Engine and Propeller Selection for Propulsion System LAPAN Surveillance UAV – 05 (LSU-05) Using Analytic and Experimental Test

Dewi Anggraeni[1)], Arifin Rasyadi Sumaryanto[2)], Encung Sumarna[3)], Awang Rahmadi[4)]
dewi.anggraeni@lapan .go.id

Abstract

The aim of the paper is to present a method for evaluating propulsion for LAPAN Surveillance UAVs-05 (LSU-05). Selection of a piston engine and propeller, which operates in its efficient region for a UAV performance's specifications, will affect the capabilities of the UAV performance. Calculation of engine power to meet the power requirement of the LSU-05 when flying cruise and climb. Furthermore, physical testing based on static thrust of engine and propeller is performed on a constructed on test bench. For selecting engine and propeller, comparison analysis between calculation and physical testing results to be conducted. It has been decided that the propulsion LSU-05 require 170 cc piston engine with 28x10 propeller blade, because it has fulfilled all consideration from activities which carried out on this study.

Key Words : engine matching, unmanned aerial vehicle, power, thrust

Nomenclature

D	: drag force	C_L	: lift coefficient
L	: lift force	C_D	: total drag coefficient
W	: airplane total weight	C_{D_0}	: body drag coefficient
W_e	: airplane empty weight	T	: thrust force
W_p	: airplane payload weight	T_c	: thrust coefficient
V	: airplane velocity / airspeed	P_{prop}	: propeller thrust power
AR	: wing aspect ratio	P_{shaft}	: shaft power
S	: wing surface area	R	: propeller radius
η_{prop}	: propeller total efficiency	η_v	: propeller profile efficiency (viscous)
η_i	: propeller inviscid efficiency (Froude)	ρ	: air density

1. Introduction

One of important phase of manned or unmanned aircraft system propulsion design is engine and propeller matching, which is require for fulfilling design requirements. The selection process between the calculation of power requirement and physical testing result of propulsion system for use in small, propeller-driven, unmanned air vehicles with Maximum take Off Weight of 75 kg for LAPAN Surveillance UAV type 05 abbreviated to LSU-05 have been done by The Aeronautic Centre of LAPAN.

The selection process begins with the calculation of engine power to meet the power needs of the LSU-05 drone when flying cruise and climb [2]. LSU-05 drone is unmanned air vehicles with Maximum take Off Weight of 75 kg and operates at maximum cruise speed of 65 knots. The engine is a piston engine with a propeller. Initial reference propeller used in the calculation of power requirements is 30x12 two-blade propeller. In the matching propeller stage, the propeller will be compared to predict the performance of some power and thrust generated by propellers. This stage using statistical software Prop Power Calculator software [3].

The next step in the selection process is to conduct a physical testing of the engine and propeller have been previously chosen which is 28x10 and 30x12 propellers. The engine physical testing is intended to measure static thrust or thrust at zero velocity. The test is performed by holding the engine in order not to move forward. The measured static thrust is function of engine revolution. This test also measures fuel consumption at certain engine revolution.

[1,2,3,4)] *Aeronautics Technology Center -LAPAN*

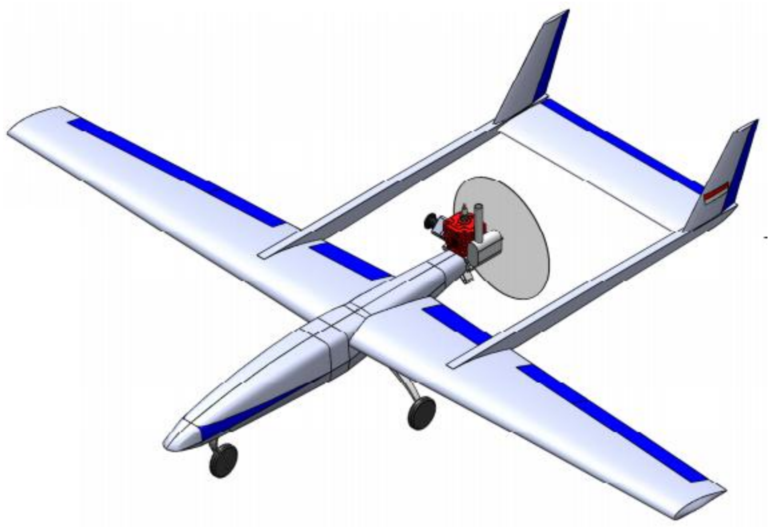

Figure 1. LAPAN Surveillance UAV – 05 (LSU-05)

Last stage selection process is to choose and decide propeller and engine which require power and thrust of LSU-05. Choosing an engine has a many consideration such as LSU-05 twin tail boom pusher configuration, propeller fixed pitch effect, propeller ground clearance, engine operation at mission profile. However, the selection engine and propeller using thrust requirements study between analytical method and physical test / static test. The result will be conformed by requirement of thrust at take-off and cruise.

2. Research and engineering Methodology

2.1. Analytical Method

2.1.1 Engine Shaft Power

Calculating engine shaft power need several data from design requirements of airplane design ; in this paper is LSU5`s configuration data. Those data are input data such as airplane maximum take-off weight (MTOW), airplane maximum cruising speed, propeller dimension, and airplane *weight to power* ratio.

Weight to power ratio is ratio of engine power for flight with certain airplane weight. Weight to power ratio is chosen from matching chart which has been decided before and related to design requirements and objectives (DRO). Weight to power ratio is main reference of engine matching or engine selection. On calculation of engine power, weight to power ratio is guidance variable to check whether engine power to fly is sufficient or not. So we need one more ratio for input data of calculation, that ratio is *thrust to weight* ratio or thrust coefficient.

Thrust to weight ratio or thrust coefficient is the ratio of the maximum thrust generated by airplane engines with a total weight of airplane. On manned or unmanned airplane, generally thrust to weight ratio is decided from rule of thumb or agreement between airplane designer. This references comes from previous airplane design. The references states that sufficient static thrust gaining airplane ability to cruise and climb **at least one-third** of the total weight of the airplane. The dimensionless thrust coefficient can be defined by this following equation [2] :

$$T_c \equiv \frac{T}{\frac{1}{2}\rho V^2 \pi R^2} \tag{2.1}$$

thrust coefficient is component of propeller generating thrust, airspeed and propeller dimension.

So after defining thrust coefficient for calculation, the first process is calculating engine shaft power required by the propeller at two loading conditions which are light loading condition and heavy loading condition. Light loading condition is defined during high speed cruise. Heavy loading condition is defined during low aircraft take-off speed. After the thrust coefficient is defined for both loading conditions, so the power needed to fly the plane can be calculated by the following equation [2] :

- *Heavy loading, low speed take – off*

$$T_c \gg 1 \, , \, \eta_{\rm i} \ll 1 \; : \; P_{\rm shaft} \; \simeq \; \frac{T^{3/2}}{(2\pi \, \rho)^{1/2}} \, \frac{1}{R} \, \frac{1}{\eta_{\rm v}}$$

(2.2)

- *Light loading, high speed cruise*

$$T_c \ll 1 \, , \, \eta_{\rm i} \simeq 1 \; : \; P_{\rm shaft} \; \simeq \; T \, V \, \frac{1}{\eta_{\rm v}}$$

(2.3)

Both thrust coefficient and inviscid efficiency according to equation [2] (2.2) / (2.3) are seen to strongly depend on the thrust and flight speed, and also on the propeller radius. In contrast, viscous efficiency does not vary much and is often considered a constant. An upper limit and estimate of inviscid Froude efficiency is related to this equation [2] :

$$\eta_i \le \frac{2}{1+\sqrt{1+T_c}}$$

(2.4)

Generation of thrust in flight requires the expenditure of power. For a propeller engine, the shaft power and the thrust are related by the definition of propeller efficiency. Propeller efficiency is the product of a viscous profile efficiency which accounts for the viscous profile drag on the blades, and an inviscid Froude efficiency which accounts for the kinetic energy lost in the accelerated propwash. The following statements are described by these equation [2] :

$$\frac{TV}{P_{shaft}} \equiv \frac{P_{prop}}{P_{shaft}} \equiv \eta_{prop}$$

(2.5)

$$\eta_{prop} = \eta_v \eta_i$$

(2.6)

All of the equations above can determining the power needed by the engine to rotate the propeller which have specific dimensions.

2.1.2 Power Requaired and Power Available

The power curve is two curves plotted on the same axis: the Power-Required curve, and the Power-Available curve. Both represent power (required or available) as functions of airspeed.

Power required is defined as the power we need to be providing (from the engine) in order for the aircraft to maintain a constant airspeed and constant altitude. The power required is a function of the drag being produced by the airframe and our true airspeed.

Power available is the maximum power that we can produce with the engine. Although engines are normally rated for a fixed maximum brake-horsepower, the power available curve doesn't show us constant power available—there is significant variation with airspeed. This is because the curve accounts for the efficiency of our propeller—which changes with airspeed—and as such represents *thrust* horsepower, not *brake* horsepower.

The difference between our power-available and power-required is our *excess power*, *power margin*, or *power reserve*. It's possible for this value to be negative at high speeds and/or altitudes, but it is normally positive—indicating that we have access to more power than we need to maintain a constant airspeed and altitude. Our power reserve is important, since it's an indication of how well we can accelerate and/or climb. At steady cruising flight conditions, power requirements can be defined by the following equation [1],

$$T_{req} = D$$

(2.7)

$$P_{req} = T_{req} V = DV$$

(2.8)

$$P_{req} = \frac{1}{2}\rho V^3 S C_{D_0} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi e AR}\right)$$

(2.9)

where Power Required is a function of flight speed at cruise condition, geometry of the wing, airplane weight and drag generated by the airplane.
And Power Available can be defined as,

$$P = TV$$

(2.10)

Power Available is function of propeller efficiency, so equation (2.10) can be defined as,

$$P_{avail} = P_{shaft} = \eta . P_{prop}$$

(2.11)

where efficiency is function of airspeed variation, density, and *power to propeller diameter* (P/D) ratio, can be described as,

$$V = \eta \left(\frac{2P}{\pi . \rho . D^2 \left(1-\eta\right)} \right)^{1/3}$$

(2.12)

From equilibrium of cruising flight equation with available shaft power and propeller diameter variation, so thrust can be defined as,

$$T = \left[\frac{\pi}{2} D^2 \rho P^2 \right]^{1/3}$$

(2.13)

2.2. Experimental Testing Method

2.2.1 Engine Static Performance Test

An engine test bench was designed and built to conduct performance test, see Fig 5. The engine was installed and instrumented and operated with two difference type of propeller which is 28x10 and propeller 30x12. Engine test is conducted in static condition where the airspeed is in zero value. The instrument which we use is load cell sensor and tachometer to measure the thrust and the rotation of it is engine in radian per minute (RPM).

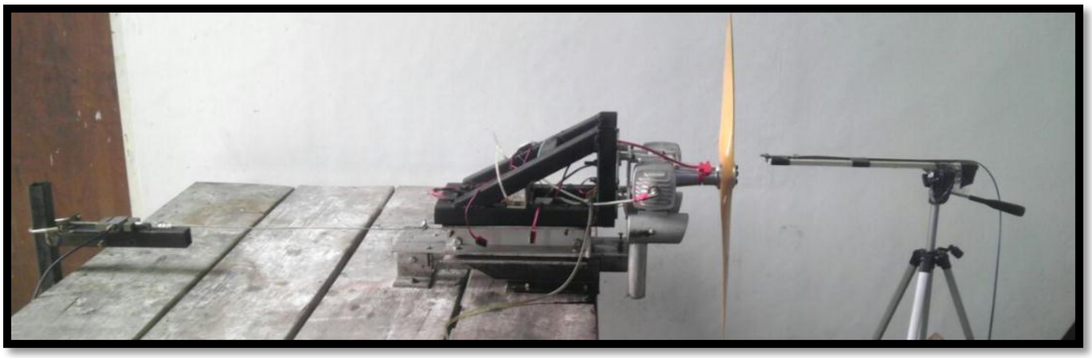

Figure 5. Physical engine testing

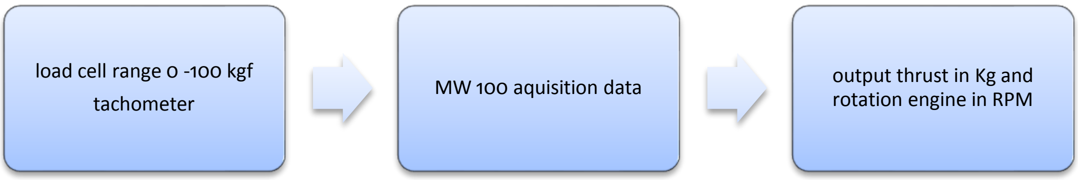

Figure 6 Ilustration of measurement process of engine testing

3. Result and Discussion

3.1. Analytical Result

3.1.1 Engine Shaft Power Calculation

Engine shaft power can be calculated with equations which have been described in methodology part. The calculation is divided into these following steps :

- Assuming *thrust to weight* ratio coefficient for both loading conditions
- Calculate thrust force and thrust coefficient for both loading conditions.
- Assuming propeller total efficiency from literature [3]. Calculate viscous efficiency.
- Calculate engine shaft power for both loading conditions.

Table 3.1 and Table 3.2 show input and output data of LSU5 UAV`s engine shaft power calculation.

Table 1 LSU5 UAV`s Engine Shaft Power Calculation Input Data

INPUT		
Max Take Off Weight (MTOW)	75	Kg
Max Cruising Speed	33.3 (65)	m/s (kts)
Target : *Weight to Power* (W/P) Ratio	65.76	at static sea – level cruise
Propeller Radius (Dimension : 30 x 12)	38,1	cm
Propeller Efficiency	0,85	literature
(T/W) Ratio at Take – Off	0,4	
(T/W) Ratio at Cruise	0,3	
Thrust coefficient at Take-Off	0,94	
Thrust coefficient at Cruise	0,68	
Viscous Efficiency at Take-Off	0.35	

Viscous Efficiency at Cruise	0.85	literature
Thrust (T) at Take – Off	294	N
Thrust (T) at Cruise	212	N
Density of Air (sea level)	1,225	kg/m³
Max Cruising Speed (Airspeed)	33,43	m/s

Table 2 LSU5 UAV`s Engine Shaft Power Calculation Output Data

OUTPUT		
Power at Heavy Loading	13.358	Watt
	18	hp
Power at Light Loading	8356	Watt
	11,2	hp
Check *: Weight to Power* (W/P) Ratio	65,65	

From calculation data shown on upper table, the required power to turn propeller with 30 x 12 dimension at heavy loading condition is 18 horsepower. At light loading condition is 11,2 hp, its meet the requirement of weight to power ratio at cruise. So we can conclude **UAV LSU5 need an engine which can supply power minimum of 18 hp.**

3.1.2 Propeller Matching

Table 3 shows propellers data of LSU-05 system propulsion, using Bolly`s two-blade propellers [3]. Fig 2 indicates when the engine speed increases, the propeller produces more power than the previous round. This power is converted to thrust by the propeller. Large propeller dimensions also affect its generated power propeller. Fig 2 also shows the effect of flying height, the higher the aircraft, propeller generated power on the wane.

Table 3 Propulsion System Data of LSU5 UAV

Propeller Diameter (in)	28	30
Propeller Pitch (in)	10	12
Maximum Allowble Propeller Rotation (rpm)	6500	6000
Shaft Power (hp) (at max rpm)	11.06	

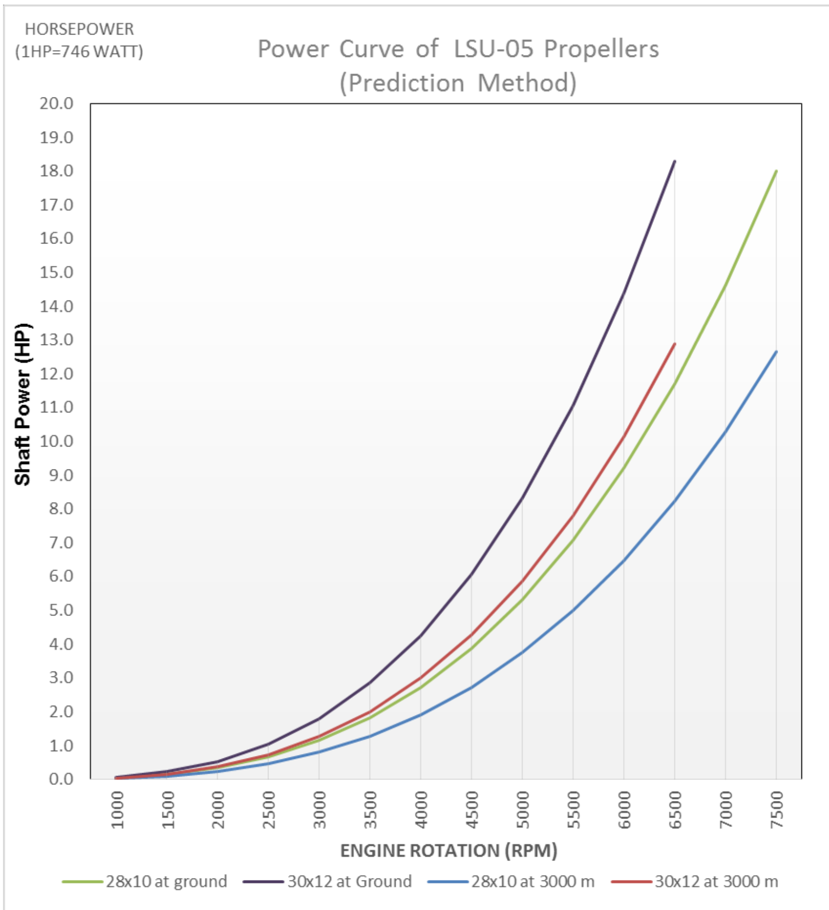

Figure 2. Shaft Power Curves of Propeller 28x10

Fig 3 showed power conversion which produced by the propeller to be an aircraft thrust. Propeller thrust is a function of airspeed. From Fig 3 can be concluded that while in static condition (zero airspeed), propeller dengan ukuran 28 x 10 can generate thrust until 23 kgf in surface condition, and for propeller 30x12 can generate until 33 kgf.. When airplane flying, upstream velocity affected thrust which have been generated by propeller. So the higher airplane`s airspeed makes propeller`s thrust reduces.

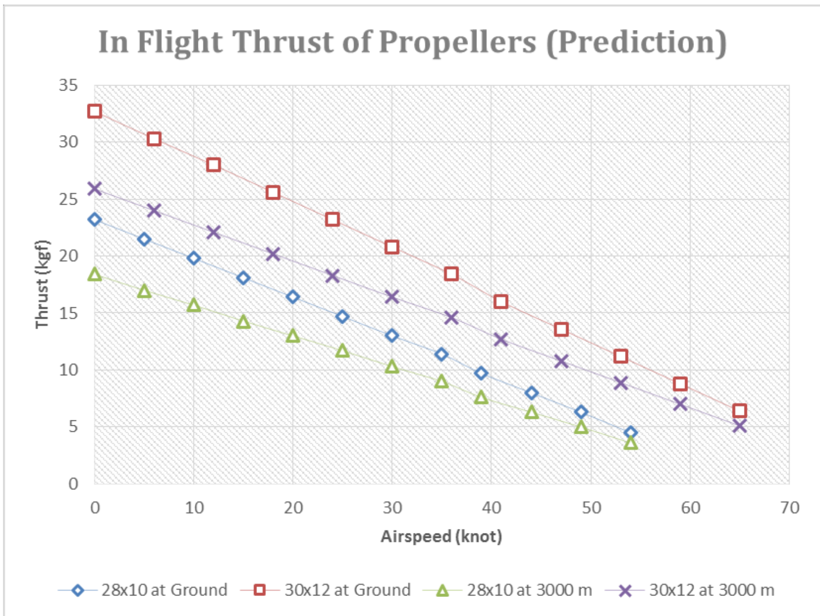

Figure 3 Thrust Curve of Propeller 28x10

Power required and power available is usually shown in graphical form, called power curve. Power required curve is a function of airspeed. While power available curve is function of engine rotation. From aerodynamics characteristic of LSU-05 UAV such as total drag, power required curve can be calculated [4]. Fig 4 shows two power curves of LSU-05, i.e. power required curve and power available curve, at climbing flight 5]. Both of curve are function of airspeed and altitude.

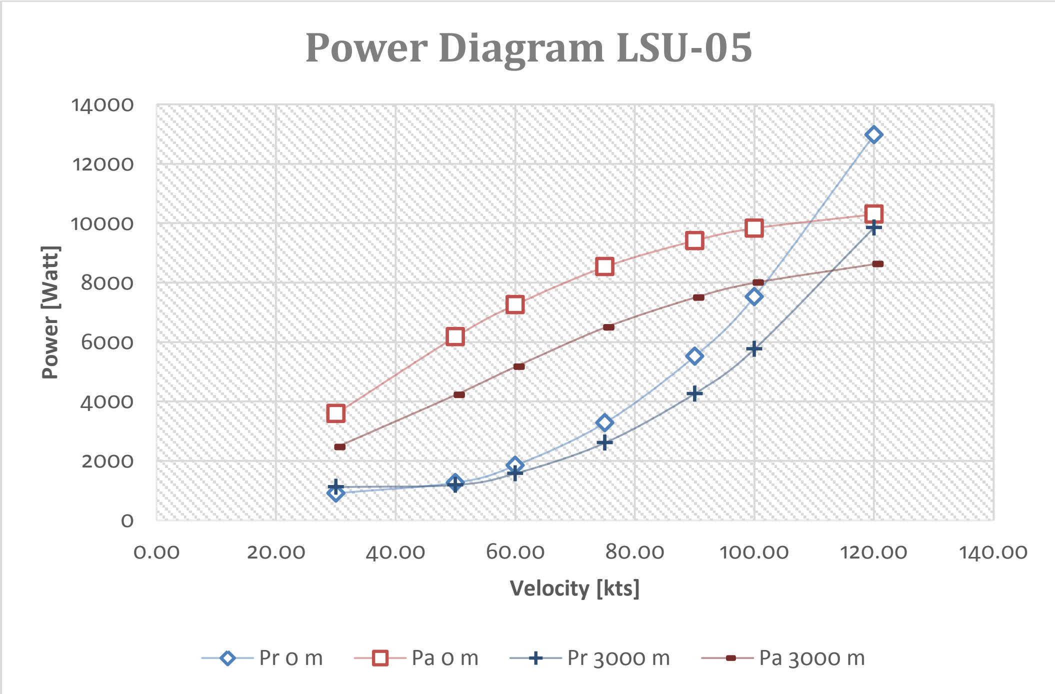

Figure 4 Power Required and Power Available Curve of LSU-05 using Propeller 28x10

The differences between power required curve and power available curve on Fig 4 shows how much excess power has generated by engine. The power required curve has been calculated at steady level cruise flight condition. Excess power or surplus power used by airplane for climb flight and making an acceleration.

All of figure above is usefull for predicting an operating diagram of LSU-05 UAV which using a piston engine. Some of curves above will be analyzed operating points with function of propeller rotation, propeller dimension, airspeed, and flight. In the last part of this publication, several operating points will be validated with data of static performance test result.

3.2. Experimental Test Result

3.2.1 Engine Static Performance Test Result

The test is conduct in ± 12 minutes, the thrust data was taken every 3 minutes to have the stable condition of the engine in every increment step of the engine rotation. Engine which we selected is 170 cc and there was two stages of testing, firstly the engine using propeller 28 x 10 and secondly using propeller 30 x 12. The data was taken twice in a same stage testing to have average and validation data during measurement process. Rotation engine data taken in minimum of 2000 RPM in idle and the maximum data rotation engine was taken in maximum throttle adjustment.

The illustration of measurement process of engine performance can be seen on Fig. 6 where the result of the process for first stage and second stage of engine testing can be seen below (see table 4. and Fig 6)

Table 4 Result Data of Propeller Static Thrust Test; Propeller 29x10 and 30x12

RPM	Fuel Consumption (mL/min)		Static Thrust (kgf)	
	28x10	**30x12**	**28x10**	**30x12**
1500	6.8	6.8	0.7	2.6
2000	9	9.52	2.3	3.45
2500	12	NA	3	NA
3000	69.84	72.08	4	8.4
3500	82	NA	6	NA
4000	93.84	92.48	9.5	15.33
4500	97.92	104.72	11.5	19.5
5000	111.52	106.78	14.8	25
5500	126.48	NA	18.4	NA
6000	130.32	NA	23.4	NA
6900	NA	NA	25.4	NA

3.3. Discussion of Comparison

For comparing the engine-propeller matching and power requirement calculation of LSU-05, at least two method are needed. First method is using prediction of static thrust – engine rotation diagram using 28 x 10 propeller. The calculation of this diagram using *Prop Power Calculator* software[3]. With assumption high wing trainer as total drag calculation and propeller constant is 1.25 from reference at that software. Second method is using result data of engine static performance test, which have been explained at previous part of this publication.
The validation of two method are presented by Fig. 7 below,

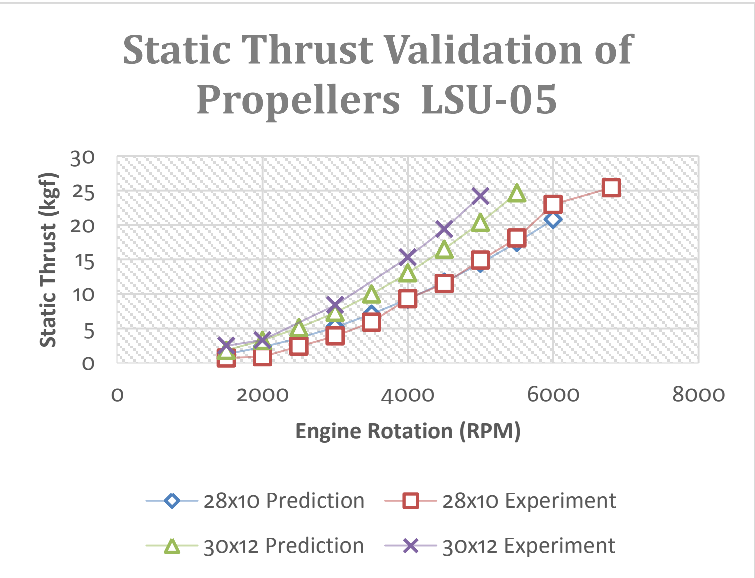

Figure 7. Result Data of Propeller Static Thrust Test; Propeller 28x10

Fig 4.4 shows the differentiation of prediction and experimental curve, it is already suspected due to several reason, as follows :

1. The static thrust calculation for prediction method, neglected any means of propulsion system to turn the propeller. The calculation only based on efficiency of propeller from references and propeller rotation. So the result data shows the effect of piston engine which turning propeller not smoothly as prediction.
2. Although static thrust calculation has been corrected by atmospheric condition at testing ground; height of location is 200 m above sea-level; there is may be some effect from atmospheric condition during the testing.

3. The propeller efficiency which has been used in calculation based on references [3], so it must be corrected by test result data.

4. Conclusions

Have been determine to analyze the static thrust calculation and the physical testing engine of LSU – 05. The thrust and power requirement of the aircraft driven by **170 cc piston engine.** Comparison studies of static thrust between analytic method and engine test showed a similar trend as chart data results (see on fig. 7), so analytic calculation **propeller two-blade 28x10 and 30x12** have been fulfilled.

5. Future Work

Plan will be carried out on upcoming activities to conduct analytic prediction and physical test for pusher three-blade propeller 28x12 as consideration of LSU-05 twin tail boom pusher configuration, propeller fixed pitch effect, propeller ground clearance, engine operation at mission profile.

6. Acknowledgement

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