Aerodynamic testing of rotors and propellers for small unmanned aerial vehicles at Technical University - Sofia

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Abstract. The recent massive introduction of small unmanned aerial vehicles (UAVs) brought the problem of absence of reliable aerodynamic data and models for propulsion systems that work at low Reynolds numbers. At the same time the new capabilities of modern measuring equipment permit detailed experimental investigations of the aerodynamic characteristics of such systems. This paper presents the results of work in this direction, carried out at, or with serious contribution of the Department of Aeronautics at Technical University of Sofia. Two test benches are presented. The first one is for static testing of small helicopter rotors. It is designed also with provisions for installation in suitable wind tunnels. The second one is a test stand for evaluation of electric power plants for unmanned aircraft vehicles. It can be used statically, or may be installed on the roof of an automobile for mobile testing. As an illustration experimental results are given for a specific model helicopter rotor and a small airplane propeller.

1. Introduction
Unmanned aerial vehicles (UAVs) find ever more applications for both military operations and civilian use in the sphere of observation or in the entertainment and cinema industry. Recent technological advances in the area of propulsion, guidance systems, and microelectronics have made possible commercially applicable small UAVs.

Nowadays, various theories are used to investigate the aerodynamic characteristics of rotors and propellers of UAVs [1]. These are the blade element theory (BET) (classical theory, which can be combined with Glauert theory), vortex methods [2] (the lifting line method and the lifting surface method), and computational fluid dynamics (CFD) methods [3], based on the numerical solution of the Euler/Navier-Stokes equations.

Blade element theory (BET) and vortex methods are fast and adaptive for small angles of attack. The airflow through rotors and propellers is complicated as there are relatively high angles of attack, causing disturbances in the flow-field downstream of the rotor. These methods have low or medium accuracy on the near-flow solution. However, their main advantage is the low-computational power requirements. CFD methods have good accuracy of the solution but they are computationally expensive. Moreover, they are affected by the mesh type and the right choice of turbulent model. Additionally, modeling is complicated by the fact that the small scale rotors and propellers operate at low-Reynolds conditions. Therefore, numerical models need to be validated by experimental data.
In this paper two test benches for the study of the aerodynamic characteristics of rotors and propellers for UAVs are described. The two test benches demonstrate different approaches to the design and construction of such equipment. The first one – for small helicopter rotors, which is designed and produced in the Department of Aeronautics at Technical University of Sofia [4], is made for academic research purposes. The second one – for small propellers, is constructed by researchers from the same department in the interest of Dronamics Ltd. quarter scale prototype program [5]. Specific experimental results from the both stands are also given.

2. Test Benches Description

2.1. Test Bench for Small Helicopter Rotors

The test bench is shown in Fig. 1. The following measuring devices are used:

- Torque transducer HBM T20WN with nominal (rated) torque of 1Nm, accuracy class 0.2 and output voltage ±10V,
- Force transducer HBM S2M with nominal (rated) force of 10N, accuracy class: 0.02 and output voltage of 2mV/V.

![Figure 1. Test Bench for Small Helicopter Rotors.](image-url)
measurement of the rotational speed. The motor is driven with Maxon ESCON 50/5 servo controller, which allows for precise regulation of the rotational speed.

In order for the pitch angle of the blades to vary, a spindle-driven mechanism is used. It is powered with the combination of Maxon GP22S spindle with gear ratio of 1:370 and the EC-22 electric motor with nominal (rated) power of 40W.

The pitch angle may be varied during rotation of the model rotor. Thus, unsteady transient operation can be studied, in order to evaluate their impact on the aerodynamic characteristics of the rotor. The spindle-driven mechanism is capable to achieve rates of change of the pitch angle of ±2.2 deg/s.

Both electric motors can be controlled automatically according to a pre-programmed test schedule. Thus, multiple operational regimes can be evaluated in one test session without the need to constantly stop, re-program and re-start of the test stand. An automatic data acquisition system is organized, which stores the experimental data in a well-structured database.

The data acquisition from the force and torque transducers is ensured by the HBM PMX measuring amplifier system. The test bench is powered by a DC power supply HY3005D2, which provides up to 300W. The test bench provides the possibility to measure the produced thrust T, [N], the torque Q, [Nm] and the angular velocity Ω, [rad/s] of model rotors with diameters of up to 1 meter and pitch angles varying from −12° to +24°.

2.2. Test Bench for Small Propellers

The brief description of the test bench and its test results was initially published in [5]. In the present paper some additional details of the measurement and control system of the stand and some
conclusions from its operation are given. The system schematic and a picture of the stand, mounted on
the roof of a passenger car are shown on Fig. 2.

The main objective of the stand was to test the propulsion system of the Dronamics small prototype
within a short period and with limited budget. The following requirements were put:

- Measure propellers with thrust up to 100 N and diameter up to 800 mm;
- To be capable of testing propellers in forward motion;
- To use "amateur robotics" hardware and sensors.

It was decided that the objective can be achieved by a mobile test stand, with a provision for
mounting on the roof of a passenger car to perform the testing at airfields that are not in use. For this
reason the stand was designed with provisions for easy assembly / disassembly and transportation.

Most critical for the small propeller bench are the thrust and the motor rotational speed
measurements. To measure the thrust with standard strain gauges, a relatively long and thin thrust
beam has to be used. After a number of experiments, a standard I-beam is selected. More detailed
information on the thrust beam can be found in [5]. The drawback of this solution is that it is
susceptible to vibrations caused by the propeller. For this reason an additional stabilizing mast that
limits the lateral vibrations of the motor mount by two side plates is installed.

For the propeller speed measurement it was judged most practicable to use latch hall sensor, placed
over the rotating case of the 'outrunner' permanent-magnet brushless motor. The signal of the sensor is
led to an interrupt digital input of the Arduino board. As far as the U11 motor has 14 poles on its case,
leading to 933 impulses per second at 4000 min-1, the signal rate turns to be challenging for the
Arduino Uno board, resulting in inaccurate rpm reading. The problem is overcome by code
optimization and restrain from any unnecessary mathematical operations in the Arduino code.

3. Experimental Results

3.1. Small Helicopter Rotor

The object of study is a hingeless rotor with inner diameter of 0.162 m and an outer diameter of
0.532 m. It has two blades which are rectangular and untwisted with a chord length of 0.025 m, as it is
shown in Fig. 3.

The blade profile is Goettingen 417. The measurement methodology is as follows:

- The rotor torque, \( Q_{hub} \), [Nm] is measured without blades to evaluate the internal friction losses
  in the bearings of the main shaft and the air friction, created by the rotor hub. This
  measurement is important as this torque later subtracted from the measured torque, \( Q_m \), [Nm],
  to derive the actual torque of the rotor without overvaluation.
- At the same time the thrust, \( T \), [N] is measured.

The torque and thrust are used to define the Figure of Merit. The Figure of Merit is introduced as
a non-dimensional measure of helicopter thrust rotor efficiency, providing a common basis for
comparison between rotors with different geometries. The following equations are used:

\[
P = Q \Omega
\]

\[
C_p = \frac{(Q_m - Q_{hub}) \Omega}{\rho A \Omega^2 R^3} = \frac{P}{\rho AV_{tip}^3},
\]

\[
C_f = \frac{T}{\rho A \Omega^2 R^3} = \frac{T}{\rho AV_{tip}^2},
\]

\[
FM = \frac{C_f^{\frac{3}{2}}}{\sqrt{2} C_p}
\]
where \( \rho = 1.225, \text{[kg/m}^3\text{]} \) is the air density; \( A = \pi R^2, \text{[m}^2\text{]} \) is the area of the rotor; \( \Omega, \text{[rad/s]} \) is the angular speed of rotation; \( R, \text{[m]} \) is the radius of the rotor; \( V_{tip} = \Omega R, \text{[m/s]} \) is the tip speed of the blades; \( P, \text{[W]} \) is the power consumption due to profile drag.

Furthermore, to ensure comparability between the results for helicopter rotors with different number of blades and thus with different rotor solidity, the following dimensionless parameter is used: 
\[
C_T/\sigma - \text{blade loading coefficient. The rotor solidity } \sigma \text{ represents the ratio between the combined surface area of all blades and the total surface area omitted by each blade for one complete revolution of the rotor: } \sigma = \frac{N_b c R}{\pi R^2} = 0.05983, \text{ where } N_b, \text{[-]} \text{ is the number of blades and } c, \text{[m]} \text{ is the chord length of the rotor blades.}
\]
3.2. Test Bench for Small Propeller

The object of study is the Menz-E 26x20 propeller, installed on T-Motor U11 KV90 electric motor. The main test results are published in [5]. Due to the schedule restrictions imposed by Dronamics small prototype program, only one round of airfield test runs was conducted. Every test run was carried out at approximately fixed car speed of 10, 15, 20 m/s and gradual increase of the motor power setting in steps of 20 - 30 s duration.

Although accompanied by technical glitches the testing was successful in general. The rotational speed data is partially corrupted at high speeds due to high vibrations. The dispersion of the thrust and the electric parameters is also significant. For this reason the experimental data had to be heavily processed. In this paper the focus is put on the processing of the test data, complementing the initial result, published in [5]. The data processing generally follows the principles stated in [6].

The applied in Matlab data processing procedure is as follows:

- Merging of the data from Arduino DAQ, the airspeed from Pitot tube anemometer and the GPS speed from Garmin GPSMAP 60CSx handheld system.
- Smoothing of the Thrust, Input current and Voltage data by moving average filter.
- Calculation of the rotational speed rate of change.
- Calculation for every time point of the propeller advance ratio (eq. 5)

\[ J = \frac{V}{n.D}, \]  
(5)
where \( D, [\text{m}] \) is the diameter of the propeller; \( V, [\text{m/s}] \) is the forward speed; \( n, [\text{s}^{-1}] \) is the rotational speed of the propeller.

- Calculation for every time point of the propeller thrust coefficient (eq. 6)

\[
C_T = \frac{F_N}{\rho n^2 D^4},
\]  

(6)

where \( \rho, [\text{kg/m}^3] \) is the measured air density; \( F_N, [\text{N}] \) is the measured thrust of the propeller.

- Creation of set of valid data points (Fig. 7.), by exclusion of data points with:
  a) Forward speed below 5 m/s;
  b) Propeller rotational speed below 1500 min-1;
  c) Thrust above 100 N - eliminates faulty thrust readings;
  d) Excessive rate of change of the rotational speed (dRPM) - eliminates RPM sensor faulty readings;

- Curve fitting with second power polynomial of the thrust coefficient in relation with the propeller advance ratio (Fig. 8.).

The limit of the rate of change of the propeller speed was varied in order to test the sensitivity of the curve fitting. The final results are presented in Table 1. The results show good stability to input data variations, which verifies the applied data processing procedure and the validity of the experiment, despite the corruption of part of the data.

**Table 1.** Curve fitting results for data sets with different margin of dRPM.

| dRPM, [s-2] | Polynomial coefficients | Rsquare | RMSE  |
|-------------|------------------------|---------|-------|
| 1.6(6)      | -0.07172; -0.07930; 0.13849 | 0.8990  | 0.0072 |
| 0.6(6)      | -0.07359; -0.07736; 0.13825  | 0.9022  | 0.0070 |
4. Conclusions

The presented test benches show the broad range of solutions that can be used for solving theoretical and practical research problems in the field of UAV propulsion. The first test bench is build at a higher technological level. It uses professional sensors and DAQ equipment, and offers high precision test results, but is somehow restricted in terms of object of study. The second test bench shows the broad capabilities of the low-cost amateur systems and open-air field testing at the price of much more inaccurate experimental data and need for heavy post-processing. If wisely used both approaches can successfully complement each other.

Currently the researchers at the Department of Aeronautics of Technical University of Sofia and Arts et Metiers ParisTech continue their efforts towards improving and enhancing both concepts.

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