International Journal of Aviation Science and Engineering
e-ISSN: 2715-6958 p-ISSN: 2721-5342

AVIA

Original Article

Load Cell Design for Measurement of Propeller Thrust

N A N Rosli [1], M A Wahid [1,*], N Othman [1], M Z Md Zain [2] and W K Wan Ali [1]

[1] Dept. of Aeronautic, Automotive and Ocean Engineering, School of Mechanical Engineering, Universiti Teknologi Malaysia, 81300, Johor, Malaysia.
[2] Dept. of Applied Mechanics and Design, School of Mechanical Engineering, Universiti Teknologi Malaysia, 81300, Johor, Malaysia.
* Correspondence: masturawahid@utm.my

Received: 5 February 2024; Accepted: 23 March 2024; Published: 10 June 2024

The design, analysis, and prototype testing of a load cell for measuring propeller thrust generated by propeller rotation in this study. Design concepts factors of safety, yield strength, stress, and strain values were evaluated using Solidworks simulation to ensure that the load cell would not fail. The force applied to the load cell is measured by four strain gauges connected in a Wheatstone bridge connection and amplified by HX711 amplifier. These instruments is then connected to Arduino and 16x2 LCD. A static testing was carried out to measure the thrust from an APC 6x4E propeller and compared with validated results to validate the accuracy of the load cell. The built-in load cell experimental results were compared to a commercialized load cell, manufacturer data and blade element momentum theory from other studies. A graph of thrust against propeller rotational speed was constructed. The rotational speed that starts to detect the thrust is about 2000RPM. The error between prototype load cell to the manufacturer, RC benchmark and BEMT is less than 1%, 0.05% and 0.05%, respectively.

Keywords: load cell; propeller thrust; rational speed; axil velocity; vibration

1. Introduction

Producing a high-quality thrust measurement is important to find the performance of aircraft propulsion, thruster or rocket. According to Hartono and Kasyofi (2019), the main system for generating thrust and convert chemical or electrical energy to mechanical energy is the propulsion system. Newton's law explained the concept of change of momentum and thrust [1]. Aircraft propulsion is classified into many classifications depending on the scheme of service and flight. The propulsion mechanism for aircraft is categorized into propeller based, air-breathing and rocket [2]. The other way of generating thrust is by the propeller. The air momentum is changed after passing through the propeller disk. Before and after passing the propeller, the change of propeller momentum is a function of axial velocity.

One type of jet propulsion is rocket propulsion. The ejection of propellant or stored matter propels a missile. The thrust force is this force created by the ejection of high-velocity matter. A thrust force is produced by the rocket engines as a function of time. It is necessary to consider the thrust performance of a rocket as a function of time in order to build a rocket that reaches the desired distance. Testing a rocket requires a good knowledge of techniques and procedures for instrumentation [3]. One of the essential parameters of rocket design is the time-thrust profile, which shows the ability of the rocket to generate thrust. This stage decides whether or not the desired thrust has been attained before the flight test is conducted. During ground testing, thrust analysis facilitates the direct contrast of different engine and fuel or propellant configurations.

In the application of UAS, the propulsion system uses propellers to generate thrust. To find the performance of the UAS, modelling the thrust is required to see whether the propeller can provide the best thrust to the UAS for different flight conditions. There are many commercially built load cells [6]; however, to measure specific load within the range of the flight mission, not many commercially build load cells can be used or if there is, the price is high. For aircraft or drone performance, thrust data varying with airspeed is required to know the power and thrust available. Unfortunately, the propeller thrust data given by the manufacturer are data for static conditions, and it is not enough for aircraft performance. For this reason, a load cell that can measure thrust for a specific load range should be fabricated. This research is to design and test a load cell specifically for measuring thrust ranging from 0.1N up to 15N generated by a propeller in a static condition. Once the load cell has been validated, this later can be used to further investigate thrust at varying airspeed.

2. Load Cell Design and Fabrication

The load cell design [6] will have three stages – design scope, concept structural analysis and finalisation of final design choice towards fabrication. Under design scope, the range of load, propeller type, material and force type is decided. Then three concepts will be established and will be evaluated for their structural performance. From the three concepts, the best concept is chosen, and the measurement instrumentation will be decided for the fabrication.

2.1. Design Scope

The designed load cell is expected to measure from 0.1N up to 15N thrust and the load applied is in bending. The SUNNYSKY X2216-5 kV: 2400II is the motor used for testing this propeller and will run from 0 to 8000 rpm. It will mainly drive a two or three blades propeller, but any number of blades can be fitted. If required, the balance would also be designed to fit various motors. The propeller chosen is 2-6×4E. The blade number of the propeller is two with a diameter of six inches and a pitch of four inches. 3 design concepts will be evaluated, and the best design concept will be fabricated and tested. The design of the load cell is drawn and analysed using Solidworks software. Aluminium 1060 – H12 Rod, the material [13] to be used for the load cell and the material properties for this load cell is written as below,

Modulus of elasticity, E: 69Gpa
Shear modulus: 26Gpa
Tensile strength: 85Mpa
Yield strength: 57Mpa
Poisson's ratio, v: 0.33
Thermal expansion coefficient: 2.4×10^{-5}/K
Thermal conductivity: 230 W/m.K

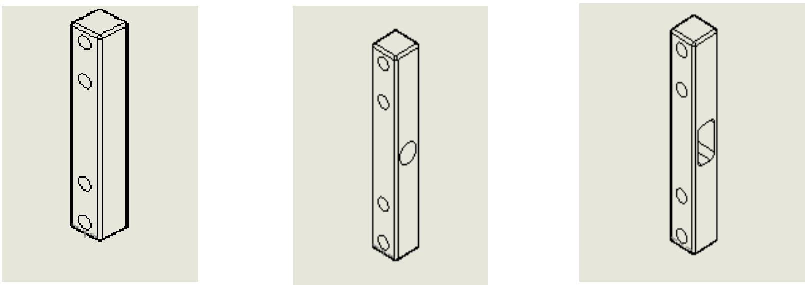
In this research, a digital tachometer is designed using infrared (IR) sensor [8] with Arduino to measure the rotational speed of the motor in RPM. For data display, Arduino and LCD are interfaced with IR sensor. Speed of any rotating object will be detected through IR sensor module that is made up of a single IR transmitter and receiver. Following are the components required to create a digital tachometer which are Arduino UNO board, 16x2 LCD, I2C module, IR sensor module containing transmitter and receiver, breadboard and connecting wires.

e-ISSN: 2715-6958 p-ISSN: 2721-5342

2.2. Design Concept Evaluation

Three design concepts of load cell are simulated in Solidwork and evaluated for final fabrication. By using analysis in the Solidworks, values of stresses, displacement and strains can straight away be obtained. To evaluate material failure requirements and behaviour, both stress and strain responses to applied loads on a system must be smaller than the allowable stress and strain of the material.

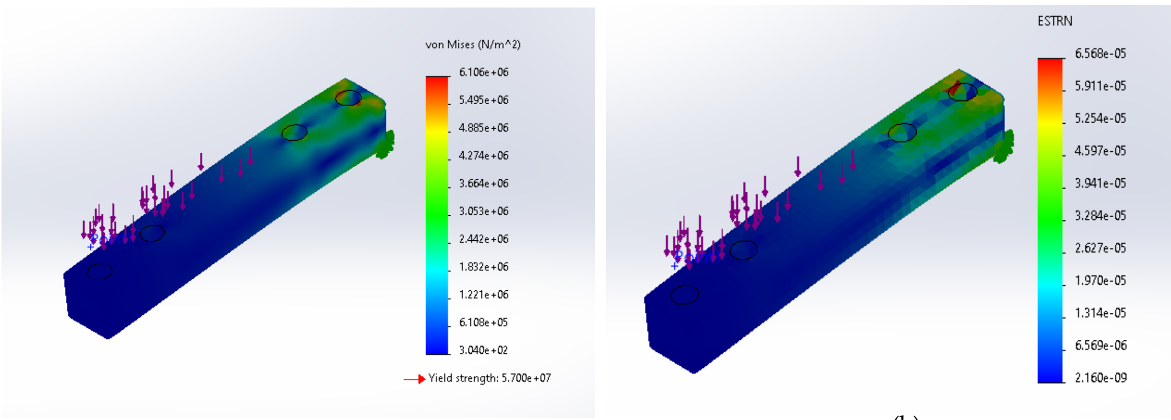
The boundary condition of the load cell during the analysis is that the side of the load cell that being attached to the platform will be fixed. Meanwhile, the point load will be applied at the side of the load cell that is attached to the propeller. The applied point load is 20N, which is the maximum load that will be applicable for the load cell. The first design of the load cell is a full solid body and without a hole in the centre. The second is with a circular hole, and the third design is with a rectangular hole as shown in figure 1.



(a) (b) (c)

Figure 1. (a) Concept 1 (no middle hole), (b) Concept 2 (circular hole), (c) Concept 3 (Rectangular hole)

Figure 2 below shows the stress and strain analysis for concept 1. The maximum Von Mises stress for this load cell design is $6.106 \times 10^{6}\ \ Pa$ which does not exceed the yield strength value $5.7 \times 10^{7}\ \ Pa$.



(a) (b)

Figure 2. (a) Von Misses Stress Value (b) Equivalent Strain Value.

The equivalent strain maximum occurs at the body part nearest to the part that is being fixed with 6.568×10^{-5} and minimum strain at the bottom part of the body where point load is applied 2.160×10^{-9}. By looking at figure 2, the body structure of the load cell will not yield since the value of maximum stress is smaller than the yield strength of the material. Table 1 below shows the results of all load cell designs based on the analysis of Solidworks simulation.

Table 1. Result analysis of load cell designs with applied load 20N

	Load Cell Design 1	**Load Cell Design 2**	**Load Cell Design 3**
Von-Mises Stress Maximum (Pa)	$6.106 \times 10^6 \ Pa$	$5.759 \times 10^6 \ Pa$	$6.141 \times 10^6 \ Pa$
Von-Mises Stress Minimum (Pa)	3.040×10^2	3.093×10^2	3.277×10^2
Equivalent Strain Maximum	6.568×10^{-5}	6.125×10^{-5}	6.840×10^{-5}
Equivalent Strain Minimum	2.160×10^{-9}	2.391×10^{-9}	3.282×10^{-9}

From the analysis, design 3 is chosen because when applying 20N load, the load cell body deformed and experienced more stress and strain compared to another two designs. Also, it can give better strain reading when applying a small load, as shown in Table 2 below. The load cell starts deformed at load 0.092N.

Table 2. Analysis of load cell design 3 deformation

Load (N)	Min displacement	Max displacement	Min strain	Max strain
0.1	1×10^{-30}	9.10×10^{-5}	1.03×10^{-11}	3.09×10^{-7}
0.5	1×10^{-30}	4.55×10^{-4}	5.12×10^{-11}	1.54×10^{-6}
1.0	1×10^{-30}	9.10×10^{-4}	1.02×10^{-10}	3.09×10^{-6}
1.5	1×10^{-30}	1.37×10^{-3}	1.54×10^{-10}	4.63×10^{-6}
2.0	1×10^{-30}	1.82×10^{-3}	2.05×10^{-10}	6.18×10^{-6}
5.0	1×10^{-30}	4.55×10^{-3}	5.12×10^{-10}	1.54×10^{-5}
10.0	1×10^{-30}	9.10×10^{-3}	1.02×10^{-9}	3.09×10^{-5}

2.3. Load Cell Fabrication and Instrumentation Setup

Aluminium alloy is a chosen material for built-in load cell, and the fabrication process is done using a lathe machine. A load cell body is installed with $120 \pm 0.5\Omega$ strain gauge in full-bridge connection. If a strain gauge is attached to a mechanical housing and the housing is subjected to stress or friction, such as weight, the gauge measures the relative compression or tension generated by that force.

Arduino act as a brain for the machine which receives source code from the software. ESC converts the DC voltage from the battery into a series of pulses applied to the motor wires in a certain order (phases) and to provide adequate power to the BLDC motor wires so that the motor turns in the proper direction [4]. This is accomplished by measuring the back EMF from each wire and powering the coil as the magnet passes through it. The potentiometer gives variable resistance, which gives reading in analogue value into Arduino board. IR sensor is used to sense the blade rotation in rpm value. Voltage and rotational speed values are displayed in the interface I2C LCD module [11] with Arduino. Figure 3 shows the circuit setup for the experiment testing. As can be seen from figure 3, the load cell is screwed to the test rig, and another end of the load cell body is attached with the brushless motor of kV rating 2400 is powered using 2S LiPo battery, 40A ESC and control using Arduino program. The number of revolutions of the revolving propeller in RPM is measured using a digital tachometer built with an IR sensor [11] and Arduino and for the display, simply connected IR sensor module to an Arduino and 16x2 LCD module.

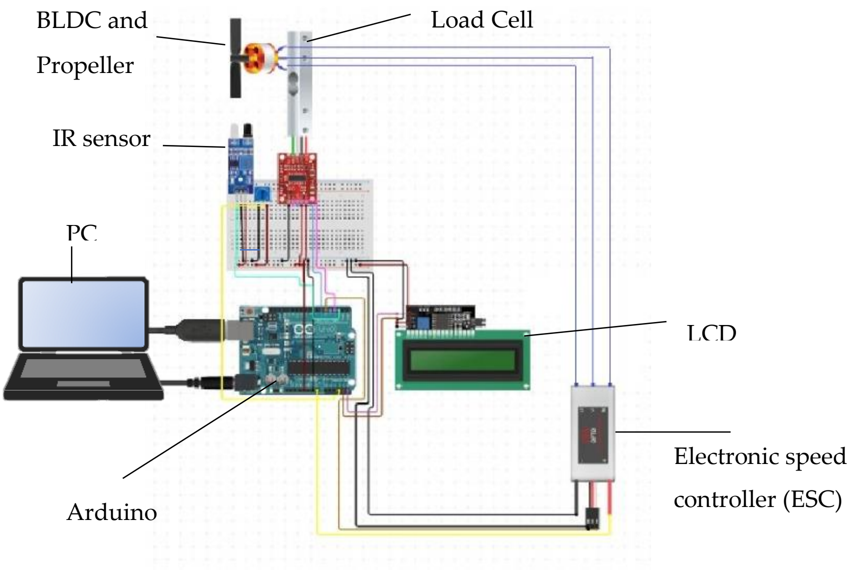


Figure 3. Schematic diagram of thrust test

3. Experimental Result and Discussion

The performance and accuracy of the fabricated load cell are validated by comparing all experimental results with a commercialized load cell, manufacturer data, RC benchmark experiment [5] and blade element momentum theory result. Performance Data files are available from APC for all propellers presently in production. These figures provide estimates of thrust, torque, and efficiency over a wide variety of model speeds and engine RPMs. All the performance data was created by a computer using the theoretical and computational approaches. RC experiment is done by other studies using series 1585 test stand. The test stand employs sophisticated software for automatic control and data logging and links to the computer via USB [5]. RC benchmark experiment is conducted using their own propulsion testing software, and the data can be recorded easily.

3.1. Experimental, Manufacturer, RC Benchmark and BEMT Results

Figure 4 shows the graph of thrust against rotational speed. The graph represents all five data of experiments, manufacturer data, commercialize load cell experiment, fabricated load cell experiment, RC benchmark experiment and BEMT analysis. As seen in the figure above, all data are overlap with each other and in a polynomial trend. Although all the data seems to have the same value, there are some percentage errors among them.

At 1000RPM, the error for fabricated is 8.247% based on the fitted equation, but above 2000RPM the error is below 1%. The vibration of load cell is not considered in the designing of the load cell. Hence, it might affect the experimental result. At 2000RPM and above, the percentage error between fabricated and RC and BEMT have lower error, and it is less than 0.05%. However, at 1000RPM, it is below 3% compared to RC benchmark and 5% for BEMT. It is to be noted, the rotational speed that produces thurst is from 2000RPM onwards. When compared to the commercialized load cell, the error is about 1% at 1000RPM, and above 2000RPM, the error is less than 0.5%.

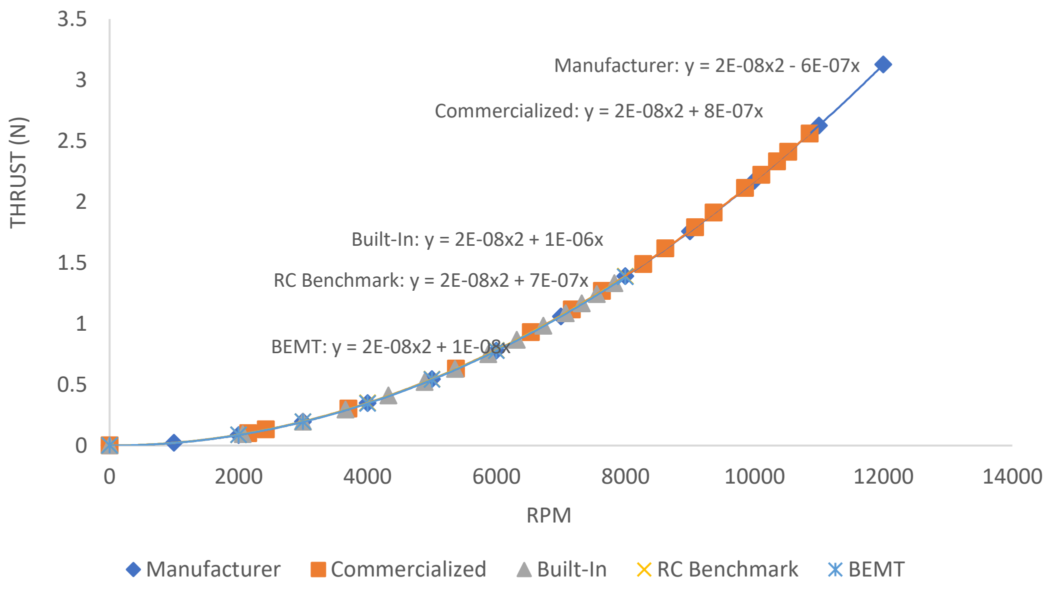


Figure 4. Thrust against RPM for all results

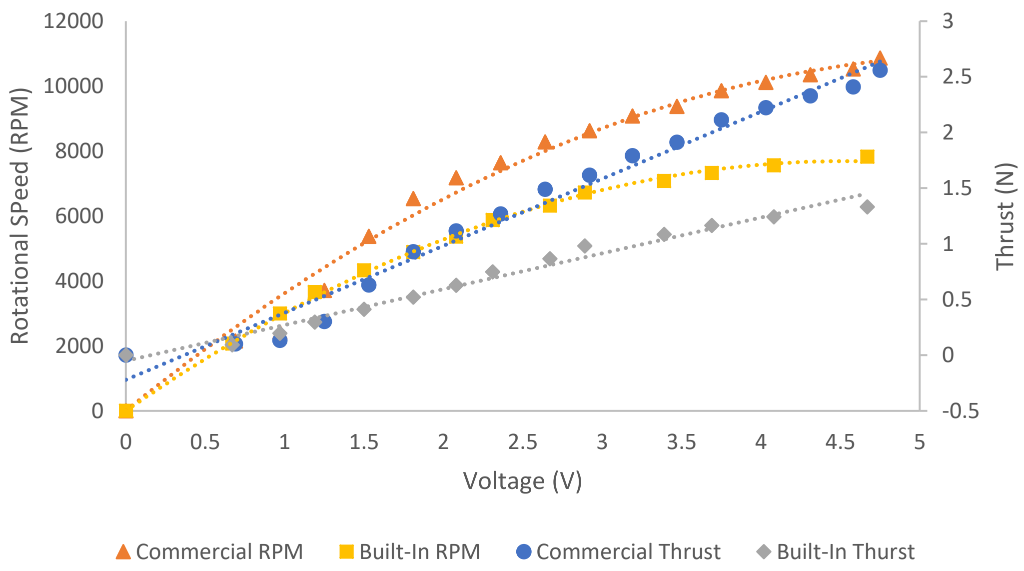


Figure 5. Graph of voltage against rotational speed and thrust

Figure 5 represent voltage against rotational speed between commercialized and fabricated load cells. Although both experiments used the same type of brushless motor, which is Sunnysky 2400kV and maximum voltage supply 5V, there are still differences in the experimental data. As the voltage increases, the value of thrust also increases. Based on the trend, errors between voltage and rotational speed are quite high, with a maximum error of 40%. Commercially built load cell percentage error is a bit lower compared to the in-house-built load cell. Therefore, the in-house-built load cell is only capable of running the motor until 7830 RPM at 4.67volt while commercially built is able to run until 10,857 rpm at 4.75volt. Thus, both load cells required large power in order to run more than 10,000 rpm. Referring to the results of commercially built load cell and in-house-built load cell, the motor start rotating at 0.69volt with 0.101N and 0.67volt with 0.092N, respectively. Figure 5 also shows the experimental data for thrust against voltage. It is also clear, maximum voltage for the built-in load

e-ISSN: 2715-6958 p-ISSN: 2721-5342

cell is 4.67V with 1.332N thrust, while the commercialize load cell has a maximum voltage of 4.75V and 2.559N thrust. These differences can be seen in figure 5 and may be due to the vibration occurring between the load cell and brushless motor during the experiment. Also, the material used for built-in load cell is aluminum compared to commercialized load cell is stainless steel. There is a difference in the calibration factor value used. Every load cell will not have the same calibration factor even though it has the same limit load value. The calibration factor is one of the factors that might affect the experimental result.

4. Conclusions

The objective of the project in terms of designing a load cell is to measure a propeller thrust ranging from 0.1N to 15N load is achieved. An objective to fabricate and test the load cell was also achieved with Solidworks simulation. From the estimated analysis calculation, the built-in load cell can measure up to 205N thrust, but during the experiment, the maximum thrust obtained is 1.332N at 4.67V, while for commercialize load cell, the maximum thrust obtained is 2.559N with 4.75V. This might be due to the limitation in this research, for example, the limit on the voltage of battery used, calibration on electronic speed controller and brushless motor. The rotational speed that starts to generate thrust is about 2000RPM. The error between the prototype load cell to the manufacturer, RC benchmark and BEMT is less than 1%, 0.05% and 0.05%, respectively. In this research, the built-in load cell is capable of running until 8000rpm due to vibration. The vibration of the load cell is not considered in the designing of the load cell. Therefore, it might affect the difference of data obtained between commercialize and built-in.

Acknowledgments

I would like to acknowledge the facilities used in Aerolab UTM Universiti Teknologi Malaysia, Johor and the funding from UTMFR grant Q.J130000.2551.21H61 and UTM Tier 1 grant Q.J130000.2524.20H30.

References

1. Khasyofi, M. and Hartono, F. 2019 Development Testing Method and Analysis Static Thrust for Propeller Based Propulsion, *IOP Conference Series: Materials Science and Engineering*,**645**(1).
2. Mattingly, J. 1996 Elements of Gas Turbine Propulsion, *Tata McGraw-Hill.*
3. Hafizah, N., Wahida, T.F., Azmin, F. and Ammar, A. 2012. Load Cell Application in Rocket Thrust Measurement System. *Applied Mechanics and Materials,* **225**, 437 – 441. doi: 10.4028
4. Brown, R.R.T. and Com, N.T. 2021 Retrieved December 1, 2020, from https://nerdytechy.com, pp1 – 6
5. Stand, T, and Robert, A. 2021 Series 1585 Test Stand Datasheet.
6. Aghili, F. 2010 Design of a load cell with large overload capacity *Transactions of the Canadian Society for Mechanical Engineering,* **34** p 3-4.
7. Honeywell International Inc. 2010. Load Cell Use in Aerospace Ground and Flight Testing Applications. March, p 1-7.
8. Lee, D., Hong, H.P., Lee, M.J., Park, C.W. and Min, N.K. 2012 A Prototype High Sensitivity Load Cell Using Single Walled Carbon Nanotube Strain Gauges *Sensors and Actuators, A: Physical* **180**, p 120-126.
9. National Instruments 1998Application Note 078 – Strain Gauge Measurements p 12.
10. National Instruments 2011 Measuring Strain with Strain Gauges, *National Instruments Measurement Fundamentals Series,* **2**, p. 1-6.
11. Projects, A. and Newton, A. 2021 'Fan Speed Measurement Using IR Sensor & Arduino', p3-8.
12. S. Goldstein. On the Vortex Theory of Screw Propellers 1929 *Proceedings of the Royal Society of London.* Series A, **123**(792) p 440 – 465.

e-ISSN: 2715-6958 p-ISSN: 2721-5342

13. Sadowski, N.B., Landman, D. and Parker, P.A. 2018 A Cost Effective Design for a Small Propeller Thrust / Torque Balance *11th International Symposium on Strain – Gauged Balances,* p. 1-19.
14. Systemes, D. 2010. An Introduction to Stress Analysis Applications with Solidworks Simulation, Student Guide, *Solidworks.*
15. Technologies, A. 1999 Practical Strain Gauge Measurements *Strain Gauges,* p.102.
16. Wilana, B. 2015 *PTTA Wulung Ground Test Procedure of Propulsion System.* Engineering Data Managements PT DID532NW5001.