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Abstract: In an effort to assess motor and propeller performance for small unmanned aerial vehicles (UAVs), a car-top test module has been developed. This device allows for characterization of propeller and motor combinations in mean flow without the investment that is inherent with wind tunnel testing. Additionally, propulsion systems can be tested for reliability in real-world environments without risk to an airframe. Measurements of the propeller efficiency, thrust coefficient, power coefficient, and temperature of the motor and the electronic speed controller as initial parameters of interest are reported. Thrust at different advance ratios is compared to data from wind tunnel testing in order to gauge the accuracy of this technique. The module performed well in its intended role, and it is recommended that similar devices be used for time-critical or low-cost applications. DOI: 10.1061/(ASCE)AS.1943-5525.0000425.

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Introduction

A team at Washington State University (WSU), developing an unmanned aerial vehicle with a hydrogen power system, has addressed the need to test propulsion configurations without access to a wind tunnel. The constructed test module mounts on the top of a car and utilizes the vehicle’s forward velocity to simulate a flight environment. The module developed for this task, called the propulsive unloading performance indicator (PUPi), is designed to quantify the performance of propeller-motor combinations intended to drive the Genii unmanned aerial vehicle (UAV; Chaney et al. 2013). This requires measurements of thrust, torque, rotational frequency, voltage, and current draw. A pitot tube is utilized to log incident airspeed. The temperature of motor and electronic speed control (ESC) under simulated flight conditions is also recorded.

Car-top testing of small or scaled aircraft and propulsion systems has precedent in academia. For example, Tigner et al. (1998) used a semiconstrained car mounting to determine stability derivatives of a small research aircraft and to tune the aircraft controller. The car-top testing technique was also used with good effect by Lundström (2012) to quantify the performance of low-Reynolds-number propellers for micro-UAVs; however, no temperature data of equipment were obtained. Wind tunnel tests of propellers suitable for small UAVs are well documented in the literature. Brandt and Selig (2011) and Merchant (2004) document information on the thrust coefficient, power coefficient, and efficiency of low-Reynolds-number propellers, but for operation below the intended power level and with smaller propellers than desired for application with the Genii UAV (Chaney et al. 2013). Similar wind tunnel tests were performed by Ol et al. (2008) and were compared to a hybrid propeller performance algorithm.

The cost of renting a university wind tunnel is roughly $500/h, without additional charges for setup or rental equipment. Scheduling concerns can cause delays or restrict the number of tests that can be performed. If research teams are willing to tolerate higher experimental uncertainty than a wind tunnel and require only relatively low-speed data (i.e., below ~30 m/s), car-rooftop testing of models becomes an attractive alternative. In addition to conventional propeller testing, modules such as PUPi could be configured to test the drag performance of aerodynamic bodies in addition to more unique tests, such as asymmetric blade effect, fuselage-propeller influence, stopped or wind-milling propellers, and the effect of spinners.

Test Setup

The PUPi system measures thrust and torque by means of a motor affixed to a rotatable shaft mounted on a translating gantry. The motor is mounted collinear to the shaft by means of an aluminum bracket. Radial bearings are used to affix the shaft to the gantry, and a linear ball-bearing slide is used to allow smooth translation of the gantry assembly. The arm of the gantry holds a counterweight that serves to balance the cantilevered motor, which otherwise would bind the linear slide. The entire unit is attached to a 0.56-m-tall steel frame that bolts to the roof rack of a car, placing the propeller out of the boundary layer. The mechanical configuration of PUPi is schematically shown in Fig. 1.
To measure thrust, the gantry is constrained longitudinally with an Omegadyne LC105-25 load cell (Omegadyne, Sunbury, Ohio). Torque is measured by attaching an Interface MB-25-170 load cell (Interface, Scottsdale, Arizona) to a 6.0-cm torque arm secured to the shaft with a set screw collar. The 0–30-mV signal from the load cells are amplified by a factor of 107.4 by two Texas Instruments INA-121P operational amplifier integrated circuits (Texas Instruments, Dallas, Texas). Vehicle airspeed is recorded using a United Sensor PBB-12-F-9-KL 717 pitot tube (United Sensor Corporation, Amherst, New Hampshire) and Ashcroft Xldp 1.5” differential water column (DWC) pressure transducer (Ashcroft, Stratford, Connecticut). The load cells and pressure transducer are logged onto a personal computer (PC) using a National Instruments (NI) cDAQ-9172 chassis with a National Instruments 9211 analog-to-digital converter module (National Instruments, Woburn, Massachusetts) and a custom-developed Labview program.

Motor rotational frequency is obtained by measuring the frequency of one of the three alternating current (ac) motor phases. One of the phases is tapped with an opto-isolator and the waveform read via the NI 9211 module. A low-pass filter algorithm is applied in Labview to remove the noise associated with the duty cycle switching present at partial-throttle conditions.

Temperatures are measured with type K thermocouples logged through the same chassis with a National Instruments 9215 thermocouple amplifier module. The thermocouple measuring motor temperature is secured on the outside of the motor can. The thermocouple measuring ESC temperature is secured to the base of the ESC’s heat sink with Kapton tape. The instrumentation configuration is given in Fig. 2.

The voltage and current of the propulsion system are also measured and recorded. Motor voltage is measured off a simple voltage divider using a National Instruments 6009 analog-to-digital converter because no more channels were available on the NI 9211. Motor current is measured by an ACS758LCB-100B hall-effect sensor, which also is tied to the NI 6009.

Independent variables for the current configuration are vehicle velocity, rotational frequency, and propeller/motor hardware selection. A basic feedback loop from the measurement of revolutions per minute (rpm) was implemented in Labview to hold the motor rotational frequency nearly constant for testing. For this purpose, a National Instruments 9401 digital in-out module was used to communicate with the motor’s electronic speed controller. This rpm hold system was useful for test-stand validation, but it may not be required for some tests. A simple remote control transmitter...
and receiver combination could be used instead if the reader does not need precise control of rpm.

Test Stand Validation

An assessment of the accuracy and precision of PUPI was performed. A series of tests were conducted to compare thrust data taken from the PUPI stand with thrust data for the same model propeller reported by Ananda (2014) using a wind tunnel. Their methodology is reported in Brandt and Selig (2011). The wind tunnel data is populated for relatively low power operation compared to the range for which PUPI was developed (150 W versus 2,000 W, respectively). As such, comparison with the data from Ananda (2014) represents a scenario with PUPI operating at the extreme low end of its useful measurement range.

A comparison of thrust coefficient for an advanced precision composites (APC) 19X12E propeller obtained with PUPI is plotted against data from Ananda (2014) in Fig. 3. Thrust coefficient, $C_t$, and advance ratio, $J$, are defined as follows:

$$C_t = \frac{T}{\rho n^2 D^4}$$

$$J = \frac{V}{nD}$$

(1)

where $V$ = airspeed, $n$ = rotational frequency in revolutions per second, $\rho$ = air density, $D$ = propeller diameter, and $T$ = thrust.

Data was collected at 3,000 rpm ± 10 by holding rotational frequency constant and parameterizing vehicle airspeed. Data was taken at 20 Hz and downsampled to six points from 2 to 22 m/s at 3-m/s intervals. Each point represents the average of several hundred samples. The error bars in Fig. 3 represent the standard deviation from the mean. Uncertainty in the reported values from Brandt and Selig (2011) and Ananda (2014) is not shown in the figure. However, due to the quality of their setup, it is assumed to be negligible compared to the experimental uncertainty in PUPI. The combined uncertainty due to load cell calibration drift, thermal effects, and hysteresis was determined to be ±0.14 N. These effects are small compared to the ±0.40 N uncertainty due to random noise. The combined uncertainty in the reported thrust for $C_t$ is ±0.42 N ± 0.003.

One source of error that is difficult to detect is oblique flow at the propeller location due to the influence of the vehicle. To observe if appreciable oblique flow is present, yarn tufts were affixed to a vertical post placed along the vehicle’s centerline. For velocities below 22.4 m/s (50 mph), appreciable obliqueness in flow was not observed. The camera and tuft inspection technique was unable to resolve the velocity vector with high accuracy, and it is assumed that some oblique flow due to the vehicle is present, but it is less than 5°. These effects, in addition to the drag of the gantry and the placement of test equipment in the propeller wake, are most likely the sources of error resulting in the deviation from wind tunnel tests.

Representative Data

The Genii UAV team has utilized PUPI to test its motor-propeller system to determine component temperatures and propeller performance with respect to advance ratio. Results of some tests are presented in Fig. 4 as an example of PUPI’s capabilities. The motor used during these tests was a Hacker A60-20 m brushless electric motor (Hacker Motor GmbH, Landshut, Germany) driven by a Castle Creations Phoenix Edge HV 80 electronic speed control.
Fig. 5. Nondimensional characteristics of the APC 26X15E propeller: (a) thrust coefficient; (b) power coefficient; (c) efficiency; maximum standard deviation in advance ratio is 0.048 [hollow squares in (c) denote high uncertainty]

(Castle Creations, Olathe, Kansas). Gforce 3S 5,000-mAh lithium polymer batteries with three packs in series and three parallel legs (9S 3P) were used. A long-duration test was performed to determine motor operating temperature, full-throttle thrust, thrust decay with battery discharge, and experimental random error. The motor was increased to full throttle, and the car advanced to 16 m/s. At 30 s, the car stopped to let faster traffic past. At 8 min, the batteries on the receiver controlling the ESC reached a critical level, and the motor began to surge as the signal became intermittent. The electric motor was shut down after 10 min, and the vehicle was parked.

Fig. 4(a) depicts the motor and ESC temperatures as a function of time. The motor and ESC started the test at an ambient temperature of 11°C and reached about 30°C and 18°C steady-state temperatures, respectively. The temperature rose at 10 min as the core of the motor and exterior began to equilibrate in the absence of forced convection. This suggests that in flight, the inside of the motor is a minimum of 6°C hotter than the outside of the can. The reduction seen at about 10.5 min was when the vehicle drove to a safe area to park.

Fig. 4(b) shows propeller thrust as a function of time. In static air, the thrust was about 65 N, and it decreased rapidly as the vehicle accelerated in the first minute. The thrust then decreased almost linearly as the batteries discharged. Thrust increased again at 8 min as the vehicle slowed down to find a safe parking spot. Fig. 4(c) shows the vehicle’s velocity with respect to time. Wind noise, as well as the driver’s ability to maintain constant velocity, caused fluctuations. The vehicle used for testing was not equipped with cruise control. The uncertainty in temperature due to the thermocouple was ±2.2°C, and the uncertainty in velocity due to the pressure transducer was ±0.5 m/s.

A characterization of an APC 26X15 propeller from 2,000 to 3,500 rpm was performed using PUPI to generate data useful for performance analysis of the Genii UAV. In addition to thrust coefficient $C_t$, the propeller’s power coefficient $C_p$, and efficiency $\eta$ were determined with respect to advance ratio, where

$$\eta = \frac{VT}{P}, \quad C_p = \frac{P}{\rho n^2 D^4}$$

and $P$ is the shaft power, determined here as the product of torque and angular frequency in radians per second. Data from these tests are presented in Fig. 5. Propeller performance was determined from rotational speed, thrust, and torque; therefore, the effect of motor and battery charge state is irrelevant.

To generate these data, the PUPI module was held at nearly constant rpm, while the vehicle parameterized velocity in 2.2 m/s increments. Each rpm trial was terminated when the propeller stopped producing thrust or when the speed limit of 24.6 m/s was reached. For clarity, only the 2000- and 3500-rpm trials are shown in Fig. 5. The average wind speed was approximately 3 m/s. Uncertainty in efficiency becomes large as thrust and torque significantly degrade with the advance ratio. The hollow squares for the 2,000-rpm trail efficiency are included to show the data trend but have standard deviations higher than 20%. Similar to the validation test data shown in Fig. 3, data taken at 20 Hz for different velocities are downsampled by averaging over velocities from 2 to 26 m/s in 4-m/s increments. The maximum standard deviation encountered in each trial is given in the figure as well. The maximum standard deviation encountered in the advance ratio was 0.048.

**Conclusions**

After performing initial tests with the PUPI module, it was determined to be a suitable indicator of propeller performance and component temperatures for the purpose of predicting the performance of the Genii UAV. The preliminary results from PUPI demonstrated that the propulsion system was functioning nominally and was suitable for flight. Future upgrades, such as streamlining the stand in the propeller wake and placing the apparatus further from the roof of the vehicle, can be made. A characterization of several UAV propellers is planned.

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Notation

The following symbols are used in this paper:

- $C_p$ = power coefficient;
- $C_t$ = thrust coefficient;
- $D$ = propeller diameter in meters;
- $J$ = advance ratio;
- $n$ = rotational frequency in revolutions per second;
- $P$ = propulsive power in watts;
- $T$ = thrust in newtons;
- $V$ = airspeed in meters per second;
- $\eta$ = propeller efficiency; and
- $\rho$ = air density in kg/m$^3$.

References


