AIAA Aviation Forum and ASCEND co-located Conference Proceedings
21 - 25 July 2025, Las Vegas, Nevada
AIAA AVIATION FORUM AND ASCEND 2025
10.2514/6.2025-3457

Comparison of Isolated and Installed Thrust of Propellers Used on Small Quadrotors

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The performance difference between isolated and installed propellers was investigated for a small quadrotor (DJI Mavic Air 2). Using a static testing rig and in-flight RPM measurements from a handheld tachometer, thrust losses during hover were quantified for two different propellers under various weight conditions. A thrust correction based on the propeller rotational rate was used to account for the center of gravity location. Results indicate that installed propellers produce less thrust at a given RPM compared to isolated propellers, with an observed maximum loss of approximately 0.01 in the thrust coefficient (C_T).

I. Introduction

Given the rise in the application of small unmanned aircraft systems (sUAS) for recreational, commercial, and research uses,[1] it is not surprising that there is a desire to know the performance capabilities of the systems and, in return, be able to maximize the performance. A large number of the sUAS available on the market are of a quadrotor design. The traditional method to determine the performance of propellers has been through wind tunnel testing where thrust and power in different conditions can be measured .[2–13] The majority of the tests have been for small-scale propellers used on fixed-wing aircraft, so static and direct advancing flow conditions are usually tested. For multirotor aircraft in flight, each propeller will experience a large range of flow angles and is influenced by the wake of adjacent propellers and the aircraft body itself. These conditions make wind tunnel testing of multirotor propellers more difficult.

Previous quadrotor propeller and motor tests performed by Deters et al.[14,15] were in static conditions and for a single propeller in isolation. For multirotors, static conditions correspond to the aircraft in hover. The purpose of these tests was to compare the different propulsion systems in hover to determine how well hover performance could be used as an indicator of overall performance. Since these tests only considered a single isolated propeller, any effects from having multiple propellers in close proximity or from the drag of the multirotor airframe due to the propeller slipstream could not be quantified.

Through flight testing of quadrotors during hover, the static installed thrust of propellers can be determined. During hover, the propellers are producing thrust equal to the weight of the aircraft plus the drag of the airframe due to the propeller slipstream and any interference effects caused by propellers in close proximity. Changing the weight of the aircraft allows for different static thrust conditions to be measured. The thrust results from flight testing can then be compared to isolated propeller results to quantify installed thrust losses.

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II. Propellers

Two propellers were tested for this paper and are shown in Fig. 1. Both propellers are designed for the DJI Mavic Air 2 (Fig. 2), a small quadrotor with a weight of approximately 1.25 lb (0.570 kg). The first propeller is a low-noise propeller from the drone manufacturer, while the second is a replacement propeller developed by Master Airscrew.

The chord and twist distribution for each propeller was measured using the PropellerScanner software created by Hepperle.[16] With this software, pictures of the front and side of the propeller are used to determine the chord and twist distributions. Figure 3 provides the chord and twist distribution for the DJI propeller, and Fig. 4 provides the Master Airscrew propeller. The true diameters listed in the figures were measured from blade tip to blade tip with the propellers fully extended. The geometry of the two propellers is compared in Figs. 5 and 6. As seen in the comparison figures, the chord distribution shape is nearly identical for the two propellers. Although the chord-to-radius values are smaller for the Master Airscrew, its diameter is longer than the DJI propeller. The actual chord measurements are very close between the propellers. A larger variation is seen in the twist distribution between the two propellers. The DJI propeller has a very linear twist distribution while the Master Airscrew has larger angles further out towards the tip.

Figure 1: DJI Air 2S Low-Noise (top) and Master Airscrew Stealth (bottom) propellers.

Figure 2: DJI Mavic Air 2.

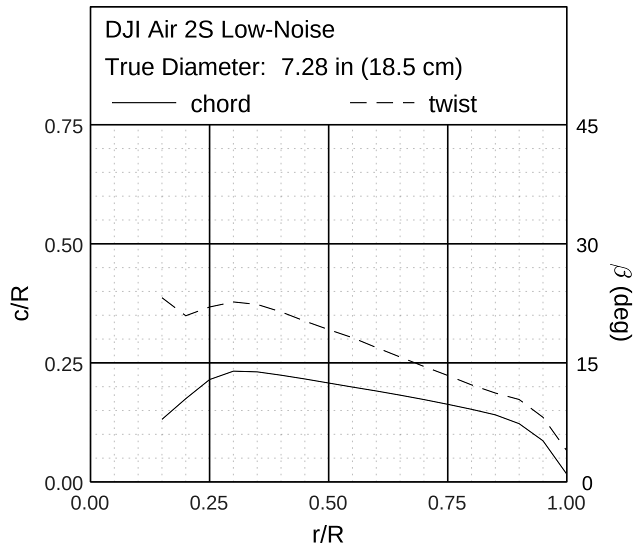

Figure 3: DJI Air 2S Low-Noise propeller geometry.

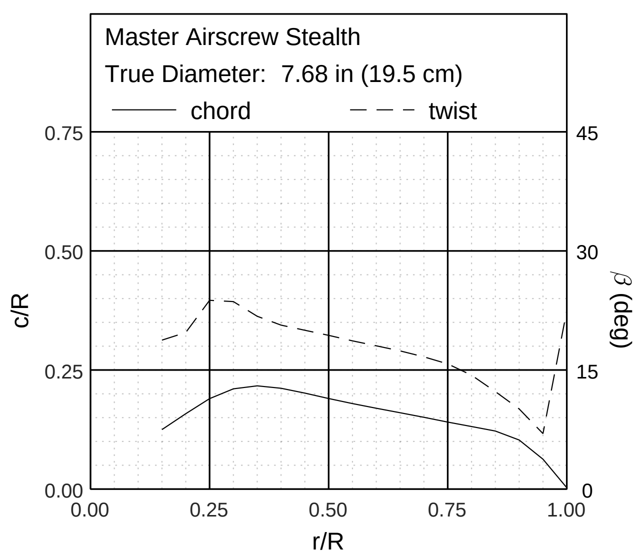

Figure 4: Master Airscrew Stealth propeller geometry.

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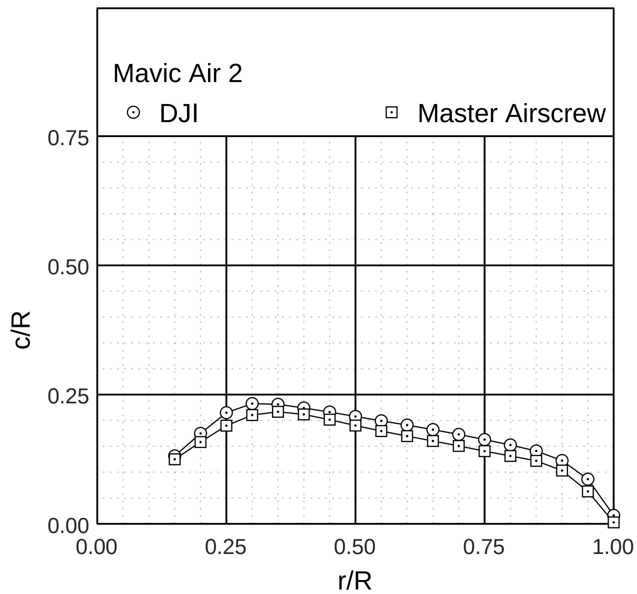

Figure 5: Chord distribution comparison between the DJI and Master Airscrew propellers.

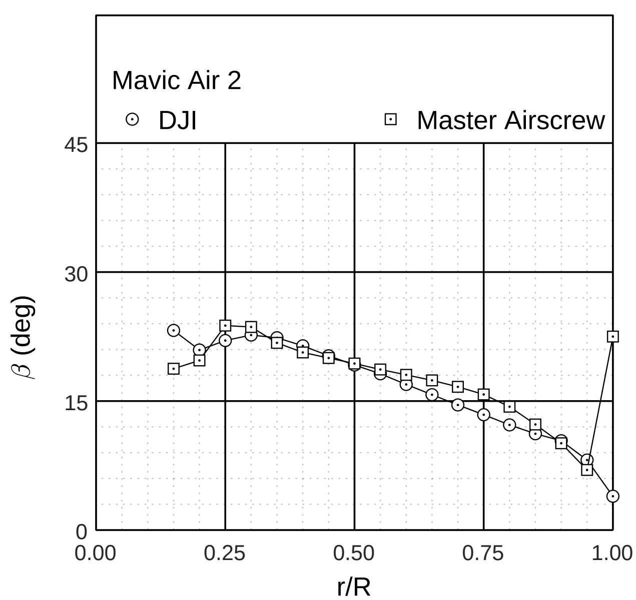

Figure 6: Twist distribution comparison between the DJI and Master Airscrew propellers.

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III. Isolated Propeller Tests

A. Testing Rig

Isolated propeller testing was performed at Indiana University using a propulsion system testing apparatus, which was previously developed[17] to measure the performance and efficiency parameters of electric propulsion system components (propellers, motors, and ESC) in a static environment. The testing rig (Fig. 7) was slightly modified for the current work and was validated by testing a similarly-sized propeller, an APC 8×3.8 SF Slow Flyer propeller with existing data available on the UIUC Propeller Database.[7]

Thrust is measured from the load cell while torque is measured using a reaction torque sensor. A computer was used to interface with a wheatstone bridge ADC to intake raw voltage measurements from the torque cell and load cell during testing. Propellers are tested through a range of RPMs with the resulting thrust and torque being measured. Propeller RPM is measured using an optical RPM meter. Ambient pressure and temperature are measured using an external pressure and temperature sensor. The component specifications for the propulsion system testing apparatus instrumentation are provided in Table 1.

Density is calculated from the equation of state

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

where R is the universal gas constant. The standard value of 1716 $\mathrm{ft^2/s^2/^\circ R}$ (287.0 $\mathrm{m^2/s^2/K}$) for air was used.

Propeller power is calculated from the measured propeller torque by

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

Propeller coefficients are calculated using the standard definitions.

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

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

where nD can be considered the reference velocity and D^2 can be considered the reference area.

The propeller Reynolds number 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 is calculated from Sutherland's formula.

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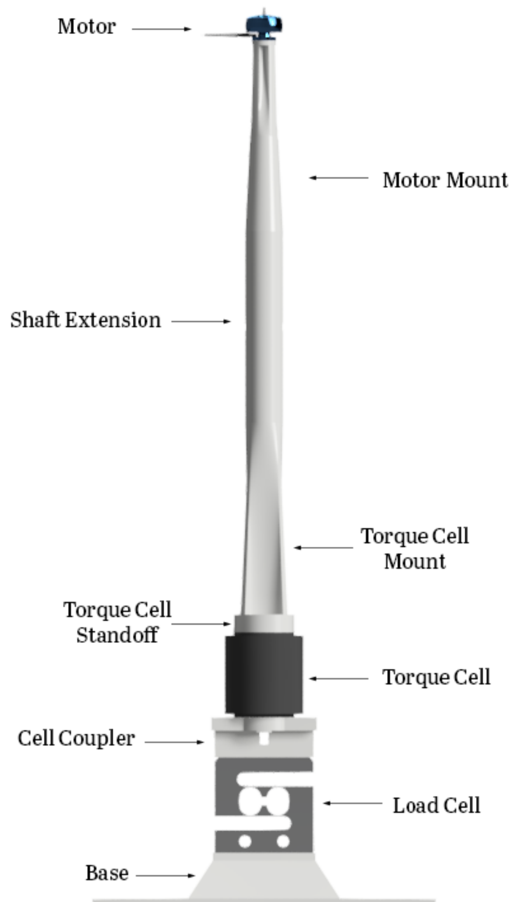

Figure 7: Static testing rig.

Table 1: Specifications of the Propulsion Testing Apparatus

Data acquisition system	Arduino Giga R1 WiFi
Sensors	
Thrust Cell	Phidgets S-Type Load Cell - 2kg
Torque Cell	Transducer Techniques 50 oz-in RTS reaction torque sensors
Wheatstone Bridge	Phidget Bridge 4-Input
RPM	Futaba Optical RPM Sensor
Pressure & Temperature	Adafruit Bosch BMP390
Drivers	
Motor	Readytosky LE2204 1800KV brushless motor
Speed Controller	Castle Phoenix Edge Lite 50
Power Supply	BK Precision
PWM Generator	Digital Pin on Arduino

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B. Propeller Performance

Results for the DJI Air 2S Low-Noise propeller are provided in Figs. 8 and 9. The right-handed version of the propeller is provided in Fig. 8 while the comparison between the right- and left-handed propellers is provided in Fig. 9. Both versions of the propellers are nearly identical in the thrust and power performance. The coefficients are nearly constant for RPMs greater than 3,000.

Figures 10 and 11 provide the results for the Master Airscrew Stealth propellers. The right-handed version of the propeller is provided in Fig. 10 while the comparison between the right- and left-handed propellers is provided in Fig. 11. Similar to the DJI propeller, the right- and left-handed Master Airscrew propellers are nearly identical in performance. The thrust and power coefficients of these propellers are also nearly constant at RPMs greater than 3,000.

The performance of the two propellers used for this research are compared in Fig. 12. The propellers are very similar in both the thrust coefficient and power coefficient. The DJI propeller does produce a slightly larger thrust coefficient.

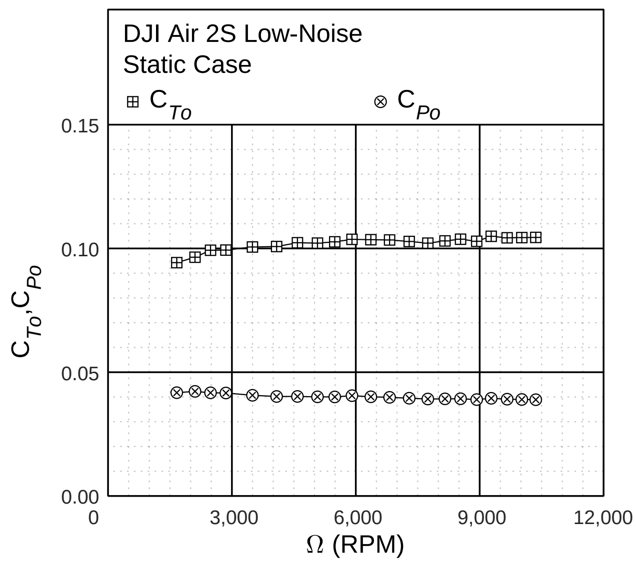
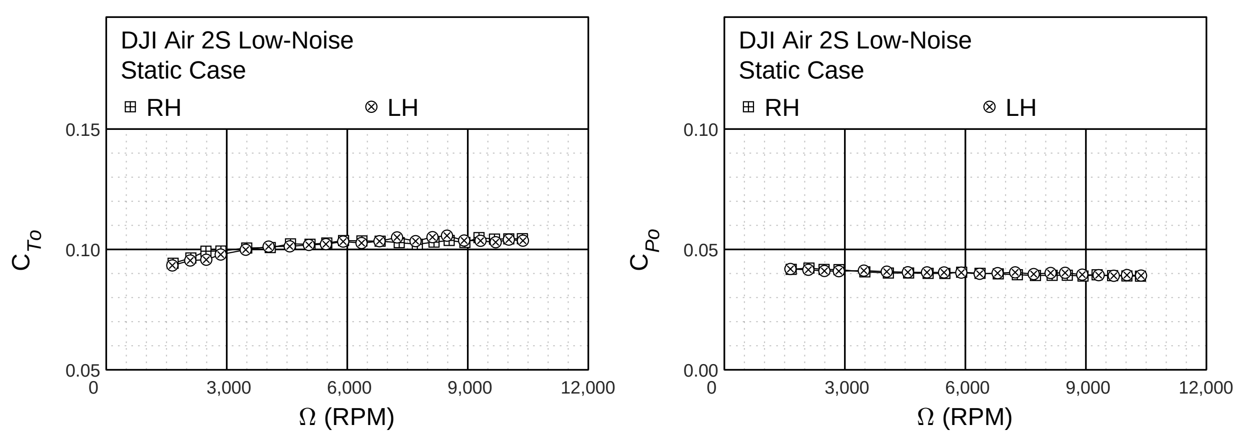


Figure 8: DJI Air 2S Low-Noise static performance.



(a) (b)

Figure 9: Comparison between the right-handed and left-handed DJI Air 2S Low-Noise propellers: (a) thrust coefficient and (b) power coefficient.

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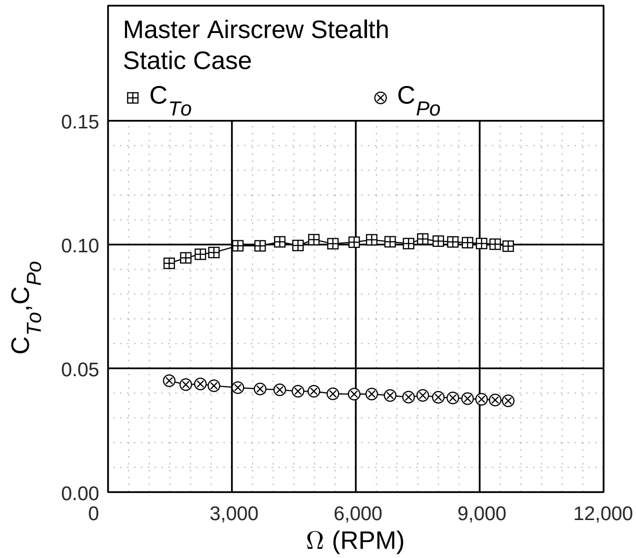
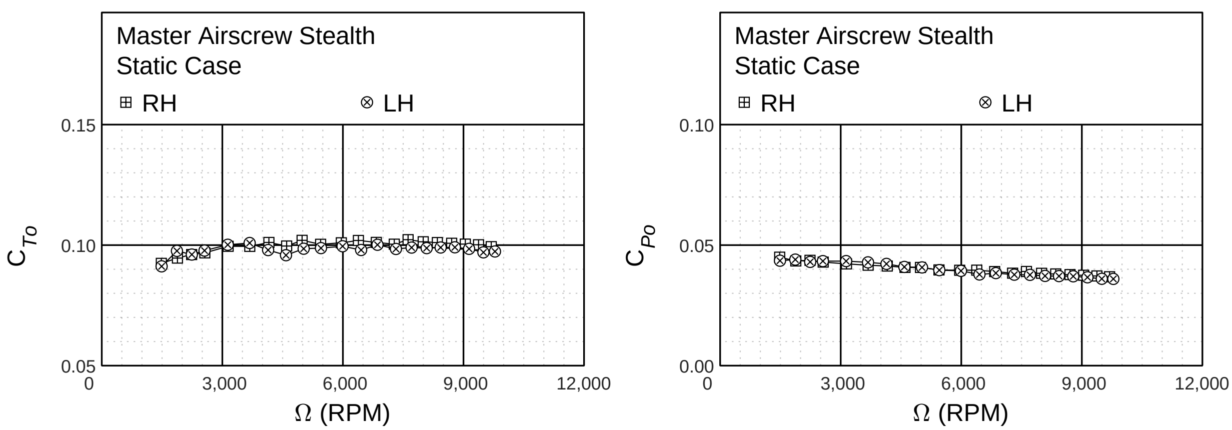
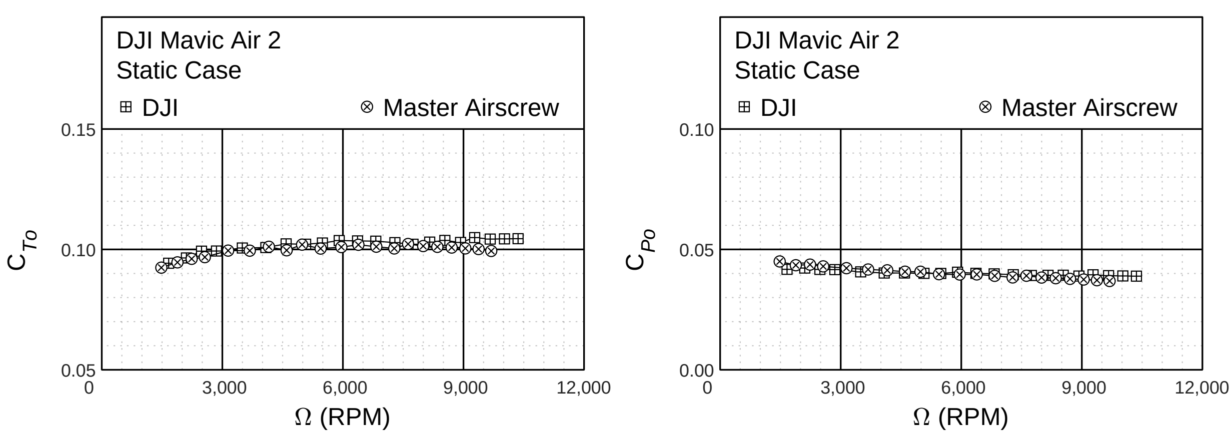


Figure 10: Master Airscrew Stealth static performance.



(a) (b)

Figure 11: Comparison between the right-handed and left-handed Master Airscrew Stealth propellers: (a) thrust coefficient and (b) power coefficient.



(a) (b)

Figure 12: Comparison between the DJI Air 2S Low-Noise and Master Airscrew Stealth propellers: (a) thrust coefficient and (b) power coefficient.

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IV. Flight Tests and Comparison

Flight tests were performed using two DJI Mavic Air 2 quadrotors with one located in Maryland and the other located in Indiana. Each quadrotor tested both propellers under different weight conditions. In-flight RPMs for each propeller were measured using a Fromeco TNC handheld tachometer while the aircraft was in hover (Fig. 13). To measure the RPMs, the following procedure was followed.

1. Prepare aircraft weight (baseline or add weights). See Fig. 14 for an example loading.
2. Measure the weight of the aircraft.
3. Measure ambient conditions: temperature, pressure, and relative humidity.
4. Start aircraft and set it to hover.
5. Measure RPM for each propeller.
6. Land aircraft.

Table 2 lists the flight tests performed for each of the propeller sets. Baseline is the aircraft's "empty" weight, i.e., no additional weights added. Seven flights were performed with the DJI Air 2S propeller, and 10 were performed with the Master Airscrew Stealth propeller. From the measured RPMs and aircraft weight, the thrust coefficient of each propeller was calculated using Eq. 3. Air density was calculated from the ambient temperature and pressure using the equation of state (Eq. 1) and then corrected for relative humidity. For the initial thrust coefficient calculations, the weight was evenly divided between the four propellers. Since flight tests were performed under different ambient conditions, the Reynolds numbers of the propellers were calculated for comparison. When compared at similar RPMs, the Reynolds number at the 75% station did not differ more than 2,000 between different flight tests and with the isolated propeller tests. Since the change in Reynolds number was small, it was deemed appropriate to plot all thrust coefficient results against RPM.

Figure 13: Measurement of propeller RPM while in flight using a handheld tachometer.

Figure 14: Example loading of additional weight on the DJI Mavic Air 2.

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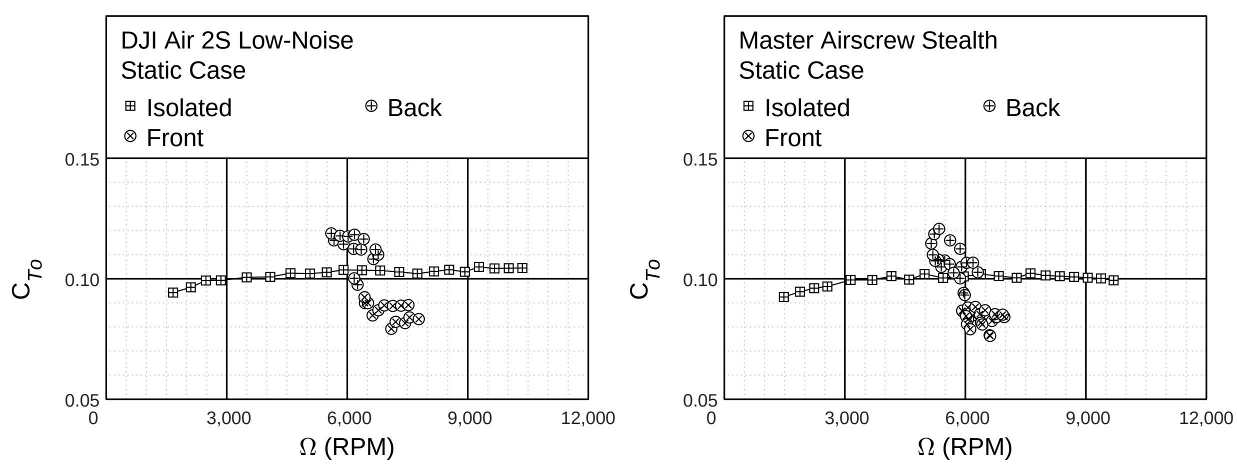
Table 2: Flight Tests Performed

DJI Air 2S Low-Noise	Master Airscrew Stealth
Baseline (×2)	Baseline (×3)
+40 g	+40 g
+80 g	+72 g
+120 g	+80 g
+160 g	+120 g
+200 g	+140 g
	+160 g
	+200 g

Figure 15 provides the thrust coefficient results when the weight is evenly divided between the four propellers. From the figure, it is seen that almost all thrust coefficients for the back propellers have a calculated thrust coefficient greater than the isolated propeller results. All front propellers have a thrust coefficient less than the isolated results. When reviewing the RPM results, the front propellers always had a larger RPM measurement even under the different loading conditions. Table 3 provides an example set of RPM measurements for the baseline aircraft using the Master Airscrew Stealth propellers. A larger RPM with the front propellers implies that the center of gravity is closer to the front and that the weight cannot be evenly divided between the propellers.

Table 3: Example RPM Measurements for Master Airscrew Stealth

Location	RPM
Front Right	6070
Front Left	6020
Back Right	5320
Back Left	5400



(a) (b)

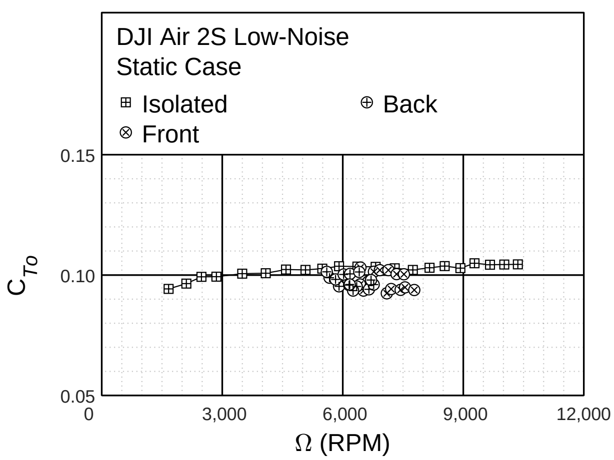
Figure 15: Calculated in-flight C_T using equal thrust for all propellers: (a) DJI Air 2S Low-Noise and (b) Master Airscrew Stealth.

Assuming that the center of gravity is very close to the centerline of the aircraft and that any installed propeller losses are similar for the front and back propellers, then a corrected thrust distribution among the propellers can be found. This thrust correction is based on the average rotational rate of the front propellers and the average rotational rate of the back propellers, and it is given by Eqs. 6 and 7. The F and B represent the front and back propeller measurements, respectively. This thrust correction does assume that the propeller pairs (either front or back) are producing the same thrust. The thrust coefficient results using the corrected thrust values are provided in Fig. 16. For the DJI propeller, every flight test coefficient is less than the isolated propeller coefficient. For the Master Airscrew propeller, nearly all flight test coefficients are less than the isolated.

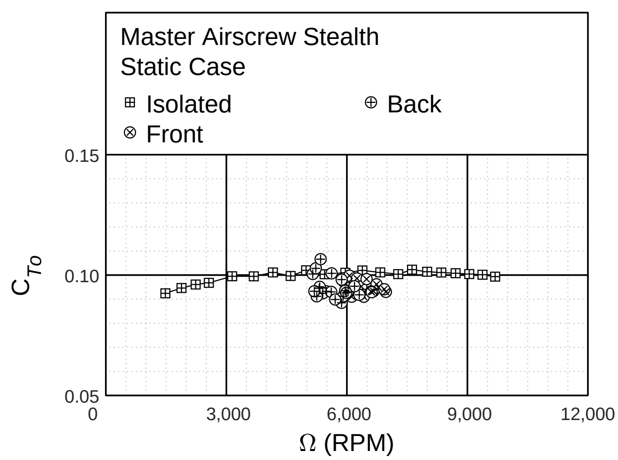
$$T_F = \frac{W}{2} \frac{n_{F_{avg}}^2}{n_{F_{avg}}^2 + n_{B_{avg}}^2} \tag{6}$$

$$T_B = \frac{W}{2} \frac{n_{B_{avg}}^2}{n_{F_{avg}}^2 + n_{B_{avg}}^2} \tag{7}$$

A flight test thrust coefficient that is less than the isolated thrust coefficient means that the installed propeller is producing less thrust at a given RPM. An installed propeller must rotate faster in order to make up for the losses. From Fig. 16, the maximum loss in C_T at a given RPM is approximately 0.01 for either propeller. At standard sea level conditions, a 0.01 reduction in C_T for the DJI propeller amounts to about 0.032 lb (0.14 N) at 6,000 RPM and about 0.044 lb (0.20 N) at 7,000 RPM. For the Master Airscrew propeller, a 0.01 reduction in C_T amounts to about 0.040 lb (0.18 N) at 6,000 RPM and about 0.054 lb (0.24 N) at 7,000 RPM.



(a)



(b)

Figure 16: Calculated flight C_T using modified thrust for front and back propellers: (a) DJI Air 2S Low-Noise and (b) Master Airscrew Stealth.

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V. Summary and Future Work

Measurements of propeller RPM while in flight were successfully accomplished for the DJI Mavic Air 2 operating with two different propellers and under various weight conditions. From the weight of the aircraft and the RPM measurements, the installed thrust coefficient of the propeller was calculated. Differences in the RPM measurements from the front and back propellers required a correction in the assumed thrust distribution to account for the center of gravity not being located at the center point between all the propellers. Future flight tests should measure the actual location of the center of gravity for more accurate results. The flight test results showed that the installed propellers produced less thrust than isolated propellers at a given RPM. A maximum loss of about 0.01 in C_T was found for both propellers.

While the use of handheld tachometers to record propeller RPMs was successful, it is limiting. Measurements must be taken within the range of the tachometers and have a good source of ambient light. The quadrotor used for this research had a hovering capability, which helped hold the aircraft stable for measurements, but this feature is not on all multirotors. This tachometer method can also pose a danger if the tachometer is being held by a person. To address the limitations and possible danger, an onboard system is being developed that could be attached to a multirotor in order to record RPMs during flight.

The onboard system being developed uses off-the-shelf components with an Arduino Uno R3 as the core. Accelerations will be measured by an Adafruit BNO055 9-DOF absolute orientation IMU, and ambient conditions (pressure, temperature, and humidity) will be measured by an Adafruit BME680 sensor. RPM measurements will be measured using a TT Electronics OPB732WZ infrared reflective switch. This onboard system will be capable of measuring the aircraft accelerations and RPMs simultaneously to ensure that the aircraft is in hover.

Acknowledgments

This research was partially funded by NSF IUSE grant award 2315560.

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