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A Micro-Sized Ornithopter Wing Design

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This paper describes the design, construction, and performance of a micro-sized ornithopter wing. A novel sectioned design that performs well and can be built quickly and inexpensively is presented. Wind-tunnel test results that demonstrate the potential of the design are also presented. The design can be built in 3 person hours and achieved a propulsive efficiency of about 83%. An inertial effect known as propeller moment was observed, and its effect on micro-sized ornithopter wing design is described.

Introduction

ORNITHOPTERS, vehicles that flap their wings to generate thrust, represent a promising alternative to conventional propeller-driven vehicles. The propulsive efficiency of flapping flight has been shown to meet and possibly even exceed that of more traditional propulsion systems.[1–3] Based on observations of birds, researchers assert that ornithopters are capable of superior maneuverability compared to fixed-wing vehicles, can take off and land without a runway, and can be made to hover more easily than conventional aircraft. Because small ornithopters can be designed to look like birds, they could also be more stealthy than conventional vehicles. These qualities make ornithopter propulsion particularly well-suited to the micro air vehicles (MAVs) being funded by DARPA for reconnaissance, surveillance, urban operations support, targeting, and biological and chemical agent detection.[4] Unfortunately, the mechanical and aerodynamic complexities inherent in ornithopter design have limited the success of most man-made ornithopters. Recent research, however, has solved some of the aerodynamic difficulties,[3,5] and new applications, like MAVs, warrant another look at ornithopter propulsion.

Previous Work

Humans have long been fascinated by flapping flight. More than 100 years ago, in 1874, Pénaud built a successful rubber-powered ornithopter.[6] Over the following 100 years, ornithopter designers mimicked Pénaud's wing designs in which a sheet of thin material was attached to a leading edge spar to form a membrane wing. However, these designs were inefficient because of their very thin cambered cross-sections and because their designers did not understand the aerodynamics of flapping flight.

More recently, some designers have begun to incorporate efficient airfoil cross-sections and aerodynamic modeling into their designs. In 1985, for example, AeroVironment, Inc. built a flying pterosaur replica with a 5.5 meter wingspan based on wing motions derived by Kroo.[7] In 1991, DeLaurier built a flying, engine-powered ornithopter with a 2.5 meter wingspan using an asymmetric airfoil designed by Selig.[8]

The wings designed for these ornithopters, however, are an order of magnitude larger than those that would be required to propel a micro-air vehicle. The structural layout of the wings and the construction techniques used to build them are not suitable for micro-sized wings. Furthermore, these designs cannot be adapted easily to take advantage of recent minimum-induced loss flapping research.[1,3] These minimum induced loss results are based on the Betz criterion for minimum induced loss propellers[9] and extensions to the Betz criterion for the forward flight of helicopters.[10] They show that an ornithopter can achieve propulsive efficiencies of about 85%, and they give the circulation distribution required to achieve this efficiency.

Objective

The goal of this project was to design and build an efficient micro-sized ornithopter wing and to experimentally characterize its performance. The project focussed on developing a structural layout and construction techniques that can be used to build efficient micro-sized wings. Wind tunnel tests were conducted to measure the wing's quasi-steady performance, namely its thrust and propulsive efficiency. The wing was scaled to accurately capture the material selection and structural layout choices involved in small flexible wing design.

Technical Approach

Overview

This project consisted of three phases: wing design, construction, and evaluation. First, an aerodynamically efficient wing that could be constructed at a small scale was designed. During the construction phase, an iterative process of fabrication and verification took place in order to ensure that the wing behaved according to design predictions. Verification was achieved through measurement of the torsional stiffness of the

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wing and the thrust it produced in static tests. During the evaluation phase, the wing was spun on a propeller balance to simulate flapping as shown in Figure 1. Spinning was used instead of flapping because the focus of the project was on the structural design problem of creating a micro-sized wing, not the unsteady aerodynamics and structural dynamics of flapping flight. This also eliminated the need to create a flapping mechanism.

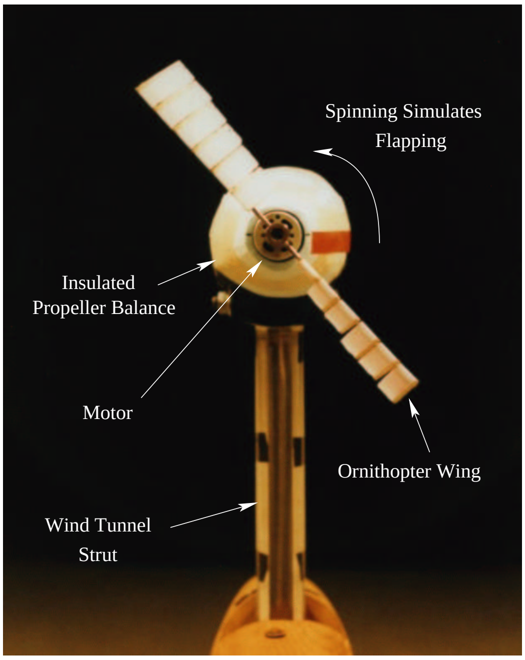

Fig. 1 Ornithopter wing fitted to propeller balance

Wing Design

Requirements

In order to be competitive with traditional propulsion systems, the wing must be efficient and easy to manufacture. To be efficient, the wing should have an airfoil cross-section and should not stall during flapping. Since the optimal ratio of airspeed to tip speed (advance ratio) for flapping flight is less than 1,[3] the wing tip must feather almost 45 degrees to avoid stall. The wing must be very torsionally compliant to achieve such a significant deformation. To be practical, the wing should also be inexpensive and the design should take into account the challenges of small-scale manufacturing.

Structural Layout

In order to twist appropriately during flight, the wing was designed to have a combination of high bending stiffness and low torsional stiffness. To achieve this combination, the wing was divided into sections supported by two spars. Each wing is divided into 6 rigid foam sections that can rotate relative to one another as shown in Figure 2. The inner spar is a solid circular rod that supports bending loads, and the outer spar is a 76μm-thick C-section that provides torsional compliance. The two spars are only connected to one another between the two wings. Only one point on each section is attached to the outer spar. The foam around the spar is cut away so that it does not prevent the spar from twisting. Thin fiberglass is used to reinforce the foam near the cutout for the spar.

Sectioning the wing has many advantages. One of the most important of these is that the wing uses aeroelastic feedback instead of sensors and actuators to achieve an efficient lift distribution. The sensors and actuators that would be necessary to achieve an efficient shape would add significant weight and would be extremely difficult to integrate at this scale. Instead, aerodynamic forces balanced by the outer spar's torsional stiffness cause the sectioned wing to twist into an efficient shape. A wing of this configuration is also easy to construct at a small scale, since it consists of a relatively small number parts whose interfaces are straightforward. Furthermore, the sectioned wing has no skin to wrinkle and degrade the aerodynamic performance when the wing twists. Finally, the sections do not contribute to the torsional stiffness of the wing, because they do not deform when the wing twists; the outer spar provides the only torsional stiffness. Sectioning the wing should not significantly degrade its aerodynamic efficiency, because most of the flow over the wing is chord-wise and does not collide with the surfaces between sections.

Spar Design

The inner spar's function is to support bending loads while allowing the outer spar to rotate freely over it. To allow free rotation of the outer spar, a circular cross-section was chosen for the inner spar. A $^1/_{16}$ inch diameter solid steel rod was chosen, although a hollow rod could have been used instead to reduce the weight while still supporting the bending loads.

The outer spar's function is to provide the correct torsional stiffness for efficient propulsion. The outer spar must be very torsionally compliant to prevent sections of the wing from stalling. Open spar cross-sections are much more torsionally compliant than closed cross-sections, so a C-shaped cross-section was chosen. Then, the aeroelastic models of the wing (see Ingram[11]) were used along with MATLAB's non-linear optimization routines to find the torsional stiffness that would yield the highest propulsive efficiency. The geometry of the C-section was chosen to achieve this optimal torsional stiffness while fitting loosely around the inner spar.

The final dimensions of the wing are summarized in Table 1.

Airfoil Selection

Once the overall structural layout of the wing was determined, the airfoil was selected. The most ap-

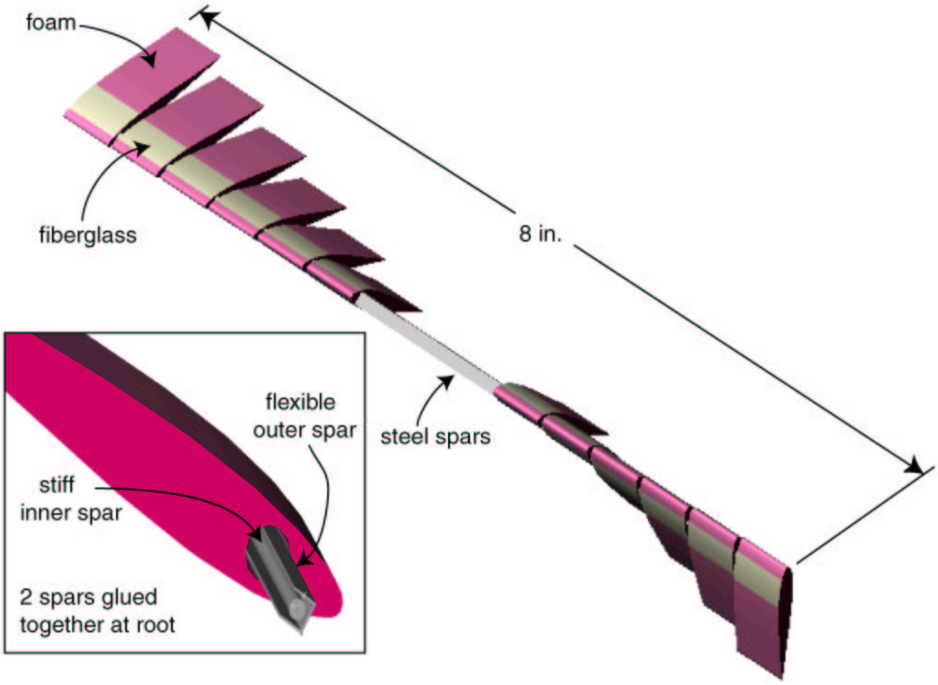

Fig. 2 The sectioned wing concept

Dimension	Value
Tip to tip span	20.3 cm
Number of sections per side	6
Section chord	3.9 cm
Section width	1.3 cm
Section airfoil	NACA0012/ E168 blend
Outer spar diameter	1.6 mm
Inner spar C-section thickness	76.2 μm
Inner spar C-section height	2.1 mm
Inner spar C-section width	1.7 mm

Table 1 Final wing dimensions

propriate airfoil for a micro-sized ornithopter is one that is suitable for low Reynolds number flight and is relatively insensitive to errors in angle of attack. In order to improve efficiency, a high lift to drag ratio is favored. Finally, the selected airfoil should be thick enough to accommodate torsionally compliant structural members. A blend between the NACA 0012 and the E168 airfoil was well suited to this application.

Construction and Verification

Two novel construction techniques were developed to build the MAV ornithopter wing. The first technique was to use a CNC sanding bit fashioned from drill rod, a short rubber tube, and a Dremel sanding bit as shown in Figure 3 to produce a smooth airfoil surface. Standard tools, on the other hand, tore out chunks from the foam. A second technique was developed to trim the outer spar's C-section. The C-section was placed over a parallel with the same width as the the vertical leg of the C-section. The C-section and parallel were then placed between pattern blocks and clamped in a vise as shown in Figure 4. The steel used to construct the outer spar was so thin that it could then be cut with a few passes of a razor blade. While the pattern blocks used for this MAV ornithopter wing had flat tops to cut a spar with uniform torsional stiffness, other patterns could easily be milled in the top of the blocks to cut a spar with a particular torsional stiffness distribution. Because of these construction techniques and the wing's simple design, only three person-hours were required to build the final wing.

After the spar was completed, its torsional stiffness was verified experimentally. The spar was used as the spring element in a torsional pendulum with known moment of inertia. Measurements of the natural frequency of this pendulum confirmed that the spar had the correct torsional stiffness.

Performance Characterization

This project used a thermally insulated propeller balance to characterize the quasi-steady performance, namely the thrust and propulsive efficiency, of the wings. Spinning the wings simulated flapping, and different rotation rates simulated different flapping frequencies. While at first spinning and flapping do not appear analogous, they are very similar motions. Both spinning and flapping are rotations of the wing about a central axis. Of course, there are differences between

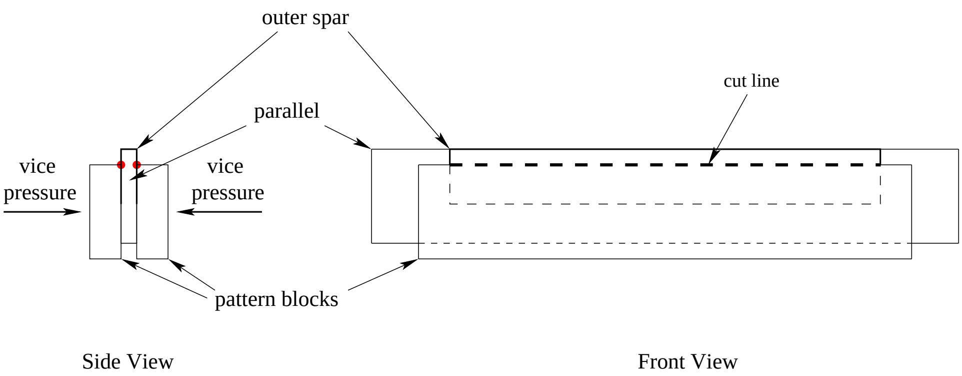

Fig. 4 Spar trimming technique

Fig. 3 CNC sanding bit

spinning and flapping. Spinning removes the structural dynamics and unsteady aerodynamics from the problem. However, since the goal of this project was to solve the structural design sub-problem of creating a micro-sized wing, it was beneficial to remove these complicating effects from the experiment.

The first performance metric, thrust, was measured directly by the propeller balance. The other metric, propulsive efficiency, was calculated:

$$\eta = \frac{\text{Thrust Power}}{\text{Motor Power Output}} = \frac{T v_\infty}{\tau \omega} \tag{1}$$

where η is the propulsive efficiency, T is the thrust produced, v_∞ is the freestream velocity, τ is the torque generated by the motor, and ω is the angular velocity of the motor. Thus, T, v_∞, τ, and ω were measured to quantify the efficiency of the wing.

The instruments used to quantify the performance of the wing are depicted schematically in Figure 5. The wings were mounted on the propeller balance shown in the center of the figure to measured thrust and torque. A strobe light shown at the left of the figure measured the angular velocity of the wings. The velocity was measured by a system of pitot-static ports corrected for temperature and humidity. The data was recorded by a computer for later post-processing.

The variables that affect the wing's performance and could be varied in this experiment were the freestream velocity and the motor angular velocity. The original strategy was to test a range of angular velocities and freestream velocities about the optimal flight conditions to capture the wing's efficiency and thrust peaks and the manner in which the wing's performance degraded under non-optimal conditions. However, a twist angle instability described in the high-speed testing section prevented testing at the optimal flight freestream velocity of 21 m/s and angular velocity of 275 rad/s. Instead, the wing was tested at 7 freestream velocities between 0 m/s and 10.7 m/s and 13 angular velocities between 0 rad/s and 262 rad/s.

Based on a complete quantitative error analysis for the experiment,[11] the most significant sources of error were the thrust and torque measurements taken by the propeller balance. Before the balance was insulated, errors caused by ambient temperature fluctuations on the same order as the expected measurements were observed. By insulating the balance and by taking frequent zero readings, more precise measurements could be be taken.

Errors in these thrust and torque measurements had a particularly large impact on the calculated efficiency under certain conditions, namely at high freestream velocities, low angular velocities, and low motor torques. This was because a small thrust measurement error, $\mathrm{d}T$, and a small torque measurement error, $\mathrm{d}\tau$, cause a calculated efficiency error, $\mathrm{d}\eta$, of

$$\mathrm{d}\eta = \frac{v}{w\tau^2}\left(\tau \mathrm{d}T - T\mathrm{d}\tau\right) \tag{2}$$

Results and Analysis

This section describes the experimentally measured performance of the MAV ornithopter wing. First, the

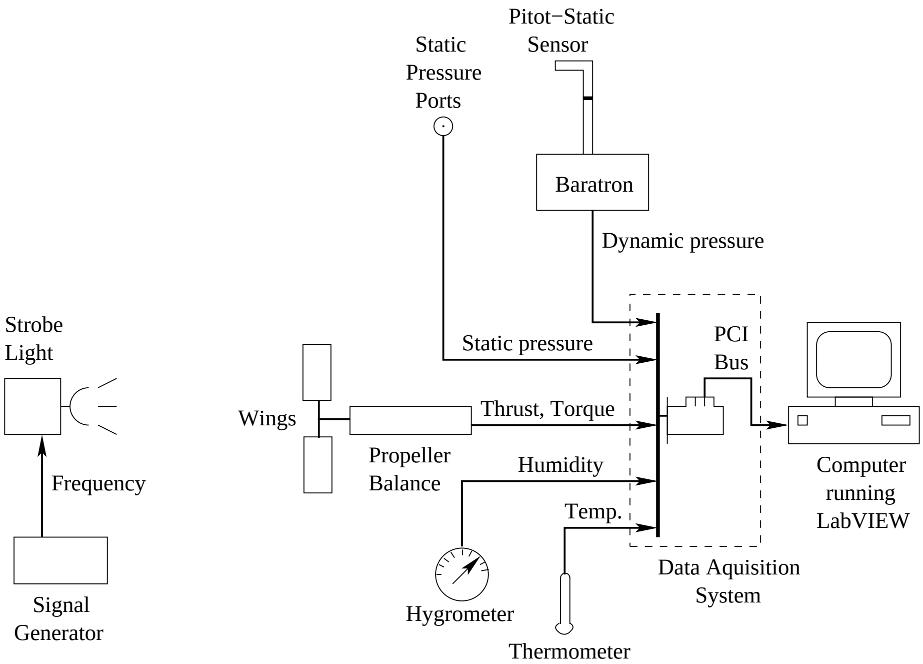

Fig. 5 Schematic of instrumentation used to quantify ornithopter wing performance

static performance results and an unexpected inertial effect discovered during static testing are discussed. Next, typical low-speed test results are presented. Finally, the difficulties encountered when testing at higher speeds are described.

Static Performance

Figure 6 shows the thrust the wing produced during static testing at various angular velocities. Since the freestream velocity is zero during static testing, the efficiency is not defined. The wing produced a peak thrust of 0.22 Newtons at an angular velocity of 180 rad/s. This is more than twice the steady level flight design thrust of 0.1 Newtons, so an ornithopter using this wing could easily accelerate for take-off from a stationary position.

However the thrust was expected to level off as the angular velocity was increased. As shown in the figure, the thrust dropped off for angular velocities greater than 180 rad/s. This was because the twist was not caused solely by the aerodynamic thrust force; there was also an inertial effect called propeller that twisted the wing. This effect was unexpected, but when it was modeled, the experimental results agreed well with theory.

Propeller Moment

Propeller moment is an inertial effect that twists the wing. Fundamentally, it is caused by rotating the wing around a non-principal axis, but it is most easily understood by considering the “centrifugal force” acting on the wing as shown in Figure 7. Consider the most outboard wing section, for example. Where the spar connects to this section, the centrifugal force acts radially outward and does not cause a torque about the spar. At the trailing edge of the section, the centrifugal force also acts radially outward, but here it has a tangential component. As shown in the side view, this tangential component causes a torque about the spar that tends to twist the wing. The propeller moment, τ_{pm}, is given by

$$\tau_{\mathrm{pm}} = (I_{\mathrm{maj}} - I_{\mathrm{min}})\,\omega^2 \sin\theta\cos\theta \tag{3}$$

where I_{min} is the moment of inertia of the airfoil about its chord, I_{maj} is the moment of inertia of the airfoil about the line perpendicular to its chord through the spar, and θ is the twist angle of the section.

When propeller moment was included in the wing models, it agreed well with the experimental results. Figure 8 shows this agreement for the 4.9 m/s case. The predicted thrust was much larger than the actual thrust when propeller moment was not modeled, but the predictions agreed well with the experimental results when propeller moment was accounted for.

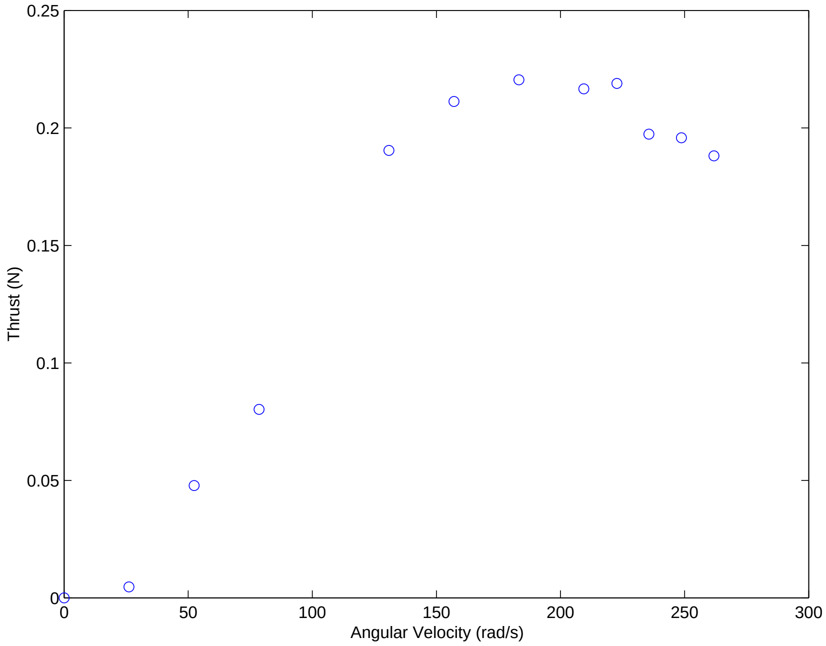

Fig. 6 Static test results

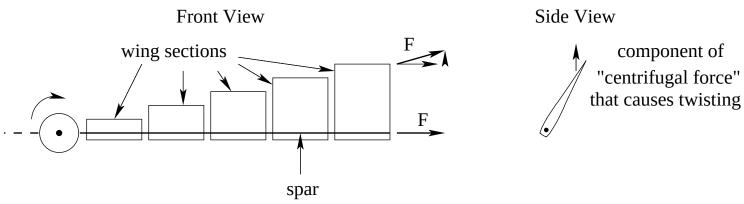

Fig. 7 "Centrifugal force" view of propeller moment

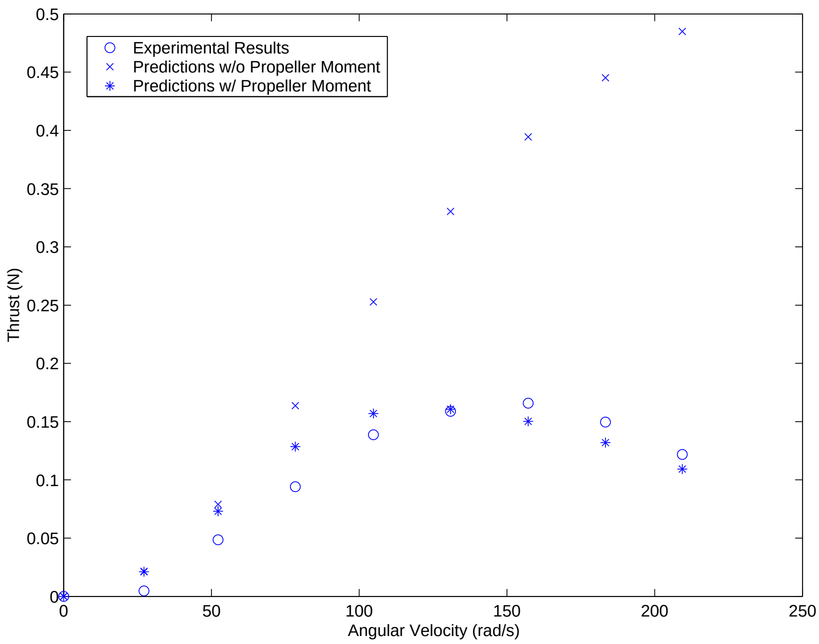

Fig. 8 Comparison of experiment with model including propeller moment

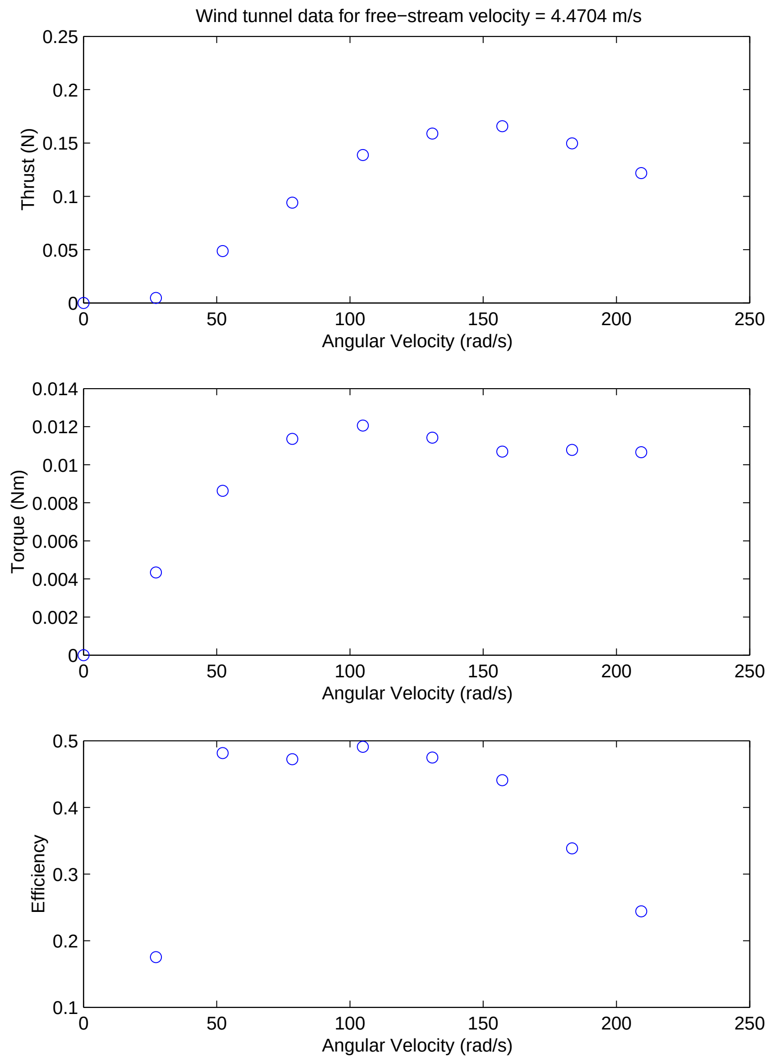

Fig. 9 Low-speed (4.5 m/s) test results

Low-Speed Performance

Figure 9 shows the data for a typical low-speed test. This data was collected at a freestream velocity of 4.5 m/s. Because of propeller moment, the thrust drops off if the angular velocity is increased above 160 rad/s. The thrust reaches a peak value of 0.17 Newtons at an angular velocity of 160 rad/s. This is 1.7 times the steady level flight design thrust, so an ornithopter using this wing would have excess power to maneuver or climb when flying at this speed. As predicted, the propulsive efficiency peaks over a range of angular velocities. In this test, the propulsive efficiency was between 45% and 50% for angular velocities between 50 rad/s and 150 rad/s. The efficiency is far lower than the desired 80% because the wing is operating well below its design speed of 21 m/s.

At higher freestream velocities, measurement errors became more significant. The results at 8.9 m/s presented in Figure 10 are one example. While the torque results vary smoothly with angular velocity, the thrust results are noisy. The thrust measurement noise in turn causes significant errors in the calculated efficiency. As described in the error analysis, the error in the calculated efficiency becomes quite pronounced at high velocities, low angular velocities, and low torques, exactly the conditions under which the calculated efficiency of 2 appears in Figure 10. Measurement noise was also more pronounced at higher freestream velocities because more air flowed over the temperature-sensitive balance elements.

High-Speed Testing

As the freestream velocity was increased, the wing produced less thrust but at higher efficiencies, as predicted. At 8.9 m/s, for example, efficiencies between 65% and 83% were measured. However, increasing the freestream velocity accentuated the sensor noise, thus reducing the precision of the results.

An unexpected twist angle instability was also encountered. At points of instability, the wing suddenly became completely twisted and began spinning very

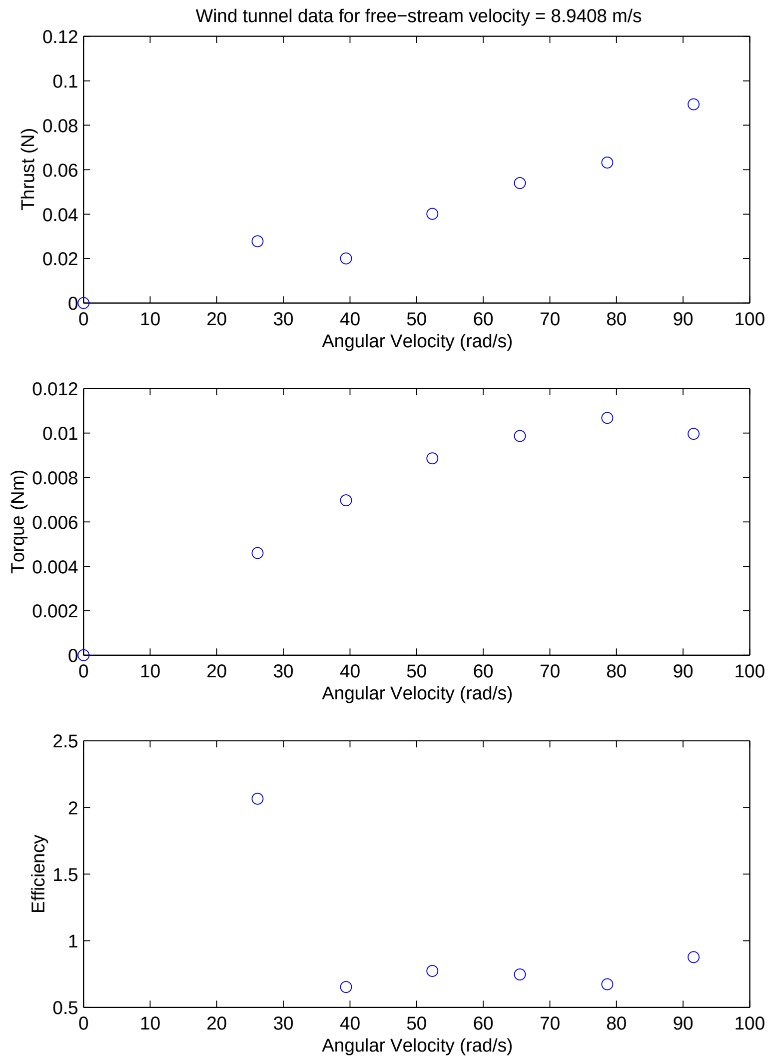

Fig. 10 Low-speed ($8.9\,{}^{\mathrm{m}}/_{\mathrm{s}}$) test results

quickly. It also generated large amounts of drag and was subjected to extreme loading. This instability prevented the performance of the wing from being characterized at its design point.

The instability can be understood by considering the motor and wing torque curves shown in Figure 11. For a given voltage, the intersections of the motor and wing torque curves are equilibria at which the motor provides exactly the torque required to spin the wing. At low and very high angular velocities, the equilibria are stable; a small increase in the angular velocity causes an imbalance in which the wing requires more torque than the motor can provide. This imbalance causes the wing to return to the equilibrium. Because the wing's torque curve dips as propeller moment becomes significant, there are also unstable equilibria. At an unstable equilibrium, a small increase in angular velocity causes excess motor torque that further accelerates the wing.

Only angular velocities for which stable equilibria exist could be tested. Unfortunately, many of the points in the original test matrix, including the expected optimal flight conditions, could not be tested. This instability will not affect the performance of true ornithopters because they do not continuously spin at one angular velocity. Spinning could be used to test future ornithopter wings as long as the angular velocity of the motor is controlled instead of the motor voltage (as in a servo-motor).

Summary

In summary, the objective of this project was to build an efficient, inexpensive, and easily-constructed micro-sized ornithopter wing and characterized its performance. The resulting design was a sectioned wing that is stiff in bending but has an easily engineered torsional stiffness distribution. This design is robust, inexpensive, and takes into account the challenges of manufacturing small-scale wings. This project also developed construction techniques to facilitate rapid, inexpensive wing production. The resulting wing's performance was partially characterized experimen-

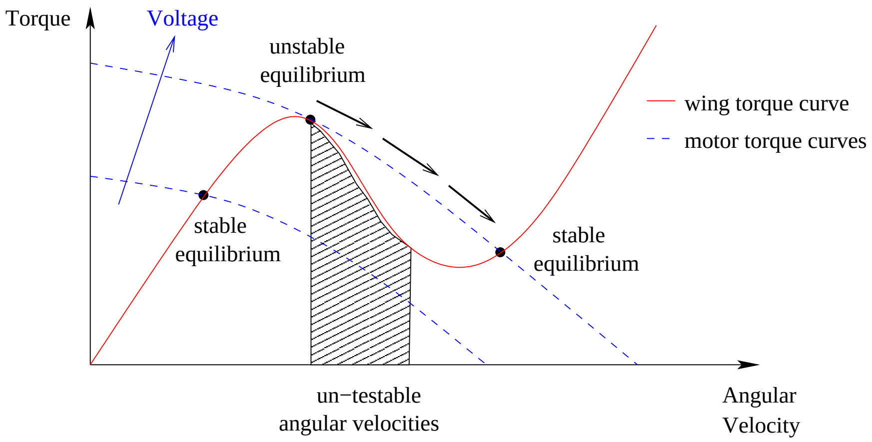

Fig. 11 Motor and wing torque curves effect on twist angle instability

tally. Although the performance characterization was incomplete, it showed that sectioning the wing was not detrimental to its performance, and thus, that sectioned wings show promise for MAV ornithopters. Testing also revealed that propeller moment is a significant effect for MAV ornithopters.

Future Work

Many improvements and refinements may be made to both the design and experimental components of this project. In the design phase, wing performance may be more accurately predicted by including the discrete sectioning of the wing and three-dimensional aerodynamic effects in the wing models. Additionally, higher efficiencies may be achieved if a spar with an optimal stiffness distribution is used instead of one with uniform stiffness. The stiffness distribution can be calculated from the optimal circulation distribution found by Hall and Hall.[3] To improve the experimental portion of the project, the high-speed twist angle instability should be eliminated. This could be accomplished by using a speed-controlled motor, and it would allow the wing's performance to be characterized across a more complete test matrix. Finally, to more accurately replicate the operating conditions of an ornithopter wing, a flapping mechanism should be constructed. This would allow the effects of wing dynamics to be examined, and it would address the challenges inherent in the design and construction of a small, light, flapping mechanism.

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