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Propulsive efficiency of small multirotor propellers in fast forward flight

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ABSTRACT

This paper presents a summary of experimental results regarding the propulsive efficiencies of small multirotor propellers, in simulated forward flight conditions. An automated test rig was used in a wind tunnel to measure propeller performance data across a range of flight speeds and angles. Propellers of various pitch were also tested and compared in these conditions. Flight angle was demonstrated to have minimal impact on efficiency within the tested range. Maximal efficiencies were demonstrated at the highest advance ratios and lowest geometric pitches tested.

1 INTRODUCTION

The extremely fast developing small 'sport' UAS industry often produces products with little to no published testing and data. Especially in the bleeding edge developments in small scale sport drones, where efficiency is key, development appears primarily guided by 'feel'. While comprehensive analyses exist for aircraft propellers and even some larger multirotor rotors, very little data is available on the extremely common 5-inch diameter propeller configurations. These configurations typically operate within a low Reynolds number, in highly oblique flow and at a considerably faster velocity than most commercial multirotors. A large volume of propeller variants exists in this regime, with varying blade geometries, blade numbers, pitch and materials. Manufacturers provide little to no information about the performance of these propellers in their target flight regimes, therefore analytic testing can allow for a more educated propeller selection for a given design.

While multirotors operating within the specified configuration utilizing 5-inch or similar diameter propellers are used primarily by hobbyists, there is a growing demand for smaller scale commercial UAS operations. However, little research has been performed regarding the performance characteristics of small UAS propellers, or even larger propellers in forward flight. Deters, Ananda Krishnan & Selig tested several 5-inch UAS propellers in axial flow, demonstrating a peak efficiency at an advance ratio of approximately 0.6, consistent over the range of tested Reynolds numbers [1], however no consideration was given to propeller performance in oblique flow. Experiments covering oblique flow include those by Theys et al, however testing was performed with larger, 9-inch propeller at low flow velocities [2, 3]. Theys concluded that Blade Element Momentum Theory was impractical, due to the lack of detailed geometry and specifications provided by manufacturers. Amir, Devin & Götz demonstrated varying trends in propeller thrust coefficient with an increase in freestream advance ratio at different flow angles. While these tests were carried out at considerably higher flow velocities, they utilized much larger 18-inch propellers [4]. A variable pitch propeller was utilized by Riccardi in order to minimize variables in propeller geometry, although the rotors used are not representative of the style of propeller commercially available [5].

2 EXPERIMENTAL SETUP

Testing was conducted within the RMIT industrial wind tunnel, using a semi-custom rig to measure propeller parameters in oblique flow.

The test rig selected is based on the commercially available RCbenchmark Series 1580 thrust stand. The thrust stand will produce a log of applied thrust, torque, motor rpm and input power, therefore allowing the efficiency of the motor to be determined. It also allows for custom input functions to be programmed.

The RCbenchmark unit was mounted to the shaft of a large stepper motor, allowing for precise and automated control of the propellers angle of incidence. Propellers chosen are from the HQProp V1S product line, due to their nominally constant blade geometry, over the range of varying pitches

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available. All chosen propellers have a 5-inch diameter, and 3 blades. 4 propellers were chosen from this series, featuring advertised pitch values of 4, 4.3, 4.8 and 5 inches. This propeller features a product code of the format HQ (diameter)x(pitch), in inches – i.e., HQ 5x4 represents the model featuring a 5-inch diameter and 4 inch advertised geometric pitch. The motor to drive these propellers chosen is the T-Motor F80 2500kv model, as it operates in a relevant RPM range to the chosen propellers, while also offering a larger thermal capacity than motors typically used with this class of propeller. The motor was operated at the nominal voltage of its recommended battery configuration, 14.8V. A T-Motor Flame 80A electronic speed controller (ESC) was used to drive the motor, while the stepper motor was driven with a Geckodrive 6203V driver. Testing was coordinated through the built-in scripting function of the RCBenchmark, allowing for control of both the test motor and stepper motor. This arrangement is depicted in figure 1, with components summarized in table 1.

Force/Torque Measurement [1]	RCBenchmark 1580
ESC [2]	T-Motor Flame 80A
Test Motor [3]	T-Motor F80 2500kv
Power Supply	Chargery Power 1500W (14.8V, 60A)
RPM Sensor	RCBenchmark Back-emf Sensor
Stepper Driver [4] (Stepper motor mounted under thrust stand)	Geckodrive 6203V
Propellers	HQProp 3 Blade V1S Series

Table 1: Testing Equipment

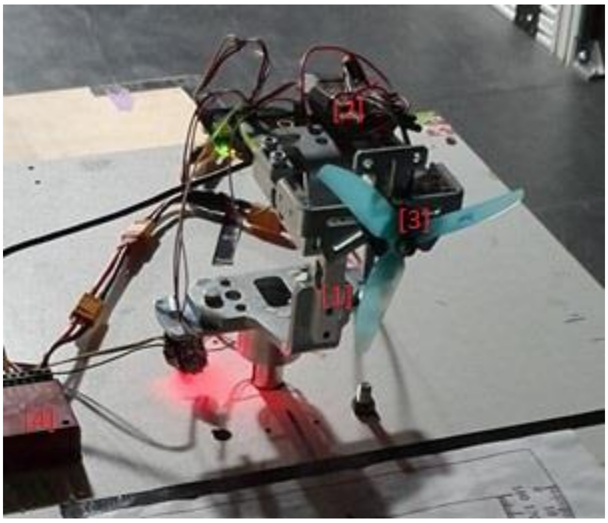

Figure 1: Test rig mounted in wind tunnel.

3 EXPERIMENTAL PROCEDURE

Testing for each propeller occurred at 3 flow speeds, and 6 flow angles, assessed as representative of typical 'sport' multirotor flight regimes, as in Table 2. Hover represents a flow angle of 0°, while traditional fixed wing flight (axial flow) represents a flow angle of 90°, depicted in figure 2.

Wind Speed U	10, 15, 20	[m/s]
Flow Angle	30, 35, 40, 45, 50, 90	[°]
Propeller Pitch	4, 4.3, 4.8, 5	[″]
Rotational Speed	10,000-Max (approx. 30,000)	[rpm]

Table 2: Testing Matrix

Each test was conducted by ramping the propeller through its rpm range, from 10,000rpm to the maximum rpm available, which varied between configurations (approx.. 30,000rpm). This ramp occurred over 45 seconds, and was repeated 3 times. This represented the maximum testing duration due to the thermal constraints of the motor, requiring a cooldown period at the end of each test.

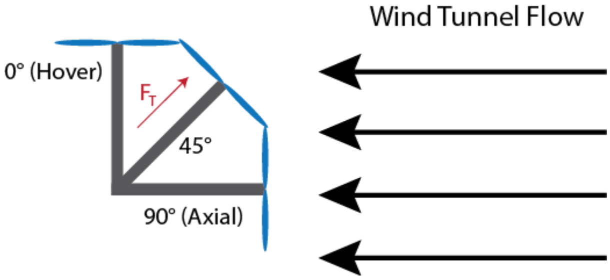

Figure 2: Angle and Force Convention.

4 ANALYSIS

Logged data available from testing is summarized in table 3:

Output Data	**Unit**
Thrust (F_T)	[N]
Mechanical Torque (M)	[Nm]
Electrical Power (P_{elec})	[W]
Angular Velocity (n)	[Hz]
Temperature (T)	[°K]
Atmospheric Pressure (P_{atm})	[Pa]
Propeller Diameter (D)	[m]

Table 2: Logged Data

$$\rho = \frac{P_{atm}}{RT} \quad (1)$$

Density was first derived using the local atmospheric conditions, for each session of testing. While data was also collected to characterize efficiency of the motor and electronic speed controller, these results were not within the scope of this test. Mechanical power was calculated from the mechanical torque measured by the thrust stand, thus eliminating motor efficiency from further calculations:

$$P_{in} = Mn \ (2)$$

Non dimensional propeller performance coefficients were calculated using the above logged data, derived from those presented by [2, 6]. Thrust and power coefficients are calculated as follows:

$$C_T = \frac{F_T}{\rho n^2 D^4}, C_P = \frac{P_{in}}{\rho n^3 D^5} \quad (3)$$

A final dimensionless coefficient is required, advance ratio:

$$J = \frac{U}{nD} \ (4)$$

Therefore, propulsive efficiency of the propeller can be calculated as:

$$n_{prop} = J\frac{C_T}{C_P} \ (5)$$

These calculations provide a propulsive efficiency value through the full range of RPM values.

4.1 Error

In order to determine data quality, a mean and standard deviation was taken for the three tests conducted at each rpm. A sample of this error measurement, for one flow speed and angle is presented in figure 3.

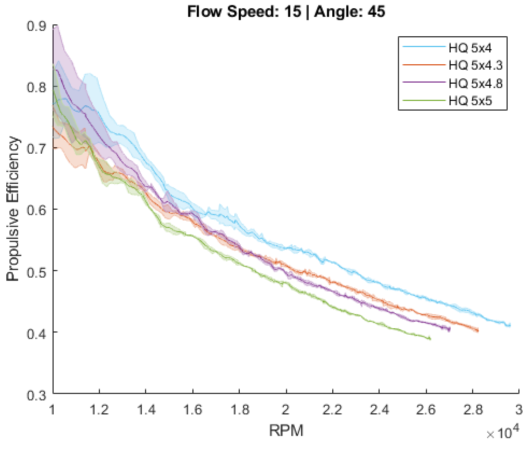

Figure 3: Sample result with standard deviation and mean

As demonstrated, where for each case the solid line represents the mean measurement and the shaded area represents the standard deviation, the highest quality data is present in the region between 18000 and the maximum of 30000 rpm. This is also evident when watching the ramp occur, as the motor reached approximately 20000 rpm with minimal throttle input, resulting in much lower data density in this range. The data was therefore 'cropped' to begin at 15000 rpm to better visualize the high quality data at the higher end of the rpm spectrum, shown in Figure 4

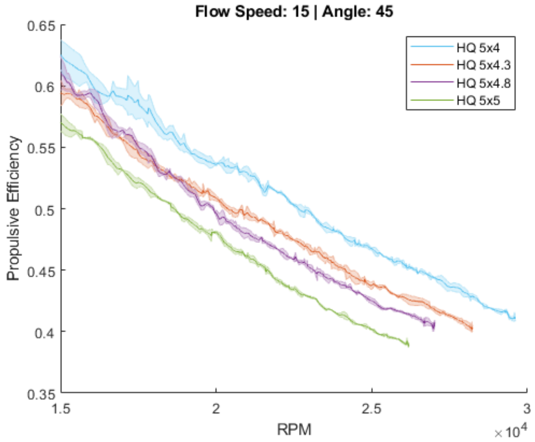

Figure 4: Sample cropped result

5 RESULTS

In all tests carried out, the greatest propulsive efficiency was achieved at the lowest measured RPM. In general, the lowest pitch propellers featured the highest propulsive efficiencies, surpassed in only a handful of tests. These results demonstrate the incompatibility of these propeller designs with efficient flight within their desired operating conditions. While no conclusions can be drawn regarding a clear trend in performance at different angles, this analysis provides evidence that flow angle does not provide a strong advantage to a high or low pitch propeller. Propulsive efficiency, however, is insufficient to fully characterize the performance these propellers. Doing so would require further definitions of flight conditions and requirements, and outside the scope of this work. Data is summarized in Figures 5 through 8.

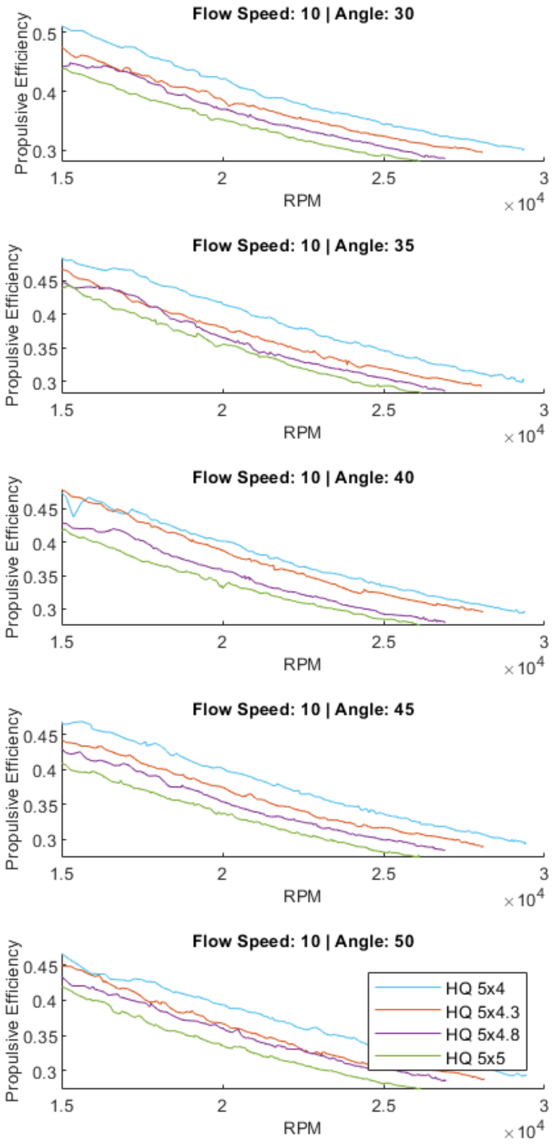

Figure 5: Results at 10 m/s

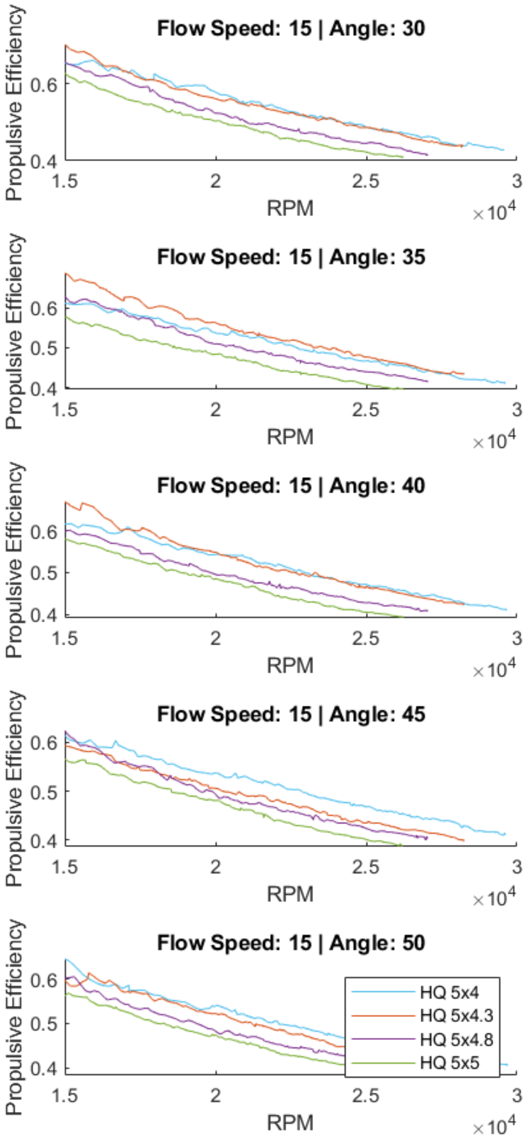

Figure 6: Results at 15 m/s

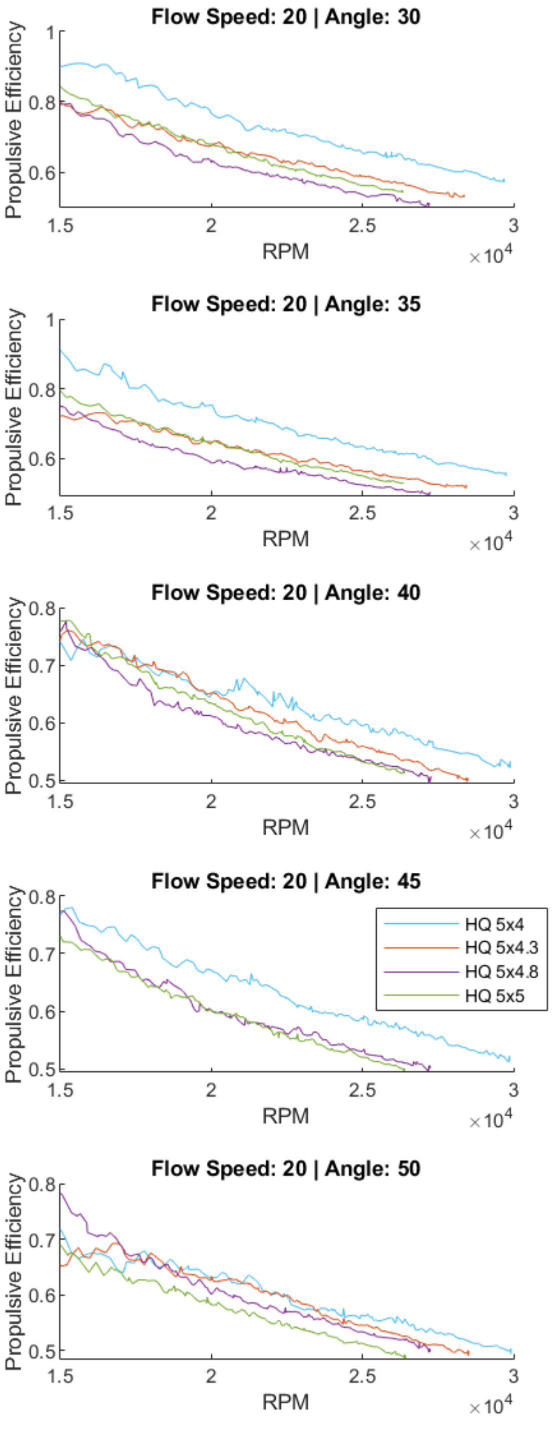

Figure 7: Results at 20 m/s

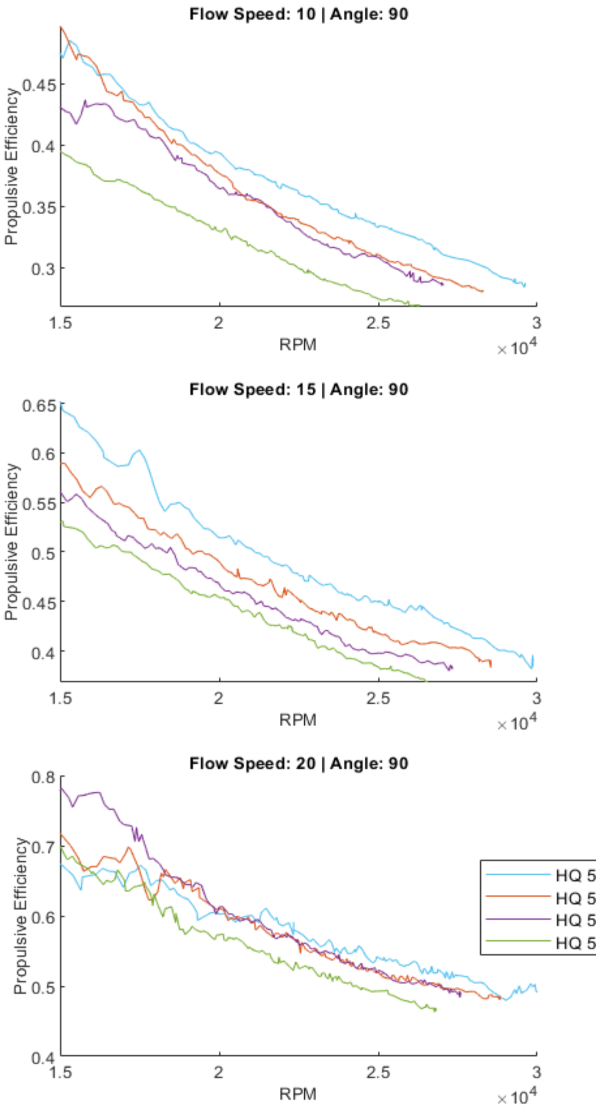

Figure 8: Results in axial flow

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[4] 5x4.3 Propeller is absent from 20 m/s, 45 degree flow due to erroneous data acquisition

6 CONCLUSION

This paper presents measurements of propeller propulsive efficiency across a range of selected forward flight regimes, such as those experienced by small ‘sport’ multirotors. In the conditions tested, all propellers experienced their maximum efficiency at their highest advance ratios. In a majority of operating modes tested, propellers with lower geometric pitch provided higher propulsive efficiencies. This indicates a greater efficiency could be achieved for this propeller class through a higher forward flight speed, lower pitch, or reduced rpm. This however would require further characterization of propeller performance across thrust values. Additionally, while flight angle within the chosen operating ranges did not have a significant impact on efficiency, the highest efficiencies were achieved in pure axial flow.

Further work in this field including rotor interactions can be viewed in the thesis of Samuel Prudden, available via the RMIT research repository: *Rotor aerodynamic interaction effects for multirotor unmanned aircraft systems in forward flight.*

ACKNOWLEDGEMENTS

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