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Engineering Notes

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Effect of Miniaturized Gurney Flaps on Aerodynamic Performance of Microscale Rotors

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Introduction

ONE of the key aspects of defense planning in the 21st century is the use of swarms of unmanned micro air vehicles (MAVs) that operate in concert with military forces in the battlefield. These unmanned flight vehicles are indispensable for aerial reconnaissance, covert imaging, battlefield management, and for damage assessment. Small-scale vehicles can also be used by civil agencies as information and communication systems, traffic control systems, and as biochemical sensors in the field.

Three basic types of MAV configurations[1] have been explored in the literature: 1) fixed wing, 2) flapping wing, and 3) rotary wing. Fixed-wing designs are unable to hover and perform controlled maneuvers in tightly constraining environments such as interiors of buildings, caves, or tunnels, and this limits their utility for many applications. In contrast to fixed-wing, insect-like flapping-wing MAVs are capable of highly maneuverable flight at the small scales, where inertial loads do not dominate and where unsteady phenomena can be exploited to enhance aerodynamic efficiency. However despite this, the complexity of the flowfield, the required blade motion, and its mechanical implementation as well as poor stability under adverse atmospheric conditions (e.g., gusts, turbulence, crosswind, or rain, etc.) can limit the performance of MAVs based on flapping motion. The third category of MAVs (based on rotary wings) shows promise to provide reliable operation over a wide range of operating conditions, including the hovering and maneuvering capabilities required to remain stationary or in motion in tightly constrained environments. However, because of their scale and flight regime very little is known about the fundamental aerodynamics of microscale rotors at low Reynolds number and the associated fluid-structure-control interactions at the small scales.

In a recent study[2] we have characterized the aerodynamic performance of small-scale rotors in the 10^3 to 5×10^4 tip Reynolds-number range that is typical of rotary-wing MAVs. Spin testing of 6-in.-diam microrotors with both baseline NACA 0012 as well as advanced geometry Eppler-61 airfoil sections was conducted. The maximum lift-to-drag ratio (L/D) that was generated for the rotor with Eppler-61 airfoil was only about 10 ($C_l \sim 0.96$ and $C_d \sim 0.1$ at $Re = 3.3 \times 10^4$), and the performance of the baseline NACA 0012 airfoil was even 50% lower at the same test conditions. These results are also consistent with recent studies conducted by Bohorquez et al.[3] and Young et al.[4] These performance indices are much lower than full-scale high-performance airfoils that exhibit L/D ratios in the range of 100–150. The reason for this is that in flows below Reynolds numbers of 5×10^4 the viscous effects become dominant,[5,6] leading to severe drag penalties, flow separation at low sectional angles of attack, and a smaller envelope of operation.

Given the poor aerodynamic efficiency ($L/D < 10$), low figure of merit (ratio of induced to total power <0.5) of microscale rotors,[2–4] and the limitations of current battery technology,[7] it is not possible to meet the flight envelope for MAVs because of extreme power requirements. With present efficiency levels the maximum endurance demonstrated by battery-powered MAVs has been ~20 min (only 35% of Defense Advanced Research Projects Agency goal of 60 min fully autonomous flight). Therefore it is critical to develop new strategies to improve the aerodynamic efficiency of microscale rotors to enable efficient, sustained, and controllable flight at the microscale. One such approach might be to exploit the behavior of microscale Gurney flaps to achieve substantial improvements in MAV aerodynamic performance.

Gurney flaps are extensively used on racecars as lift augmentation devices.[8] Gurney flaps are situated close to the airfoil's trailing edge and protrude out normal to the airfoil surface. Activating such a flap on the pressure side of the airfoil (close to the trailing edge) creates a region of high pressure on the lower surface of the airfoil (upstream of the Gurney flap), thereby increasing the airfoil lift. The suction region behind the flap also helps to alleviate flow separation at high angles of attack. A disadvantage of such flaps is that they cause a significant increase in the pressure drag.[8] This is a result of high pressure buildup upstream of the Gurney flap, coupled with a reduced pressure region created downstream of the Gurney (i.e., behind the airfoil's trailing edge). This adversely affects the overall airfoil L/D ratio. Another important limitation is that Gurney flaps generate a significant nose-down pitching moment that limits the utility of such flaps when applied to full-scale rotor airfoils.

However, at the microscales (Reynolds numbers $< 5 \times 10^4$) pressure drag is insignificant compared to the viscous forces. Therefore, although a Gurney flap will augment airfoil lift, the resulting drag penalty is not expected to be significant. This creates a novel solution to improving L/D ratios for microscale airfoils. Furthermore, the low aspect ratio and relatively high torsional stiffness of microrotor blades implies that the nose-down pitching moments generated by the Gurney is not expected to degrade performance. Indeed miniaturized Gurney flaps deployed close to the trailing edge of the microblades could enable significant enhancements in MAV aerodynamic performance, with minimal increase in complexity, system weight, or actuation power.

In this study, small-scale model tests (with and without Gurney flap deployment) are conducted using a 15-cm-diam microrotor system to evaluate the effectiveness of Gurney flaps for microrotorcraft. Previous work by Giguere et al.[9] and Storms et al.[10] on Gurney flap scaling has shown that for optimal performance the flap needs to be submerged within the local boundary layer. Therefore a possible scaling parameter is the boundary-layer thickness at the trailing edge on the pressure side of the baseline airfoil. Predictions using Reynolds-averaged Navier–Stokes computations show that the

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boundary-layer thickness for airfoil sections along the micro-rotor-blade span range from about 1.5–2.5% of airfoil chord. Therefore for our testing we selected a Gurney flap with ∼2% chord height and ∼2% chord thickness. To confirm the validity of the optimal Gurney flap scaling, we also performed tests for an oversized flap (10% chord height) that protrudes beyond the local boundary layer. Tests were also conducted to study the effect of Gurney flap thickness and Gurney flap location.

Microrotor Experiments

Microrotor blades with 6 in. (15.24 cm) diam are spin tested. The blades are fabricated using electric discharge machining (EDM) machining to enable accurate control over manufacturing tolerances and provide a smooth surface finish. The attached Gurney flap is comprised of strands of wire (see Fig. 1a) with a diameter of 0.2 mm affixed with a cyanoacrylate adhesive to the microrotor blade. The Gurney flap shown in Fig. 1 has a height of 2% of airfoil chord and thickness of 2% of chord. The blade planform is rectangular (no taper, sweep, or twist), aspect ratio is 3.8 (7.6-cm radius and 2-cm cord), and airfoil section used is NACA 0012.

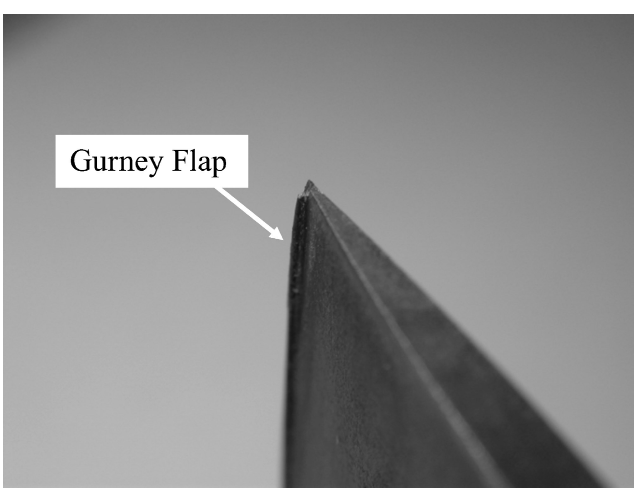
Microrotor Test Platform

The experimental setup consists of a highly sensitive load cell (least count 0.02 g) for measuring rotor thrust, a laser light source coupled to a frequency counter to measure rotor speed, and a microcoreless dc motor with associated fixtures that connect the microblades to the motor output spindle. The motor is driven by means of a dc power supply. The diameter of the microrotor is restricted to a maximum of 6 in., and a clearance of 10 in. (more than twice the rotor radius) is maintained to mitigate ground effect. Figure 1b shows the test setup with the microrotor blades, micro-dc motor, hub attachment fixtures, tachometer, and load cell. The blades can be connected to the hub at adjustable collective pitch settings. The microblades with the optimal geometry Gurney flap (2% height, 2% thickness located at the trailing edge) are tested at 2000 rpm (tip Mach number is 0.05, and tip Reynolds number is 1.9×10^4) in room temperature (297 K) and low-humidity environment.

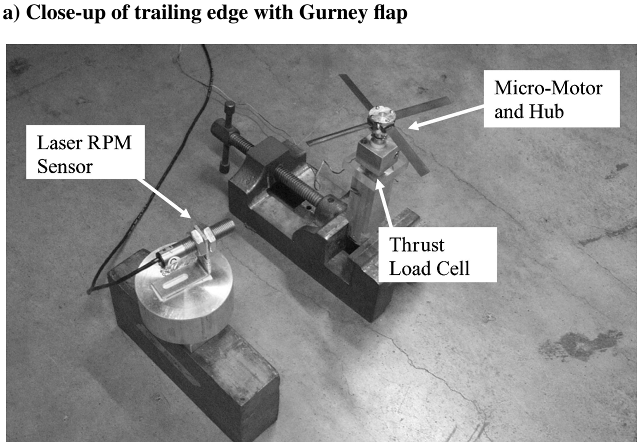
Additionally microrotor blades equipped with nonoptimum flap geometries are tested for three cases: 2% height, 2% thickness at 90% chordwise station; 10% height, 2% thickness at trailing edge; and 2% height, 10% thickness at trailing edge. These tests are also run at the same test conditions as before (Mach number 0.05, Reynolds number 1.9×10^4, and room temperature) so that a direct comparison can be made.

Test Results

The microrotor blades are tested at several blade collective pitch settings ranging from 0 to 9 deg. For each pitch setting, the rotor thrust and power consumption is measured, both with and without attached Gurney flaps. Figure 2 shows measurements of the rotor thrust and power consumption for several different blade pitch settings for the case of a 2% height, 2% thickness Gurney flap located at the trailing edge. The results indicate that the rotor thrust has increased substantially (between 50 to 75%) as a result of the Gurney

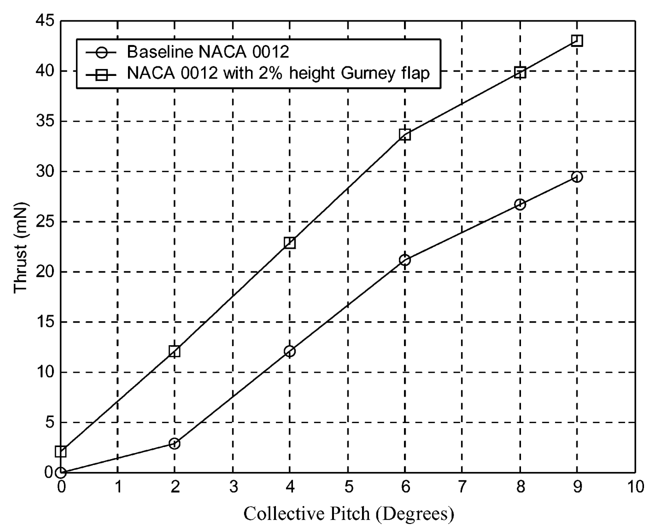


a) Close-up of trailing edge with Gurney flap

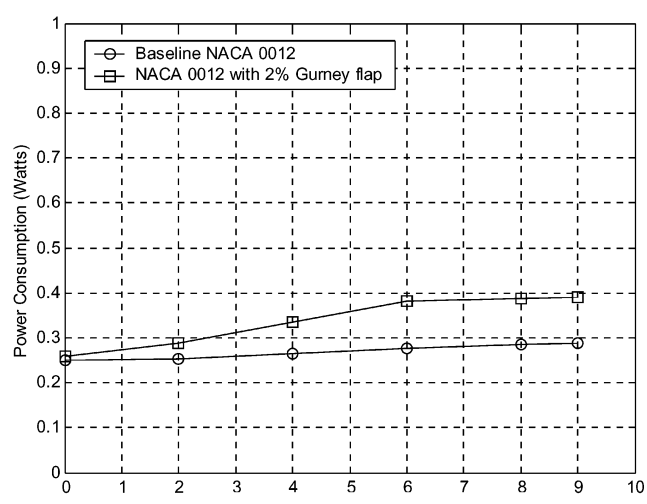


b) Microrotor test platform

Fig. 1 Microrotor test rig with 2-cm chord NACA 0012 blade with attached Gurney flap.

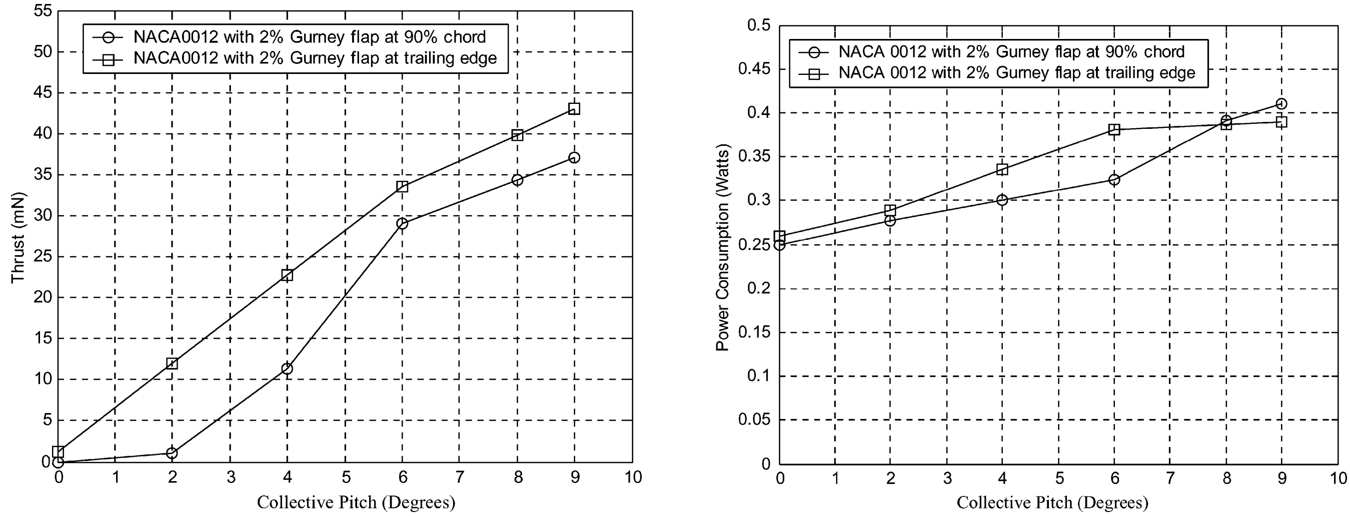


a) Rotor thrust vs blade collective pitch setting



b) Rotor power consumption vs blade collective pitch setting

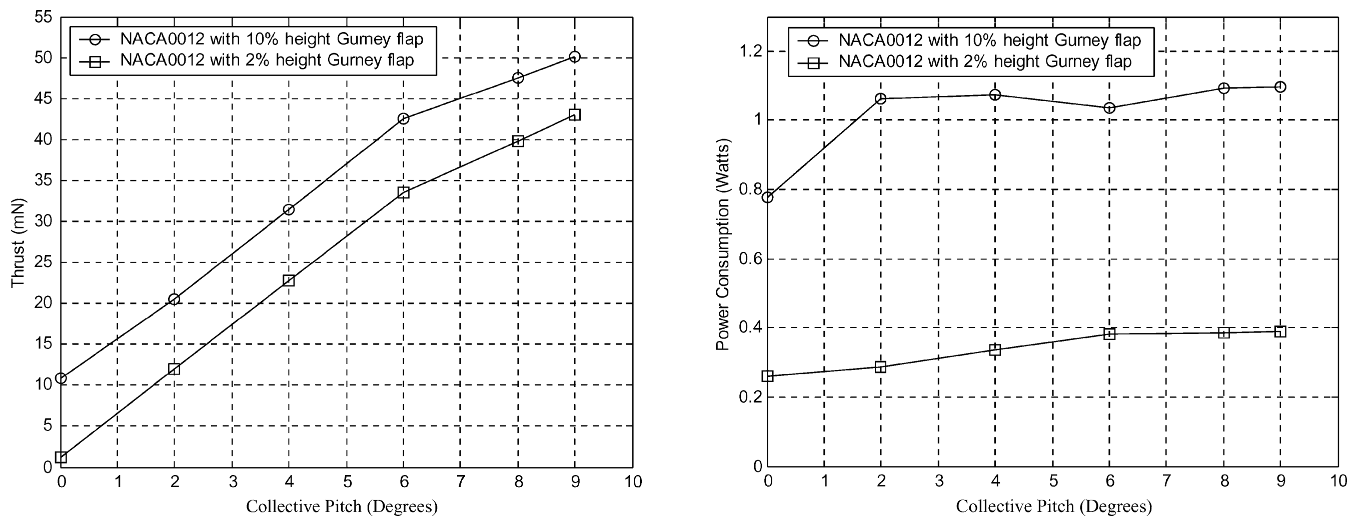
Fig. 2 Comparison of microrotor (with NACA 0012 blade section) equipped with 2% chord height trailing-edge Gurney and baseline response; blade tip Mach number = 0.05, temperature = 297 K, and blade tip Reynolds number = 19×10^3.



a) Rotor thrust vs blade collective pitch setting

b) Rotor power consumption vs blade collective pitch setting

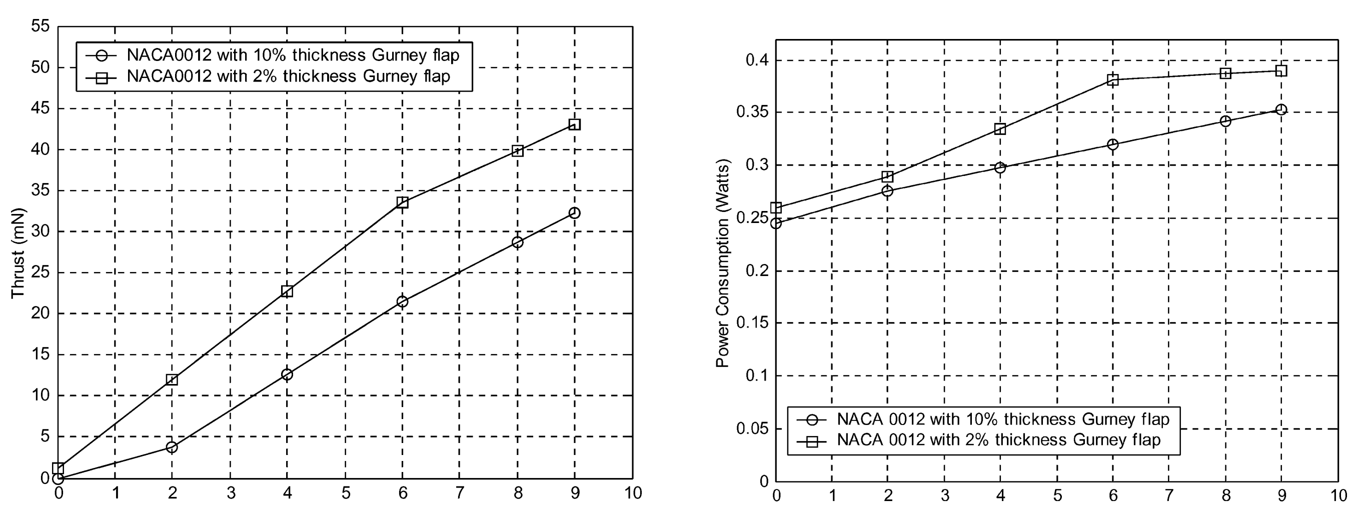
Fig. 3 Comparison of Gurney flap at trailing edge and 90% chord station. The height of Gurney flap is 2% chord; blade tip Mach number = 0.05, temperature = 297 K, and blade tip Reynolds number = 19×10^3.



a) Rotor thrust vs blade collective pitch setting

b) Rotor power consumption vs blade collective pitch setting

Fig. 4 Comparison of Gurney flaps of 2% chord and 10% chord height located at the trailing edge; blade tip Mach number = 0.05, temperature = 297 K, and blade tip Reynolds number = 19×10^3.



a) Rotor thrust vs blade collective pitch setting

b) Rotor power consumption vs blade collective pitch setting

Fig. 5 Comparison of Gurney flaps of 2% chord and 10% chord thickness located at the trailing edge; blade tip Mach number = 0.05, temperature = 297 K, and blade tip Reynolds number = 19×10^3.

flap deployment, while the rotor power consumption has increased between 20 to 30%, leading to an overall improvement of thrust to power ratio of about 30%.

Next, we moved the 2% height and 2% thickness Gurney flap toward the leading edge (90% chordwise station) and repeated the test (Fig. 3). This configuration allows us to study the effect of flap location. The results indicate that as the Gurney flap is moved forward the flap loses effectiveness and the overall thrust-to-power ratio decreases. This is because of the low-pressure suction pocket that is generated behind the Gurney flap on the lower airfoil surface. Next a flap of 10% chord height and 2% chord thickness was attached to the trailing edge and tested (Fig. 4). This configuration enables study of the effect of flap height on performance. As was expected, the microrotor thrust did increase (about 30%); however, the power consumption increased greatly (by 450%), confirming that the pressure drag increases precipitously for flap heights that are significantly greater than the local boundary-layer thickness. The final test case was a 2% height, 10% thickness Gurney flap attached to the trailing edge. This flap geometry allows us to examine the effect of flap thickness. Figure 5 sums up the results, and it is clear that the thicker flap produces significantly lower thrust with only a marginal reduction in the power penalty. The test results shown in Figs. 2–5 were in fact quite consistent with our previous computational-fluid-dynamics predictions published in Ref. 11.

Conclusions

Small-scale microrotor tests (blade tip Reynolds number $< 2 \times 10^4$) indicate that by deploying a 2% height and 2% width Gurney flap located at the trailing edge the microrotor thrust can be increased by 50 to 75% over a range of angles-of-attack settings, with only about 20–30% power penalty. The weight of the Gurney flap used in these tests was less than 0.01% of the micro-rotor-blade mass. These results demonstrate that miniaturized trailing-edge Gurney flaps show strong potential to enhance the aerodynamic efficiency of micro flight vehicles, with a minimal increase in complexity, system weight, or power penalty.

It was determined that the desired Gurney flap location for the microscale rotor is at the trailing edge. This is because when the flap is located at the trailing edge the suction pocket of separated air behind the Gurney does not lower the pressure on the bottom airfoil surface. It was shown that moving the Gurney flap upstream from the trailing edge to 90% chord station results in about 15% reduction in the microrotor's thrust-to-power ratio. The desired flap height and thickness were determined to be of the order of the local boundary-layer thickness ($\sim$2% of airfoil chord). If the flap height is significantly lower than the boundary-layer thickness, it fails to generate high pressure on the lower airfoil surface. On the other hand, if the flap height is significantly greater than the local boundary-layer thickness the pressure drag increases dramatically and begins to make a significant contribution to the overall drag penalty. Similarly if the flap width is too large, the flow contours around the airfoil begin to resemble a bluff body, and the performance degrades.

The results presented in this study demonstrate that trailing-edge Gurney flaps (if properly sized based on the local boundary-layer thickness) can provide a novel solution to enhancing the aerodynamic efficiency of rotary-wing micro air vehicles operating at low Mach numbers and low Reynolds numbers.

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