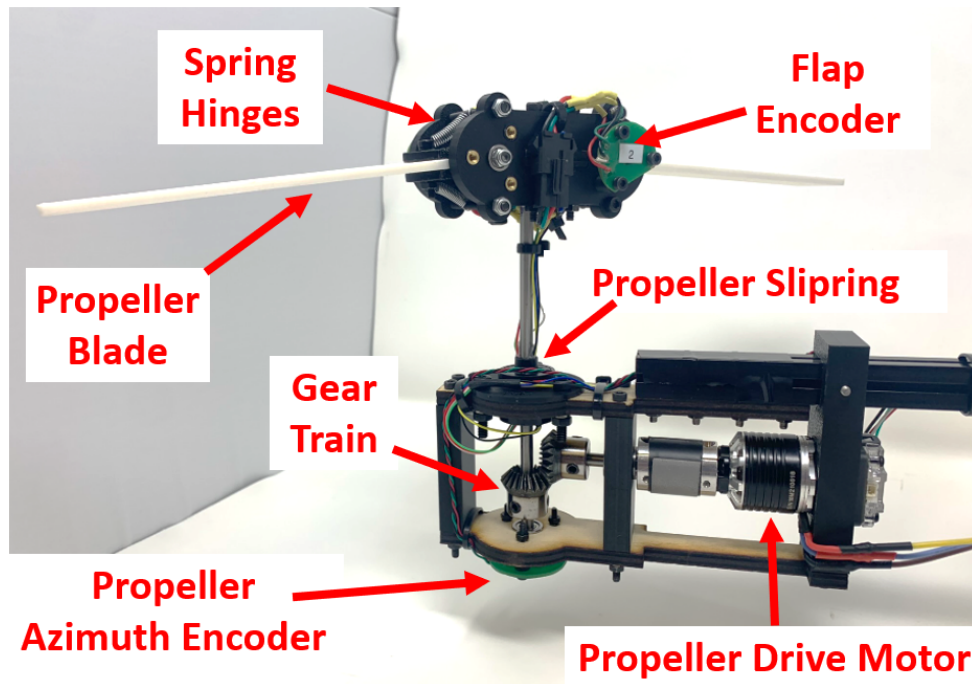


Figure 4.10: Closeup of the articulated propeller hub.

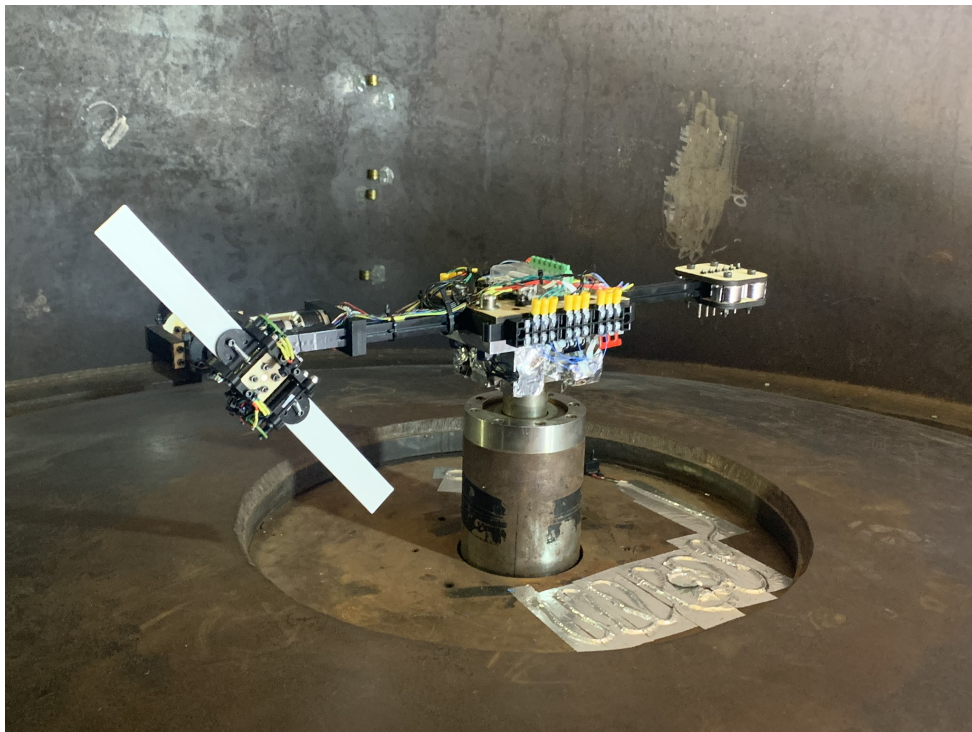


Figure 4.11: Propeller flapping experiment mounted inside the vacuum chamber.

4.2.2 Propeller Flapping Experimental Results

The system was tested at rotor speeds Ω of 75 and 100 RPM, and at propeller speeds Ω_p between 160 to 240 RPM. Figure 4.12 shows the periodic flapping results over one propeller revolution for both propeller blades. Figure 4.13 shows the experimental results over a range of rotor and propeller speeds. For each case, the rotor speed was set and then the propeller speed was adjusted. Tables 4.3 and 4.4 shows the maximum flapping angle recorded for each case.

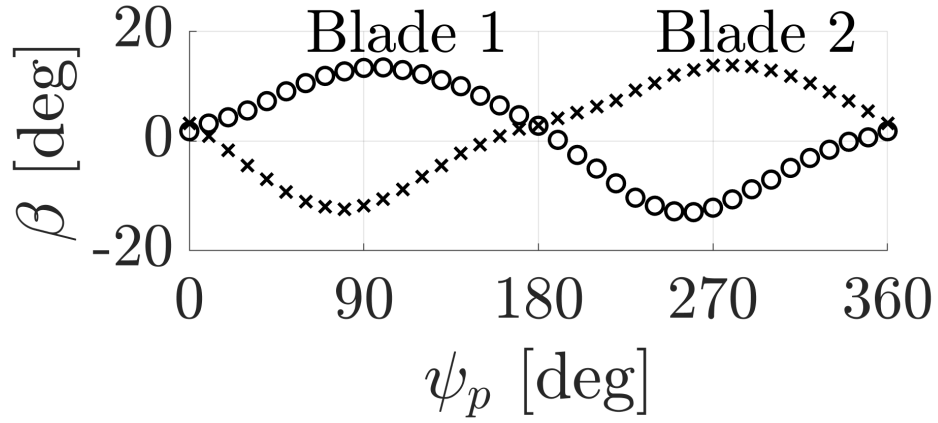


Figure 4.12: Propeller flapping results for both propeller blades at $\Omega = 75$ RPM and $\Omega_p = 180$ RPM.

Table 4.3: Maximum flapping angle for $\Omega = 75$ RPM.

Ω_p [RPM]	$\max(\beta_p)$ [deg]
160	13.1
180	13.5
200	14.6
220	18.5

Table 4.4: Maximum flapping angle for $\Omega = 100$ RPM.

Ω_p [RPM]	$\max(\beta_p)$ [deg]
180	19.0
200	20.0
220	22.2
240	24.3

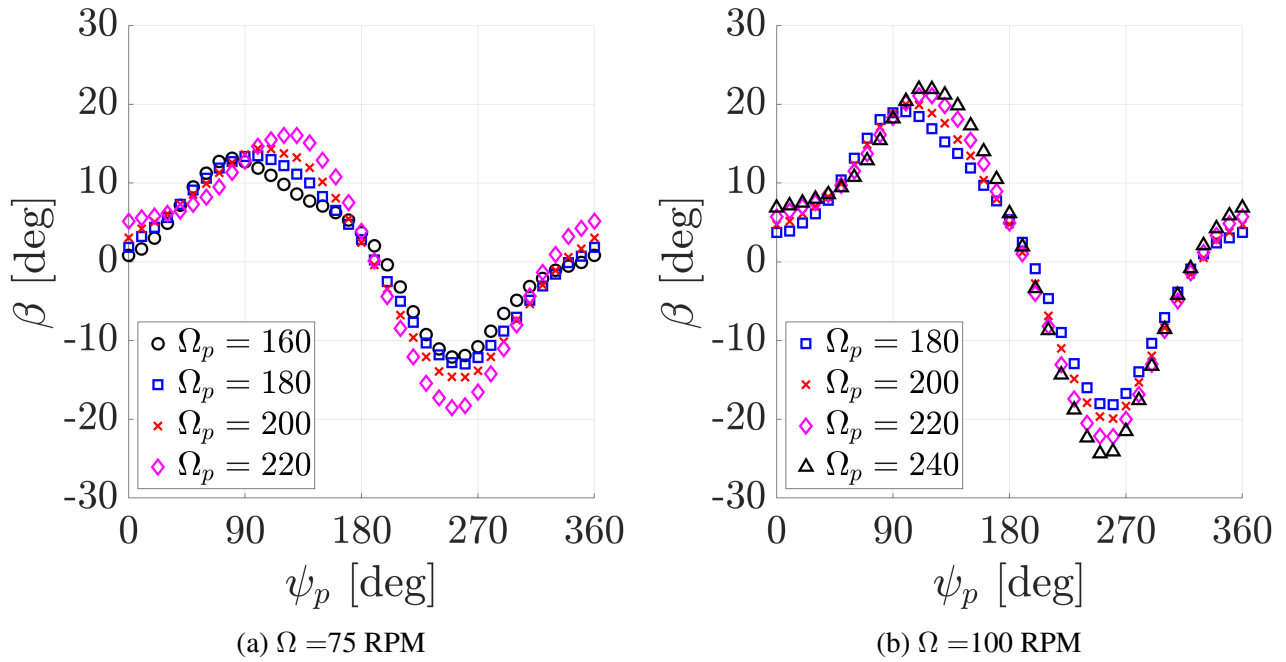


Figure 4.13: Propeller flapping motion due to inertial loading in the vacuum chamber. Speeds given in RPM.

From Figure 4.13, Table 4.3, and Table 4.4, several observations can be made:

- The response is sinusoidal in nature.
- The response agrees with the qualitative prediction shown earlier in Figure 4.4.
- For a given rotor speed, increasing the propeller speed increased the maximum flap deflection.
- For a given propeller speed, increasing the rotor speed increased the maximum flap deflection.

In the next section, an analytical model was developed to describe the propeller flapping motion.

4.2.3 Propeller Flapping Motion Analytical Model

To gain insight into the physics of the propeller flapping motion, a simple analytical model was derived from first principles. The overall objective of this section is to model the propeller flapping motion β_p in a vacuum. The final result of this derivation will be the propeller blade flapping equation of motion for a propeller-driven rotor in a vacuum. After the derivation, several solution methods are presented and the predicted results are compared to the experimental results.

The propeller blade flapping equation of motion was derived by defining the position, velocity, and acceleration of a point P on the propeller blade and then integrating the inertial loads over the propeller radius. Figure 4.14 shows an overview of the key variables.

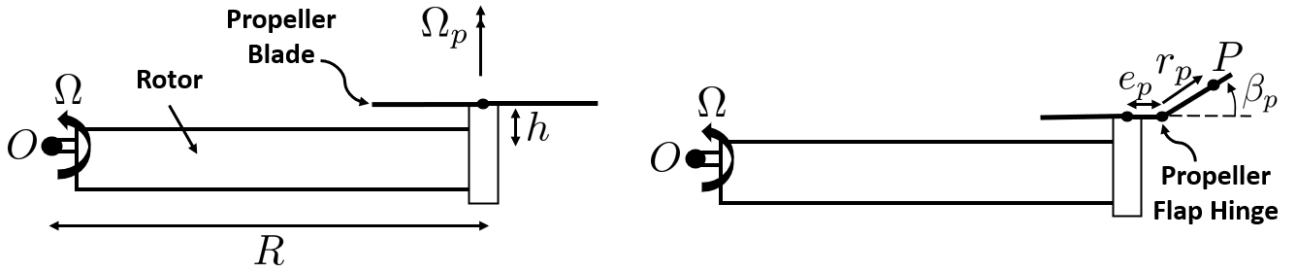


Figure 4.14: Parameters for the propeller flapping model.

The modeling steps are as follows:

1. Define the reference frames of interest.
2. Find the position $\underline{R}_P$, velocity $\underline{V}_P$, and acceleration $\underline{A}_P$ of point P on the propeller blade.
3. Find the inertial moment M_I about the flap hinge by integrating the acceleration of point P along the propeller blade.

Following these steps results in the following inertial moment M_I about the propeller flap hinge:

$$\begin{aligned}
M_I = & I_p \ddot{\beta}_p + (S_p(e_p + R)\Omega^2 \cos \psi_p + I_p \Omega^2 \cos^2 \psi_p + I_p(\Omega_p^2 - \Omega^2) + e_p S_p \Omega_p^2) \beta_p \\
& - S_p h \Omega^2 - 2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p
\end{aligned} \tag{4.15}$$

where $I_p = (1/3)m_p R_p^3$, $S_p = (1/2)m_p R_p^2$, h is the propeller offset ahead of the main rotor 1/4 chord location, m_p is the propeller blade mass per span, and e_p is the propeller flap hinge offset. Note that the Coriolis term in inertial moment M_I equation is:

$$CorF = -2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p \tag{4.16}$$

where the $I_p + e_p S_p$ is the equivalent inertia due to flap hinge offset e_p and the $\sin \psi_p$ term denotes whether the propeller blade is moving towards or away from the main rotor center of rotation. Next, the propeller flapping equation of motion can be found by examining the moments acting on the propeller flapping hinge, shown in Figure 4.15.

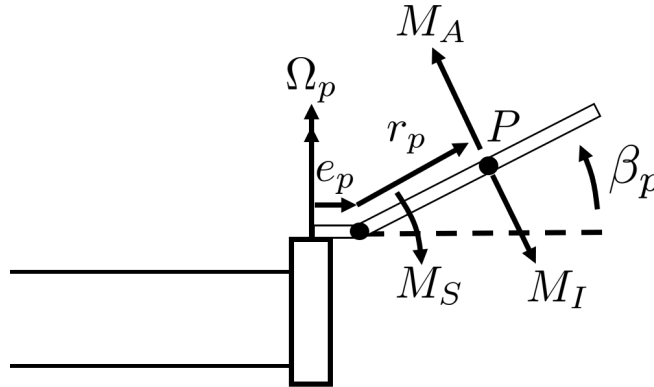


Figure 4.15: Moments acting on the propeller flapping hinge.

From Figure 4.15, the sum of the moments on the propeller flap hinge is:

$$M_I + M_A = M_S \quad (4.17)$$

where M_I is the inertial moment, M_A is the aerodynamic moment, and M_S is the flap hinge spring restoring moment. The aerodynamic moment M_A is zero because of the vacuum chamber and the flap hinge restoring moment is simply:

$$M_S = k_p \beta_p \quad (4.18)$$

Combining the expression for the inertial moment M_I , equation 4.15, and the flap hinge spring moment, equation 4.18, with the moment balance about the flap hinge, equation 4.17, yields the propeller flapping equation of motion:

$$\begin{aligned} I_p \ddot{\beta}_p + (S_p(e_p + R)\Omega^2 \cos \psi_p + I_p \Omega^2 \cos^2 \psi_p + I_p(\Omega_p^2 - \Omega^2) + e_p S_p \Omega_p^2 + K_\beta) \beta_p \\ = S_p h \Omega^2 + 2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p \end{aligned} \quad (4.19)$$

The main rotor rotation Ω has several impacts on the propeller flapping equation of motion. First, there are additional propeller stiffness terms $S_p(e_p + R)\Omega^2 \cos \psi_p$ and $I_p \Omega^2 \cos^2 \psi_p$. Second, the main rotor rotation Ω reduces the propeller stiffness by $I_p(\Omega_p^2 - \Omega^2)$. Third, a constant $S_p h \Omega^2$ is present on the right hand side of the equation. Finally, the main rotor rotation Ω is present in the Coriolis coupling term $2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p$. The solutions to equation 4.19 are studied in the following sections.

4.2.4 Solutions to the Propeller Flapping Equation of Motion

Three different methods were utilized to study the response of the propeller flapping equation (equation 4.19):

1. Numerical Periodic Solution - An optimization scheme was employed to numerically determine the periodic coefficients that best satisfy the propeller flapping equation of motion.
2. Time Marching - The propeller flapping equation of motion was numerically integrated using MATLAB's *ode45* function. This method captured nonlinearities and the impacts of individual terms.
3. Harmonic Balance Method - The periodic coefficients were directly inserted into the equation of motion and solved for analytically. This method was tedious but provides physical insight into the propeller flapping motion.

4.2.4.1 Method 1: Numerical Periodic Solution

For a periodic response, the propeller flap response β_p is de-constructed into a constant term β_0 , a lateral cyclic term β_{1c} , and a longitudinal cyclic term β_{1s} :

$$\beta_p(\psi_p) = \beta_0 + \beta_{1c} \cos \psi_p + \beta_{1s} \sin \psi_p \quad (4.20)$$

The objective of the numerical periodic solution method is to determine the β_0 , β_{1c} , and β_{1s} terms for the propeller. Using equation 4.20, the time derivatives of the flap motion are:

$$\dot{\beta}_p(\psi_p) = \Omega_p(-\beta_{1c} \sin \psi_p + \beta_{1s} \cos \psi_p) \quad (4.21)$$

$$\ddot{\beta}_p(\psi_p) = -\Omega_p^2(\beta_{1c} \cos \psi_p + \beta_{1s} \sin \psi_p) \quad (4.22)$$

A numerical optimization scheme was employed to find the periodic coefficients. This scheme was simple to implement, does not require small angle assumptions, and could be easily extended to include the propeller aerodynamic moment.

Consider the hinge moment balance, equation 4.17:

$$M_I + M_A = M_S$$

$$0 = M_I + M_A - M_S$$

For any given values of β_0 , β_{1s} , and β_{1c} , there will be a residual error $\epsilon(\psi_p)$ for each propeller azimuth ψ_p in the hinge moment balance equation:

$$\epsilon(\psi_p) = M_I + M_A - M_S$$

Equations 4.18 and 4.15 were used to calculate the hinge and inertial moments, respectively, for each propeller azimuth ψ_p . This residual error was transformed into its harmonic components over one propeller revolution:

$$\epsilon_0 = \int_0^{2\pi} \epsilon(\psi_p) d\psi_p \quad (4.23)$$

$$\epsilon_{1c} = \int_0^{2\pi} \epsilon(\psi_p) \cos \psi_p d\psi_p \quad (4.24)$$

$$\epsilon_{1s} = \int_0^{2\pi} \epsilon(\psi_p) \sin \psi_p d\psi_p \quad (4.25)$$

where these integrals were calculated numerically. An optimization scheme was employed that seeks

to minimize the error vector:

$$\underline{\epsilon} = \begin{bmatrix} \epsilon_0 \\ \epsilon_{1c} \\ \epsilon_{1s} \end{bmatrix} \quad (4.26)$$

by minimizing the total error J :

$$J = \underline{\epsilon}^T \underline{\epsilon} \quad (4.27)$$

Using this scheme, the optimizer adjusted values for β_0 , β_{1s} , and β_{1c} until a minimum error was achieved. MATLAB's *fmincon* optimizer was used and executed quickly. Figure 4.16 shows the results for numeric periodic solution results for the $\Omega = 75$ RPM, $\Omega_p = 200$ RPM case. The predicted results show good agreement with the experimental results. Using this solution method, $\beta_0 = 1.6^\circ$, $\beta_{1c} = -0.2^\circ$, and $\beta_{1s} = 16.2^\circ$. This solution method captures the large sinusoidal response that was observed in the test data.

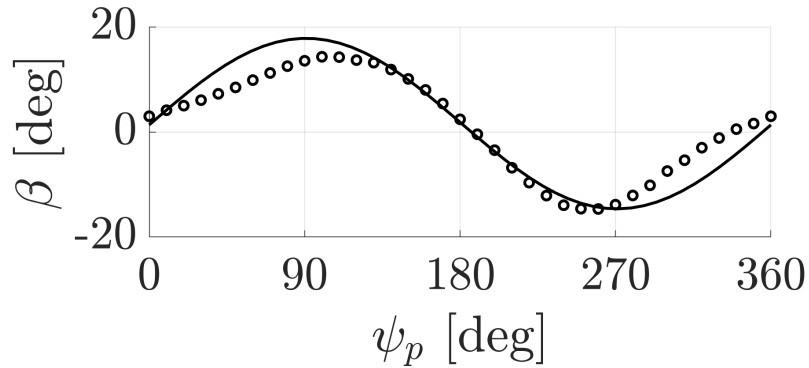


Figure 4.16: Comparison between predicted (solid line) and experiment (dots) for the $\Omega = 75$ RPM, $\Omega_p = 200$ RPM case.

4.2.4.2 Method 2: Time Marching

For the time marching method, equation 4.19 was numerically simulated with MATLAB's *ode45* function. Figure 4.17 shows the result compared to the experimental data over two propeller revolutions. A slight, 0.1% numerical damping was added to equation 4.19 to remove high frequency oscillations that were associated with the flap spring. Figure 4.17 shows the predicted time marching solution captures the experimental data well.

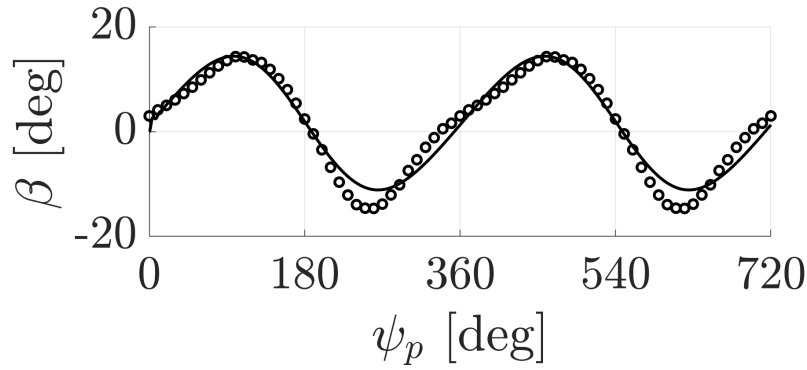


Figure 4.17: Time marching results for the $\Omega = 75$ RPM, $\Omega_p = 200$ RPM case. Solid line is the prediction, dots are experimental data.

The advantage of the time marching approach is that the original equation of motion can be modified with ease. This enabled the relative importance of key terms to be determined. To further understand this point, the Coriolis coupling term $2(I_p + e_p S_p)\Omega\Omega_p \sin \psi_p$ was eliminated from the original propeller flapping equation (equation 4.19). This new equation can be written as:

$$\begin{aligned}
 I_p \ddot{\beta}_p + (I_p \Omega^2 \cos^2 \psi_p + S_p(e_p + R)\Omega^2 \cos \psi_p + I_p(\Omega_p^2 - \Omega^2) \\
 + e_p S_p \Omega_p^2 + K_p)\beta_p = S_p \Omega^2 h + \cancel{2(I_p + e_p S_p)\Omega\Omega_p \sin \psi_p}
 \end{aligned}
 \tag{4.28}$$

Figure 4.18 shows the time marching results for Equation 4.28. It is clear from Figure 4.18 that without the Coriolis coupling term, $2(I_p + e_p S_p)\Omega\Omega_p \sin \psi_p$, that the large flapping motion is not captured. The numerical solution quickly converged to a value of $1.6^\circ \pm 0.2^\circ$, meaning the cosine terms and the higher harmonic content in equation 4.19 are not dominant for this case. This indicated that the Coriolis coupling term was the primary mechanism for the propeller flapping motion seen in the vacuum chamber. Next the analytic periodic solution method is presented.

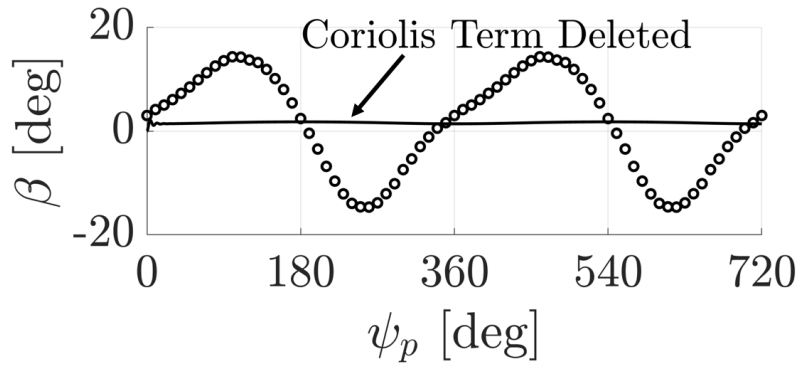


Figure 4.18: Time marching result for equation 4.28 for the $\Omega = 75$ RPM, $\Omega_p = 200$ RPM case. Without the Coriolis term present, the sinusoidal motion does not occur.

4.2.4.3 Method 3: Harmonic Balance Method

The analytical solution method assumes a periodic response, equation 4.20, using β_0 , β_{1c} , and β_{1s} . For simplicity, only the steady and first harmonics are considered. This method directly inserts the periodic flapping response into the flapping equation of motion, collects like terms, and then algebraically solves for β_0 , β_{1c} , β_{1s} in terms of physical parameters of the system. The primary advantage of this method is that closed form expressions for β_0 , β_{1c} , β_{1s} are found. The propeller flapping

equation (equation 4.19) is repeated here for convenience:

$$\begin{aligned} I_p \ddot{\beta}_p + (S_p(e_p + R)\Omega^2 \cos \psi_p + I_p \Omega^2 \cos^2 \psi_p + I_p(\Omega_p^2 - \Omega^2) + e_p S_p \Omega_p^2 + K_\beta) \beta_p \\ = S_p h \Omega^2 + 2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p \end{aligned}$$

To simplify the solution process, the following expressions are used:

$$A = I_p \Omega^2$$

$$B = S_p(e_p + R)\Omega^2$$

$$C = I_p(\Omega_p^2 - \Omega^2) + e_p S_p \Omega_p^2 + K_\beta$$

$$D = 2(I_p + e_p S_p) \Omega \Omega_p$$

Using these simplifying expressions, the flap equation of motion, equation 4.19, simplifies to:

$$I_p \ddot{\beta}_p + (A \cos^2 \psi_p + B \cos \psi_p + C) \beta_p = S_p h \Omega^2 + D \sin \psi_p \quad (4.29)$$

Inserting the propeller periodic flapping motion, equations 4.20 and 4.22, into equation 4.29, ignoring higher harmonic content, and grouping periodic (constant, $\sin \psi_p$, $\cos \psi_p$) terms on both sides yields:

Constant expression:

$$\beta_0 \left(\frac{1}{2} A + C \right) + \frac{1}{2} B \beta_{1c} = S_p h \Omega^2 \quad (4.30)$$

Cosine expression, $\cos \psi_p$:

$$\beta_0 B + \beta_{1c} \left(\frac{3}{4} A + C - I_p \Omega_p^2 \right) = 0 \quad (4.31)$$

Sine expression, $\sin \psi_p$:

$$\beta_{1s} \left(\frac{1}{4} A + C - I_p \Omega_p^2 \right) = D \quad (4.32)$$

We now have three equations with three unknowns. The next few sections solve these equations and discuss trends.

4.2.5 Longitudinal Flapping Response β_{1s}

From equation 4.32, the value for β_{1s} can be solved for explicitly.

$$\beta_{1s} = \frac{D}{\frac{1}{4} A + C - I_p \Omega_p^2}$$

Plugging in the terms for A , B , and C yields:

$$\beta_{1s} = \frac{2\Omega\Omega_p(I_p + e_p S_p)}{\frac{1}{4} I_p \Omega^2 + I_p (\cancel{\Omega_p^2} - \Omega^2) + e_p S_p \Omega_p^2 + K_\beta - \cancel{I_p \Omega_p^2}}$$

Note that the $I_p \Omega_p^2$ term in the denominator cancels out. The expression for β_{1s} reduces to:

$$\beta_{1s} = \frac{2\Omega\Omega_p(I_p + e_p S_p)}{K_\beta + e_p S_p \Omega_p^2 - \frac{3}{4} I_p \Omega^2} \quad (4.33)$$

From equation 4.33 it is clear that a large, β_{1s} response is predicted as Ω_p is in the numerator. This indicates that when $\psi_p = 90^\circ$, the flap response will be at a large positive value, and when

$\psi_p = 180^\circ$ the flap response will be a large negative value. Figure 4.19 shows the propeller flapping orientation.

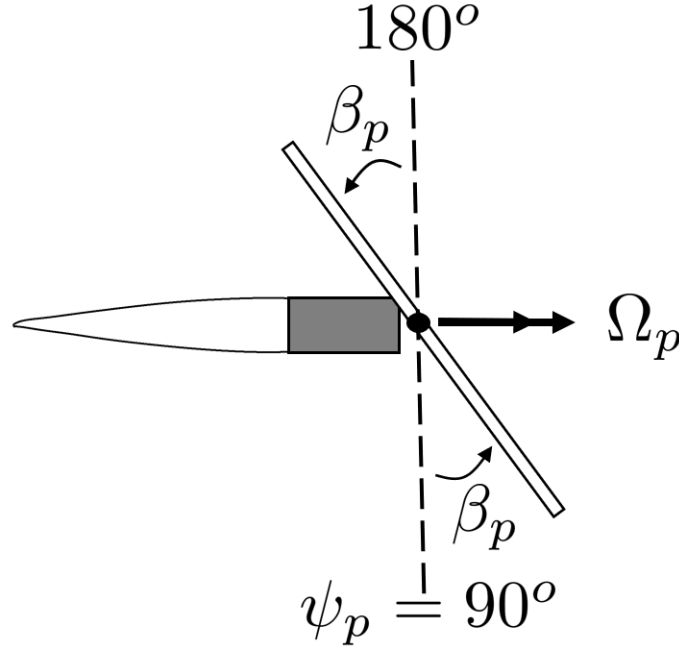


Figure 4.19: Propeller flapping motion at $\psi_p = 90^\circ$ and 180° . View is from rotor tip looking towards the rotor root.

It can be seen that for a clockwise spinning propeller, the inertial forces cause the propeller blade to flap up at $\psi_p = 90^\circ$ and to flap down at $\psi_p = 270^\circ$. Note that if a counter-clockwise spinning propeller is used, a value of $-\Omega_p$ is used in the analysis and thus the propeller flapping motion is reversed.

The β_{1s} expression, equation 4.33, is a function of the propeller design (K_p , I_p , S_p , e_p), the propeller speed Ω_p , and the rotor speed Ω . It is *not* a function of the location of the propeller on the rotor blade, as the parameter R is missing from the equation 4.33. This means the Coriolis coupling and resulting β_{1s} for a propeller at located 1/2 span of the main rotor is the same as a propeller located at the main rotor blade tip.

This Coriolis coupling is a function of both the rotor rotational speed Ω and the propeller rotational speed Ω_p . For a conventional isolated rotor, increasing the rotational speed of the rotor blade acts to stiffen the blade, and thus can reduce the isolated rotor blade flapping motion. Figure 4.13 shows that for the propeller-rotor speeds tested in the vacuum chamber, increasing the propeller rotational speed increases the Coriolis coupling factor and thus *increases* the propeller blade flapping motion. This observation is investigated in the following section.

4.2.6 Explanation for Large β_{1s} Response

The most counter-intuitive finding from the experimental data was that, for the range of conditions tested, increasing either the propeller RPM or the rotor RPM increased the propeller flap response. When studying the isolated rotor blade flapping equation of motion, increasing the rotor RPM stiffens the blade, and thus flapping should reduce. To explain this discrepancy, consider the simple example propeller flapping diagram in Figure 4.20. This diagram considers only the spring force (SF), the centrifugal force (CF), the inertial force (IF), and the Coriolis force (CorF).

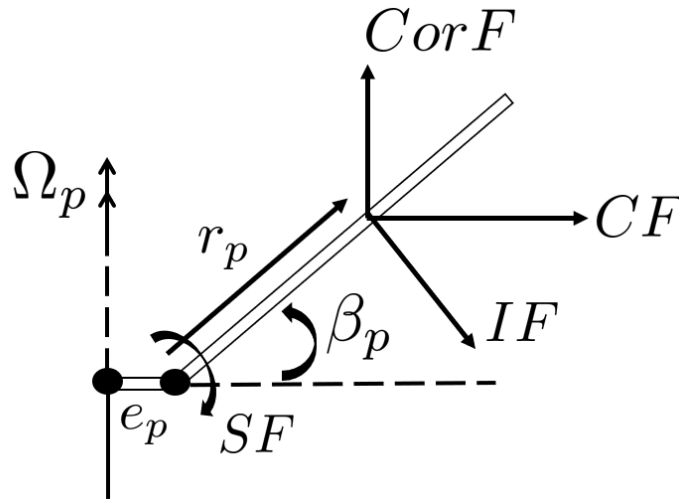


Figure 4.20: Simplified propeller flapping diagram.

For Figure 4.20, the integrated sum of the moments at the hinge must be equal to 0:

$$SF = CorF - IF - CF$$

Assuming a hinge offset e_p and integrating this over the propeller radius yields:

$$K_p \beta_p = 2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p - I_p \ddot{\beta}_p - (I_p + e_p S_p) \Omega_p^2 \beta_p$$

$$I_p \ddot{\beta}_p + (1 + \frac{e_p S_p}{I_p} + \frac{K_p}{I_p \Omega_p^2}) \Omega_p^2 I_p \beta_p = 2(I_p + e_p S_p) \Omega \Omega_p \sin \psi_p$$

Dividing both sides by $I_p \Omega_p^2$ yields:

$$\frac{\ddot{\beta}_p}{\Omega_p^2} + (1 + \frac{e_p S_p}{I_p} + \frac{K_p}{I_p \Omega_p^2}) \beta_p = 2(1 + \frac{e_p S_p}{I_p}) \frac{\Omega}{\Omega_p} \sin \psi_p \quad (4.34)$$

The non-dimensional propeller flap frequency ν_p is defined as:

$$\nu_p^2 = 1 + \frac{e_p S_p}{I_p} + \frac{K_p}{I_p \Omega_p^2} \quad (4.35)$$

Now consider the propeller has a periodic flapping motion that consists of just β_{1s} :

$$\beta_p(\psi_p) = \beta_{1s} \sin \psi_p$$

$$\ddot{\beta}_p(\psi_p) = -\Omega_p^2 \beta_{1s} \sin \psi_p$$

Inserting the sinusoidal periodic motion and non-dimensional propeller flap frequency into equation

4.34 yields:

$$\beta_{1s}(\nu_p^2 - 1) \sin \psi_p = 2\left(1 + \frac{e_p S_p}{I_p}\right) \frac{\Omega}{\Omega_p} \sin \psi_p$$

Solving for β_{1s} :

$$\beta_{1s} = \frac{2}{\nu_p^2 - 1} \left(1 + \frac{e_p S_p}{I_p}\right) \frac{\Omega}{\Omega_p} \quad (4.36)$$

An explanation for the increase in β_{1s} can be seen by examining the non-dimensional propeller flap frequency ν_p and the β_{1s} expression in equation 4.36. Figure 4.21 shows the reduction in non-dimensional propeller flap frequency ν_p as a function of the propeller speed Ω_p . For equation 4.36, as the non-dimensional propeller flap frequency ν_p is in the denominator. A reduction in flap frequency ν_p results in an increase in β_{1s} , shown in Figure 4.22.

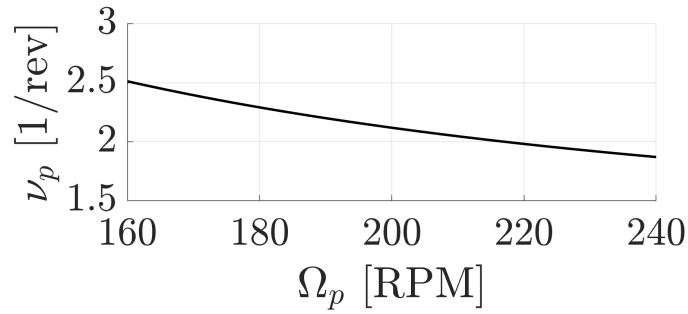


Figure 4.21: Propeller non-dimensional propeller flap frequency reduces as propeller RPM increases.

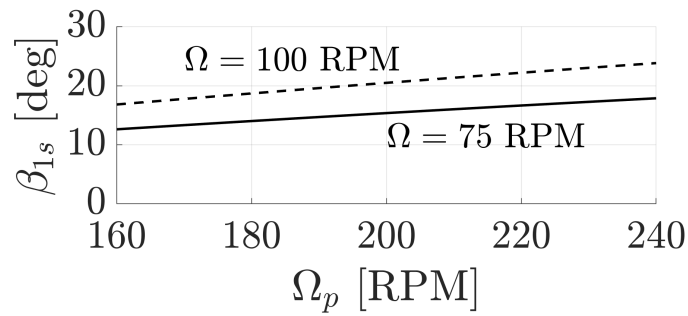


Figure 4.22: Expected β_{1s} behavior over propeller speeds Ω_p tested in the vacuum chamber.

However, consider the limit as $\Omega_p \rightarrow \infty$:

$$\lim_{\Omega_p \rightarrow \infty} \beta_{1s} = \frac{2}{\nu_p^2 - 1} \left(1 + \frac{e_p S_p}{I_p}\right) \frac{\Omega}{\Omega_p} = 0$$

The long term behavior of β_{1s} over a large range of Ω_p is shown in Figure 4.23. As propeller speed Ω_p increases from low to medium speeds, initially an increase of β_{1s} is observed. This trend is observed in the experimental test data from the vacuum chamber. From Figure 4.23, eventually the β_{1s} value reaches a maximum, and then a decrease in β_{1s} is seen as the propeller centrifugal force increases. Increasing the rotor speed Ω shifts the plot upward. Next, the β_0 and β_{1c} solutions are studied.

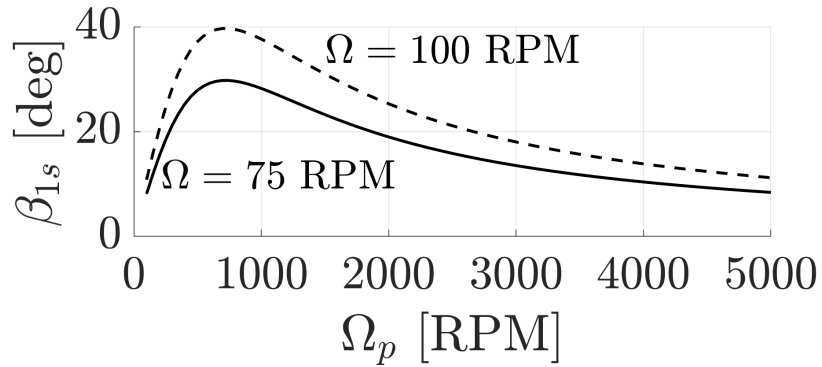


Figure 4.23: Expected β_{1s} behavior over a wide range of propeller speeds.

4.2.7 Constant β_0 and Lateral β_{1c} Response

Equation 4.30 and 4.31 contain the β_0 and β_{1c} parameters, and the equations are shown here for convenience:

$$\beta_0 \left(\frac{1}{2} A + C \right) + \frac{1}{2} B \beta_{1c} = S_p h \Omega^2$$

$$\beta_0 B + \beta_{1c} \left(\frac{3}{4} A + C - I_p \Omega_p^2 \right) = 0$$

These equations can be written in a linear form:

$$\begin{bmatrix} \frac{1}{2}A + C & \frac{1}{2}B \\ B & \frac{3}{4}A + C - I_p\Omega_p^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_{1c} \end{bmatrix} = M \begin{bmatrix} \beta_0 \\ \beta_{1c} \end{bmatrix} = \begin{bmatrix} S_ph\Omega^2 \\ 0 \end{bmatrix}$$

where M is the 2x2 matrix of physical parameters. The solution to the linear equation is then:

$$\begin{bmatrix} \beta_0 \\ \beta_{1c} \end{bmatrix} = M^{-1} \begin{bmatrix} S_ph\Omega^2 \\ 0 \end{bmatrix}$$

Let $\det M$ be the determinant of matrix M . Then:

$$\begin{bmatrix} \beta_0 \\ \beta_{1c} \end{bmatrix} = \frac{1}{\det M} \begin{bmatrix} \frac{3}{4}A + C - I_p\Omega_p^2 & -\frac{1}{2}B \\ -B & \frac{1}{2}A + C \end{bmatrix} \begin{bmatrix} S_ph\Omega^2 \\ 0 \end{bmatrix} = \frac{S_ph\Omega^2}{\det M} \begin{bmatrix} \frac{3}{4}A + C - I_p\Omega_p^2 \\ -B \end{bmatrix}$$

Now the terms for A , B , and C are plugged back in:

$$\beta_0 = \frac{1}{\det M} (K_\beta - \frac{1}{4}I_p\Omega^2) S_ph\Omega^2 \quad (4.37)$$

$$\beta_{1c} = \frac{1}{\det M} S_phR\Omega^2 \quad (4.38)$$

From equations 4.37 and 4.38, several observations can be made. First, it is clear that both quantities are a function of the offset between the propeller and the rotor 1/4 chord h . Increasing this offset has a strong impact on β_0 and β_{1c} . Additionally, both β_0 and β_{1c} have Ω^2 in the numerator, indicating that they are functions of the centrifugal force.

Insight on the coupling between β_0 and β_{1c} can be obtained by examining the rotor blade. Figure

4.24 shows a rotor with an exaggerated offset h . As the main rotor blade spins at some rotational speed Ω , a centrifugal force is created. The centrifugal force acts in a line from the center of rotor rotation. At the center of propeller rotation, the angle that the centrifugal force makes is h/R . This means there is some projection of the rotor's centrifugal force in the h direction.

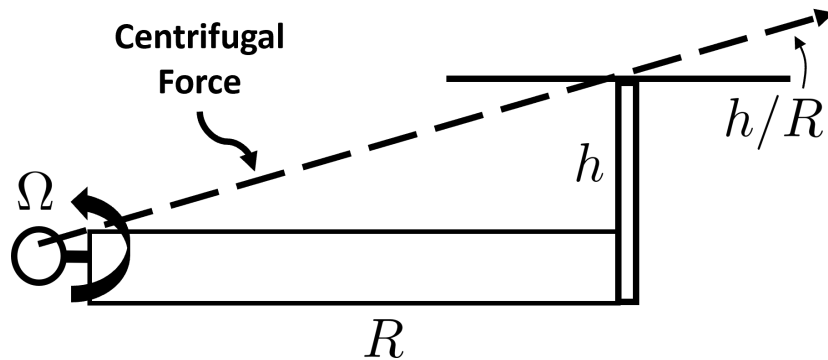
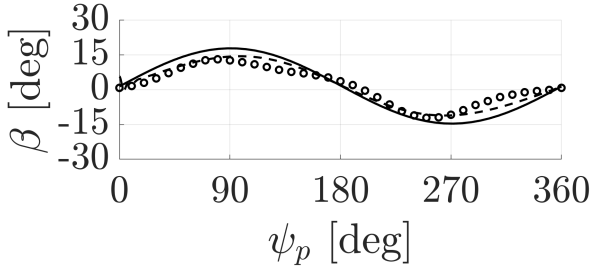


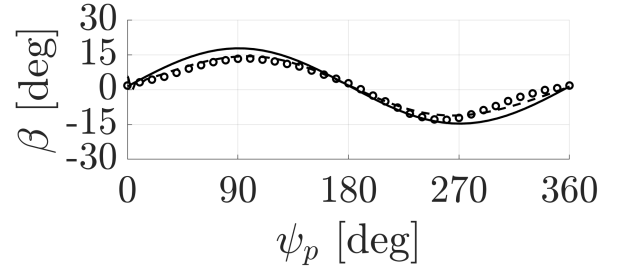
Figure 4.24: The rotor's rotation Ω results in centrifugal loading. Diagram dimensions exaggerated for clarity.

4.2.8 Comparisons with Simple Model

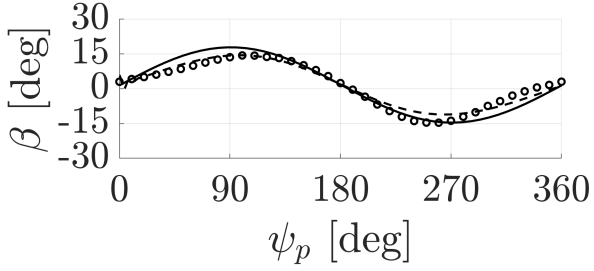
The predictions from the three solution methods discussed in Section 4.2.4 are compared to the experimental data in Figures 4.25 and 4.26. The harmonic balance method gives the same result as the numerical periodic solution method, and so only the harmonic balance method result is shown. The large, 1 per propeller rev sinusoidal motion is well captured. However, it is worth noting that at the 100 rotor RPM and 220, 240 propeller RPM case there seems to be a disagreement between the predictions and the experiment. The 1 per propeller rev does not capture the maximum peak seen in the experimental data for those cases. This indicates higher harmonics are present in the experimental data. Higher harmonics are captured using the comprehensive analysis, which is detailed in the next section.



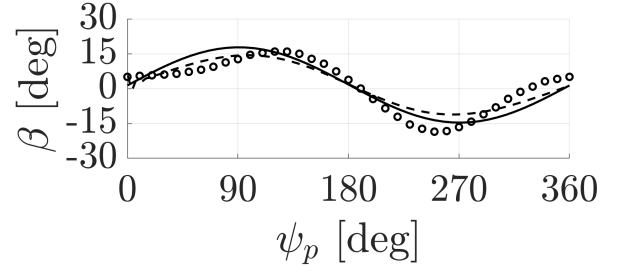
(a) $\Omega_p = 160$ RPM



(b) $\Omega_p = 180$ RPM

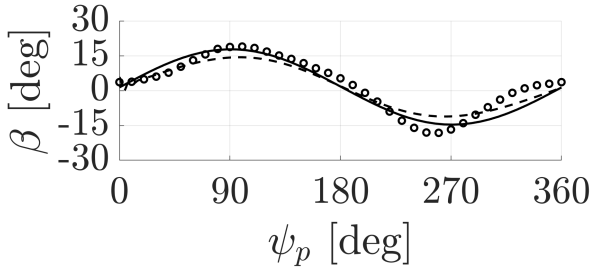


(c) $\Omega_p = 200$ RPM

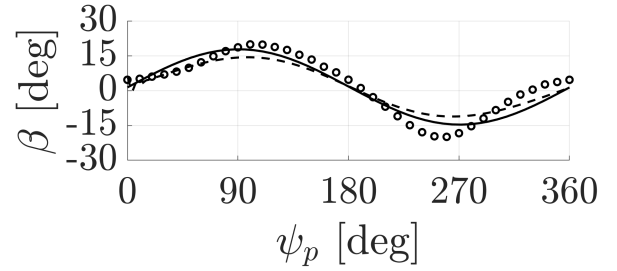


(d) $\Omega_p = 220$ RPM

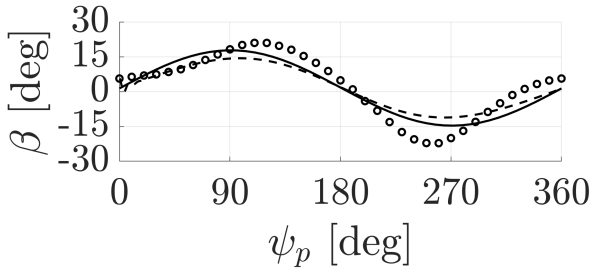
Figure 4.25: Predicted versus experimental results for $\Omega = 75$ RPM. Dots are experimental, solid line is the harmonic balance method solution, and dashed line is the time matching solution.



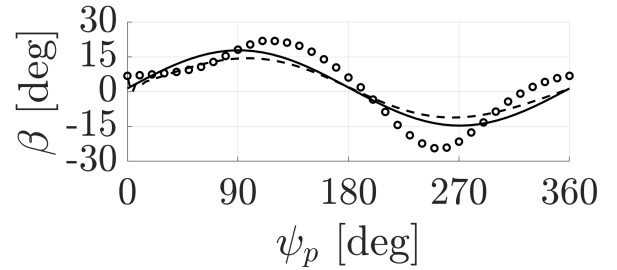
(a) $\Omega_p = 180$ RPM



(b) $\Omega_p = 200$ RPM



(c) $\Omega_p = 220$ RPM



(d) $\Omega_p = 240$ RPM

Figure 4.26: Predicted versus experimental results for $\Omega = 100$ RPM. Dots are experimental, solid line is the harmonic balance method solution, and dashed line is the time matching solution.

4.2.9 Comparison with Comprehensive Analysis

The simple analytical model was instructional for understanding the physics of the propeller flapping problem. One drawback of this hand-derived simple model was that only the first harmonic of propeller flapping motion was predicted. From this, it was clear that a comprehensive analysis methodology was needed for more rigorous modeling the propeller-driven rotor system.

Figure 4.27 shows the comprehensive rotorcraft model of the vacuum chamber propeller flapping experiment. The propeller, propeller hub, propeller shaft, rotor, and rotor shaft are modeled as rigid components, with suitable sectional properties. ERA models the propeller flapping hinge as a joint between two nodes. Four joints are present: two commanded and two free. Commanded joints are at the rotor/propeller hubs to prescribe the rotor/propeller rotational speeds. Free joints are the flapping hinges, one for each propeller blade. The flapping joint included the equivalent spring stiffness K_p . The periodic solution was obtained with a sufficient number of harmonics and the Newton-Raphson method. Figures 4.28 and 4.29 on the next page show the predicted results compared to experimental for 75 and 100 rotor RPM, respectively.

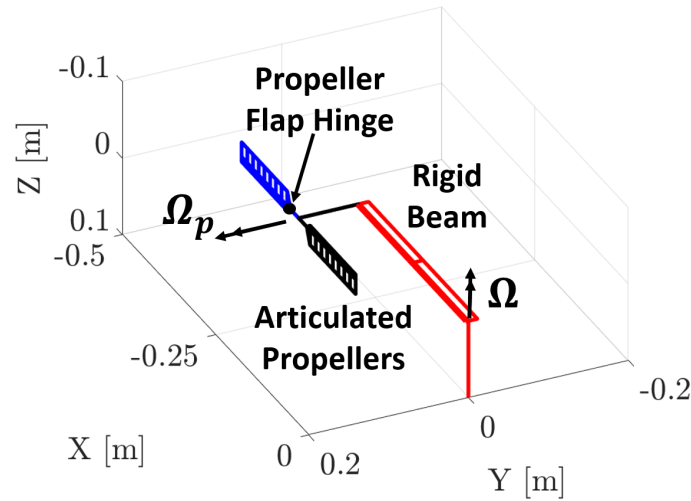


Figure 4.27: Vacuum chamber experiment modeled in ERA.

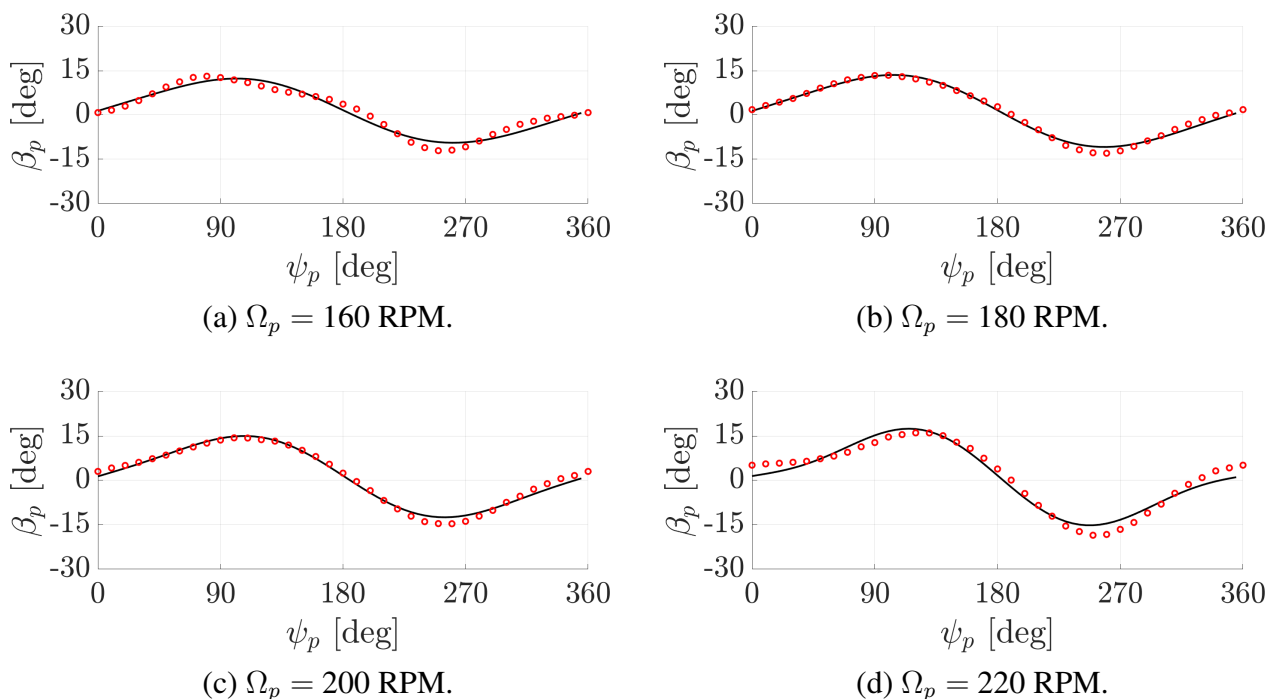


Figure 4.28: Propeller flapping experimental results (dots) versus ERA predictions (solid line) for 75 main rotor RPM.

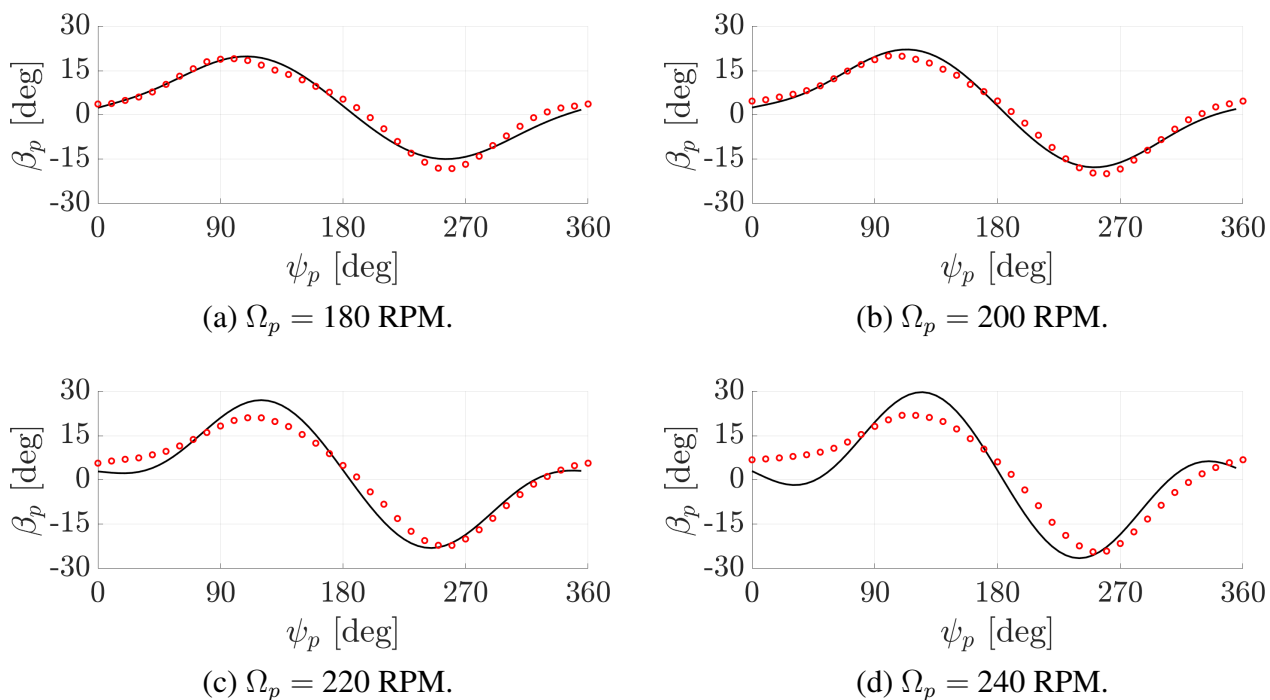


Figure 4.29: Propeller flapping experimental results (dots) versus ERA predictions (solid line) for 100 main rotor RPM.

The comprehensive analysis predictions show good agreement with the experimental data, and predicts the trends first observed in the experimental data shown in Figure 4.13. Figure 4.30 shows the comprehensive analysis predicted propeller/rev harmonic content. The analysis predicts that the propeller flapping motion increases with propeller and rotor speeds, and higher harmonics are present as well. These higher harmonics work to sharpen the peak response around 90° and 270° propeller azimuth ψ_p . After this experiment, the next focus was on how propeller loads influence rotor blade loads.

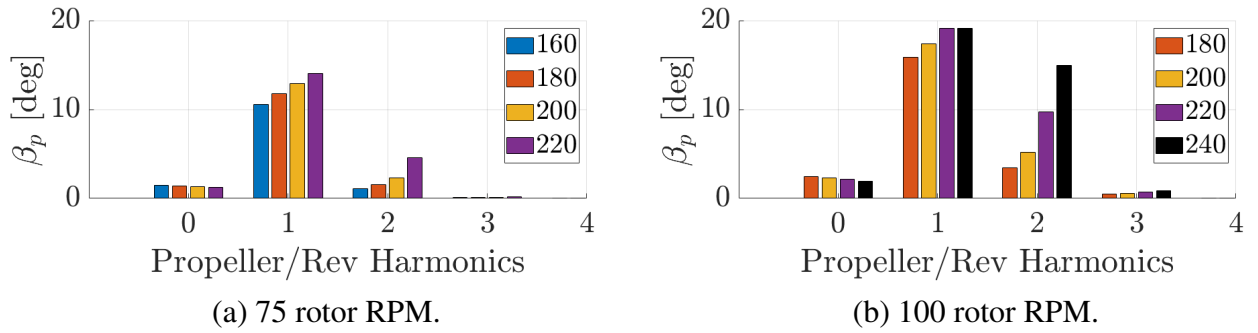


Figure 4.30: Predicted propeller flap harmonics for various propeller RPMs using comprehensive analysis. Legend indicates propeller RPM.

4.3 Vacuum Chamber Experiment #2: Rotor-Propeller Loads

After the first vacuum chamber experiment, the importance of studying the inertial loading of the propeller-driven rotor was evident. The objective of the second vacuum chamber experiment was to show how the rotor-propeller Coriolis moment influences the rotor blade loads. Strain gauges on the main rotor blade measured rotor blade loads, and a 6 DOF load cell on the rotor blade tip measured propeller loads. Propeller speed was swept from 0 to 5000 rpm for main rotor speeds of 0, 25, or 50 rpm.

Figure 4.31 shows the test apparatus that was constructed for this experiment. The same rotor,

propeller, propeller tip load cell, and tip nacelle that was used in the propeller loads hover experiment, detailed in Section 3.3, were used for this vacuum chamber experiment. Power and signal wires were passed through the rotor blade. The vacuum chamber experiment used the same tip load cell arrangement that was described in Section 3.3.2.

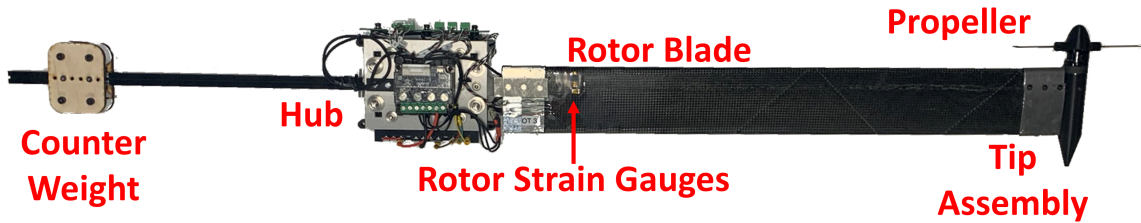


Figure 4.31: Propeller-driven rotor loads experiment setup. Top down view.

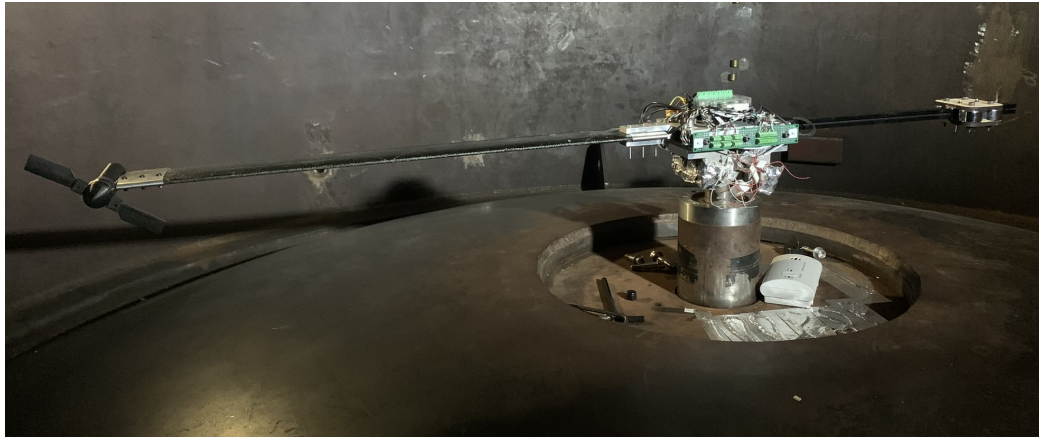


Figure 4.32: Propeller-driven rotor loads experiment mounted inside the vacuum chamber.

4.3.1 Comprehensive Model for Propeller-Rotor Loads Experiment

Figure 4.33 shows the propeller-driven rotor comprehensive model and propeller reference frames. The propeller was modeled as a rigid propeller, offset from the rotor blade 1/4 chord line h by 2 in. The main rotor blade was modeled as elastic. Table 4.5 contains the properties for this experiment.

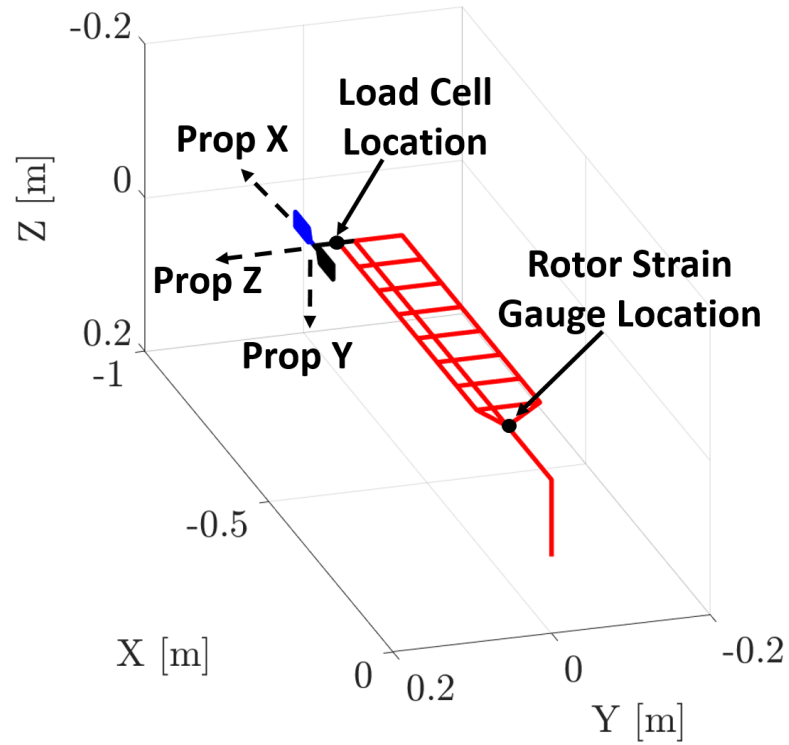


Figure 4.33: ERA model and propeller reference frame. Note that the load cell location has some physical offset from the propeller hub.

Table 4.5: Main rotor parameters for rotor-propeller loads vacuum chamber experiment.

Rotor Radius, R	31 in
Rotor Strain Gauge Location	7 in
Rotor Root Cutout	3.5 in
Rotor Collective/Twist	0 deg
Rotor Structure in ERA	Elastic
Rotor Sectional mass, m	0.40 kg/m
Rotor Flap Stiffness, EI	22.8 Nm ²
Rotor Torsional Stiffness, GJ	25.3 Nm ²
Rotor RPM, Ω	25, 50 RPM
Propeller Radius, R_p	3 in
Propeller Collective/Twist	0 deg
Propeller Structure in ERA	Rigid
Propeller Root Cutout, R_{po}	0.75 in
Number of Propeller Blades, N_{bp}	2
Propeller Offset, h	2 in
Propeller Blade Mass, $m(R_p - R_{po})$	1.8 grams
Propeller RPM, Ω_p	1000:500:5000 RPM

4.3.2 Predicted and Experimental Results

Figure 4.34 shows the main rotor blade loads that were measured in the vacuum chamber. The rotor blade torsion load, originating from the propeller-rotor Coriolis interaction was well captured. The propeller Coriolis moment results in a rotor blade torsional moment. Figures 4.35 to 4.38 show the predicted and experiment results for the propeller load cell loads, as well as the predicted propeller per rev harmonics. For both 25 and 50 rotor RPMs, the predicted versus experimental results show close agreement. Additionally, 0, 2, and 4 propeller/rev harmonics are visible in the harmonic analysis, coming from the 2 bladed propeller that was tested.

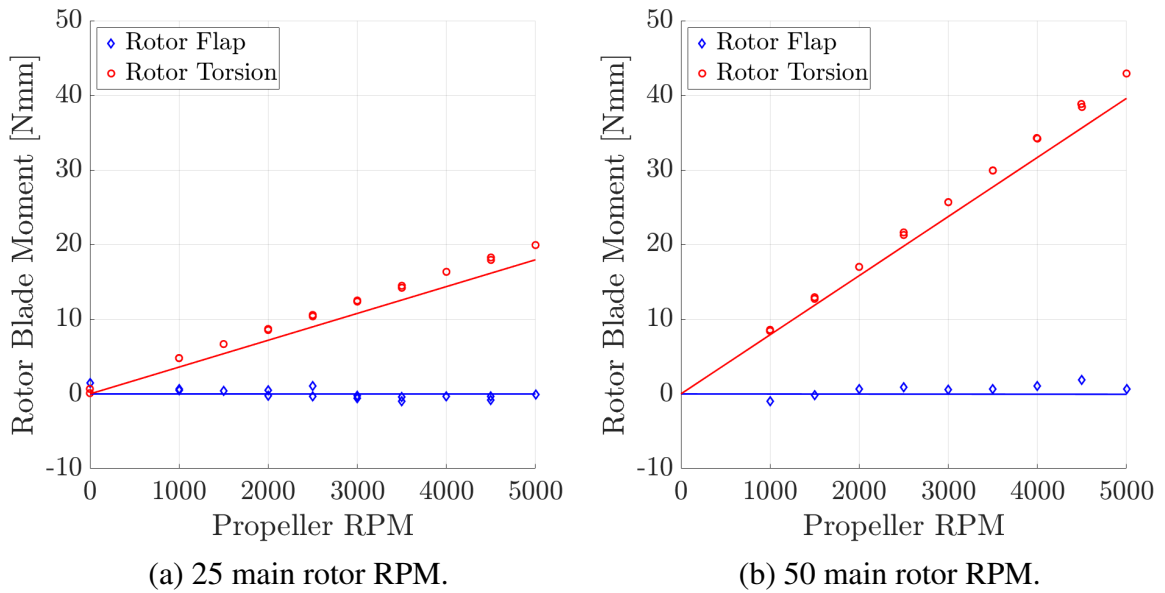


Figure 4.34: Rotor blade loads. Experimental (dots) versus comprehensive analysis predictions (solid line).

From these tests, the vacuum chamber has proven effective for testing rotor-propeller inertial couplings. Future designs should be validated in the chamber in conjunction with using the comprehensive rotorcraft model to predict loads. The next section will compare propeller loads during isolated axial flight to those during propeller-driven rotor operation.

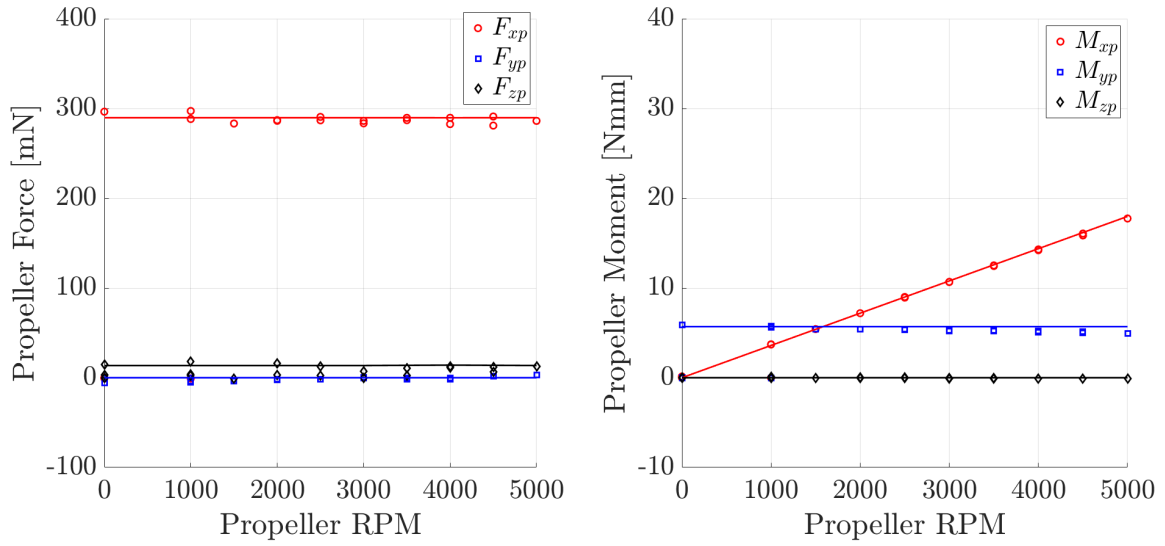


Figure 4.35: Experimental (dots) versus ERA predictions (solid line) for propeller load cell loads at 25 rotor RPM.

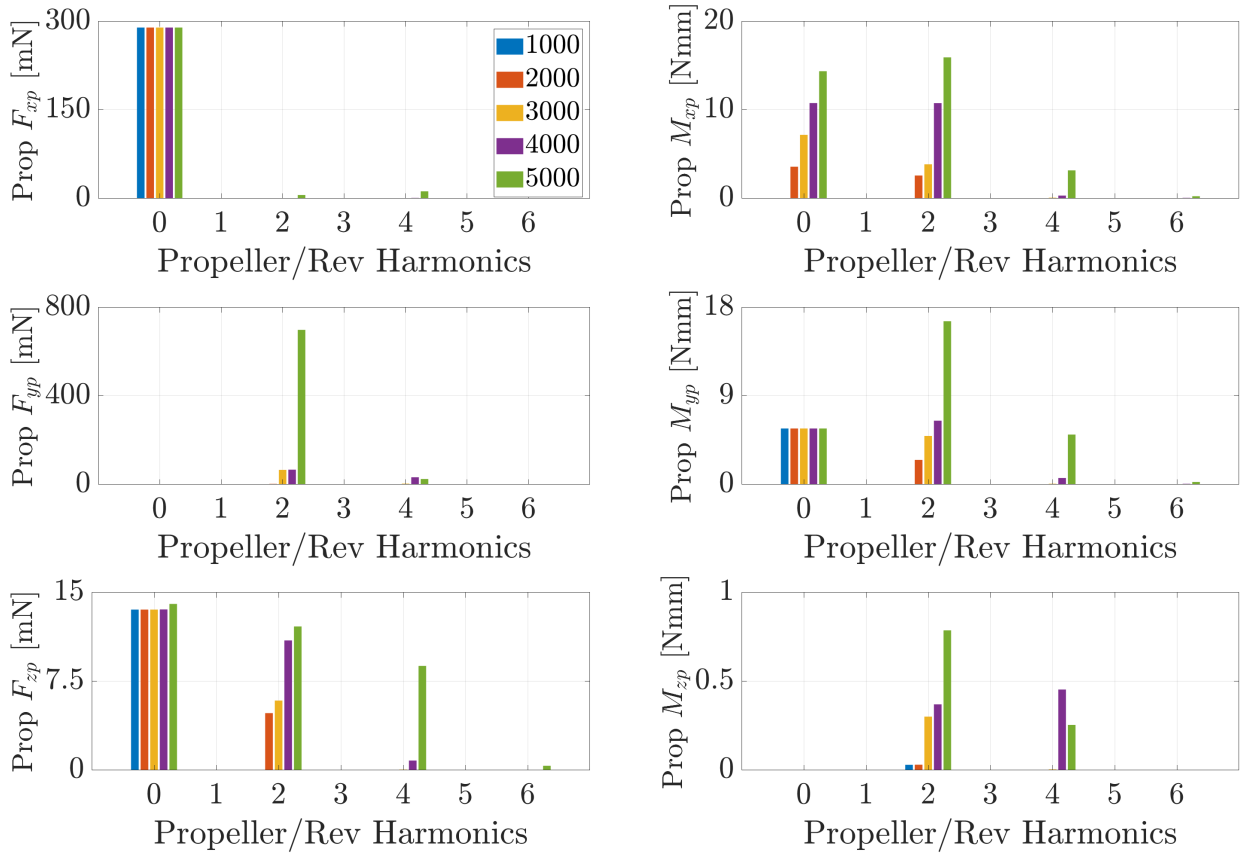


Figure 4.36: Predicted propeller harmonics for 25 rotor RPM for various propeller RPMs. Legend indicates propeller RPM.

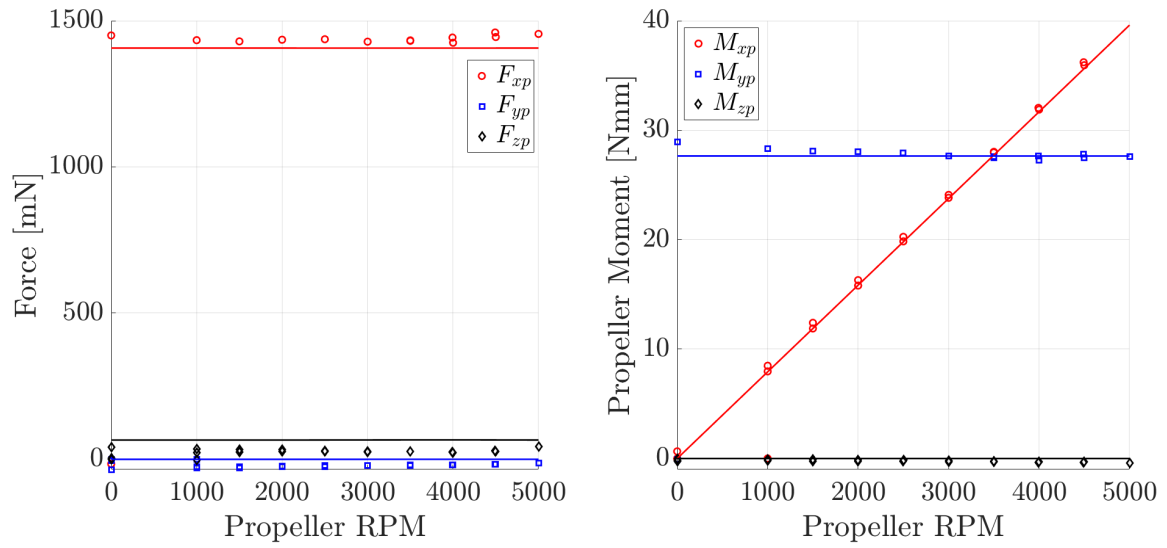


Figure 4.37: Experimental (dots) versus ERA predictions (solid line) for propeller load cell loads at 50 rotor RPM.

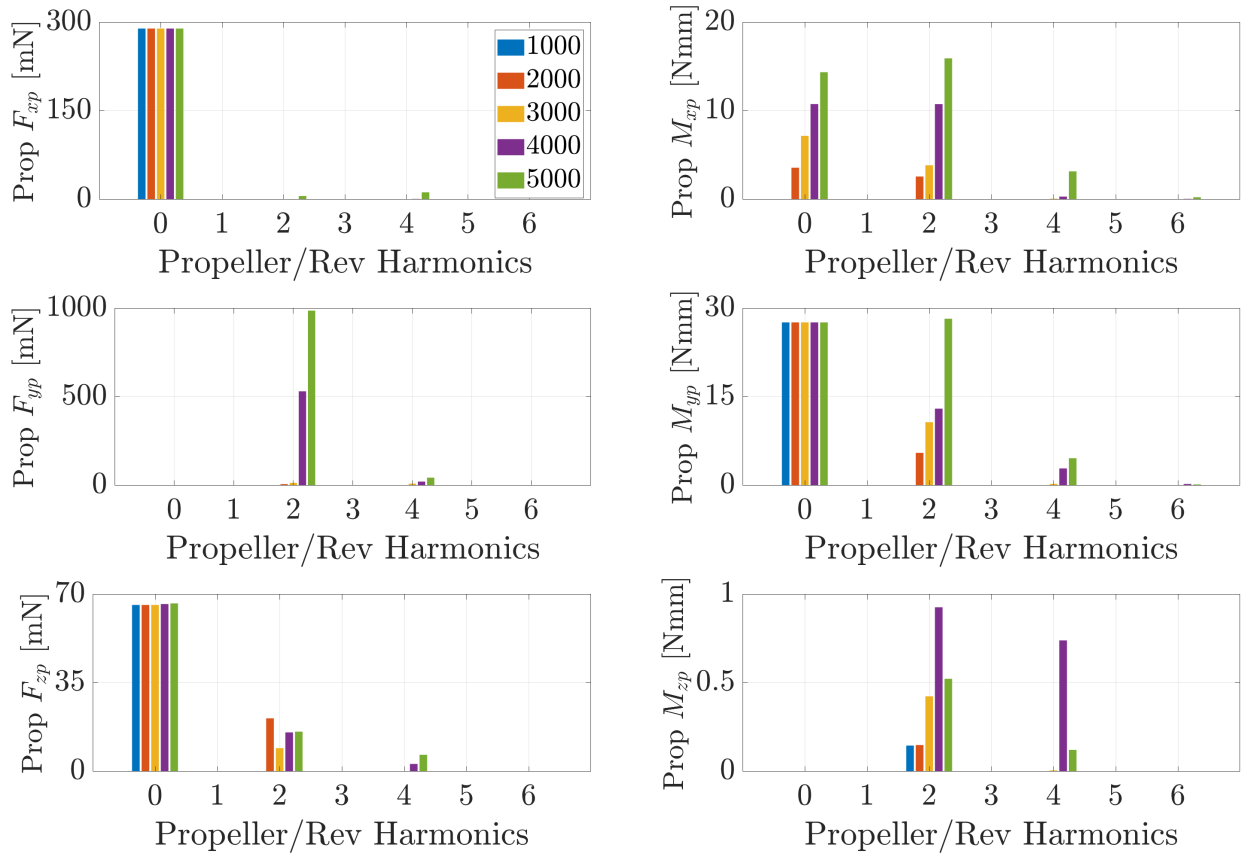


Figure 4.38: Predicted propeller harmonics for 50 rotor RPM for various propeller RPMs. Legend indicates propeller RPM.

4.4 Propeller Rotary Flight vs Axial Flight

Over the course of the propeller driven rotor research program, numerous isolated propellers have been tested in axial flight in a wind tunnel. These isolated propellers are then placed on a hovering rotor blade, and in the past have failed due to the unique propeller driven rotor loading environment. This section seeks to quantify the differences between isolated propeller testing, called axial flight, and during propeller driven rotor operation, called propeller rotary flight.

Figure 4.39 shows the axial flight condition. During isolated propeller testing, the propeller is fixed in a wind tunnel and the propeller's climb velocity v_c is equal to the freestream air velocity v_∞ . The primary loading on the propeller is from aerodynamic effects. The propeller hub is not moving, so no additional inertial loads are present.

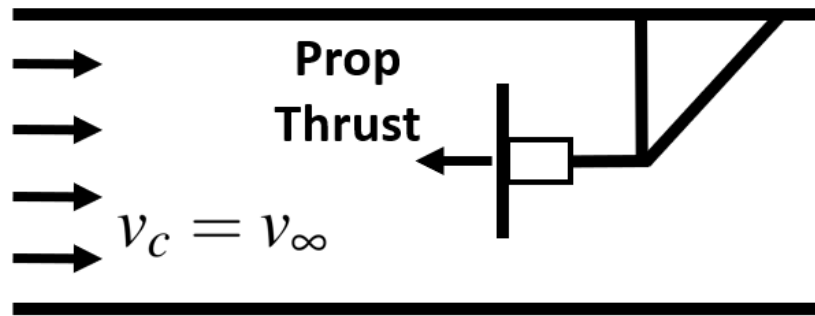


Figure 4.39: Propeller in axial flight, such as during isolated propeller wind tunnel test.

Figure 4.40 shows the propeller rotary flight condition. During propeller driven rotor operation, a propeller located at r experiences a climb velocity v_c equal to the incoming airspeed Ωr , where Ω is the rotor rotational speed. The propeller hub is attached to the rotor blade and moving in a circular manner. Propeller rotary flight has two main differences from axial flight. First, the incoming climb velocity that the propeller experiences is not uniform across the propeller. The difference in climb

velocity across the propeller (tip-to-tip) is $2\Omega R_p$. Second, the inertial loading on the propeller is significant. This comes from the rotor centrifugal forces (proportional to Ω^2), and the rotor-propeller Coriolis force (proportional to $\Omega_p\Omega$). These differences will be explored using the validated using the comprehensive rotorcraft analysis methodology.

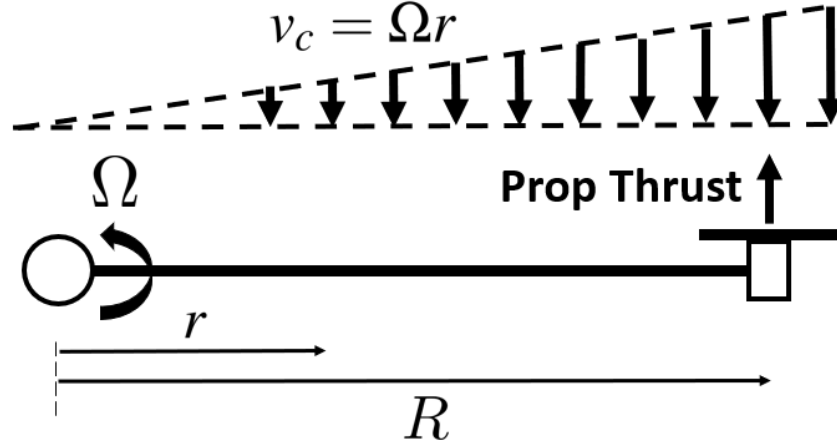


Figure 4.40: Propeller in rotary flight, such as during propeller driven rotor operation.

4.4.1 Comprehensive Analysis Models for Propeller Rotary and Axial Flight

Figure 4.41 shows the ERA propeller rotary flight model. Here the propeller used in the TVF26 dataset is mounted to the tip of a 1m rigid beam. The rigid propeller blade had a fixed pitch set to 35 deg root collective, and the propeller blade had no twist. The propeller hub has a 2 inch rotor chordwise offset h from the rigid beam's quarter chord location. The same propeller geometry was used for axial flight. For axial flight, the rigid beam is removed and the propeller hub fixed to a ground node. Axial flight is achieved by simply increasing the freestream air velocity.

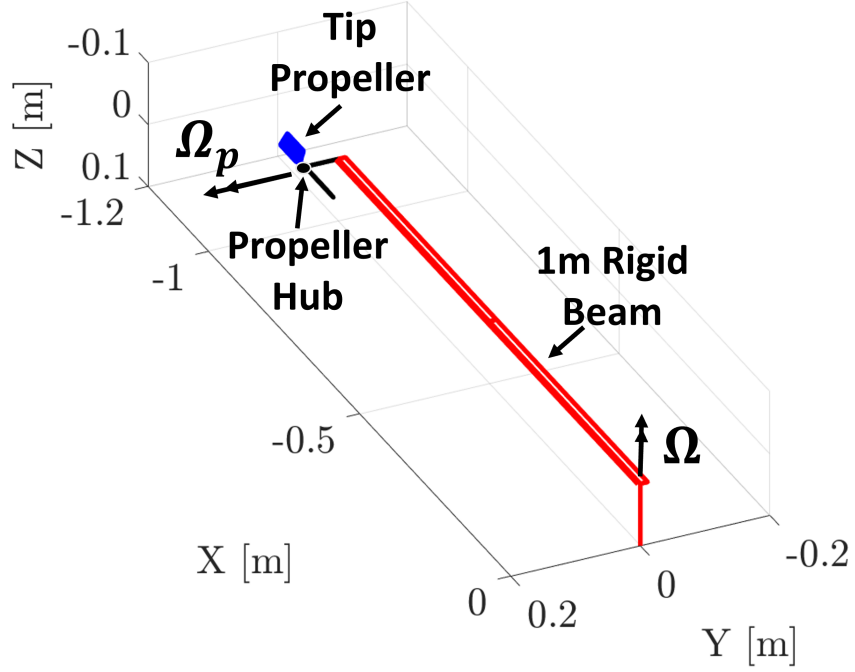


Figure 4.41: Propeller in rotary flight, such as during propeller driven rotor operation.

4.4.2 Cases Examined

To illustrate the differences in propeller rotary and axial flight, three different cases were computed. First, an axial flight model was run and v_∞ was varied between 0-10 m/s. Secondly, the propeller rotary flight mode case was ran using the same propeller model as the axial flight case. However, instead of varying the flight speed v_∞ , here the rotational rate Ω of the rigid beam was varied. This results in:

$$v_c = \underbrace{v_\infty}_{\text{Axial flight}} = \underbrace{\Omega R}_{\text{Rotary flight}}$$

The third and final case was the propeller rotary flight mode, but with no aerodynamics. This case highlights the inertial loads on the propeller. The results of these cases are shown in the next section.

4.4.3 Propeller Rotary vs Axial Flight Results

Figure 4.42 show the three cases: axial flight with aerodynamics, propeller rotary flight with aerodynamics, and propeller rotary flight without aerodynamics. All non-dimensional loads are compared using the same atmospheric density. For axial flight, only rotor thrust and torque loads are produced. However, in rotary flight there are loads in every direction.

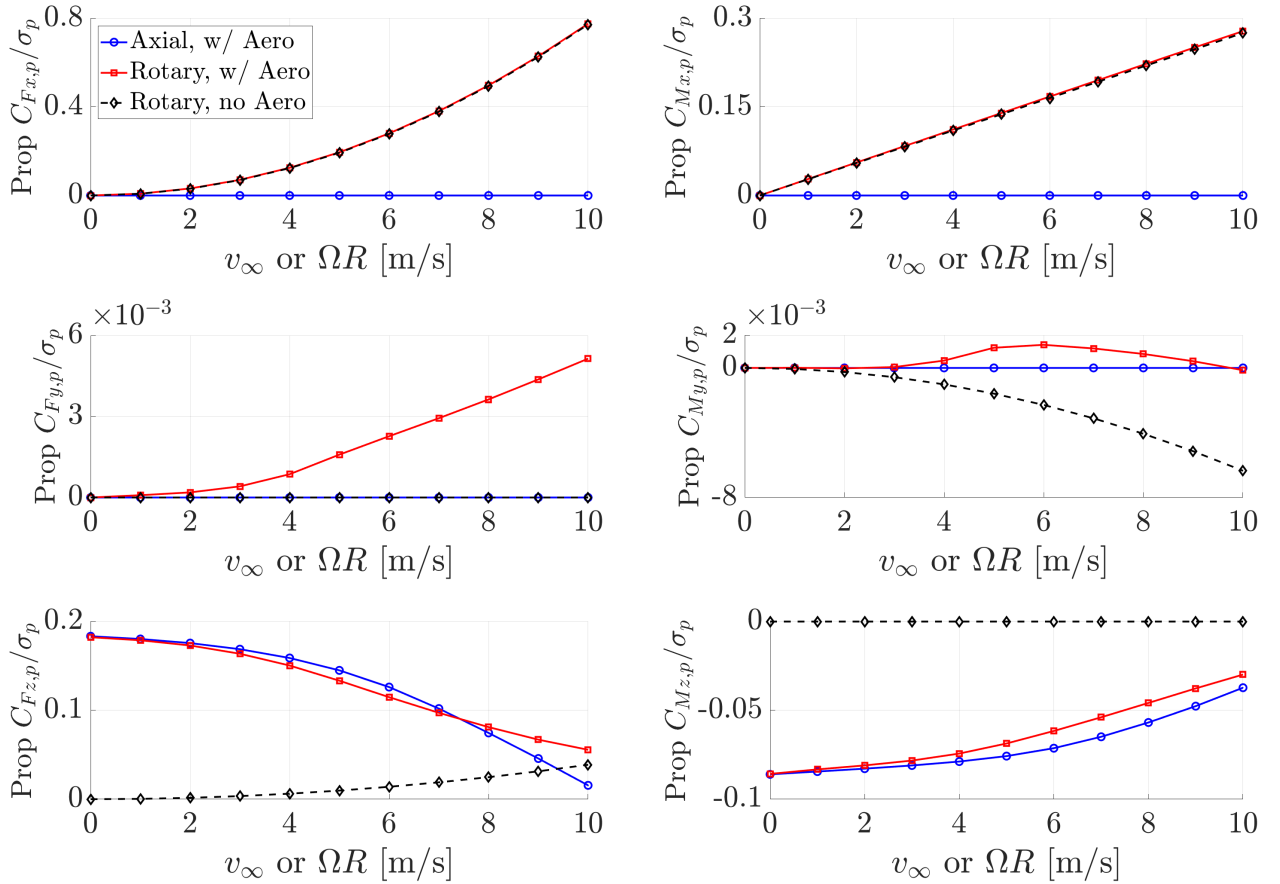


Figure 4.42: Comparison of propeller rotary flight vs axial flight.

Using these results, several observations can be made regarding rotary flight. Table 4.6 summarizes these results. First, the propeller F_{xp} has a large value related to the rotor centrifugal force (CF). Second, the propeller has a small forward chordwise offset h which results in a portion of the rotor CF force acting in the propeller thrust direction. Third, the rotor-propeller Coriolis moment results in

large M_{xp} values. Finally, the propeller F_{yp} , M_{yp} , and M_{zp} all have slight variations compared to axial flight resulting from propeller climb variation, shown earlier in Figure 4.40.

Table 4.6: Propeller hub loads in rotary flight.

Propeller Load	Inertial	Aerodynamic
F_{xp}	Rotor CF w/ Prop Mass	Small
F_{yp}	Small	Propeller climb variation
F_{zp}	Rotor CF (h/R), small	Propeller thrust
M_{xp}	Coriolis moment	Small
M_{yp}	Small	Propeller climb variation
M_{zp}	Small	Propeller torque/drag

4.5 Summary and Conclusions

While attempting to improve propeller-driven rotor hover performance, propellers of various spar sizes and strengths suffered root failures. An assessment of the experimental outcomes led to the conclusion that these failures were likely due to the inertial propeller-rotor couplings during propeller-driven rotor operation instead of aerodynamic interactions. The Coriolis force originates from spinning a propeller on a rotating rotor, and results in sinusoidal loading of the propeller blade. This generates a pitching moment on the propeller, which can couple with the main rotor blade torsion mode. The resulting problem has since been termed the propeller-driven rotor swirl phenomenon.

Two vacuum chamber experiments were developed to study the propeller blade loads from inertial forces. First, a propeller flapping characterization experiment was conducted to study propeller flap motion at various rotor and propeller speeds. In the vacuum chamber, the propeller blade underwent large sinusoidal motions. A first-principles model was developed to explain the propeller blade motion. Second, a propeller-rotor loads vacuum chamber experiment was conducted using the same propeller-driven rotor blade and propeller configuration as Section 3.3. The results showed good

agreement with the comprehensive model.

From the first vacuum chamber study on propeller flapping characterization, the following conclusions are made:

- In the vacuum chamber, without the presence of aerodynamic forces, the Coriolis force bends the propeller blades in a sinusoidal fashion.
- For the range of propeller and rotor speeds tested, increasing the propeller speed or the rotor speed resulted in increased the peak amplitude of the sinusoidal motions.
- The motion of the propeller blade is dominated by the sinusoidal Coriolis force. The cosine terms in the propeller flapping equation are significantly smaller than the sinusoidal terms. For example, at $\Omega = 75$ RPM, $\Omega_p = 220$ RPM, $\beta_{1c} = 0.2^\circ$ and $\beta_{1s} = 16.2^\circ$, which is 81 times the motion.
- The Coriolis force is large and is not dependent on the propeller location along the rotor blade span. The Coriolis moment on the propeller hub is $2I_p\Omega\Omega_p\sin\psi_p$, and hence does not have a term associated with the distance from the main rotor hub.
- The β_0 and β_{1c} are coupled and are a function of the offset h , which physically exists from the need to place the propeller ahead of the rotor blade leading edge.
- The β_{1s} increases for the range of propeller and rotor speeds tested in this study. However as propeller speed Ω_p increases, β_{1s} peaks and then eventually decreases to a smaller value.

From the second vacuum chamber study on rotor-propeller loads, the following conclusions are made:

- The variation in propeller Coriolis moment with propeller and rotor speeds was well captured.

- The rotor-propeller Coriolis moment results in a propeller pitching moment and a rotor blade torsional moment.

Some conclusions are made regarding propeller-driven rotor twirl phenomenon:

- Propeller-driven rotor twirl phenomenon originates from the rotor-propeller Coriolis interaction coupling with rotor and propeller structural modes.
- Two failure modes were studied for the propeller-driven rotor twirl phenomenon: one steady and one oscillatory. The static failure results from the rotor-propeller Coriolis moment exceeding the rotor blade torsional strength. The oscillatory failure results from 2 bladed propeller harmonics interacting with the rotor blade torsional mode at resonance.
- A two bladed propeller results in a steady and oscillatory load being imparted to the rotor blade torsion mode. Increasing the number of propeller blades above two removes the oscillatory load, but increases the steady load. Without the oscillatory load, rotor blade torsional resonance can be avoided.
- Propeller rotary flight brings significant loading on the propeller. This is most evident in the propeller F_x (from rotor centrifugal loading), M_x (from rotor-propeller Coriolis coupling), and F_z (from a propeller hub offset h/R).

The next chapter documents an investigation on a propeller-driven rotor swashplateless control concept.

Chapter 5: Swashplateless Control

This Chapter details the experiments of a swashplateless control concept for a propeller-driven rotor. First, the proposed strategy is described and experimental results for the small scale are presented. Next, the swashplateless propeller-driven rotor control authority is compared to a rotor using conventional swashplate control. The Chapter ends with a summary and conclusions.

5.1 Propeller-Driven Rotor Control Experiments

The 2.7 ft diameter test stand and 3D printed rotors, shown in Figure 5.1, were used to develop and characterize the propeller-driven rotor control experiments. This was the same hardware that was used in the variable propeller placement investigation that was presented earlier in Section 3.4.1. The small test stand enabled rapid experimentation and development, whereas the 3D printed rotors allowed for the propeller-driven rotor design to be adjusted in a systematic manner.

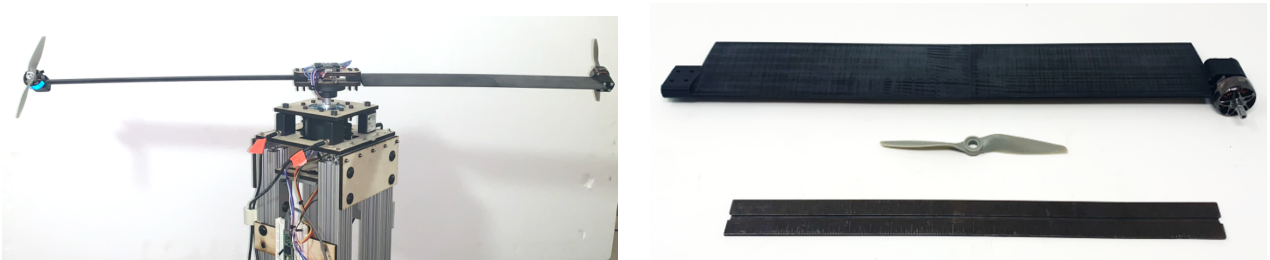


Figure 5.1: The propeller-driven rotor swashplateless controls research utilized the 2.7 ft diameter test stand and 3D printed rotor blades. Full details on the test stand are in Section 3.4.1, and details on the 3D printed main rotor are in Section 2.1.2

5.1.1 Proposed Propeller-Driven Rotor Control Strategy

A conventional rotorcraft uses a swashplate mechanism to adjust the rotor blade angle around the rotor azimuth. The propeller-driven rotor control strategy takes advantage of the large difference between the main rotor rotational speed (250 RPM) and the tip propeller rotational speed (5000 RPM) to generate rolling and pitching moments for primary control of the aircraft. The tip motor and propeller are rigidly attached to the tip of the main rotor blade with a slight upward tilt. As such, a component of the tip propeller thrust acts in the vertical direction of the rotor disk, shown in Figure 5.2.

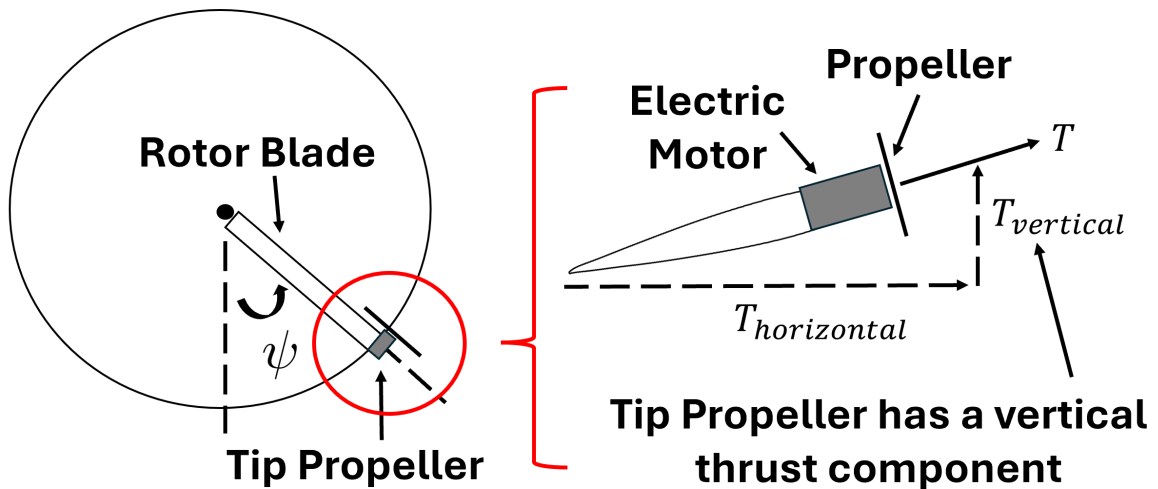


Figure 5.2: Top down view of rotor plane. The tip propeller has a component of vertical thrust that was used to generate control moments for the rotor.

The propeller-driven rotor combines the 1/rotor rev excitation of a swashplate from a conventional rotor with the fast electronics of a quadrotor. For stable flight, a quadrotor dynamically adjusts propeller RPM for control and lift. The scheme utilizes electric motors as high frequency actuators, capable of quickly increasing/decreasing rotational speed. The propeller-driven rotor's control moments are generated by increasing the propeller rotational speed on one side of the rotor disk while reducing the rotational speed on the opposite side of the rotor disk. Figures 5.3 and 5.4 shows how rotor rolling

and pitching moments are generated, respectively.

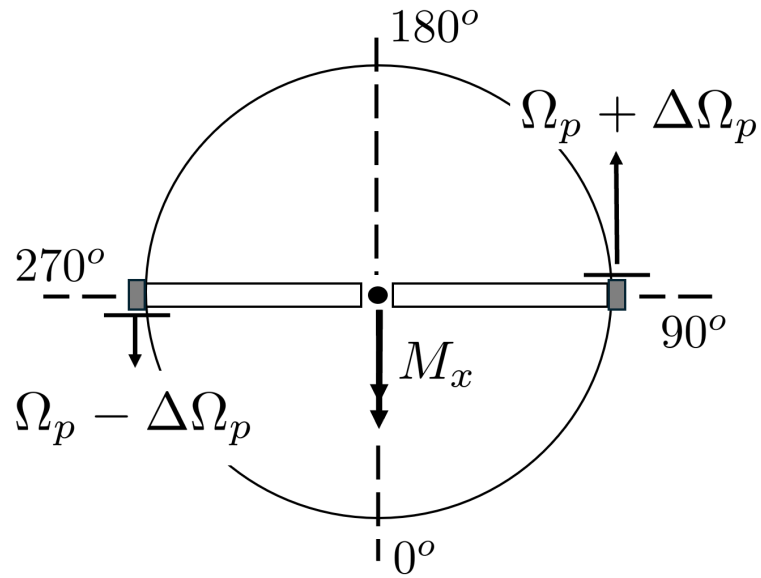


Figure 5.3: Rolling moment strategy.

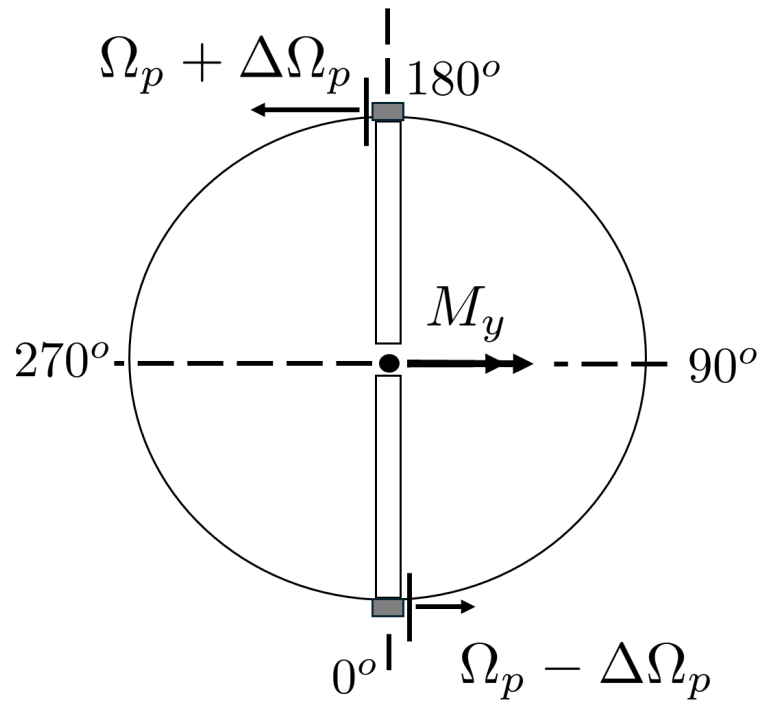


Figure 5.4: Pitching moment strategy.

The strategy works by adjusting the propeller speed, and thus the vertical portion of propeller thrust, at specific locations around the rotor azimuth. Consider the propeller is spinning at some nominal rotational speed $\Omega_{p,0}$. A positive rolling moment was generated by increasing the propeller speed at $\psi = 90$ and decreasing the propeller speed at $\psi = 270$. This corresponds to adding a $\Omega_{p,1s} \sin \psi$ portion to the propeller speed, thus:

$$\Omega_p(\psi) = \Omega_{p,0} + \Omega_{p,1s} \sin \psi$$

A similar strategy can be considered for the pitching moment. For a positive pitching moment, the propeller speed must decrease at $\psi = 0$ and increase at $\psi = 180$. This results in a $-\Omega_{p,1c} \cos \psi$ portion being added to the nominal propeller speed $\Omega_{p,0}$. Dropping the minus sign for convince, the final strategy results is the propeller speed variation with rotor azimuth ψ as:

$$\Omega_p(\psi) = \Omega_{p,0} + \Omega_{p,1s} \sin \psi + \Omega_{p,1c} \cos \psi \quad (5.1)$$

where $\Omega_{p,1s}$ and $\Omega_{p,1c}$ represent the longitudinal and lateral propeller RPM variations, respectively.

5.1.2 Propeller Tip Angle δ

For propeller-driven rotor control strategy development, the vertical portion of propeller thrust is directly related to the control moment magnitude. As such, the angle δ between the rotor blade chord and the tip propeller thrust vector was adjusted. This propeller tip angle δ is shown in Figures 5.5. A larger propeller tip angle δ tilts the propeller thrust in the vertical direction, and thus causes a larger moment with a slight reduction of propulsive thrust.

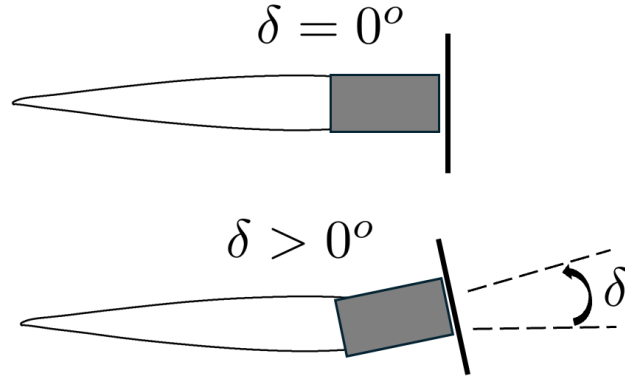


Figure 5.5: Propeller tip angle δ increases the vertical component of propeller thrust and thus creates a larger moment.

5.1.3 Open Loop Motor Control

Due to the limited number of slipping channels on the propeller-driven rotor test stand it was not possible to implement closed-loop propeller RPM control. Instead, the open loop motor throttle commands u were adjusted. The motor throttle u is the Pulse Width Modulated (PWM) value to the motor controller, and has been normalized between 0-100%. A microcontroller was added to the propeller-driven rotor test stand to control the input throttle setting to the motor. The motor throttle consists of a nominal portion u_0 and components for the longitudinal u_{1s} and lateral u_{1c} variations. Additional details on the motor controller and brushless motor performance can be found in [Section 2.2](#).

Instead of directly controlling propeller speed, such as in [equation 5.1](#), the microcontroller adjusted the motor throttle based on the rotor azimuth ψ as:

$$u(\psi) = u_0 + u_{1c} \cos \psi + u_{1s} \sin \psi \quad (5.2)$$

The values of u , u_0 , u_{1c} , and u_{1s} are normalized between 0-100% of the motor's throttle range.

For example, Figure 5.6 shows the motor throttle u over one rotor azimuth with a u_0 value of 30% and a u_{1s} variation of 5%. Additionally, there is some time delay between the input signal and propeller speed, which can result in some cross-axis coupling with the moments. The time delay is comprised of the motor response, the propeller dynamics, and the rotor response.

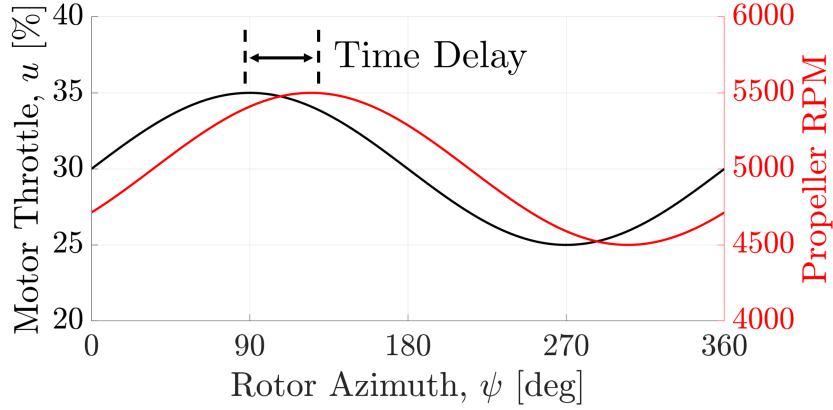


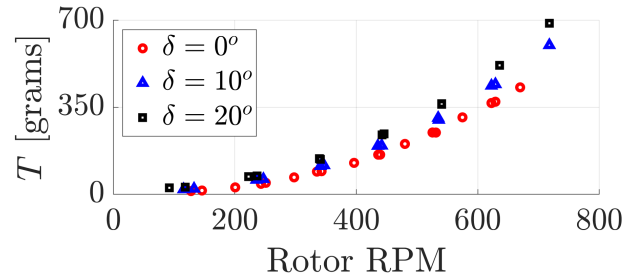
Figure 5.6: Motor throttle variation over one rotor azimuth with $u_0 = 30\%$ and $u_{1s} = 5\%$. Some time delay is expected between the motor throttle and the propeller speed.

5.1.4 Experimental Results

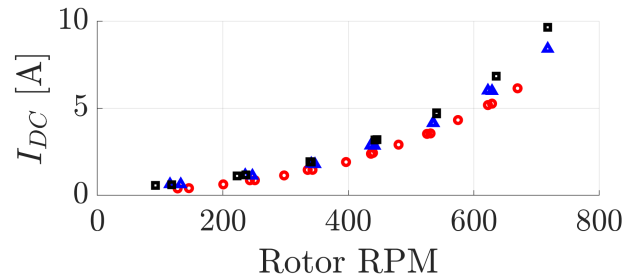
The propeller-driven rotor with various propeller tip angles δ of 0° , 10° , and 20° was characterized in two experiments. In the first experiment, an RPM sweep of the main rotor was performed and the main rotor's thrust, electrical power, and propeller RPM were recorded. This sweep was accomplished by gradually increasing the nominal motor throttle u_0 while the u_{1s} and u_{1c} values were set to 0%. In the second experiment, the rotor's rolling and pitching moments were characterized by changing either u_{1s} or u_{1c} independently. The main rotor was held at a constant rotational speed of 250 RPM while either u_{1s} or u_{1c} were adjusted. The resulting change in rotor moments, rotor thrust, and DC electrical power were recorded.

5.1.5 Experiment 1 - Propeller-Driven Rotor RPM Sweep

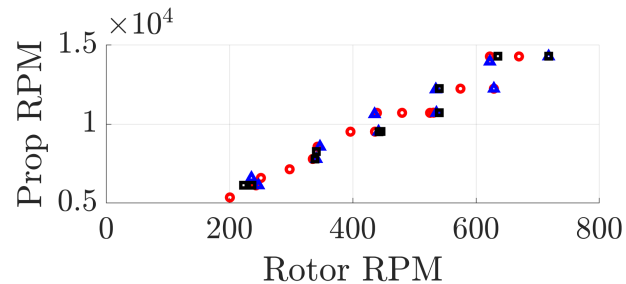
The 2.7 ft diameter propeller-driven main rotor blades with propeller tip angles δ of 0° , 10° , and 20° were tested up to a main rotor rotational speed up to 700 RPM. The motor input throttle u_0 was increased and the resulting rotor thrust, rotor electrical power, and propeller speed were recorded. All tests were conducted at a main rotor collective of 8 deg. These results are shown in Figure 5.7. The same metrics for main rotor thrust loading coefficient C_T/σ , electrical power loading coefficient C_{Pe}/σ , and the propeller/rotor RPM slope m that were introduced in Section 3.4.2 are used.



(a) Main rotor thrust vs main rotor RPM.



(b) DC Current vs main rotor RPM.



(c) Propeller RPM vs main rotor RPM.

Figure 5.7: Propeller-driven rotor tip results with different δ angles at a main rotor collective of 8 deg.

Table 5.1 presents the measured performance metrics for this test. The rotor thrust loading coefficient C_T/σ increased by 78% between the $\delta = 0^\circ$ to 20° for a 24% increase in an electrical power loading C_{Pe}/σ . This increased thrust was expected as a portion of the propeller thrust was directed in the vertical direction. This vertical propeller thrust was used to generate control moments in the following experiment. Additionally, Table 5.1 shows an increase in I_o and the propeller RPM offset $\Omega_{p,offset}$ with an increase in the propeller tip angle δ . This was expected as the larger tip angle δ results in more propeller thrust directed upwards at a cost of less propulsive thrust being used to rotate the main rotor.

Table 5.1: Propeller-driven rotor performance with various propeller tip angles δ . Metrics are defined in Section 3.4.2.

δ	0°	10°	20°
C_T/σ	0.071	0.094	0.127
C_{Pe}/σ	0.0455	0.0495	0.0566
$I_o[A]$	0.63	0.89	0.88
m [Propeller RPM/Rotor RPM]	17.7	17.2	17.0
$\Omega_{p,offset}$ [Propeller RPM]	2075	2250	2320
T/P_{DC} at 500 Rotor RPM [N/W]	0.0569	0.0599	0.0623

5.1.6 Experiment 2 - Control Characterization

After the propeller-driven rotor RPM sweep performance sweep was conducted, the control experiment characterized the variation in motor commands to rotor moments. The tip motor's input throttle u_o was set such that the main rotor spun at 250 RPM, and the control inputs u_{1s} and u_{1c} were varied from 0 to 10% of the motor's throttle range.

Figure 5.8 shows the change in electrical power while using the propeller-driven rotor control scheme. Electrical power was found to increase by 24.5%, 21.7%, and 22.9% for tip propeller angles δ of 0° , 10° , and 20° , respectively. Figures 5.9 and 5.10 on the next page show the rolling and pitching

moments with change in u_{1s} and u_{1c} , respectively. This control scheme resulted in satisfactory on-axis control, with little coupling between the axes. Additionally, increasing the tip angle linearly increased the control moments.

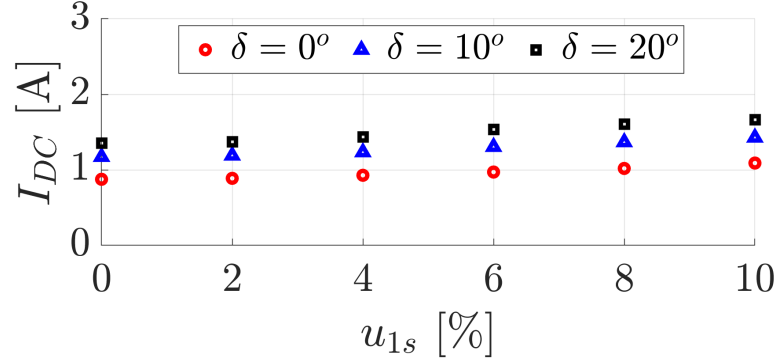


Figure 5.8: Change in DC current for a u_{1s} variation at 250 rotor RPM. Similar results were observed for u_{1c} .

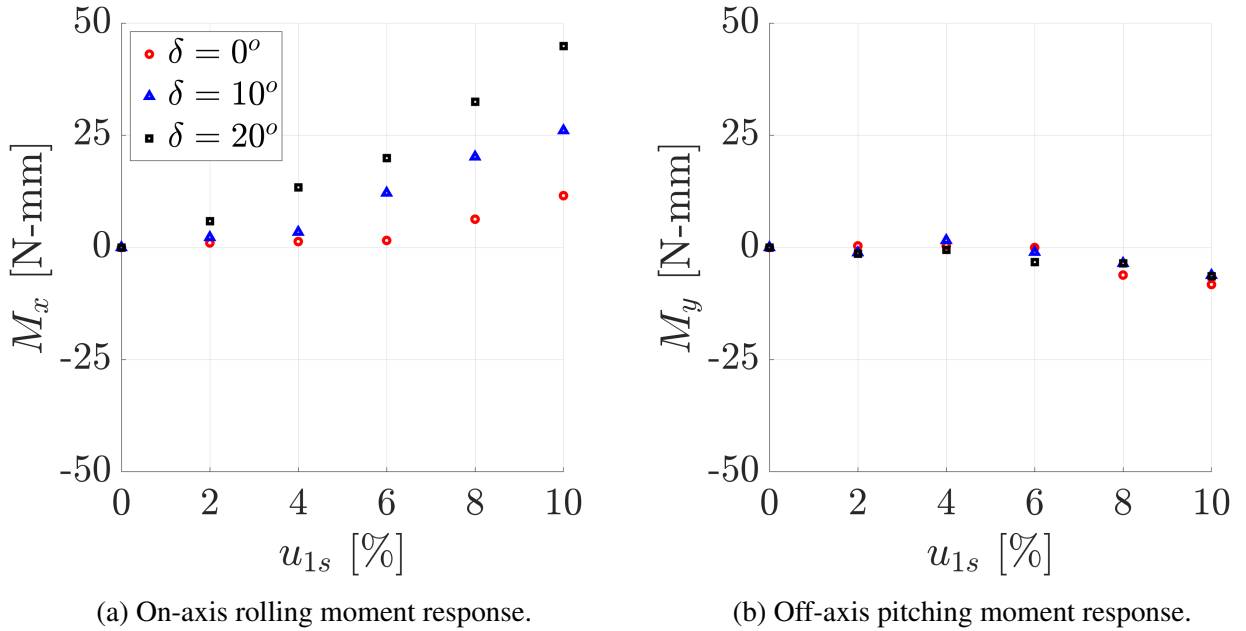


Figure 5.9: Rolling moment M_x and pitching moment M_y variation with u_{1s} at 250 main rotor RPM with a fixed main rotor collective of 8 deg.

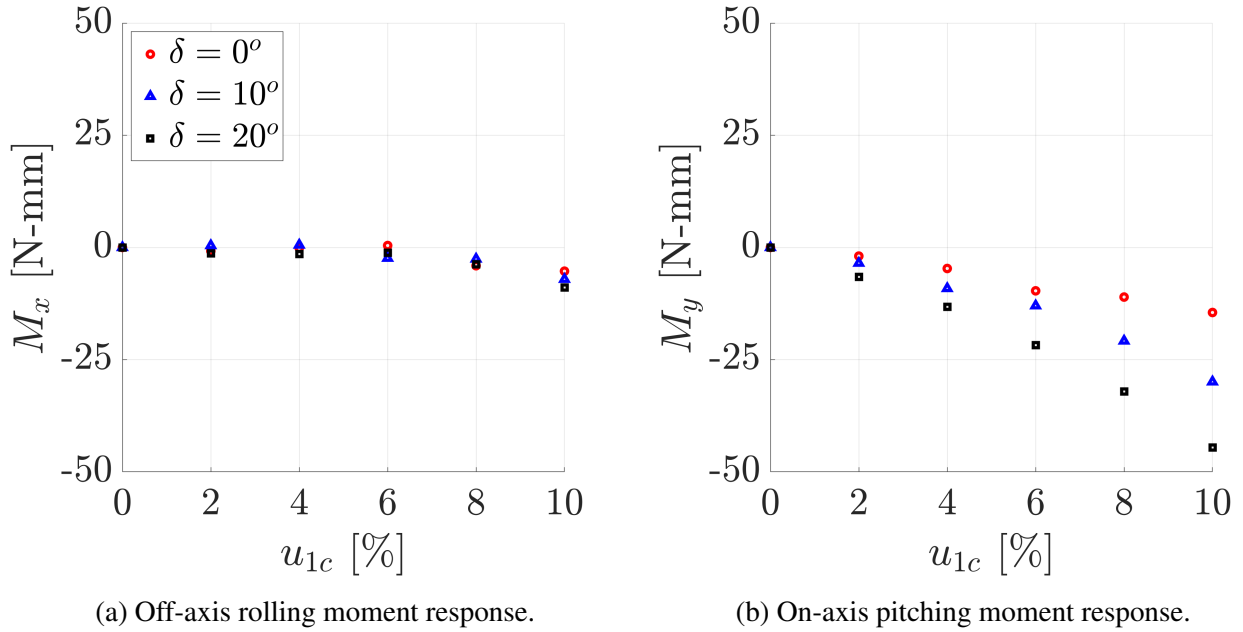


Figure 5.10: Rolling moment M_x and pitching moment M_y variation with u_{1c} at 250 main rotor RPM with a fixed main rotor collective of 8 deg.

5.2 Comparisons with Conventional Swashplate Control

The next step was to compare the propeller-driven rotor control authority to a conventional swashplate. As such, the final set of experiments involved a measuring the rolling and pitching moments of a shaft-driven rotor using a swashplate. Figure 5.11 shows the 6 ft diameter, 2 bladed hingeless rotor that was tested. This was the same composite rotor blade and test stand used in Section 3.3.

The 6 ft diameter, shaft-driven rotor blade experiments were conducted at the University of Maryland's Hover Testing Facility. Table 5.2 contains specifications on the 6 ft diameter rotor. While the 2.7 ft diameter rotor blades and the 6 ft diameter rotor blades are operated at different tip speeds and had different planforms, the presented results have been nondimensional to rotor tip speed and blade area. This ensures a representative physics were captured between the two rotors. Additionally,

all control comparisons were conducted at the same rotor collective of 8 deg for both rotors.

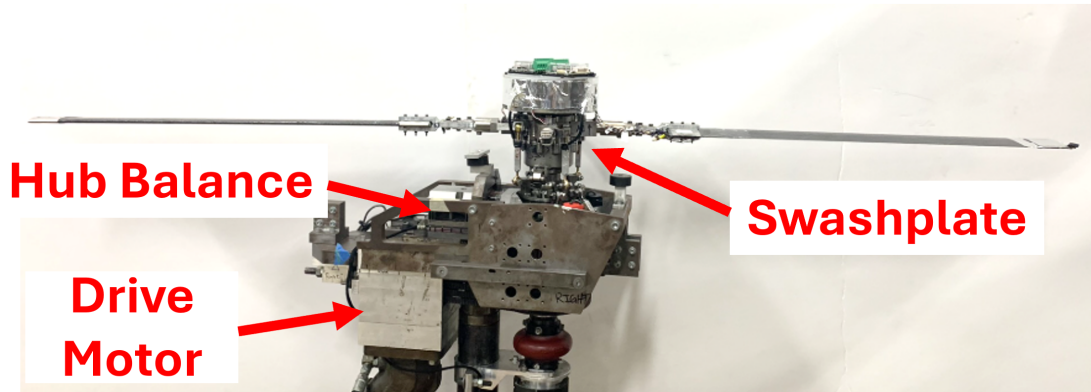


Figure 5.11: Conventional rotor test stand using 6 ft diameter composite rotor blades.

Figures 5.12a to 5.12d show the results of a collective sweep using the 6 ft diameter rotor. The collective sweep was between 2 and 14 degrees of rotor root collective while the rotor cyclics were set to 0, and the corresponding rotor thrust and power were recorded. The peak figure of merit for the rotor was found to be 33% for the untwisted rotor. After the collective sweep, the rotor control moments to cyclics were recorded.

Table 5.2: Conventional rotor test stand characteristics.

Rotor Radius R	36 in
Rotor Chord c	3.15 in
Rotor Aspect Ratio R/c	11.4
Number of Rotor Blades	2
Rotor RPM	400
Rotor Flap Frequency	1.78/rev
Rotor Airfoil	NACA0012
Rotor Solidity σ	5%
Rotor Collective θ_0	2 to 14 deg
Rotor Twist	None
Rotor Cyclics	-4 to 4 deg

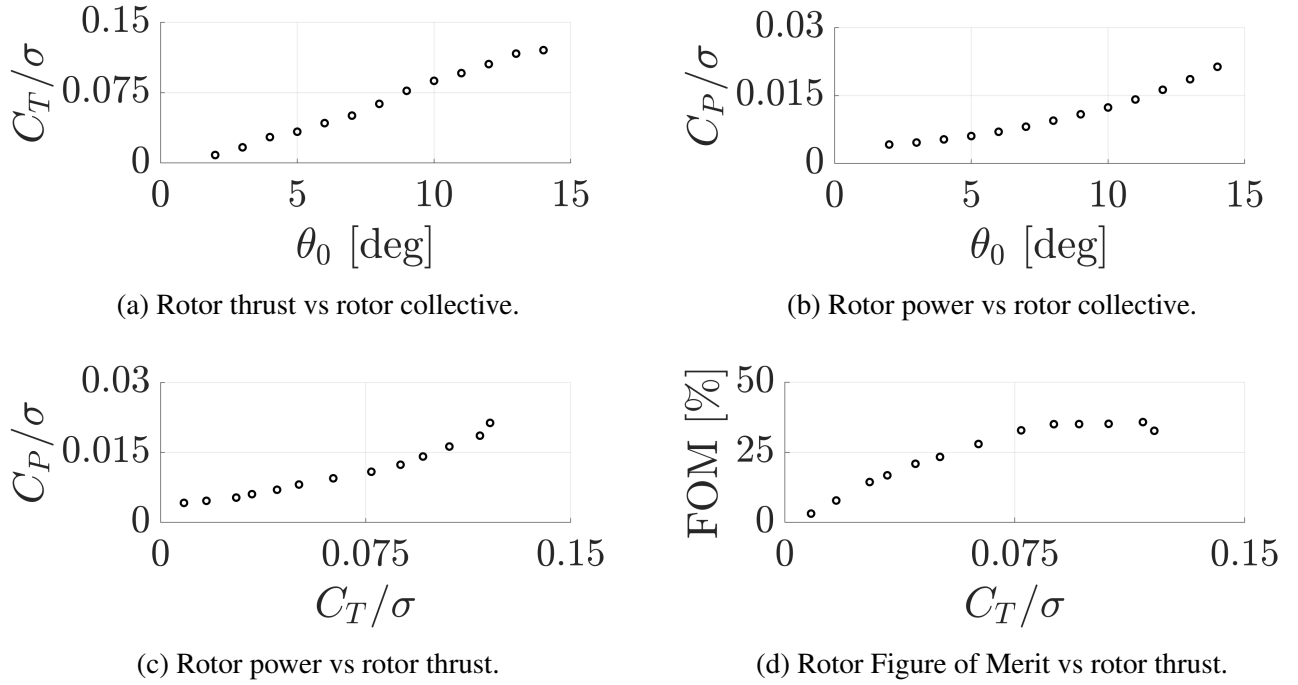


Figure 5.12: Isolated rotor performance characteristics.

5.2.1 Swashplate Control Sweeps

Next, the rotor collective was fixed at 8 degrees and a swashplate cyclic sweep was performed at 400 rotor RPM. The 8 degrees rotor collective was the same as the 3D printed 2.7 ft diameter rotors used in the propeller-driven rotor control experiments. The swashplate produced 1 per rotor revolution input on pitch angle as:

$$\theta(\psi) = \theta_0 + \theta_{1c} \cos \psi + \theta_{1s} \sin \psi \quad (5.3)$$

where θ_0 is the rotor collective, whereas θ_{1s} and θ_{1c} are the longitudinal and lateral swashplate inputs, respectively. The rotor's rolling C_{mx} and pitching moment C_{my} coefficients are defined as:

$$C_{mx} = \frac{M_x}{\rho A (\Omega R)^2 R}$$

$$C_{my} = \frac{M_y}{\rho A (\Omega R)^2 R}$$

For the experiment, the swashplate sweeps were conducted by varying one cyclic input while the other cyclic was kept at 0. Figures 5.13 and 5.14 show the results for the longitudinal and lateral sweeps compared to their predicted values, respectively. The control response to a given swashplate input was calculated by solving the rotor blade flapping equation of motion [20]. The predicted results show good agreement with the experimentally measured values.

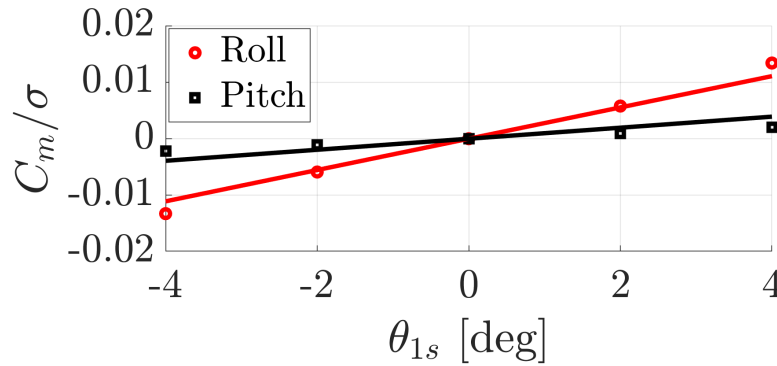


Figure 5.13: Measured (dots) and predicted (lines) rotor longitudinal cyclic sweeps at 400 main rotor RPM.

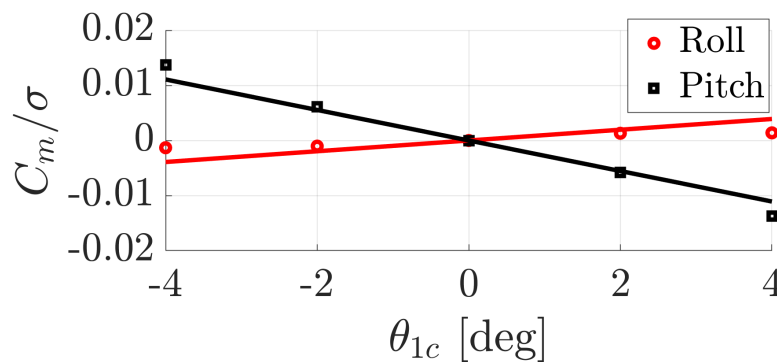


Figure 5.14: Measured (dots) and predicted (lines) lateral cyclic sweeps at 400 main rotor RPM.

5.2.2 Propeller-Driven Control vs Swashplate Control Comparison

The control response can be compared by determining the control derivative for each input. The control derivative relates the control input u to the control moment C_m , and can be written as:

$$\frac{C_m}{\sigma} = \frac{d(C_m/\sigma)}{du} u$$

where $d(C_m/\sigma)/du$ was determined by examining the slope of the lines in Figures 5.15 to 5.18. For the swashplate control, the control moment derivatives were found to be:

$$\frac{C_{mx}}{\sigma} = \frac{d(C_{mx}/\sigma)}{d\theta_{1s}} \theta_{1s} = 0.0034 \frac{1}{deg} \theta_{1s}$$

$$\frac{C_{my}}{\sigma} = \frac{d(C_{my}/\sigma)}{d\theta_{1c}} \theta_{1c} = -0.0034 \frac{1}{deg} \theta_{1c}$$

A similar argument was made for relating the propeller-driven rotor control to the propeller-driven rotor inputs u_{1s} and u_{1c} . Consider the propeller-driven rotor $\delta = 0^\circ$ longitudinal control derivative relative to C_{mx}/σ :

$$\frac{d(C_{mx}/\sigma)}{du_{1s}} = 0.0004 \frac{1}{\%}$$

Comparing the value of $\frac{d(C_{mx}/\sigma)}{du_{1s}}$ to $\frac{d(C_{mx}/\sigma)}{d\theta_{1s}}$ yields:

$$\frac{d(C_{mx}/\sigma)}{d\theta_{1s}} \frac{du_{1s}}{d(C_{mx}/\sigma)} = \frac{0.0034}{0.0004} = 8.75 \frac{\%}{deg}$$

Indicating that for the $\delta = 0$ case, 8.75% motor variation creates the same control moment as 1 deg of swashplate input.

Figures 5.15 to 5.18 compare the control response for both the swashplate and propeller-driven rotor control schemes. It can be seen that the $\delta = 20^\circ$ cases produces nearly the same magnitude as the swashplate cyclic controls. Tables 5.3 and 5.4 compare the propeller-driven rotor control derivative value and their value relative to the swashplate control scheme. These results show that for the $\delta = 20^\circ$ case, a motor input variation of about 2.3% is equivalent to 1 degree of cyclic variation.

Table 5.3: Comparison of longitudinal control derivatives.

δ [deg]	$\frac{d(C_{mx}/\sigma)}{du_{1s}}$ [1/%]	$\frac{d(C_{mx}/\sigma)}{d\theta_{1s}} \frac{du_{1s}}{d(C_{mx}/\sigma)}$ [%/deg]
0	0.0004	8.75
10	0.0009	3.89
20	0.0015	2.25

Table 5.4: Comparison of lateral control derivatives.

δ [deg]	$\frac{d(C_{my}/\sigma)}{du_{1c}}$ [1/%]	$\frac{d(C_{my}/\sigma)}{d\theta_{1c}} \frac{du_{1c}}{d(C_{my}/\sigma)}$ [%/deg]
0	-0.0005	7.12
10	-0.0010	3.50
20	-0.0015	2.31

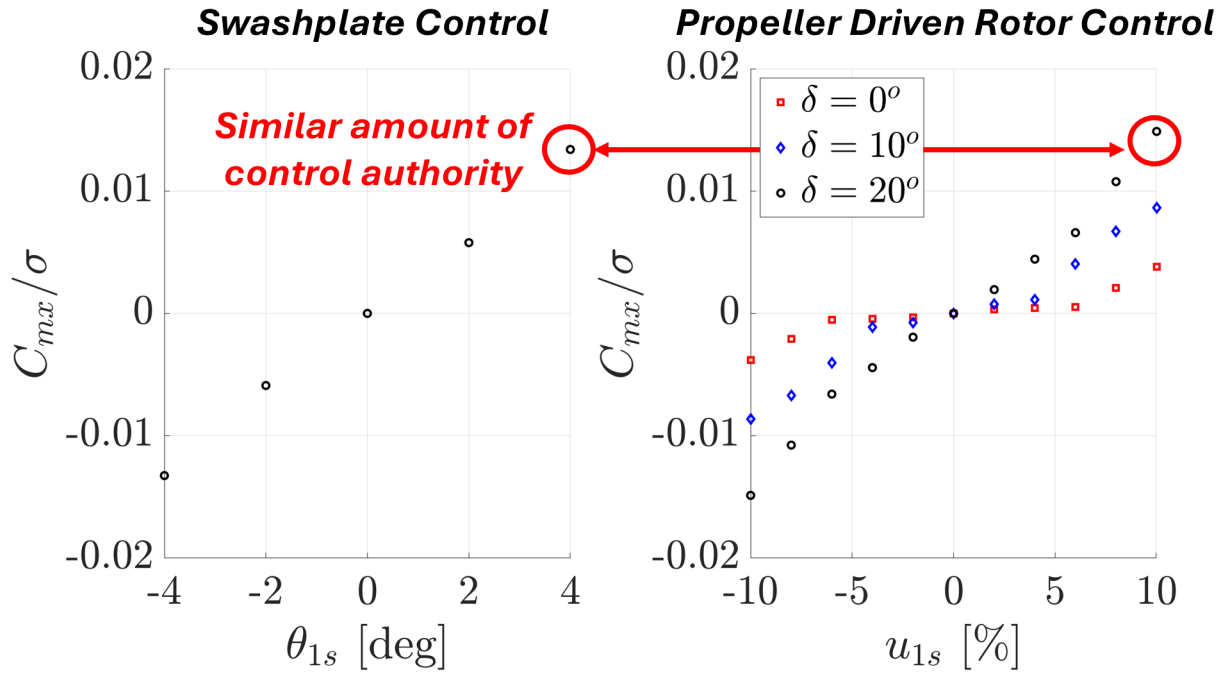


Figure 5.15: Comparisons of rotor rolling moment to longitudinal input.

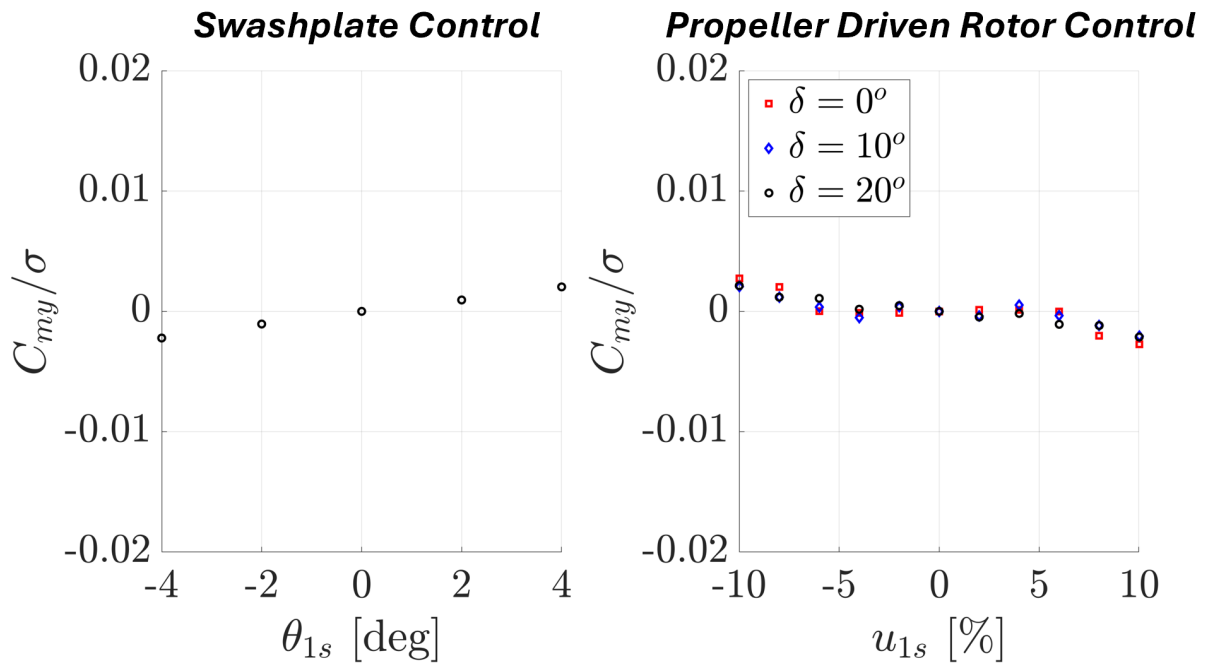


Figure 5.16: Comparisons of rotor pitching moment to longitudinal input.

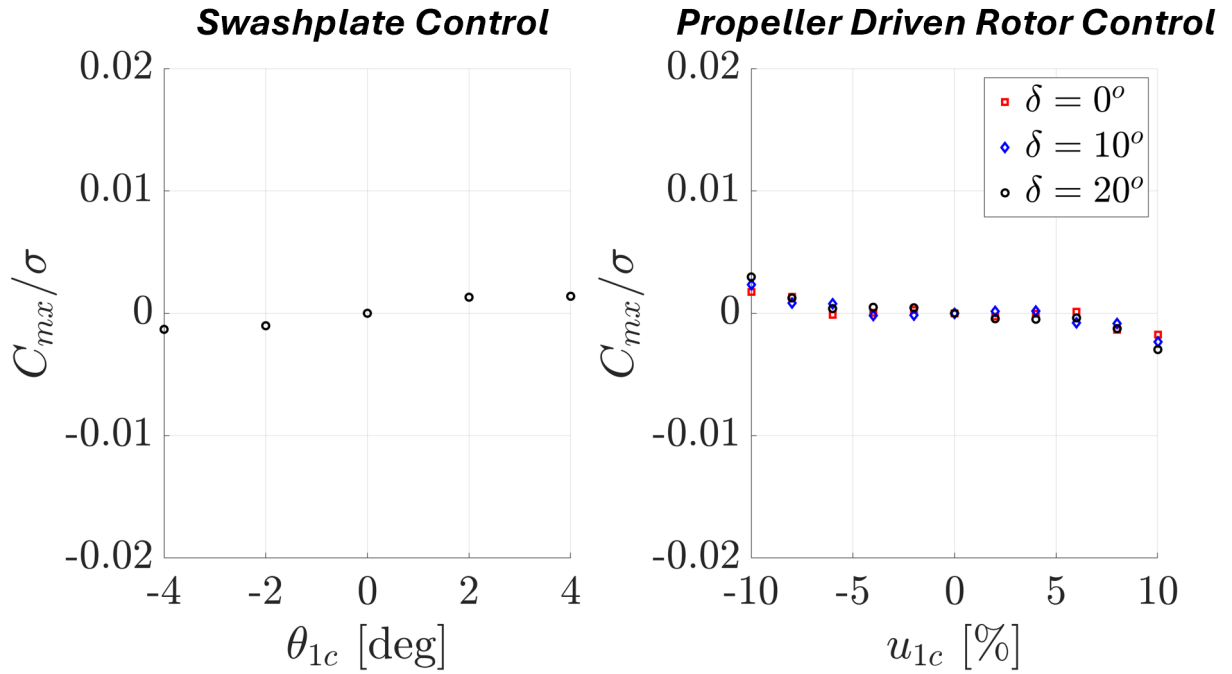


Figure 5.17: Comparisons of rotor rolling moment to lateral input.

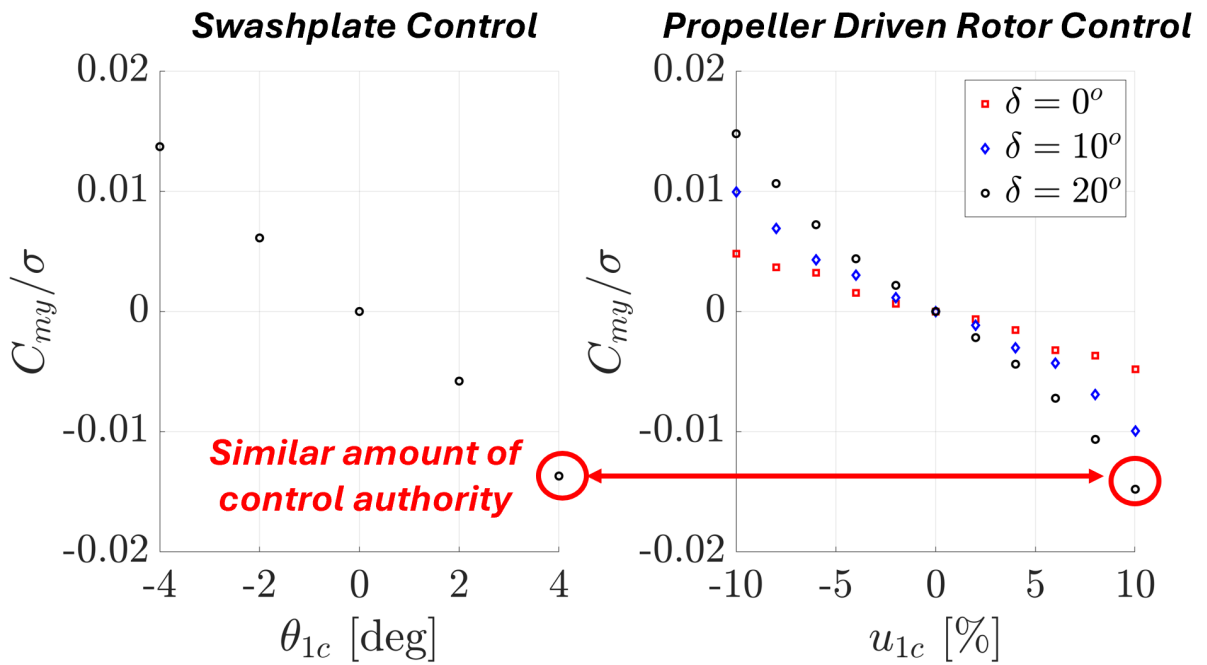


Figure 5.18: Comparisons of rotor pitching moment to lateral input.

5.3 Conclusions

This study documents a novel control methodology for a propeller-driven rotor, where propeller speed was modulated around the main rotor azimuth. A 2.7 ft diameter propeller-driven rotor test stand was fabricated to experimentally develop and evaluate the novel swashplateless control scheme. The 3D printed rotors enabled rotor blade parameters, such as propeller tip angle δ and motor location, to be varied in a systematic manner. After characterizing the motor throttle variation to control moment performance, a 6 ft diameter rotor with a conventional swashplate was tested. This enabled the propeller-driven rotor control scheme to be directly compared to a conventional shaft-driven rotor with a swashplate. From this study, the following conclusions were made:

- The propeller-driven rotor control scheme was found to produce similar control moments as a conventional swashplate system. For the tip propeller angle $\delta = 20^\circ$ case, 2.3% of motor throttle variation was equivalent to 1 degree of swashplate input.
- For a tip propeller angle δ of 20° , increasing u_{1s} by 10% required 22.9% additional electrical power.
- Varying the motor throttle with rotor azimuth produced satisfactory on-axis control moments and had negligible cross coupling with the off-axis.

Chapter 6: Summary, Conclusions, and Future Work

Throughout this work the fundamental concept of a propeller-driven rotor was explored both experimentally and analytically. The focus of the research revolved around propeller-driven rotor hover performance, dynamics, and controls. This chapter summarizes the research, presents key conclusions, and discusses areas of future work.

6.1 Summary

The research started by exploring the feasibility of a propeller-driven rotor and comparing it to a conventional shaft-driven rotor. A composite rotor blade was developed that enabled the propeller tip assembly to be rigidly bolted to the end of the main rotor blade. Isolated propeller testing in the Low Turbulence Wind Tunnel at NSWC Carderock characterized propeller performance at various axial flight speeds and conditions. Hover testing of the 5.5 ft diameter propeller-driven rotor enabled a simple analytical performance model to be developed that capture general trends of propeller performance, propeller/rotor RPMs, and propeller-driven rotor power. During initial testing, a tip propeller broke during propeller-driven rotor operation. This suggested that the loads on a propeller-driven rotor are different than the loads seen during propeller axial flight.

After the feasibility experiment, a second hover test was performed with the purpose of measuring tip propeller loads during propeller-driven rotor operation. The tip assembly was redesigned

to incorporate a 6 DOF load cell to measure propeller hub loads, and the signal wires were passed through the main rotor blade composite shell. As a checkout test, a wind tunnel test was performed on the isolated non-rotating rotor blade (acting as a wing) and the tip propeller load cell. After this, a hover test was performed on the propeller-driven rotor. Propeller hub loads recorded a large, previously unmodeled, propeller pitching moment. Propeller-driven rotor performance remained quite poor compared to a isolated shaft-driven rotor.

In an effort to reduce propeller power, the impact of propeller placement on main rotor blade span was explored. A propeller was placed at $1/2R$, $3/4R$, and R (i.e. tip) on the main rotor blade, and propeller-driven rotor thrust, rotor/propeller rotational speeds, and power were recorded. Three cases were compared: constant rotor thrust, constant propeller RPM, and constant rotor RPM. The results indicated that the midspan propeller required less power compared to a tip mounted propeller. shaft-driven testing of the rotor blades also found that the midspan mounted propeller had a similar rotor C_P/σ compared to an isolated rotor (ie, one without a nacelle).

While conducting experiments with the 2.7 ft diameter test stand, a swashplateless control concept was developed for the propeller-driven rotor. The propeller was tilted at a slight angle δ with respect to the rotor blade chord, and propeller speed was modulated around the rotor azimuth to produce control moments. A 2.7 ft diameter test stand was fabricated to explore and characterize the concept. 3D printed rotor blades were developed to facilitate systematic variations of key parameters, such as the rotor blade tip design. The swashplateless propeller-driven rotor control was compared to a conventional swashplate and it was found to have similar control authority.

For the next experiment, the focus returned to the 6 ft diameter hover test stand. While testing propeller-driven rotors at higher rotor rotational speeds, numerous tip propellers suffered propeller blade root failures. This halted the hover experiment and prompted an investigation into propeller

loads during propeller-driven rotor operation. A vacuum chamber experiment was created to remove aerodynamic loads and isolate inertial loads. The experiment measured propeller flapping motion at various rotor and propeller speeds. A large 1 per propeller rev sinusoidal propeller flapping motion was observed. In an effort to understand this result, two models were developed: first, a simple analytical model, and then a comprehensive rotorcraft analysis model. The resulting phenomenon was later termed the propeller-driven rotor twirl phenomenon.

The propeller-driven rotor twirl phenomenon arises from the rotor-propeller Coriolis moment interacting with rotor blade structural modes. As the propeller spins on the rotating rotor blade, a Coriolis moment is generated that acts to bend the propeller. A simplified one-way coupling analysis was developed between the propeller Coriolis load and the rotor blade torsion mode. The interaction between the Coriolis moment and rotor blade torsion was the suspected failure of the various propeller seen in this research.

The vacuum chamber experiment highlighted the need for a comprehensive rotorcraft analysis framework to model propeller-driven rotor performance and loads. To address this need, a multi-body finite element model was developed to study the propeller-driven rotor concept. The comprehensive model allowed for arbitrary rotor/propeller typologies to be modeled, and joints are able to model various degrees of freedom. The comprehensive rotorcraft analysis methodology was validated using various hover and vacuum chamber datasets.

A final vacuum chamber experiment involving propeller-rotor loads was conducted. Strain gauges on the rotor blade measured loads from propeller-driven rotor operation, and the propeller tip assembly with the 6 DOF load cell was employed to measure propeller hub loads. Loads were measured as rotor and propeller speeds were varied, and validated with comprehensive analysis. The rotor-propeller Coriolis interaction results in a rotor blade torsional load.

6.2 Key Conclusions

From this work, there are several key conclusions.

6.2.1 Hover Performance

1. Axial flight testing in the Low Turbulence Wind Tunnel was an excellent method of characterizing isolated propeller efficiency. For the low Reynolds number propellers used in this research, the maximum propulsive efficiency seen experimentally was only 45%.
2. For a constant rotor collective θ_0 , there is a linear relationship between rotor and propeller rotational speeds.
3. The modeling approach of assuming the propeller located at x_p has a climb velocity $v_c = x_p(\Omega R)$ was found to be a satisfactory predictor of propeller-driven rotor performance.
4. During initial feasibility testing it was found that adding the fully exposed tip motor to the isolated rotor blade had a significantly negative impact on performance. At a rotor collective of 8 deg, the thrust coefficient reduced by 12.5% while the torque coefficient increased by 91.5%.
5. For the 2.7 ft diameter propeller-driven rotor experiment featuring variable propeller placement, the propeller located at the rotor blade half span location resulted in a 50% electrical power coefficient reduction compared to the tip mounted propeller. Later comprehensive modeling was able to predict these trends, leading to the development of a simplified non-dimensional physics model.
6. Shaft-driven testing of the rotor blades with various propeller placements found that the propeller

located at $1/2R$ had a similar C_P/σ as a rotor blade without a nacelle.

7. A simplified expression for propeller-driven rotor power was found to be $P_{PDR} = \frac{C_Q}{\eta_p} \rho A (\Omega R)^3$ that showed that propeller-driven rotor power P_{PDR} increased with rotor blade design and nacelle drag C_Q and decreased as propeller efficiency η_p increased. For a propeller-driven rotor design with a streamlined nacelle and propeller efficiency $\eta_p = 0.85$, this corresponds to 17% additional power compared to an isolated, conventional shaft-driven rotor.
8. Propeller placement has the following impacts on hover performance. First, the location and rotor configuration determines the propeller climb ratio λ_{cp} . The propeller should be placed at a location with a λ_{cp} corresponding to a maximum propeller climb ratio η_p . Second, the loads for the propeller generally increase significantly with rotor spanwise placement, with a slight reduction in propeller thrust. Finally, placing the propeller further down the rotor blade reduces the torsional frequency of the rotor blade, and thus issues with dynamic coupling increase.
9. While considering scaling effects, the main rotor should have a low disk loading to prevent the rotor/propeller tipspeeds from approaching Mach 1. Additionally, a major benefit was predicted due to Reynolds number scaling effects on the propeller. Scaling from a Reynolds number of 50,000 to 1,000,000 increased the maximum C_l/C_d of a Clark-Y airfoil from 20 to 120.
10. For a well designed propeller-driven rotor (ie high-efficiency propeller and optimum spanwise placement on the rotor blade), the power is comparable to a single-main rotor helicopter design.

6.2.2 Dynamics

On the topic of the propeller-driven rotor twirl phenomenon:

1. Numerous propellers failed during propeller-driven rotor hover testing. This suggested the loading environment for the propellers rotors was different than axial flight.
2. As the propeller spins on the rotor blade, the propeller mass is moving radially into/away from the rotor center of rotation. This results in a Coriolis force that acts to push/pull the propeller blade in the tangential direction.
3. Propeller-driven rotor twirl phenomenon originates from coupling of the rotor and propeller modes through Coriolis loads induced on the propeller by the rotor. The rotor-propeller Coriolis interaction resulting in a pitching moment for the propeller and a rotor blade torsional moment.
4. While studying the one-way coupling between the propeller and the rotor blade, two failure modes were identified: one steady and one oscillatory. The static failure results from the rotor-propeller Coriolis moment exceeding the rotor blade torsional strength. The oscillatory failure results from a 2 bladed propeller harmonics interacting with the rotor blade torsional mode at resonance.
5. Increasing the number of propeller blades increases the steady Coriolis moment, on both the propeller and the rotor blade.
6. Propellers with one or two blades should not be used to avoid rotor blade torsional resonance.

On the topic of the propeller flapping vacuum chamber experiment:

1. A large 20 deg, one per propeller rev sinusoidal flapping motion was observed for the propeller.

2. For the speeds in the experiment, as rotor speed increased the propeller flap response increased.
3. For the speeds in the experiment, as propeller speed increased the propeller flap response increased.
4. A propeller flapping equation of motion was derived to describe the experimental results. The Harmonic Balance Method assumed a periodic response and the propeller flap values of β_0 , β_{1c} , and β_{1s} were expressed in terms of propeller-driven rotor parameters. The β_{1s} results from rotor speed Ω and propeller speed Ω_p , and is not a function of propeller spanwise placement. The β_0 and β_{1c} terms are coupled, and are functions of rotor speed Ω , chordwise offset h , and propeller spanwise placement.
5. Comprehensive rotorcraft modeling showed that propeller per rev harmonics increased as rotor and propeller speeds increased. This results in a tightening of the sinusoidal peaks that matches the experimental data.

On the topic of the rotor-propeller loads vacuum chamber experiment:

1. As rotor and propeller speeds increased, the rotor-propeller Coriolis moment increased and was measured on both the propeller hub loads and the rotor blade torsional load.
2. The comprehensive analysis predicted the results seen in the experimental data. Careful modeling of the tip propeller assembly was required to adequately capture inertial loads.

6.2.3 Swashplateless Controls

1. The method of varying propeller rotational speeds with rotor azimuth resulted in excellent on-axis control and minimal off-axis control. These are desired properties in a control system.

2. For the propeller tip angle $\delta = 20$ deg case, a 2.3% motor throttle variation was equivalent to 1 deg of swashplate input. However, increasing u_{1s} or u_{1c} by 10% required 22.9% additional electrical power.
3. 3D printing small scale rotor blades was found to be an effective method of rapidly prototyping propeller-driven rotor blades with various tip geometries and propeller spanwise placements.

6.3 Future Work

This work can be extended in both experimental testing and analysis.

6.3.1 Experiments

1. The discovery of the swirl phenomenon represents an interesting opportunity for experimental testing. More specifically, determining the correct propeller design for the propeller-driven rotor configuration remains an open question. The solution must contain two key features. First, the propeller should have a high propulsive efficiency and a low nacelle drag. Second, the propeller design must be capable of withstanding the inertial loads resulting from the Coriolis moment and the rotor centrifugal force. Testing on various propeller hub designs (articulated, gimbaled, hingeless) is needed to adequately answer the loads question.
2. High required propeller power is one barrier for propeller-driven rotors. For this research, this has been due to low Reynolds numbers of 50,000 that have low lift and high drag. The propeller airfoils, planform, and operating speeds should be designed to facilitate a high propulsive efficiencies, with a target propulsive efficiency of 85% or higher. Propeller designs should be validated in axial flight and propeller rotary flight before propeller-driven rotor operation.

3. An understanding of the propeller blade load variations with propeller azimuth ψ_p are needed to address the swirl phenomenon. The propeller flapping vacuum chamber experiment must be expanded to include propeller blade loads, in flap, lag, and torsion. Additionally, strain gauges should be used on the rotor blade to measure rotor blade loads with propeller azimuth ψ_p . Vacuum chamber, hover, and isolated propeller testing are needed to address this issue. This test stand should be expanded to include propeller stability tests as well.
4. Forward flight testing is needed to continue development of the propeller-driven rotor concept. This opens up a new regime of performance, loads, and stability testing at various forward flight conditions. In hover, the climb velocity v_c seen by the propeller is uniform around the rotor azimuth. This is not true in forward flight, as the advancing side and retreating side of the rotor speed must impact propeller performance. This introduces a time varying, or harmonic, element to the propeller climb velocity v_c , which is sure to lead to additional discoveries.
5. The swashplateless control concept should be applied to the 6 ft diameter propeller-driven rotor test stand to investigate the scalability of the proposed design. Additionally, the propeller should be placed at locations other than the rotor blade tip. This experiment should also characterize the brushless DC motor control response and its impact on propeller-driven rotor control. A full system identification approach should be employed for future coupling with propeller-driven rotor flight dynamics modeling.
6. After successful demonstration of the swashplateless propeller-driven rotor control concept, a logical next step is the development of a free-flying propeller-driven rotor UAS. A “flying rotor design” would be a complete departure from conventional rotorcraft and would not have a fuselage, tail rotor, or swashplate. This custom propeller-driven rotor aircraft would require a clean

sheet design, and feature a custom flight controller that uses the motor azimuth variation logic described in Chapter 5. Additionally, the custom nature of the aircraft should enable the ability to easily modify propeller spanwise placement and δ angles. Power and control gains for various configurations should be examined.

7. A particle image velocimetry (PIV) analysis would shed light on several areas of propeller-driven rotor performance. First, the measurement of propeller induced velocity in propeller rotary flight would capture the impact of uneven climb velocity experienced across the propeller disk. Second, the nacelle geometry has a strongly negative impact on rotor thrust and power. Capturing the rotor blade wake interactions with the nacelle, at various spanwise locations, would help in assisting future design considerations. Finally, propeller chordwise offset distance h on propeller-rotor wake should be investigated.
8. The final area of investigation is propeller-driven rotor aeroacoustics. During propeller-driven rotor hover testing, the propeller-driven rotor has an unique acoustic signature. It is dominated by the high frequency propellers, which change in pitch as they revolve around the main rotor azimuth. The propeller acoustic pitch increases when moving towards an observer, and reduces when moving away. This unique noise signature has been captured on videos of rotor tests, but has not been rigorously investigated. Systematically studying propeller-driven rotor noise is essential for future design considerations. A follow up study on propeller-driven rotor acoustics using the University of Maryland Rotorcraft Anechoic Facility is recommended.

6.3.2 Analysis

1. A simplified one-way analysis between propeller loads influencing rotor torsion loads was presented. This was educational but simplistic in nature, and should be expanded to include a two-way coupling analysis. The key with two-way coupling is how rotor blade motions affect propeller loads. After creation of the fully coupled system, a stability analysis should be conducted to predict propeller failures during propeller-driven rotor operation.
2. Forward flight analysis is needed to explain experimental results from the forward flight wind tunnel tests. The time varying loads will introduce rotor-propeller loads that are hard to capture experimentally. The comprehensive rotorcraft methodology developed for this work can be expanded to include forward flight analysis. Additionally, the propeller stability properties with the propeller-driven rotor swirl phenomenon should be predicted for various flight speeds and conditions.
3. A unexplored topic of this work is how the propeller wake interacts with the main rotor wake. While a PIV experiment was discussed as future work, this task should be accompanied by a detailed CFD analysis. The ERA comprehensive analysis model can couple with the HELIOS CFD tool using the delta air loads approach. Various induced velocity models can be explored. A challenge for this approach is the high computational complexity required for adequate time resolution, as the propeller speed is often 100-1000's of times larger than the rotor speed and a propeller azimuth spacing of 0.25 deg is required. However, if such a problem was tackled then phenomenon observed in the proposed experimental PIV datasets could be explained. This CFD based approach could also be extended to predict propeller-driven rotor noise.

Bibliography

- [1] Gibbings, D., “The Fairey Rotordyne - Technology Before Its Time,” *The American Journal*, Vol 108.1089, 2004, pp 565-574.
- [2] Schwartz, A. W., Reader, K. R., and Rogers, E. O., “An Unmanned Air Vehicle Concept with Tipjet Drive,” *Journal of the American Helicopter Society*, Vol. 39, No. 3, 1994, pp 67-74.
- [3] Haas, D., Silberg, E. J., and Kimmel, K., “The Navy’s Aerodynamics Laboratory-100 years of Experimental Aerodynamics from A-1 to DDG-1000,” American Institute of Aeronautics and Astronautics SciTech Forum, National Harbor, MD, Jan. 13-17, 2014.
- [4] Larwood, S., and Saiki, N., “Aerodynamic Design of the Cal Poly Da Vinci Human Powered Helicopter,” American Helicopter Society Vertical Lift Aircraft Design Conference, San Francisco, CA, Jan. 17-19, 1990.
- [5] Saetti, U., Enciu, J., and Horn, J., “Flight Dynamics and Control of an eVTOL Concept Aircraft with a Propeller-Driven Rotor,” *Journal of the American Helicopter Society*, Vol. 67, No. 3, 2022, pp 153-166.
- [6] Saetti, U., Enciu, J., and Horn, J. F., “Performance and Design Optimization of the F-Helix eVTOL Concept,” Proceedings of the 75th Annual Forum of the Vertical Flight Society, 2019.
- [7] Ulrich, E., Humbert, S., and Pines, D., “Pitch and Heave Control of Robotic Samara Micro Air Vehicles,” *Journal of Aircraft*, Vol. 47, No. 4, 2010, pp. 1290-1299.
- [8] Ulrich, E., “Design, Development, Analysis, and Control of a Bio-Inspired Robotic Samara Rotorcraft,” PhD Dissertation, University of Maryland, College Park, MD, 2012.
- [9] Bhardwaj, H., Hla Win, S. K., Thura Win, L. S., Sufiyan, D., and Shaohui, F., “P.I.D. Based Sliding Mode Control of Asynchronous Multi-actuator Monocopter,” IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Delft, Netherlands, July 2021.
- [10] Bhardwaj, H., Cai, X., Thura Win, L. S., and Shaohui, F., “Nature-Inspired in-Flight Foldable Rotorcraft,” *Bioinspiration & Biomimetics*, Vol. 18, May 2023, pp. 1-15.
- [11] Rehm, H., “Quad-I-Chopter,” *Drehmflight Blog*, June 2, 2024. [Online]. Available: <https://www.drehmflight.com/post/quadichopter>. [Accessed: Feb. 20, 2026].
- [12] Saxena, A., and Chopra, I., “Design, Development, and Hover Testing of a Mach-Scale Swashplateless Rotor Using Brushless DC Motor-Actuated Trailing Edge Flaps for Rotor Primary Control,” *Journal of the American Helicopter Society*, Vol. 62, No. 2, 2017, pp. 1-12.
- [13] Saxena, A., and Chopra, I., “Wind Tunnel Testing of a Swashplateless Rotor with Compact Brushless Motor Actuated Flaps for Primary Control,” *Journal of the American Helicopter Society*

ety, Vol. 65, No. 6, 2020, pp. 1-16.

- [14] Gul, S., and Datta, A., “Development of an Aeromechanics Solver for Loads and Stability of Hingeless Tiltrotors,” *Journal of Aircraft*, Vol. 60, No. 1, 2022, pp. 143–159.
- [15] Brown, R. and Chopra, I., “Characterization and Modeling of Brushless DC Motors and Electronic Speed Controllers with a Dynamometer,” Vertical Flight Society’s International Powered Lift Conference 2020, San Jose, CA, Jan. 2020.
- [16] Maurya, S., “Investigation of Compound Rotorcraft Aeromechanics Through Wind-Tunnel Testing and Analysis,” PhD Dissertation, University of Maryland, College Park, MD, 2022.
- [17] Wang, X., “Wind Tunnel Test on Slowed Rotor Aeromechanics at High Advance Ratios,” PhD Dissertation, University of Maryland, College Park, MD, 2022.
- [18] Saxena, A., “Primary Control of a Mach Scale Swashplateless Rotor Using Brushless DC Motor Actuated Trailing Edge Flaps,” PhD Dissertation, University of Maryland, College Park, MD, 2015.
- [19] Leishman, J. G., *Principles of Helicopter Aerodynamics*, Cambridge University Press, New York, NY, 2000, Chapter 2.
- [20] Johnson, W., *Rotorcraft Aeromechanics*, Cambridge University Press, New York, NY, 2013, Chapter 6.