Application of multi-axis force/torque sensor system for experimental study of small unmanned aerial vehicles propulsion systems – Preliminary results

V Serbezov\(^1\), H Panayotov\(^2\), M Todorov\(^1\), S Penchev\(^2\)

\(^1\) Technical University of Sofia, Department of Aeronautics, blvd. Kliment Ohridski 8, Sofia, 1000, Bulgaria
\(^2\) Technical University – Sofia, Plovdiv Branch, Department of Transport and Aviation Engineering, 4000 Plovdiv, Bulgaria

vserbezov@tu-sofia.bg

Abstract. The experimental evaluation of the performance of small propellers plays important role in the process of multicopter UAV design perfection. This paper presents a small UAV propeller test stand, based on a multi-axis Force/Torque sensor system. The system makes possible to measure the thrust, torque and the pitching moment or lateral force (when in oblique flow) of the tested propeller. The data processing of the experimental results is discussed. Results for static, axial flow and oblique flow conditions are presented. Some conclusions about the measurement methodology are drawn. The results verify that the test bench has good accuracy and is easy for operation.

1. Introduction

The small multirotor unmanned aerial vehicles (UAV) have already taken their place in the society and continue to spread, but they are still far from technological maturity. The propulsion system of such UAV uses small propellers that work at low Reynolds numbers and in very wide range of propeller angles of attack. This features makes the analytical and computational performance evaluation of such propellers quite challenging. For this reason the development of facilities and methodologies for experimental testing plays an important role in the further improvement of the propulsion systems of small UAV. Initial work in this direction was reported in 2011 by Brant and Selig [1], but it covered testing of small propellers only in axial flow. In 2017 efforts to explore UAV propeller characteristics at conditions close to real operation were undertaken in the Plovdiv branch of Technical University – Sofia by Panayotov and Penchev [2]. The test stand was designed with provision to test propellers in wind tunnel at 0 to 90 degrees angle of attack, but it was capable to measure only the thrust of the propeller, while the propeller power had to be estimated from the electric power of the motor. Meanwhile more experimental results by different researcher teams were published with the use of multi-axis force/torque transducers or measuring systems [3,4]. The use of multi-axis measurement systems allowed the measurement not only of the thrust and torque, but also of the pitching moment at nonzero angles of attack of the propeller.

The availability of a six-axis force/torque transducer system at the Department of Aeronautics at Technical University – Sofia made possible the upgrade of the test stand that was previously designed...
in the Plovdiv’s branch of the University. The aim of this paper is to describe the new stand and to present the initial test results at static, axial flow and oblique flow conditions.

2. Experimental Setup

The test bench uses ATI-AI Nano-25 six-axis force/torque transducer and WirelessFT data acquisition system (Fig. 1). The sensor mount was designed with the following provisions:

- The mount can be fixed to any table in order to perform propeller static testing, as shown on fig.1;
- The mount can be easily attached to the frame of the test bed used in the Technical University of Sofia, Plovdiv Branch (Fig.2):

- Sensor support tube can be rotated in its holders to allow testing the propeller at different angles of attack, when installed in the wind tunnel;
- The stand can be fitted with any brushless outrunner electric motor with M3 x 16/19 mm mounting holes;
- Tested propellers can be of diameter up to 254 mm (10”). In the particular case APC 10x4.7 propeller was tested (the same as in [2]).

A significant problem that emerged during first system tests was the thermal instability of the transducer, resulting in noticeable zero-load readings drift, caused by the heat coming from the electric motor and
conducted through the interconnection structure. The problem was largely eliminated by thermally isolating the transducer from the motor and placing the transducer under an aerodynamic fearing. Even though the thermal drift should be considered by the test methodology.

3. Experimental Results

3.1. Static Propeller Operation

For this experiment a stabilized power supply, with precise voltage and current measurement was used, allowing fine calculation of motor power. The propeller rotational speed was measured using an optical tachometer. For every measurement point the following parameters were calculated:

- The propeller power in Watts:
  \[ P_{prop} = T_z \frac{2\pi n}{60} \]  
  where \( T_z \) [N.m] is the torque measured by the transducer along axis OZ, \( n \) is the rotational speed in 1/min;

- The electric motor power in Watts:
  \[ P_e = U \cdot I \]  
  where \( U \) [V] and \( I \) [A] are the supply voltage and current, measured in the power supply unit;

- The electric motor efficiency (including the efficiency of the electronic speed controller):
  \[ \eta_e = \frac{P_{prop}}{P_e} \]

The results for propeller thrust are shown on fig.3 and for propeller power on fig.4. The results for the electric efficiency are presented in table1.

![Figure 3. Propeller Static Thrust.](image1)

![Figure 4. Propeller and electric motor power.](image2)

| Propeller rotational speed, [min\(^{-1}\)] | 2174 | 2883 | 2930 | 3789 | 4331 | 4730 | 4840 | 4959 |
|-------------------------------------------|------|------|------|------|------|------|------|------|
| Electric efficiency                       | 0.4006 | 0.5068 | 0.5058 | 0.5898 | 0.6160 | 0.6374 | 0.6291 | 0.6259 |
3.2. Axial Flow Conditions

The experiment was conducted in the ULAK-1 wind tunnel at Technical University – Sofia, Branch Plovdiv. The tests were at airspeeds of 5, 10 and 15 m/s. The propeller rotational speed was varied between 2000 and 8000 min\(^{-1}\). The airspeed and rotational speed were measured with the equipment described in [2]. The obtained data was processed to be expressed in dimensionless form:

\[ J = \frac{V}{nD}, \]  
(4)

where \( J \) is the propeller advance ratio; \( D, [\text{m}] \) is the diameter of the propeller; \( V, [\text{m/s}] \) is the speed of the airflow; \( n, [\text{s}^{-1}] \) is the rotational speed of the propeller;

\[ C_p = \frac{\pi T_z}{30 \rho n^2 D^3}, \]  
(5)

where \( C_p \) is the propeller power coefficient; \( D, [\text{m}] \) is the diameter of the propeller; \( \rho, [\text{kg/m}^3] \) is the measured air density;

\[ C_T = \frac{F_z}{\rho n^2 D^4}, \]  
(6)

where \( C_T \) is the propeller thrust coefficient;

Finally the propeller efficiency \( \eta_p \) is calculated:

\[ \eta_p = J \frac{C_T}{C_p}, \]  
(7)

The results are shown on fig.5 for the thrust, fig.6 for the power and fig.7 for the efficiency coefficients. Although some of the data points at low rotational speeds are outliers, the obtained data is sufficient for evaluating the propeller performance parameters and to apply polynomial fit to it. The propeller efficiency is calculated, based on the fitted curves for the \( C_T \) and \( C_p \). The results show good resemblance with the theory. Further refinement of the test accuracy can be expected with the improvement of the test methodology.

![Figure 5. APC 10x4.7 Propeller Thrust Coefficient.](image-url)
3.3. Oblique Flow Conditions

The test conditions are the same as in axial flow experiment, except the support tube of the sensor is rotated at a given positive angle along axis OX (see fig.1). The main objective of the experiment is to test the ability of the sensor to measure the lateral force, generated by the propeller when operating in oblique flow. The lateral force is measured by the Fy channel of the sensor (giving negative reading for upwards oriented force vector).

For commonality reasons the results are expressed in dimensionless form, by defining propeller lateral force coefficient $C_{lat}$ in analogy with the propeller thrust coefficient:
The $C_{lat}$ results for 25 degrees angle of attack of the propeller, airflow speed of 5, 10, 15 m/s and rotational speeds between 2900 and 7800 rpm are shown on fig. 8. The results show near-linear relation of the lateral force coefficient and the propeller advance ratio. The results are encouraging for the further exploration of the small propeller performance in oblique flow at different angles of attack.

$$C_{lat} = \frac{F_y}{\rho n^2 D^4}, \quad (8)$$

3.4. Rotational Speed Measurement by Vibrations Frequency Analysis
The ability of the WirelessFT system to collect data at high sample rates allows the rotational speed calculation to be performed by analyzing the frequency spectrum of the radial vibrations, caused by the propeller unbalance. The vibrations are sensed by the Fy channel of the transducer (see fig. 1). The analysis is performed using fast Fourier transformation (FFT) in Matlab. As far as the experiments were performed with sample rate of 100 Hz, the analyzed spectrum was limited to $0 – 50$ Hz, corresponding to rotational speeds of $0 – 3000$ min$^{-1}$. Tests were performed with several fragments of the Fy record. The presented example is taken from the oblique flow tests of the propeller at angle of attack of 25 degrees, airflow speed of 5 m/s and recorded rounded rpm of 2900 min$^{-1}$ (fig 9). In this case it is apparent that the propeller vibrations are combined with oscillations aliquot to the sensor support structure natural frequency.

The results of performing FFT and the calculation of the single-sided amplitude spectrum in Matlab are shown on fig. 10. The peak at 49.38 Hz is clearly distinguishable, corresponding to the rotational speed of 2963 min$^{-1}$.

The performed tests show the ability of the multi-axis force/torque transducer to be used for rotational speed measurement. The advantage of this method is the reduction of the number of the sensors in the system. More experiments at higher sensor sampling rates should be conducted to verify the method for the whole rotational speed range of the tested propeller.

4. Conclusions
The preliminary results obtained by the small propeller test bench, based on six-axis force/torque sensor confirm its good accuracy and applicability for applied research purposes. The experiments included cases of propeller static, axial flow and oblique flow operation. In combination with electric measurement equipment the test bench can be used for performance evaluation of the whole UAV propulsion system including the electric motor and power transmission. The possibility of determining
the propeller rotational speed by analysing its vibrational frequencies, collected by the force/torque sensor is also examined and confirmed.

![Figure 9. Signal recorded by the Fy channel of the transducer.](image1)

![Figure 10. Single-Sided Amplitude Spectrum of Fy(t). Amplitude maximum at 49.38 Hz.](image2)

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