Development Testing Method and Analysis Static Thrust for Propeller Based Propulsion

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Abstract. Propulsion system development involved aircraft manufacturer and engine or propeller manufacturer to perform test and evaluation. The main of this research was propulsion testing for unmanned aerial vehicle by evaluating thrust in static condition. Static thrust testing was conducted by force measurement using load cell and data acquisition systems. Thrust measurement result was compared with analytical method and computer fluid dynamic simulation. Analytical method in this paper used vortex blade element theory to calculated static thrust meanwhile Computational fluid dynamic was running both 2 dimension and 3 dimension simulation. Vortex blade element theory analysis combined with computational flight dynamic simulation for propeller aerofoil at 70% location. Test result compared with analytical and CFD calculation using non dimensional parameter. Analytical calculation deviated 5.08% from experiment meanwhile CFD calculation give 13.56% but still in error tolerances. Error tolerances considered from friction force, sensor accuracy and air density correction with total 6.33 kgf.

1. Introduction
Propulsion system is the main system to generate thrust and convert chemical or electric energy to mechanical energy. Mechanical energy is used to change air momentum and generate thrust. The principle on the change of momentum and thrust was explained by Newton law [1]. Aircraft propulsion divided into several classification based on operational and flight regime. Aircraft propulsion system divided into propeller based, air breathing and rocket [2]. Some aircraft propulsion system generate change of momentum in different way. The example is rocket propulsion that produce thrust using fuel and oxidizer reaction without burning reaction with air meanwhile air breathing propulsion using oxygen from air to burn fuel in combustion chamber.

The other way to generate thrust is using propeller. Propeller generated thrust by changing air momentum after passing propeller disk. Change of momentum from propeller as function of axial velocity before and after passing propeller. Propeller analysis explained by several theory such axial momentum theory, general momentum theory, blade element theory and vortex theory [1]. Momentum theory is classical theory for propeller analysis. Propeller is replaced by thin disk model and airflow around propeller described by stream tube with constant pressure at each section. In the other hand blade element theory model propeller from each cross section as airfoil. Each airfoil produced lift and drag and convert to torque and thrust using trigonometry principle. The integration of thrust and torque at each cross section was thrust and torque of the propeller.
The objective of this research was to develop static thrust calculation method and validate with test data. Test methodology used load cell and data acquisition system to record thrust and propeller revolution. Test execution was held at PT Dirgantara Indonesia facilities in Bandung.

2. Static Thrust Experiment

2.1. Static Thrust Measurement

Static thrust model is different from dynamic thrust or advanced thrust. Calculation model for static thrust estimation is function of rotational speed, meanwhile dynamic thrust is influenced by airspeed.

\[ Ts = 1.283 \times 10^{-12} RPM^2 D^4 \rho Kt \]  

Static thrust measurement was performed at Indonesian aerospace using load cell data acquisition system as illustrated in Figure 1. The aircraft was connected to load cell using wire or belt. Data acquisition system recorded thrust data from several throttle setting from idle to maximum rpm. Figures 1 showed test method and illustration for static thrust measurement.

![Figure 1. Test component and illustration static thrust measurement](image)

Test procedures and preparation for this measurement referred to test document released by Indonesian aerospace. Before engine start, aircraft position have to be located at ground level condition. Landing gear structure and belt that was connected to load cell have to be installed completely. Emergency panel switch for engine shutdown have to be installed for safety.

Test execution was held several times at Bandung and Pangandaran. Ground test mostly held in Bandung and flight test was perform in Pangandaran. Table below showed the example of test data was taken at April 2015, as on Table 1.

| Propeller Revolution (rpm) | Thrust (Kgf) |
|----------------------------|--------------|
| 2000                       | 1.7          |
| 3700                       | 11.8         |
| 5000                       | 22.1         |
| 5600                       | 28.3         |
| 6000                       | 33.6         |

Static thrust data from this measurement is corrected by friction from aircraft tire and ground. Friction force is calculated by pulled aircraft using dynamometer. Maximum force recorded before aircraft move from static condition was identified as rolling friction force.

Error analysis from static test is considered from instrument accuracy, friction forces and air density correction. Instrument accuracy is about 0.25 kilogram forces based on load cell specification. Friction force is about 4.5 kilogram forces and density correction is 1.58 kilogram forces. Total error is about 6.33 kilogram forces. Random error was not considered because of amount of data was limited. Some data at low rpm didn’t record during test. It influenced data quality and test result.
3. Propeller Modelling and Simulation

3.1. Propeller CAD Model

Propeller model for simulation reconstructed using reverse engineering method. Propeller model was created using mould and manual measurement in order to get propeller dimension and cross section profile. Propeller cross section generated by propeller model or propeller dummy made from polyurethane material as shown in figure 2-a below.

![Propeller model from polyurethane](image)
![Propeller CAD model](image)

(a) Propeller model from polyurethane  (b) Propeller CAD model

Figure 2a-b. Propeller model and CAD model

Propeller geometry such as pitch and chord are measured by calipers. 20 cross sections are selected to measured and created propeller geometry and generated CAD (Computer Aided Design) model. CAD model as shown in figures 2.a-b is reconstructed using commercial CAD software. For computational fluid dynamic simulation, CAD model would be modified in order to create mesh or topology. Some geometry simplification to create CAD model such as simplified and reduces number of section in CAD software.

3.2. Computational Fluid Dynamic Simulation

Propeller simulations both 2 dimension and 3 dimension are conducted using commercial CFD software. Two-dimension simulation purpose was to generate aerofoil characteristic data (Cl and Cd) and it used for analytical calculation [6]. Three-dimension simulation directly calculate static thrust in several rotation speed with setting engine form idle to maximum power (2000-6000 rpm).

![Mesh and domain](image)
![3D simulation](image)
![2 D simulation](image)

(a) Mesh and domain  (b) 3D simulation  (c) 2 D simulation

Figure 3. CFD analysis from 3D and 2D simulation result

2D simulation is calculated at airspeed 0.37 M and Reynolds number (Re) 500,000. This condition is based on propeller rotation at 4000 rpm and airfoil section at 70% from hub considered as average condition during test. 3D simulation performs at ISA and steady state with “opening” boundary condition. Meshing for this simulation used unstructured mesh with 2 fluid domain (rotary and stationary). Total mesh that used for rotary and stationary domain was about 1.6 millions. Rotary domain shaped cylindrical with diameter 1.2 of propeller and thickness 0.4 diameter of propeller [7]. Stationary domain diameter was 11 and thickness 7 times of propeller diameter. Stationary domain and rotary domain connected by “interface”. Rotary domain simulated using frozen rotor approximation with variation of 2000, 3000, 4000, 5000 and 6000 rpm.
3.3. Analytical Calculation Using Vortex Blade Element Method
Analytical calculation using vortex-blade element method is combination from blade element theory and momentum theory method [1]. Calculation process was iteration process using value of induced velocity and free stream velocity. Accuracy of this method determined by aerofoil characteristic. Aerofoil characteristic for this calculation was taken from CFD simulation at 70% from hub. Assumption from this calculation that aerofoil at 70% hub represented aerofoil characteristic of propeller. Even though this condition deviate from real condition but this approximation needed to simplified calculation. The result would be compared with experiment and CFD simulation.

3.4. Result and Discussion
The result of static thrust calculation are shown at Figure 3 and Table 2. Dot and blue line (experiment corrected) is experiment data after correction with friction and conversion to standard sea level [8]. The red line is CFD simulation and blue line is analytical calculation. As we can see, both simulation and analytical calculation showed the same tendency or trend with experiment result. The value from both calculation was in error range of experiment.

![Comparison Static Thrust at Standard ISA](image)

**Figure 4.** Comparison static thrust from analytic

Non dimensional comparison showed analytical calculation gave accuracy 5.08% meanwhile computational fluid dynamic simulation gave accuracy -13.56%. Static thrust calculation from CFD simulation was lower than analytic calculation and experiment. Even though this differences was in error range, thrust at low speed test data was not too close with experiment. If we see in figure 4, there was no thrust data between 2000-3500 rpm. Thrust data at low rpm should be added to validate static thrust calculation.

**Table 2.** Result and comparison static thrust non-dimensional parameter

| Calculation Method | Static Thrust Coefficient (Kt) | Deviation from Experiment (%) |
|--------------------|--------------------------------|-------------------------------|
| Experiment         | 0.59                           | 0                             |
| Analytic           | 0.62                           | 5.08                          |
| CFD                | 0.51                           | -13.56                        |
4. Conclusion
Static thrust determination using experiment, analytic and computer fluid dynamic simulation method could be used for aircraft development. The result from all method gave the same tendency and deviate in range of error margin. Error margin was 6.33 kgf, it was considered from instrument error, friction forces and atmosphere condition. Friction force measured using dynamometer by pulling aircraft and record maximum force before aircraft displace from initial position. Static thrust calculated from analytical calculation and CFD simulation and it could be compared with test data and gave deviation between 5.08-13.56 %. Analytical calculation using vortex blade element method was good enough to predict static thrust using aerodynamic data from aerofoil at 70% from hub.

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