Development of small propeller test bench system

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Abstract. A set of performance analysis was performed on Master Airscrew 10X7 Electric propeller. The airfoil geometry was extracted by cutting and scanning a number of blade cross-sections. Experimentally, the test was performed at Institut Teknologi Bandung using 40 cm x 40 cm rectangular test section wind tunnel. The experimental rig was built using 3 load cells designed to measure thrust and torque. For data comparison, theoretical and numerical analysis were also done using Momentum-Blade Element method and Computational Fluid Dynamics. Compared with the previous study, the experimental data shows good agreement with most of the reference data. The theoretical data overestimated the thrust value by around 20\% and underestimated the torque value by 30\% at max, but the performance curve follows the similar trend with the experimental data. Both the thrust and torque value of the numerical data shows better agreement when fitted to experimental data by around 10\%. While it may need more propeller samples analyzed to draw general conclusion, the three methods performed in this research showed analogous results and could be used for a particular stage of research depending on the level of accuracy needed.

1. Introduction
Drone usage have been significantly risen in the past few years. For small-scaled drones, propellers are popular not only for its abundance, but also its cheap price while fulfilling their function [1-2]. However, the performance charts for the smaller propellers are not usually provided, leading to trial-and-error in the propeller matching stage [3]. Brandt [1] performed a test for 79 small commercial propellers ranging from 9 to 11\" while varying the RPM and wind tunnel speed to sweep over a range of advance ratios to obtain thrust and power coefficients. In this paper, an attempt was made to build a small propeller test bench that fits into wind tunnel in Institut Teknologi Bandung with a test section of 40 x 40 cm cross-section. The test bench were designed to measure thrust and torque of the propeller, while the user able to freely adjust the RPM. To ensure the results were valid, a method for calibrating the thrust and torque was developed and the test bench was used to measure a 10x7\" Master Propeller Electric Propeller. The measured thrust and torque was compared with the experimental result performed by Brandt. To examine the degree of validity of theoretical and numerical method, reverse-larrabee method and Computational Fluid Dynamics model were also compared to the experimental results [4-6].

2. Test bench design
The test bench was built equipped by 3 main sensors to measure thrust, torque, and RPM. In Brandt’s experiment, the test bench was built using an external load cell (max 10 lbs ~ 4.535 kg) to measure thrust. The torque was measured by a reaction torque transducer behind the propeller motor engine. A photoreflector was used to measure shaft RPM. Considering the configuration of existing wind tunnel in ITB and the cost needed to build the test bench, some types of sensor were picked for comparison.
2.1. Sensor choice

In this research, the measurement methods take into consideration were three types for thrust, three types for torque and two types for RPM.

2.1.1. Thrust measurement method. To measure thrust, the three methods considered were force balance, beam deflection, and pressure difference. Using force balance method, there were two options: internal force balance and external force balance. However, both methods have their own problems. For internal force balance, the configuration of strain gage and the complexity of development made this method costly. External force balance takes more space outside the test section it may not be suitable if the room for experiment is too cramped.

The beam deflection method utilizes beam deflection as a means of measuring thrust. Nowadays it is pretty common to use load cell strain gage to measure forces in general, usually in one direction. Due to how common the usage of load cell, it is pretty cheap and gives reasonable result within its load range provided the proper calibration.

Measuring propeller thrust using pressure difference method is measuring momentum difference in practice. The pressure behind the propeller is measured using pitot tube or five-hole probe for more accuracy. The pressure in front of the propeller is measured by the pitot tube used for wind tunnel flow velocity measurement. The thrust produced by the propeller is calculated by integrating the pressure difference with the propeller area. Although the method looks promising in theory, the flow fluctuates behind the propeller, making the pressure reading a bit more difficult without proper data logging.

Considering the three options above, the load cell strain gage was chosen due to the common usage and accuracy.

2.1.2. Torque measurement method. The torque measurement methods considered were brake dynamometer, angle deflection and motor power measurement. Using brake dynamometer, a rotating propeller will stop accelerating rotationally given enough torque to counter it. The torque is generated by putting a brake to a disc connected to the propeller in one shaft. The force, multiplied by its radius from the shaft, will produce torque that is adjusted by the brake power. As the external force balance method, the space needed for this method is a bit much especially inside the test section. It also needs active iteration to counter the torque that makes it a bother when not automated.

If a shaft is subjected to torque, it will be twisted. The twist distance/angle may be calculated and correlated to torque with proper calibration. The reaction torque transducer used by Brandt was also made using this principle, however the torque is measured by the strain gage deflection. Knowing the torque is multiplication of force and reference length, the angle deflection could be represented by load cell deflection at a certain range.

Power is multiplication of torque and angular velocity. That means we can measure torque indirectly by measuring the motor power, that is done by multiplying the electrical current and the voltage. However, the motor itself transmit the power to the propeller imperfectly, meaning there will be some energy losses by the motor itself. If the motor efficiency along its working range is known, this method will be viable.

The torque transducer would be a better choice if not for its expensive cost. In this research, the torque generated by propeller was measured by two load cells that measure the force at a certain range from the propeller itself. The brake dynamometer would use too much space, and measuring the motor power needs the motor efficiency data.

2.1.3. RPM measurement method. The RPM can be measured using photoreflector or by measuring the motor frequency. Photoreflector reflects light generated by a source and gives the RPM count by the frequency it is reflected. By measuring motor frequency, 2 of 3 cable phase is used to measure the “offline” frequency, but it will need to be calibrated due to motor and propeller frequency difference. Due to compatibility with microcontroller, RPM was measured by the motor frequency.

2.2. Propeller test bench design result

The test bench was made using three 3 kg capacity single-point bending load cell to measure thrust and torque. The RPM was measured by brushless RPM sensor. To connect the data to the computer, Arduino
Nano is used as Analog-Digital Converter [7]. The components used are shown in Table 1 and Figure 1. The design result of the test bench is shown in Figure 2. For calibration, the mode with the load cell force directions and reference length is shown in Figure 3. In this case, \( a = 3.5 \text{ cm} \) and \( l = 9 \text{ cm} \).

**Table 1.** Components used for propeller test bench.

| No | Components                                      | Amount |
|----|-------------------------------------------------|--------|
| 1  | RCX 2836-9 880KV Outrunner Brushless Motor     | 1      |
| 2  | Load Cell 3kg                                   | 3      |
| 3  | Load Cell Driver                                | 3      |
| 4  | Electric Speed Control                          | 1      |
| 5  | Brushless RPM Sensor                            | 1      |
| 6  | Servo motor                                     | 1      |
| 7  | Power Supply                                    | 1      |
| 8  | Breadboard                                      | 1      |

**Figure 1.** Components used for propeller test bench.

**Figure 2.** Propeller Test Bench
3. Test bench calibration and results

The test bench was calibrated using applied known loads [6-8]. Originally, the load cell L2 was the only one supposed to show numbers when thrust is applied to the test bench. Likewise, the load cell L1 and L3 was supposed to be the only ones measuring the force that causes torque load. However, that is not the case as there will be some interference among the sensors or manufacturing errors. All load cells gave their readings when the test bench was subjected to either thrust or torque. Calibration was done to convert the readings into proper thrust and torque value. For thrust calibration, the loads applied are 0, 154, 254, 354, 454, 554 and 654 grams. For torque calibration, the loads applied are 0, 52, 115, 165 and 197 grams, equivalent to 0, 468, 1035, 1485 and 1773 g.cm. The calibration was done upscale and downscale 5 times.

3.1. Calibration results

For thrust calibration, L2 showed the most reading as intended. L1 and L3 gave very small reading like it was caused by interference only. For torque calibration, L2 gives the smallest reading, but L1 and L3 showed different scale of reading although both was intended to read torque force. Figure 4 shows the raw calibration result, and the fit from 5 times calibration is shown in Figure 5.

To convert raw readings to proper thrust and torque, the calibration factor matrix needed to be formed. The basic idea was to apply force and moment balance equation:

\[ \sum F = 0 \quad (1) \]
\[ \sum M = 0 \quad (2) \]

For thrust calibration fit, the factor used (A) is used as shown in equation (3):

\[ A_1(L_1 + L_3) + A_2L_2 = T \text{ (gram)} \quad (3) \]

The factor A1 was used on both L1 and L3 due to their interference behavior on thrust measurement. For torque calibration fit, the factor (B) used on L1 and L3 were different because of the difference in calibration readings due to the difference in reference length from the applied load to the respective load cell. The length factor (K) used is defined as:

\[ K = \frac{l-a}{l+a} = \frac{9-3.5}{9+3.5} = 0.44 \quad (4) \]

The basic equation used for torque is:

\[ B_1(KL_1 + L_3) + B_2L_2 = Q \text{ (g.cm)} \quad (5) \]

The calibration matrix can be defined as:

\[ \begin{bmatrix} B_1K & B_2 & B_3 \\ A_1 & A_2 & A_3 \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \end{bmatrix} = \begin{bmatrix} Q \\ T \end{bmatrix} \quad (6) \]

To calculate A and B, the outputs measured from the calibration fit was used. From thrust calibration fit:

\[ L_1 = -0.00289481, L_2 = 0.162146671, L_3 = -0.002067894, T = 154 \text{ gram} \quad (7) \]
Figure 4. Thrust reading (left) and Torque reading (right) from calibration

\[ A_1((-0.00289481) + (-0.002067894)) + A_2(0.162146671) = 154 \text{ gram} \]  
(8)

\[ B_1((0.44)(-0.00289481) + (-0.002067894)) + B_2(0.162146671) = 0 \text{ g.cm} \]  
(9)

From torque calibration fit:

\[ A_1((0.00578) + (0.061825)) + A_2(-0.00043) = 0 \text{ gram} \]  
(10)

\[ B_1((0.44)(0.00578) + (0.061825)) + B_2(-0.00043) = 468 \text{ g.cm} \]  
(11)

Completing equation (8) and (10) yields \(A_1 = 6.063\) and \(A_2 = 949.943\), while completing (9) and (11) yields \(B_1 = 7271.643\) and \(B_2 = 149.8582\). Put into matrix (6), the calibration matrix became:

\[
\begin{bmatrix}
3199.523 & 149.8582 & 7271.643 \\
6.063 & 949.943 & 6.063
\end{bmatrix}
\begin{bmatrix}
L_1 \\
L_2 \\
L_3
\end{bmatrix}
= \begin{bmatrix}
Q \\
T
\end{bmatrix}
\]  
(12)
3.2. Experimental results compared with theoretical and numerical results
The propeller Master Airscrew 10x7" Electric geometry was extracted to perform theoretical and numerical CFD analysis [4,7]. The theoretical analysis was done using Reverse-Larrabee method, which incorporates propeller momentum and blade element theory in nondimensional form. For the airfoil Cl and Cd data, the airfoil geometry from 75% radius was extracted and analyzed using CFD. For numerical CFD analysis, the model used was made to represent the experimental conditions as shown in Figure 6. The compared results of Brandt [1], this research experiment (Exp), theoretical (Teo) and numerical (CFD) method are shown in Figure 7.
Figure 7. Compared results of reference, experimental, theoretical and numerical method.

The experimental results (circle) mostly shows good agreement with the reference (full-line). The CFD method (dashed line) also shows good agreement with experimental results, but the difference in results gets larger as the RPM goes up. This may be caused by the single mesh configuration used in all RPM and tunnel flow velocity, while the mesh needs to be more dense as the Reynolds number goes up. The theoretical method mostly overestimates the thrust produced and underestimates the power generated by the propeller. This may be caused by the assumption used in momentum and blade-element theory, which ignores the presence of the hub.
4. Conclusion
The test bench experimental results shows good agreement with the reference. This means the test bench design and the calibration method is acceptable for further use. However, the test bench is still improvable in the means of the components quality. In theory, the better the quality of the components, the more precise (the more narrow the error bars) the measurement will be, but it will be much more costly. The CFD model is also acceptable and is usable to analyze propellers of the similar case, possibly representing closely of the experimental method. The theoretical Reverse-Larrabee method seems to be falling behind in terms of accuracy. This may be caused by the degree of assumptions used. A theoretical method using a more accurate assumption may represent better in this case.

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