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Propeller Performance Measurement for Low Reynolds Number UAV Applications

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The recent boom in Unmanned Aerial Vehicles (UAV) and Micro Air Vehicles (MAV) aircraft development creates a strong demand for accurate small-diameter propeller performance data. Small-diameter propellers as defined in this paper (diameter 6 inches to 22 inches), operate at low Reynolds numbers (typically between 30,000 and 300,000), rendering performance scaling from larger counterparts inaccurate. An Integrated Propulsion Test System (IPTS) has been designed, developed and validated at Wichita State University (WSU). A large number of propellers have been tested and a reliable database of performance data has been created. This paper discusses the salient features of this measurement system and propeller test data for a few propellers.

Nomenclature

α	=	angle of attack
β	=	yaw angle
A2D	=	analog-to-digital
CFD	=	computational fluid dynamics
C_T	=	thrust coefficient
C_P	=	power coefficient
C_Q	=	torque coefficient
D	=	propeller diameter
IPTS	=	integrated propulsion test system
J	=	advance ratio
μ	=	freestream viscosity
n	=	revolutions per second
η_P	=	propeller efficiency
Ω	=	radians per second
P_P	=	shaft power
q	=	dynamic pressure (Tunnel)
Q	=	torque
ρ	=	freestream density
RPM	=	revolutions per minute
$R_{0.75}$	=	¾ radius length
R_e	=	Reynolds number (Based on chord at 0.75% radius location)
R/C	=	radio control
T	=	thrust
U'	=	freestream velocity (Corrected)
V_t	=	total velocity
WOZ	=	wind off zero

I. Introduction

UNMANNED Aerial Vehicles (UAV) and Micro Aerial Vehicles (MAV) development has boomed over the last decade. Besides military and commercial applications, these few years have also witnessed an increase in the

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number of radio controlled (R/C) airplane hobbyists and amateur R/C airplane designers. The hobby of flying R/C airplanes is slowly turning into a professional sport with competitions not only encouraging hobbyist to improve off-the-shelf designs but also challenging engineering students in universities to design mission specific aircraft (e.g., AIAA Design/Build/Fly competition). Obviously, the propulsion system directly contributes to the success of such airplanes. In summary, the growing interests related to UAV, MAV, and R/C airplanes require the use of small-diameter propellers and therefore creates a demand for performance data.

Although sufficient performance data for large propellers is available, it cannot typically be applied to smaller UAV aircraft. Small-diameter UAV and model aircraft propellers operate at lower Reynolds numbers, typically between 30,000 to 300,000 (based on chord at ¾ radius location and sea level conditions). Designers and hobbyist have commonly relied on recommendations from layman and vendors when selecting propellers for their aircraft. Such a situation is less than ideal and limits a UAV or R/C flyers ability to achieve consistent performance improvements. As an aid to the designer, most engine manufacturers recommend a propeller pitch and diameter combination that could be used with their engines.[1] But, no supporting performance or test data is made available to the user thereby placing the recommendation in question.

One can use computational tools to predict the prospective propellers performance using theoretical and analytical schemes, such as Computational Fluid Dynamics (CFD), Vortex methods, Blade Element Theory, Momentum Theory or a combination thereof.[2] The principal limitation is that off-the-shelf commercially available propellers may not be easy to model, since accurate geometry or airfoil performance data is necessary. Unfortunately most of the off-the-shelf small-diameter propellers do not use a specific airfoil as such. A larger variety of the wooden propellers simply have a flat bottom, cambered top cross-section, while other propellers may use a combination of modified airfoils (http://www.apcprop.com/Engineering/engineering_design.html). In any case, this data is not made available to the end user, thus limiting the accuracy with which performance predictions may be attempted. A requirement for the existence of a standard experimental propeller performance database is therefore obvious.

Although, work in this direction has been previously attempted, its progress has been limited, primarily due to difficulties with the associated measurement systems.[3-7] Most efforts concentrated on wind tunnel testing using complex systems and propellers with diameters larger than 24 inches.[4,5] Interestingly, the investigators acknowledged the difficulties faced when entering the Reynolds number regimes considered in this publication. Lastly, measurement systems used for marine propellers of similar diameter have existed, but their adaptation to aircraft propellers has not been successful.[8] These shortcomings serve as the motivation to design and develop an accurate measurement system, that is sufficiently sensitive, highly repeatable and caters to performance measurements for propellers with diameters from 6 inches to 22 inches, operating in the 30,000 to 300,000 Reynolds number regime. An obvious outgrowth is to also create a reliable propeller performance database to serve designers and hobbyists for propeller selection.

A measurement system, using dedicated components has been designed, developed and tested at the Wichita State University. This paper highlights the measurement system features, testing, results, and some interesting observations.

II. Experimental Apparatus

The measurement system is divided into three sub-parts, namely, the Sensor/Motor Platform, Signal conditioning and Power and the Data processing systems. Each sub-system is comprised of electronic instrumentation and components as shown in Figure 1.

The 3 ft x 4 ft Low Speed Wind Tunnel at Wichita State University is an open return type capable of achieving dynamic pressure of up to 38 psf or 1.14×10^6 Reynolds number per foot. Figure 2 shows a photograph of the tunnel and lab.

The Sensor/Motor Platform is mounted on a C-Strut located inside the wind tunnel test section. The balance is a precision 2-component instrument that measures thrust and torque and has a full scale (FS) rated output accuracy of ±0.05%. The adapter that connects the motor and the load cell is designed to work with different motors, thus allowing testing of a larger range of propeller diameters. The AstroFlight's Cobalt family, electric motors are currently being used with this setup.[1]

Propeller revolution-per-minute (RPM) measurements, used for calculating Advance Ratio (J) are recorded using a magnetic pickup. This sensor requires a metallic tab to spin with the propeller and is capable of measuring a maximum of 20,000 targets/s. The RPM sensor is mounted directly on the motor and its proximity to the spinning tab is adjustable.

The 3 ft x 4 ft Low Speed Wind Tunnel facility is equipped with a pitot-static probe and a high precision 1-psid Honeywell's precision pressure transducer, having a rated output accuracy of 0.05% FS, used for measuring test-section dynamic pressure and calculating J. The signal output from this transducer along with the propeller balance and RPM sensor are processed through a series of signal conditioners, amplifiers and isolator modules, which are located outside the tunnel's test section. The magnetic pickup is powered by an independent 10-volt DC power supply. The power to the motor is supplied by a high amperage/voltage precision control DC power supply.

Data acquisition is accomplished using a 16-bit analog-to-digital (A2D) board in conjunction with a Pentium® 4 laptop computer. The data is collected and reduced using a self-authored Visual Basic® for Applications program that writes the data directly to a Microsoft® Excel spreadsheet. This program completely automates the data reduction process and is capable of configuring the A2D board. The data processing routine accounts for blockage due to the spinning propeller as described by Glauert.[9] Non-dimentionalized propeller performance plots of thrust coefficient (C_T), power coefficient (C_P), torque coefficient (C_Q) and propeller efficiency (η_P) verses J, and a summarized performance table, are automatically generated and archived.

Standard propulsion equations have been used to calculate non-dimensionalized performance parameters. Amongst these are coefficients for thrust Eq. (1), coefficient for power Eq. (2), where power is determined using Eq. (3), coefficient of torque Eq. (4) and the propeller efficiency Eq. (5). Forward velocity, propeller RPM and diameter are combined into the Advance Ratio parameter determined using Eq. (6). The Reynolds number is calculated for each datapoint for chord at ¾ radius location using Eq. (7), where the total velocity at ¾ radius location is given by Eq.(8).

$$C_T = \frac{T}{\rho \cdot n^2 \cdot D^4} \tag{1}$$

$$C_P = \frac{P_p}{\rho \cdot n^3 \cdot D^5} \tag{2}$$

where,

$$P_p = \Omega \cdot Q \tag{3}$$

$$C_Q = \frac{Q}{\rho \cdot n^2 \cdot D^5} \tag{4}$$

$$\eta_p = J \cdot \frac{C_T}{C_P} \text{ or } \eta_p = \frac{T \cdot U'}{P_p} \tag{5}$$

$$J = \frac{U'}{n \cdot D} \tag{6}$$

$$\mathrm{Re}_{0.75} = \frac{\rho \cdot V_t \cdot C_{0.75}}{\mu} \tag{7}$$

where,

$$V_t = \sqrt{(U')^2 + (\Omega \cdot R_{0.75})^2} \tag{8}$$

Propeller selection (Figure 3.) for evaluation is limited only by the test section physical size and motor availability. A few propellers were selected early in the effort to repeat runs previously conducted by Asson, for validation and comparison purposes.[6]

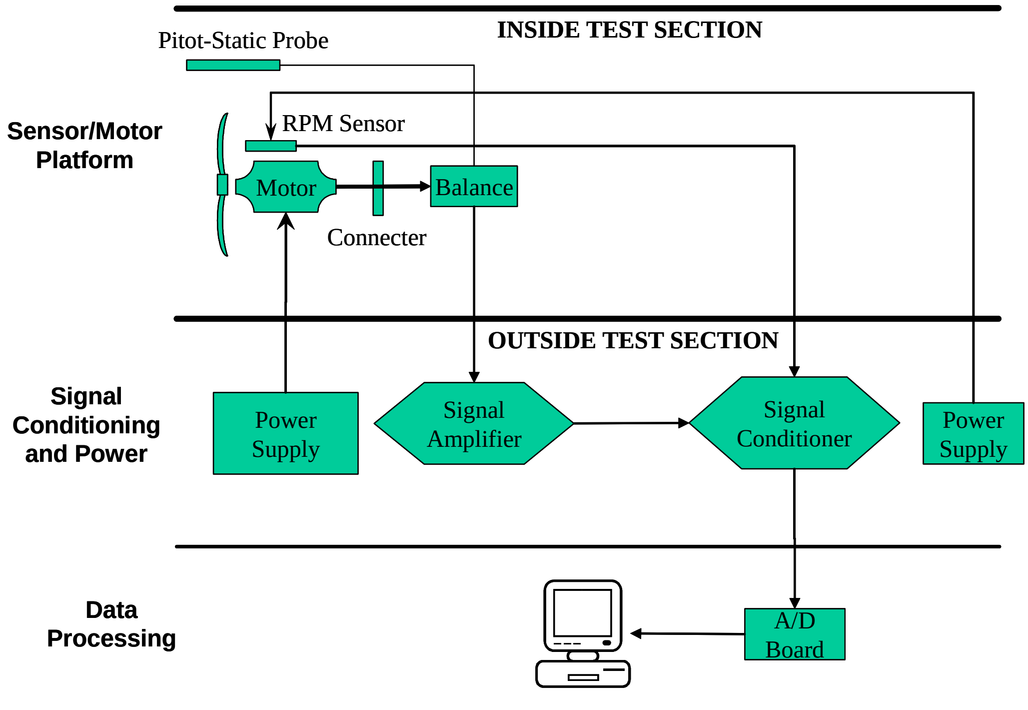

Figure 1. Measurement system block diagram.

Figure 2. 3'x 4' Low Speed Wind Tunnel, Wichita State University.

Figure 3. Sample propellers that have been tested.

III. Experimental Procedure

During the experiments either the RPM or the forward velocity, or both, need to be adjusted to vary the advance ratio and map complete performance curves. Although various combinations of RPM and velocity are possible, varying the tunnel-q is most time efficient. Calculations based on Combined Blade Element and Momentum Theory are used to select the required tunnel-q step sizes.[2]

The motor is operated at constant power as limited by the maximum continuous current and voltage specified by the motor manufacturer.[1] This limit is easily enforced by setting "never exceed" values on the power supply current and voltage outputs.

As mentioned earlier, the data reduction routine incorporates propeller slipstream momentum corrections[9], and uses the resulting corrected velocity values for further performance parameter calculations.[2] Wind-off-Zero (WOZ) readings are taken at the start and end of each run and the average WOZ values are tared from the collected data, thus compensating for minor temperature effects that might occur during a test.

Each sensor was calibrated before using the Integrated Propulsion Test System (IPTS) for tests. The load cell was calibrated insitu, using dead weights. A calibration apparatus that applies pure thrust and torque loads, was specially designed and used for this purpose. The balance behavior is very linear and minimal interactions are observed. To enhance results these interactions are accounted for in the final balance behavior matrix.[9]

Although the RPM indicator calibration is not necessary, computer readings are verified using a calibrated strobe light and a frequency counting multimeter. The tunnel's q measurement transducer is calibrated and cross-checked using a manometer.

IV. Results and Discussion

Performance data for a wide range of propellers, spanning the diameters stated in the goals, has been obtained. Since all the data cannot be shown in this article, only a few representative results are shown for the purpose of illustration.

The first experiments using the new apparatus were aimed towards evaluating the measurement system accuracy and verifying its repeatability.

To establish confidence, the first experiments were similar to those conducted by Asson.[6,7] Information needed for this purpose, such as tunnel q, and data points collected are backed out from performance plots in Asson's thesis.[6] These runs were conducted at fairly low tunnel q's and the RPM was limited to 3,000, since his apparatus had vibrational issues.[6] The propellers examined were the 14-4, 14-6 and the 16-6 propellers belonging to the Zinger family, with the first number indicating propeller diameter and the second number defining pitch in inches (http://www.zingerpropeller.com/). It should be noted that the pitch number in model or R/C aircraft terminology is defined as the distance, in inches, a propeller would cover in one revolution.

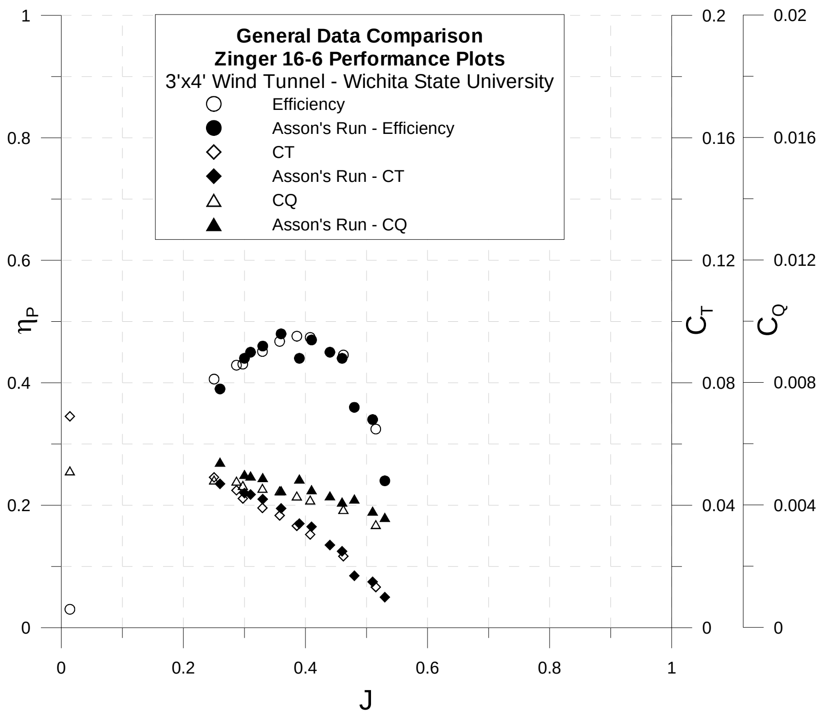

Figure 4. IPTS result Comparison with Asson's data[6].

The comparative results with Asson's run (filled symbols) for the Zinger 16-6 propeller are shown in Figure 4, with WSU IPTS results (open symbols). As is observed, data collected by the IPTS system matches that of Asson's experiment.[6] Similar results are observed for other propellers.

This experiment was repeated for all the above-mentioned propellers at similar conditions to verify WSU IPTS data repeatability and quality. Minimal variations are observed in data collected by the IPTS as compared to Asson's data, although the variation in Asson's data can be attributed to the operational limitations imposed by his apparatus.

Once the runs for Asson's thesis were successfully duplicated, the apparatus installation sensitivity to tunnel flow angularity was checked. This test was performed by comparing a baseline run at 0° pitch angle (α) and yaw angle (β), to runs at ±3° in α and β respectively. The results in terms of C_Q and C_T versus J are shown in Figure 5a and Figure 5b. As can be observed, C_Q (Figure 5a) is not notably affected by changing the propeller disc plane orientation in any direction, whereas C_T (Figure 5b) is quite sensitive to change in pitch. However, the fact that the result for both +3° α and –3° β match, suggests that any flow angularity present in the tunnel test section is negligible.

The next tests demonstrate the WSU IPTS's ability to provide high quality repeatable data. As an example, Figure 6 shows the performance data for two separate runs conducted using a 3-Blade, Master Air Screw 16-8 propeller. Efficiency, η_P is plotted along with C_Q, C_T and C_P as a function of J. The data for these two runs, conducted on two different days, compares well. Although only a limited amount of repeat data is shown, repeat runs are performed for all propellers that are tested.

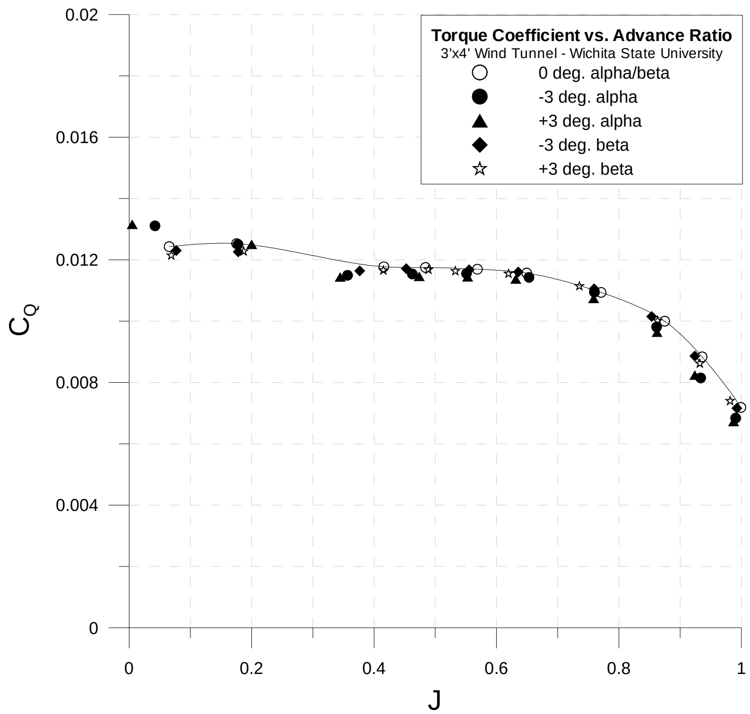

Figure 5a. α and β sweep plots of C_Q vs. J.

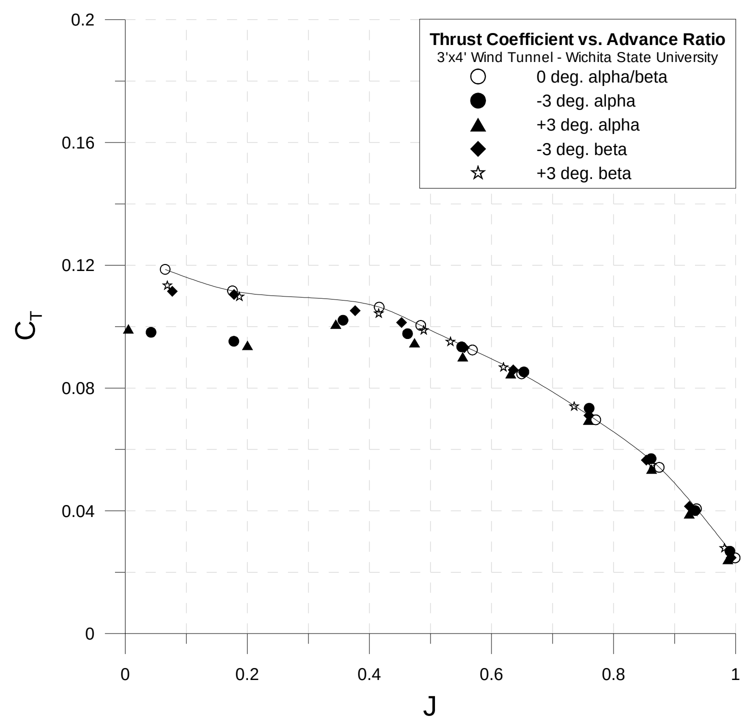

Figure 5b. α and β sweep plots of C_T vs. J.

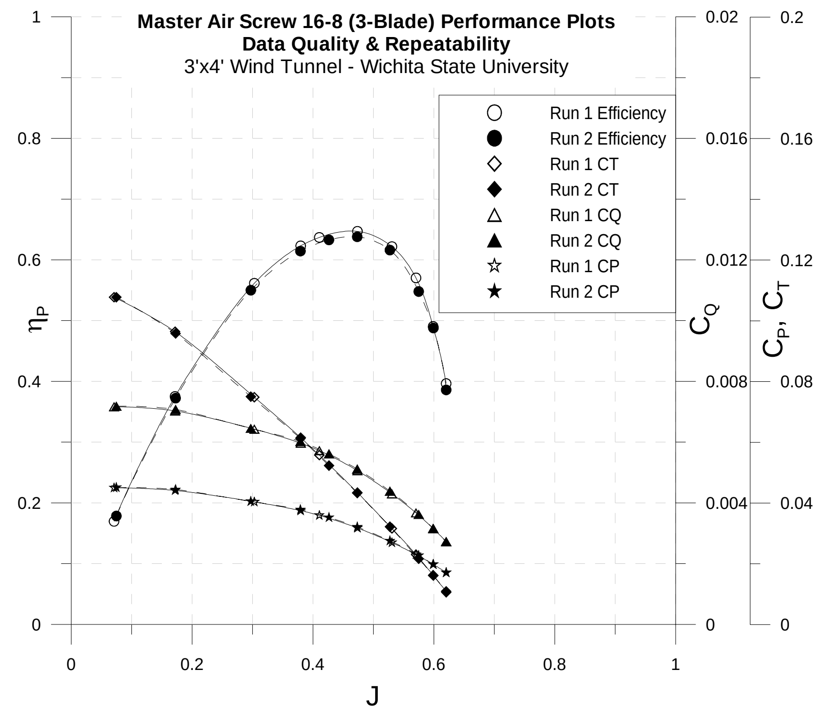

Figure 6. Example plots illustrating data repeatability.

Interestingly, comparison runs were also performed for two geometrically similar, but different propellers made by the same manufacturer. These tests are designed to investigate the manufacturer's product reliability and the variance in performance due to manufacturing. Contrasting results are shown in Figure 7a and Figure 7b. As can be observed, there is a distinct variation in performance of Zinger 16-6 propellers (Figure 7a.), especially in the efficiency and thrust coefficient, compared to a very minor variation in data of APC 16-12E propellers (Figure 7b.).

The tests discussed above help verify the setup, procedure and establish confidence in the data quality. The data acquisition and reduction program, as mentioned previously, directly outputs four performance plots of η_P, C_Q, C_T and C_P as function of J and a summary table, per test, as shown in Figure 8. For the purpose of illustration, performance plots of a few randomly selected propellers, spanning the range of diameters covered under this project, are shown in Figure 9 to Figure 12.

To this date over 60 propellers have been tested and their performance mapped. More propellers are being added to this list on a regular basis. High repeatability is observed in data collected from all propellers tested using IPTS. The system, as mentioned earlier, is well behaved.

Sensitivity and uncertainty analysis performed prior to the experiment setup and throughout the apparatus development utilized the Kline-McClintok method.[10,11] The uncertainties in the coefficients are dependent on the particular propeller and the advance ratio, and are typically about 0.05% in C_T and C_Q and about 0.003% in C_P.

Also, as mentioned earlier, the other important observation made is that scatter in repeat run data increases as Reynolds number decreases (e.g., when spinning the propellers below 3,000 RPM at tunnel speeds less than 50 ft/s). As an interesting note, significant Reynolds number effects on propeller performance curves are observed, that will be discussed in the forth-coming publications.

A web page for propeller data is planned for the near future, for more information please contact the authors.

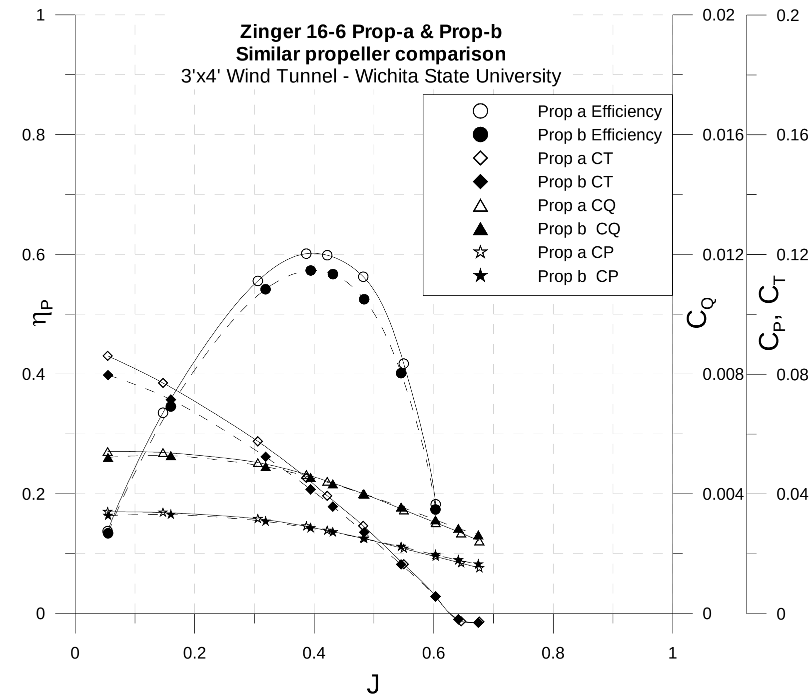

Figure 7a. Example plots illustrating performance variation for two separate Zinger 16-6 propellers.

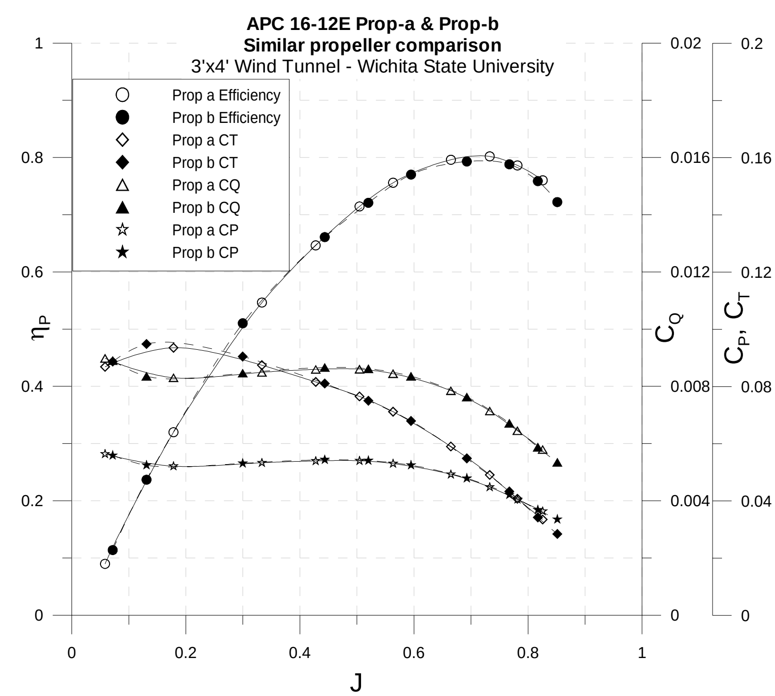

Figure 7b. Example plots illustrating performance variation for two separate APC 16-12E propellers.

		SUMMARY			
PROP	EAPC	DIA	12	PITCH	12
	q(psf)	U (ft/s)	T (lb)	Q (in-lb)	RPM
	0.07	6.90	3.10	3.90	6,323
	0.42	17.95	2.75	3.70	6,131
	2.32	43.71	2.77	3.67	6,304
	3.25	51.89	2.72	3.82	6,431
	4.41	60.65	2.47	3.76	6,398
	5.78	69.60	2.29	3.76	6,431
	8.37	83.92	1.94	3.67	6,533
	11.10	96.82	1.56	3.46	6,641
	13.42	106.56	1.24	3.24	6,833
	16.35	117.70	0.81	2.82	7,069
J	η_P	C_T	C_P	C_Q	$Re_{0.75}$
0.07	0.10	0.1187	0.0781	0.0124	90,370
0.18	0.25	0.1117	0.0787	0.0125	87,860
0.42	0.60	0.1064	0.0740	0.0118	91,495
0.48	0.66	0.1004	0.0738	0.0118	93,845
0.57	0.72	0.0924	0.0735	0.0117	94,069
0.65	0.76	0.0846	0.0727	0.0116	95,349
0.77	0.78	0.0696	0.0687	0.0109	98,233
0.87	0.75	0.0542	0.0628	0.0100	101,239
0.94	0.69	0.0407	0.0555	0.0088	105,054
1.00	0.55	0.0247	0.0452	0.0072	109,706

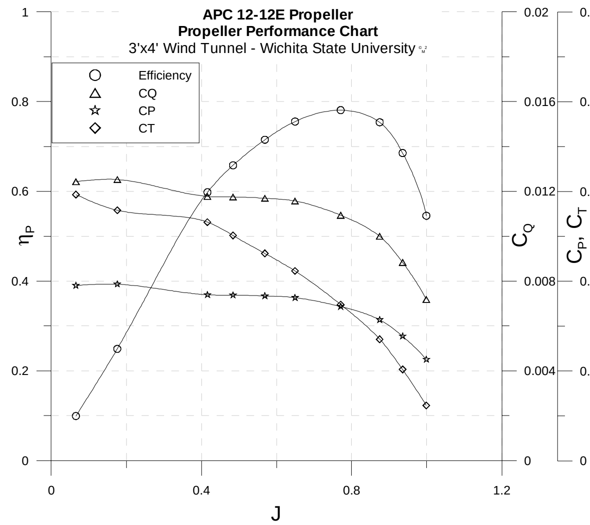

Figure 8. Data reduction code output file example.

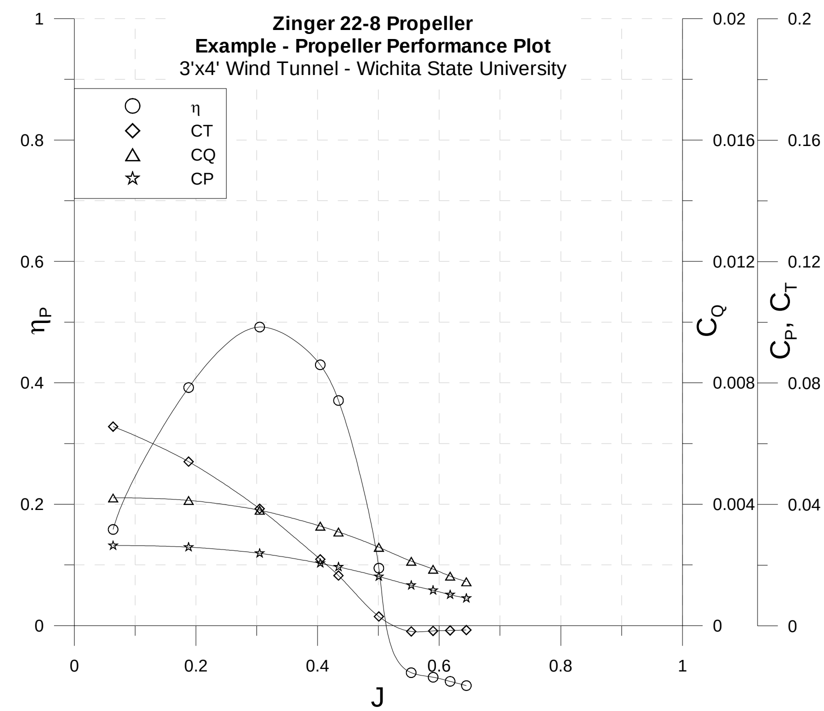

Figure 9. Example Performance plots for Zinger 22-8 propeller.

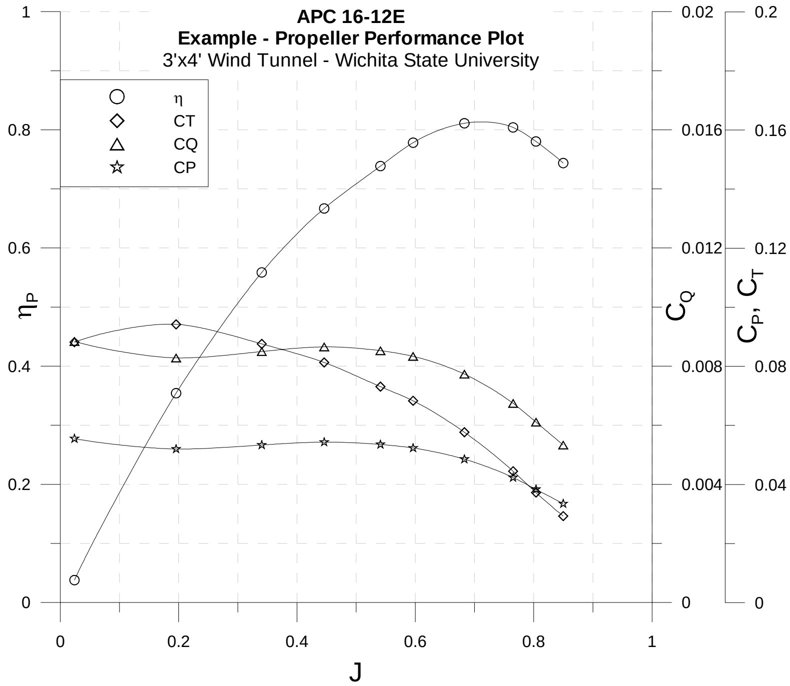

Figure 10. Example Performance plots for APC 16-12E propeller

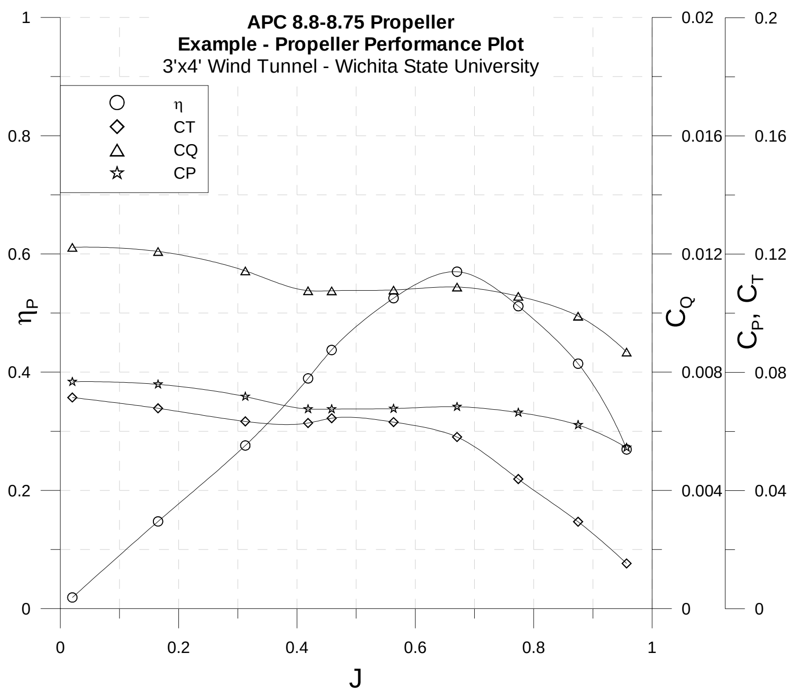

Figure 11. Example Performance plots for APC 8.8-8.75 propeller

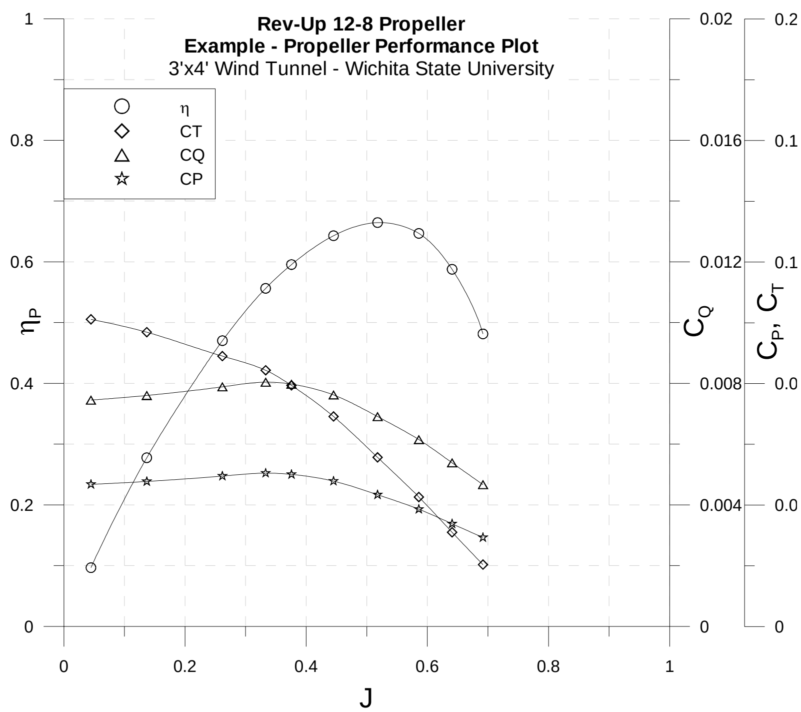

Figure 12. Example Performance plots for Rev-Up 12-8 propeller

V. Conclusions

A need for small-diameter propeller performance data, for low Reynolds number UAV, MAV, and R/C hobby aircraft applications, exists. A new test apparatus has been developed to address this need. The following conclusions are offered based on the project's results and the observations:

- The goal of designing and developing an accurate measurement system has been met
- A reliable propeller performance database has been created and new data is being added on a regular basis
- Results from the sensitivity and repeatability studies affirm the measurement systems reliability
- The apparatus is very sturdy and its sensitivity and repeatability is not affected at high motor RPM and tunnel speeds
- Lastly, the low uncertainties in measurements increase confidence in data

The tests conducted so far also demonstrate the systems time efficiency. An entire experiment can be completed within ten to fifteen minutes. Additionally, the ability to quickly change propellers or motors greatly reduces wind tunnel occupancy time, which can prove very valuable.

A website is under preparation for public access to the propeller performance data. Moreover, this system will be a valuable experimental tool for investigators to not only measure and determine propeller performance experimentally, but to also gain insight needed to further improve or optimize small-diameter propellers.

Acknowledgments

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