Static Performance Results of Propellers Used on Nano, Micro, and Mini Quadrotors

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An increase in the number of small quadrotors has created the interest in having performance data on the propellers used by these aircraft. With an aircraft size less than 5 in and propellers diameters less than 3 in, these quadrotors are typically referred to mini, micro, or nano by hobbyists and manufacturers. The size of the propellers used on these aircraft operate at low Reynolds numbers that are typically less than 50,000 for diameters up to 3 in and less than 20,000 for diameters up to 2 in. Static performance testing of the propellers used on 11 small quadrotors was completed. For propellers with diameters less than 1.4 in, the torque produced was too small to accurately measure.

I. Introduction

The use of Small Unmanned Aircraft Systems (sUAS) for recreational, commercial, and research has seen rapid growth.[1] With this growth comes the need for more performance data of these systems. A subset of the sUAS are small quadrotors that are classified by manufacturers and users as mini, micro, or nano. There does not seem to be a set standard that defines the differences between these classifications with hobby groups. Usually aircraft size or propeller size are used by some groups, but interestingly, weight is not included. The Defense Advanced Research Projects Agency (DARPA) defined a Micro Air Vehicle (MAV) as a vehicle that cannot exceed 6 in (150 mm).[2] DARPA later defined a Nano Air Vehicle (NAV) as vehicle with a wingspan of less than 3.9 in (100 mm) and weight of less than 0.35 oz (10 g).[3] The quadrotors tested for this paper are between 1.8 in (45 mm) and 5 in (127 mm) measured diagonally from motor shaft to motor shaft, and they have propeller diameters that range from 1.2 in (30 mm) to 2.6 in (66 mm). The weights for these aircraft range from 0.4 oz (11.5 g) to 2.5 oz (72 g). While all of the aircraft fall under the MAV definition, the smallest quadrotors meet the size limit of the NAV definition but exceed the weight requirement. However, since these quadrotors are mainly used for recreational purposes, this paper considers that the aircraft fall between the nano and mini classifications used by hobbyists and the quadrotor manufacturers.

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Table 1: Quadrotors Tested

Aircraft	Weight	Aircraft Size	Propeller Diameter
Cheerson CX-10C	0.52 oz (15 g)	1.8 in (45 mm)	1.2 in (30 mm)
Cheerson CX-10SE	0.42 oz (12 g)	1.8 in (45 mm)	1.2 in (30 mm)
Crazyflie	0.67 oz (19 g)	5.0 in (127 mm)	1.85 in (47 mm)
Dromida Hovershot	2.5 oz (72 g)	4.8 in (121 mm)	2.25 in (57 mm)
Dromida Kodo	1.4 oz (40 g)	4.2 in (106 mm)	2.25 in (57 mm)
Dromida Verso	1.2 oz (34 g)	4.4 in (113 mm)	1.975 in (50 mm)
Estes Proto X	0.4 oz (11.5 g)	2.0 in (51 mm)	1.2 in (30 mm)
Hubsan X4 H107	1.4 oz (40 g)	3.6 in (92 mm)	2.15 in (55 mm)
JJRC H36	0.78 oz (22 g)	2.6 in (65 mm)	1.23 in (31 mm)
Parrot Mambo	2.2 oz (63 g)	4.8 in (121 mm)	2.6 in (66 mm)
Syma X12S	0.47 oz (13.3 g)	2.0 in (51 mm)	1.35 in (34 mm)

While performance data of small-scale propellers are available, most of the propellers have diameters greater than 3 in (76 mm).[4–16] Prior to this series of tests, the smallest propeller tested by the authors was the 1.85-in propeller used by the Crazyflie.[9,17] The purpose of this paper is to add to the available data on propellers with diameters less than 3 in (76 mm) and specifically propellers with diameters less than 2 in (51 mm). The low Reynolds numbers present with these small propellers make it difficult to predict the performance. Propellers with a diameter of less than 3 in typically experience Reynolds numbers below 50,000. For diameters of less than 2 in, Reynolds numbers less than 20,000 are common. Because of the size of these propellers, the magnitude of the thrust and torque produced is small making it more difficult to measure.

II. Aircraft Tested

Static performance results from the propellers of 11 small quadrotors are presented in this paper. The list of the quadrotors is given in Table 1. This table provides the weight, size, and propeller diameter of each quadrotor. Here size is defined as the diagonal distance from motor shaft to motor shaft. For each quadrotor, two propellers were tested. In this paper, the two propellers for each quadrotor are distinguished with the labels right-handed (RH) and left-handed (LH). The right-handed propellers spin counter-clockwise when viewed from the front, and some propeller manufacturers refer to them as tractors. The left-handed propellers spin clockwise and can be referred to as pushers.

As seen in Table 1, the propellers range in diameters from 1.2 in to 2.6 in. The aircraft range in size from 1.8 in to 5.0 in, and they range in weight from 0.4 oz to 2.5 oz. As shown in Fig. 1, the larger aircraft generally weigh more. The Crazyflie is an outlier to the general trend as it is the largest aircraft in size but is also one of the lightest. Figure 2 shows the propeller diameter versus the quadrotor weight. The trend in this figure is clearer in that heavier aircraft generally have larger propellers as would be expected.

Pictures of each quadrotor are provided in Figs. 3–13. The two Cheersons, the Estes, and the Syma are all advertised as nano quadrotors. The JJRC is unique from this set in that the propellers have four blades. The propellers for the JJRC are also shrouded. The Dromida Verso is designed to also fly upside down, so its propellers were additionally tested in reverse. The Crazyflie is the only aircraft from this set that is not ready to fly when purchased. The Crazyflie is an open source kit that allows the user to add new sensors and modify software of the aircraft.
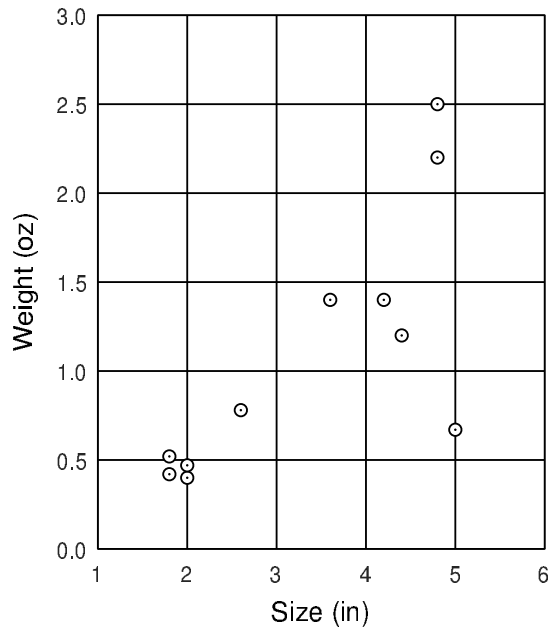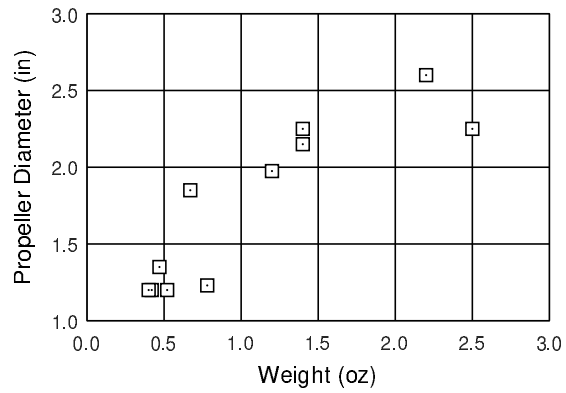
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Figure 1: Quadrotor weight vs size.

Figure 2: Quadrotor propeller diameter vs weight.

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Figure 3: Cheerson CX-10C.

Figure 4: Cheerson CX-10SE.

Figure 5: Crazyflie 1.0 (picture from Crazyflie website[18]).

Figure 6: Dromida Hovershot.

Figure 7: Dromida Kodo (picture from Dromida website[19]).

Figure 8: Dromida Verso.

Figure 9: Estes Proto X.

Figure 10: Hubsan X4 H107.

Figure 11: JJRC H36.

Figure 12: Parrot Mambo.

Figure 13: Syma X12S.
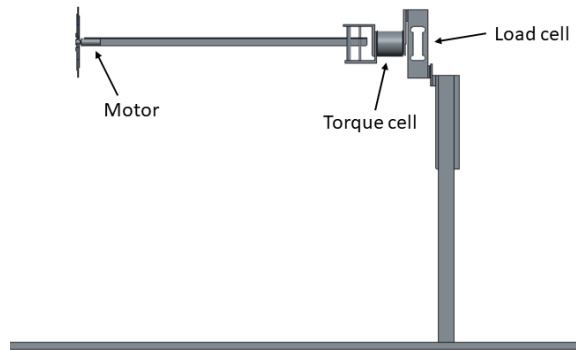
Figure 14: Propeller thrust and torque balance.

III.   Experimental Methodology

A.   Equipment

Propeller tests were conducted in the UIUC Aerodynamics Research Laboratory (ARL) using the thrust and torque balance shown in Fig. 14. Since only static performance was measured for this research, the balance was set up outside of a wind tunnel. The propellers were mounted to the motor so that the thrust force was pointed toward the balance. With this propeller configuration, the propwash was directed away from the balance so that it would not interfere with the measurements.

Thrust was measured using a 0.3 kg (0.66 lb) load cell manufactured by Load Cell Central. The torque from the propeller was measured using a reaction torque sensor (RTS) from Transducer Techniques. A 5 oz-in (0.706 N-m) transducer was used. The locations of the load and torque cells are shown in Fig. 14

Each propeller was tested using a Medusa MR-012-030-4000 brushless motor using a Castle Creations Phoenix Edge Lite 50 speed controller. To provide power to the motor, a BK Precision power supply was used. Propeller RPM was measured through the speed controller. The ambient pressure and temperature were measured using sensors on the data acquisition system.

B.   Testing Procedure

During a static performance test, the thrust and torque were measured over a range of RPMs. An Al Volo FDAQ 400 Hz data acquisition system[20] was used to measure thrust, torque, RPM, voltage, current, ambient temperature, and ambient pressure; the instrumentation setup is similar to that used in Dantsker et. al.[21] To control RPM, a PIC18 based microcontroller was used to generate a PWM signal between 900 and 2100 μsec in 100 μsec increments, which was sent to the speed controller. Each increment was commanded for 20 sec, allowing for 8000 data points to be collected for each RPM. Specifications regarding the data acquisition system are summarized in Table 2.

C.   Calibration

Since the DAQ system only recorded voltages from the torque transducer and load cell, each voltage was converted to a physical measurement through calibration curves. Thrust calibration used precisely measured weights and a low-friction pulley system to create an applied axial load to simulate thrust on the load cell. By increasing and decreasing a known force on the load cell, a linear relationship between the thrust and voltage was determined. For torque calibration, the precision weights were used with a known moment arm to create a torque, and by adding and removing weights, a linear relationship between the torque and voltage was calculated. These calibration procedures were performed regularly to ensure consistent results, and any change in the calibration slopes were 1% or less.

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Table 2: Specifications of the Static Testing Apparatus

Data acquisition system	Al Volo FDAQ 400 Hz system
Sensors	
Thrust Cell	0.3 kg load cell by Load Cell Central
Torque Cell	5 oz-in reaction torque sensor by Transducer Techniques.
Wheatstone Bridge	Al Volo Load Cell Interface
Motor RPM	Al Volo Castle ESC Interface
Ambient Conditions	Al Volo Temperature and Pressure Sensor
Drivers	
Motor	Medusa MR-012-030-4000 brushless motor
Speed Controller	Castle Creations Phoenix Edge Lite 50
Power Supply	BK Precision
PWM Generator	PIC18 based microcontroller

D.   Data Reduction

Using the measured ambient pressure p and temperature T, the air density ρ was calculated from the equation of state

$$p = \rho R T \tag{1}$$

where R is the universal gas constant. The standard value of 1716 ft^2/s^2/°R (287.0 m^2/s^2/K) for air was used.

Propeller power P is calculated from the measured propeller torque Q by

$$P = 2\pi n Q \tag{2}$$

where n is the rotations per second of the propeller. Performance of a propeller is typically given in terms of the thrust coefficient C_T and power coefficient C_P, defined as

$$C_T = \frac{T}{\rho n^2 D^4} \tag{3}$$

$$C_P = \frac{P}{\rho n^3 D^5} \tag{4}$$

where D is the propeller diameter. The value nD can be considered the reference velocity and D^2 can be considered the reference area.

The propeller Reynolds number reported here is calculated based on the rotational speed and chord at the 75% blade station. The Reynolds number is defined as

$$Re = \frac{\rho V c}{\mu} \tag{5}$$

where the viscosity μ was calculated from Sutherland's formula.

IV.   Performance Testing Results

The static performance results for the propellers are provided in this section. The order of the propeller results follows Table 1. As mentioned earlier, both the right-handed and left-handed propellers were tested for each quadrotor. It is expected that the two propellers should be exact mirrors and provide the same performance. By testing both, any variation in the performance can be documented. In order to compare the performance of the right-handed and left-handed propellers for each quadrotor, their results are provided on the same plot. For five of the propeller pairs, the power coefficient plot is not provided. These five propeller

Table 3: Performance Data at Maximum RPM

Aircraft	Propeller Diameter	Max RPM	Max Thrust	Reynolds Number	Tip Mach Number
Cheerson CX-10C	1.2 in (30 mm)	47,000	0.14 oz (4.0 g)	14,000	0.21
Cheerson CX-10SE	1.2 in (30 mm)	47,000	0.14 oz (4.0 g)	14,000	0.21
Crazyflie	1.85 in (47 mm)	20,000	0.36 oz (10 g)	20,500	0.14
Dromida Hovershot	2.25 in (57 mm)	30,000	1.1 oz (31 g)	30,500	0.26
Dromida Kodo	2.25 in (57 mm)	30,000	1.1 oz (31 g)	30,000	0.26
Dromida Verso	1.975 in (50 mm)	30,000	0.70 oz (20 g)	26,000	0.23
Estes Proto X	1.2 in (30 mm)	47,000	0.12 oz (3.4 g)	13,500	0.21
Hubsan X4 H107	2.15 in (55 mm)	30,000	0.95 oz (27 g)	30,000	0.25
JJRC H36	1.23 in (31 mm)	30,000	0.34 oz (9.6 g)	12,000	0.14
Parrot Mambo	2.6 in (66 mm)	29,000	1.8 oz (51 g)	33,000	0.29
Syma X12S	1.35 in (34 mm)	31,000	0.18 oz (5.1 g)	12,000	0.16

sets all had diameters less than 1.4 in. The amount of torque produced by these propellers was too small to be accurately measured by the 5 oz-in torque cell. Measuring the power consumption of the motor during the tests was considered as an alternative method of obtaining power data; however, there was difficultly in measuring the current during the testing time for this research. Future testing of propellers of these sizes will consider looking at measuring the power consumption again.

To aid in the discussion of the propellers, Table 3 provides some performance data at the maximum RPM tested for each propeller pair. Listed in the table are the thrust measured at the maximum RPM, the Reynolds number for the 75% blade station, and the tip Mach number. Even at the maximum RPM, the tip Mach number did not exceed the incompressible limit of $M = 0.3$. For the propellers with diameters of less than 1.4 in, the Reynolds number is less than 15,000. For the rest of the propellers, the Reynolds number is about 30,000 or less.

The thrust coefficient results for the two Cheerson aircraft are shown in Figs. 15 and 16. As mentioned earlier, accurate results of torque were not measured for these propellers, so a power coefficient plot is not provided. The thrust results for the propellers are very similar in terms of magnitude for both aircraft.

Figure 17 provides the performance results for the Crazyflie. Results for the Dromida Hovershot and Dromida Kodo are provided in Figs. 18 and 19, respectively. These three sets of propellers include the power coefficient results. While torque measurements could be measured for these propellers, the values are still small. To highlight the small torques produced by these propellers, results from the Crazyflie are used. With a diameter of 1.85 in, the Crazyflie propeller produces approximately 0.07 oz-in of torque at 20,000 RPM. This torque value is only about 1.4% of the full scale range of the torque transducer.

The Dromida Verso results are provided in Figs. 20–22. The first figure compares the right-handed and left-handed propellers during normal operation. Since this quadrotor is designed to also fly upside down, the propellers were additionally tested while spinning in the reverse direction. Figure 21 compares the right-hand propeller during normal and reverse operation, and Fig. 22 compares the left-hand propeller. It is interesting to note that for both the right-hand and left-hand propellers, more thrust is produced while the propeller is spinning in the reverse direction.

The thrust results for the Estes Proto X are provided in Fig. 23. The Estes was another aircraft where reliable torque data was not measured. Figure 24 provides the performance results for the Hubsan X4 H107, and Fig. 25 provides the thrust results for the JJRC H36. The propeller for the JJRC H36 is different from the rest of the propellers tested in that it has four blades instead of two. The four-bladed propeller is also mounted in a shroud on the aircraft. The thrust results shown in Fig. 25 are for the propeller without the shroud.

Performance results for the Parrot Mambo are shown in Fig. 26. The Mambo propeller was the largest in this series of tests with a diameter of 2.6 in. The Syma X12S is the final aircraft, and the thrust results are provided in Fig. 27. The Syma has the largest propeller for which torque was not obtained (diameter of 1.35 in).

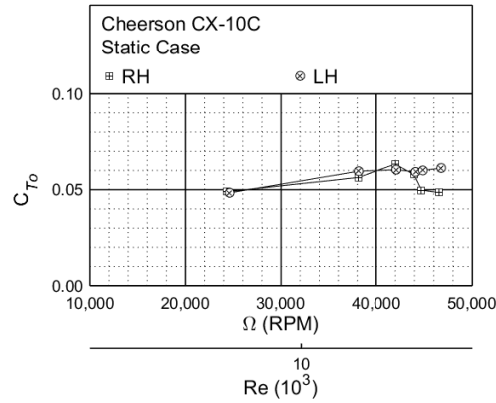American Institute of Aeronautics and Astronautics

Figure 15: Static thrust performance of the right-handed and left-handed propellers of the Cheerson CX-10C.
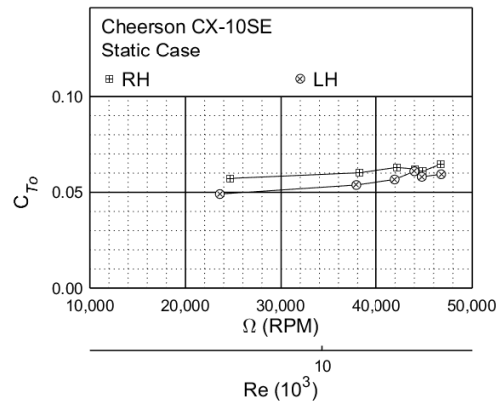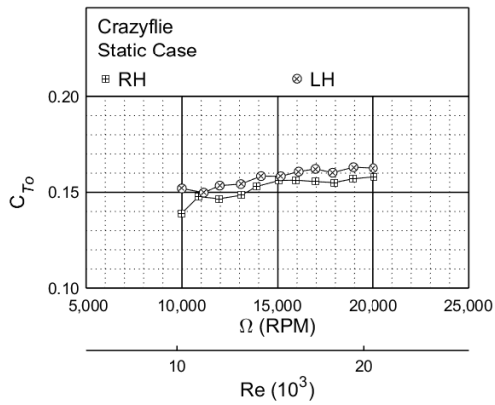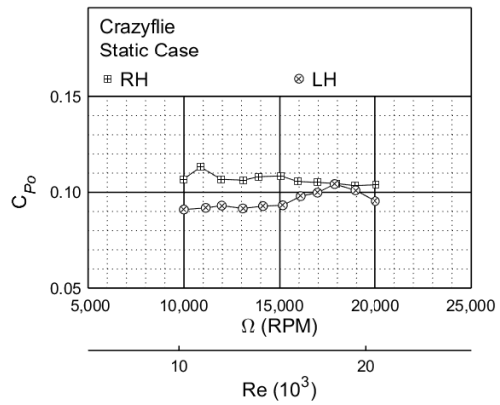

Figure 16: Static thrust performance of the right-handed and left-handed propellers of the Cheerson CX-10SE.

For each aircraft, the right-handed and left-handed propellers reasonably had the same performance characteristics as to be expected. For the Dromidas and the Hubsan, there were differences at the lower RPMs but the results converged at the higher RPMs. Whether these differences are accurate should be investigated further. Since the thrust and torque are small at the lower RPMs, the differences could be from measurement error. For the propellers tested, the general trend is that the C_T and C_P values are nearly constant especially at the higher RPMs. The two exceptions to this observation are from the JJRC H36 and the Parrot Mambo. For these two aircraft, the propellers show more of an continuously increasing trend in C_T.

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Figure 17: Static performance of the right-handed and left-handed propellers of the Crazyflie: (a) thrust coefficient and (b) power coefficient.
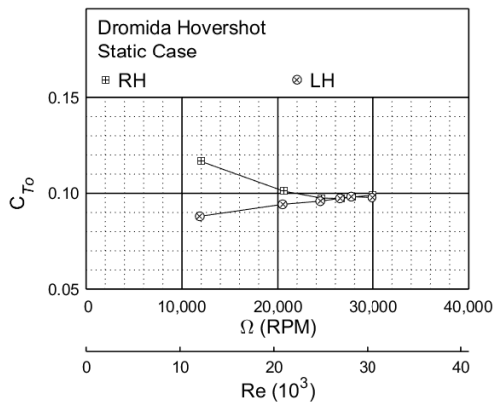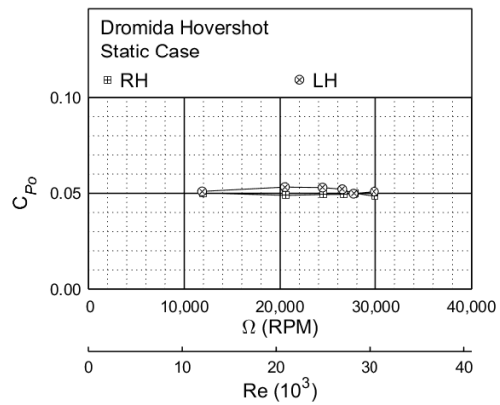
Figure 18: Static performance of the right-handed and left-handed propellers of the Dromida Hovershot: (a) thrust coefficient and (b) power coefficient.
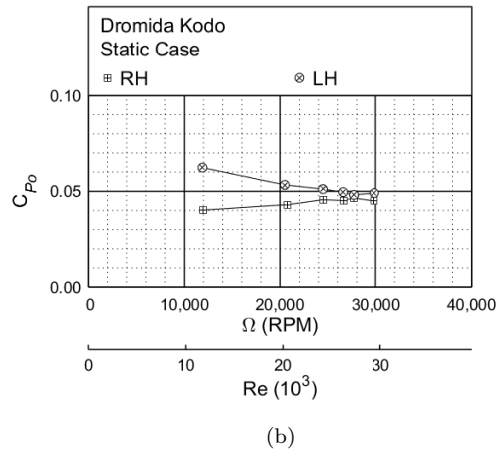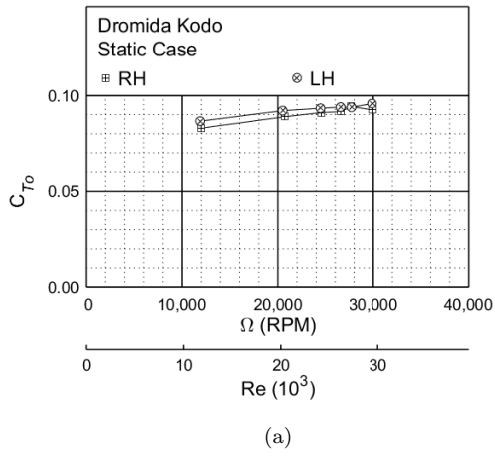
Figure 19: Static performance of the right-handed and left-handed propellers of the Dromida Kodo: (a) thrust coefficient and (b) power coefficient.
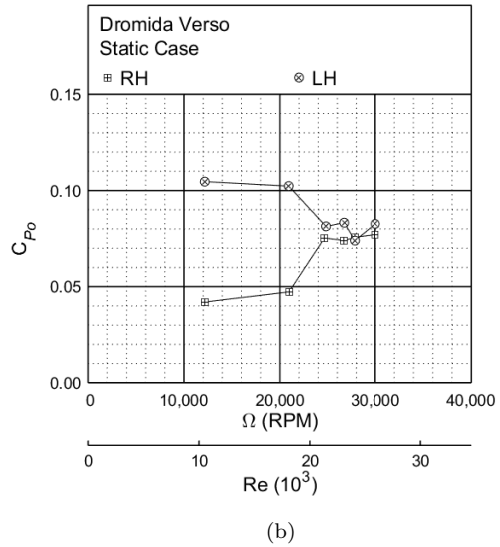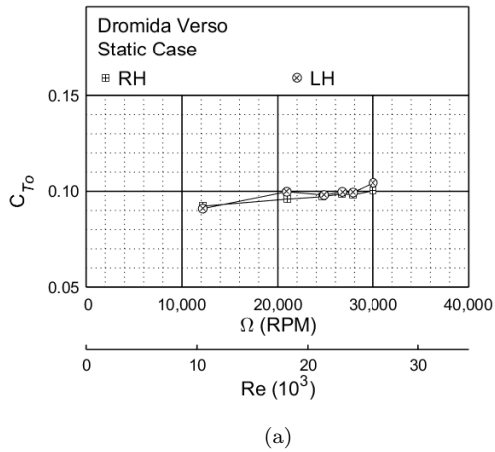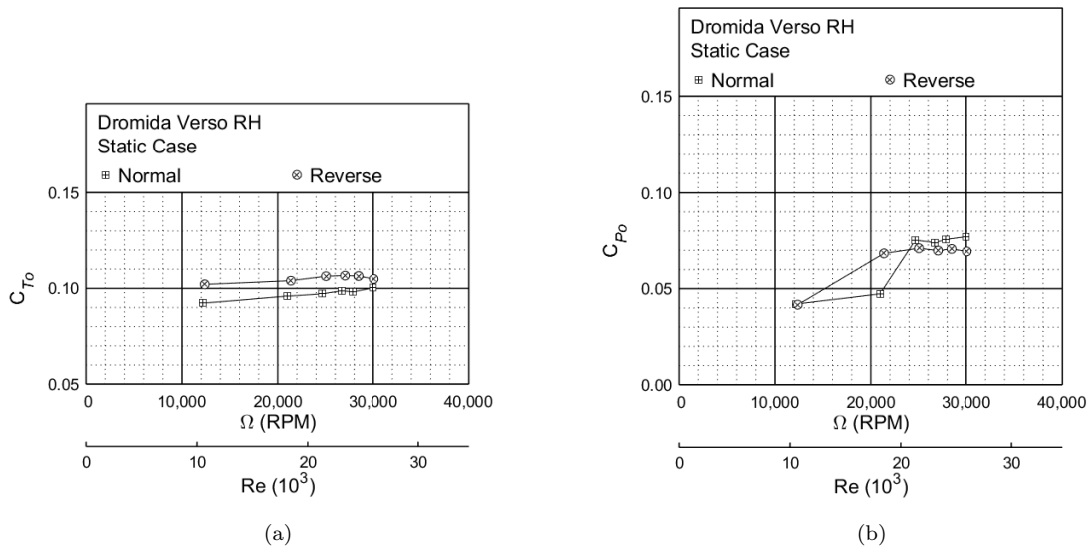

Figure 20: Static performance of the right-handed and left-handed propellers of the Dromida Verso: (a) thrust coefficient and (b) power coefficient.

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Figure 21: Static performance of the right-handed propeller of the Dromida Verso in the normal and reverse configuration: (a) thrust coefficient and (b) power coefficient.
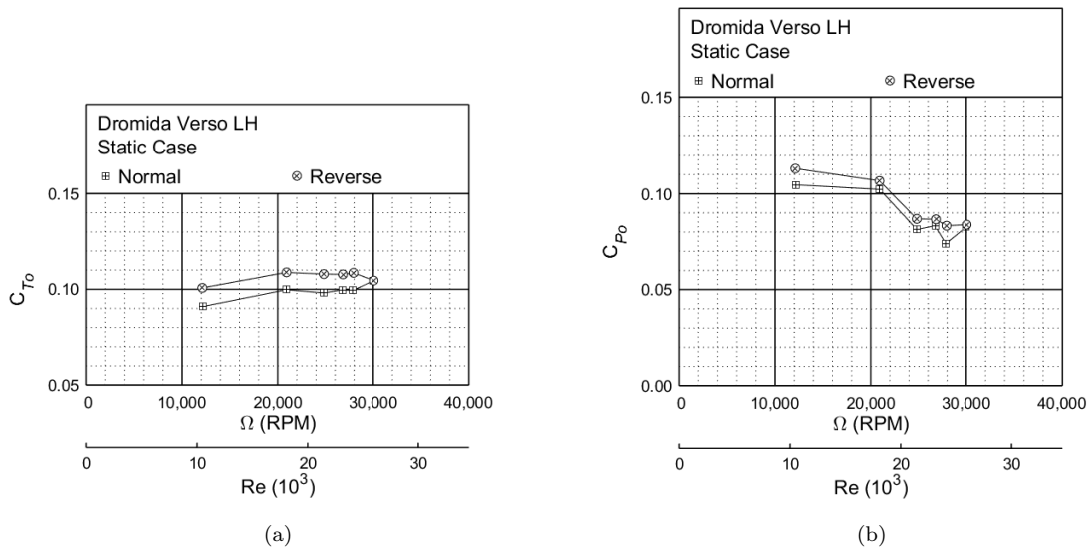

Figure 22: Static performance of the left-handed propeller of the Dromida Verso in the normal and reverse configuration: (a) thrust coefficient and (b) power coefficient.
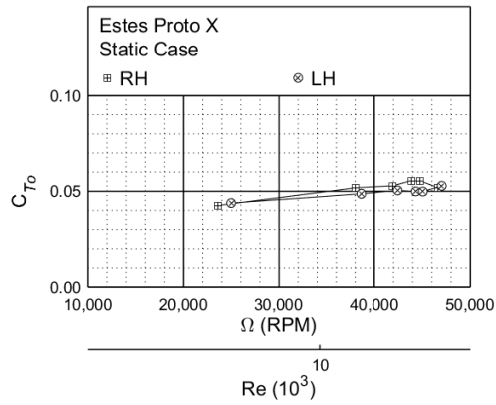
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Figure 23: Static thrust performance of the right-handed and left-handed propellers of the Estes Proto X Nano.
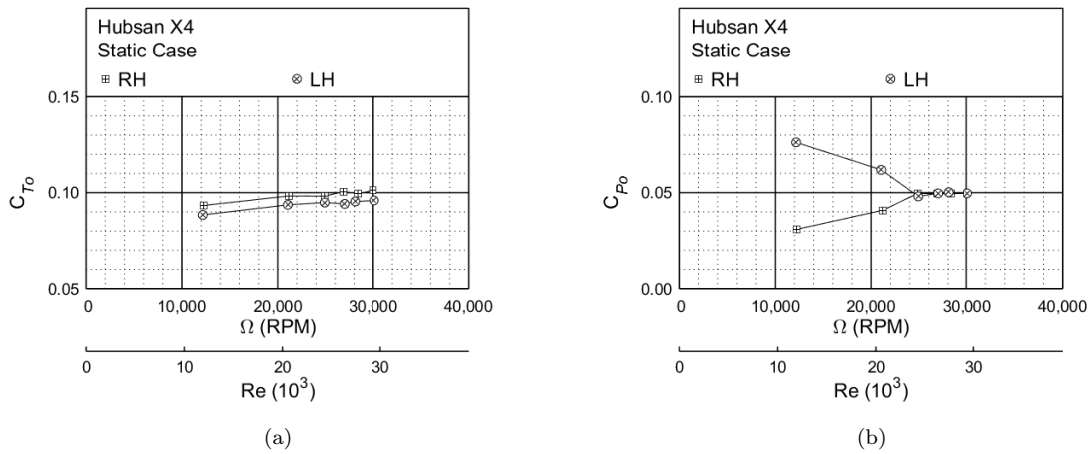

(a)

(b)

Figure 24: Static performance of the right-handed and left-handed propellers of the Hubsan X4 H107: (a) thrust coefficient and (b) power coefficient.
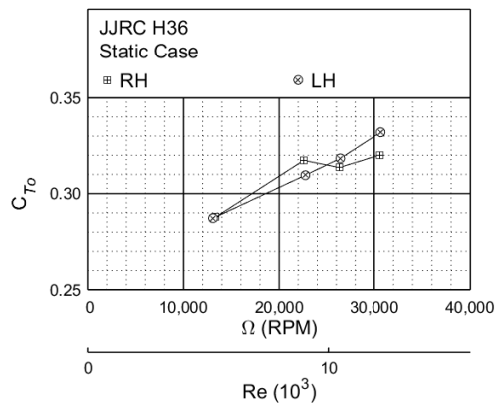

Figure 25: Static thrust performance of the right-handed and left-handed propellers of the JJRC H36.

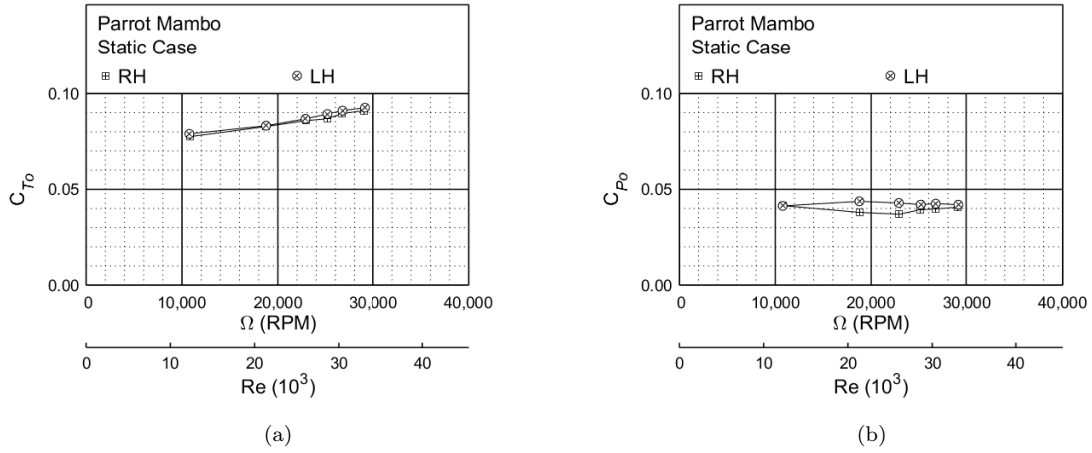American Institute of Aeronautics and Astronautics

Figure 26: Static performance of the right-handed and left-handed propellers of the Parrot Mambo: (a) thrust coefficient and (b) power coefficient.
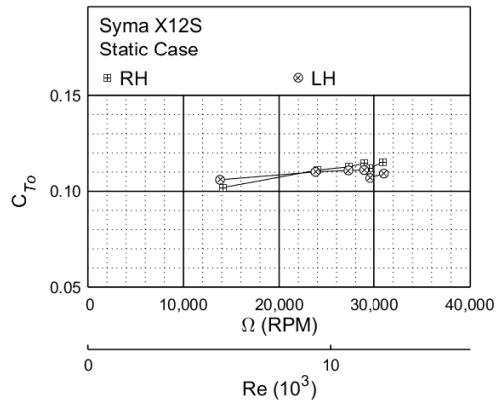

Figure 27: Static thrust performance of the right-handed and left-handed propellers of the Syma X12S.

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V.   Conclusions

To fill the need of providing performance data on the propellers used on small quadrotors, the propellers of 11 aircraft were tested under static conditions. The diameters of these propellers ranged from 1.2 in to 2.6 in. The small thrust and torque values produced by these propellers created difficulty in accurately making measurements. While thrust results were obtained for each propeller, accurate torque measurements for the propellers of five aircraft were not. The propellers without torque measurements all had diameters of less than 1.4 in. Future work will reconsider the possibility of using the power consumption of the motor as a method to measure the power for the propellers.

The results from this series of tests provides an important addition to the collection of propeller data available on small aircraft. Results from these tests will also be used in further research on wind tunnel testing of the smallest quadrotors from this report.

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