Development of Propeller Test Rig and Evaluation of Propeller Performance

Dr. R.K. Tripathi[1], Mr.Vidit Tiwari[2], Ishaan Khunger[3], Pragya Berwal[3]

1. *Associate Professor, Department of Aerospace Engineering, University of Petroleum & Energy Studies, Dehradun*
2. *Lab incharge, Department of Aerospace Engineering, University of Petroleum & Energy Studies, Dehradun*
3. *Department of Aerospace Engineering, University of Petroleum & Energy Studies, Dehradun*

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Abstract - ***In the reciprocating and rotary aircraft engines propellers are used for providing appropriate power to the aircraft to move forward. Propeller is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between forward and rear surfaces of airfoil shaped blades and air is accelerated behind the blade. The propeller dynamics is modelled by both Bernoulli's equation and Newton's Third Law. This paper focuses on fabricating a propeller test rig for calculating the thrust of the propeller and hence measures the propeller performance. A 2-stroke spark ignition engine of Yamaha RX 100 is mounted over a beamed structure i.e. trike with which a 2-blade propeller is attached. Load cell, a transducer, is used to measure the thrust. The one end of the load cell was connected to the trike on which engine was mounted and another end was connected to a rigid beam. The S.I. engine rotates the propeller which in turn produces the thrust to move the trike forward. Our objective was to study the effect of advance ratio, thrust coefficient, power coefficient and speed power coefficient on propeller efficiency at constant blade angle. These parameters play a vital role in deciding the take-off thrust of an aircraft. To achieve the objective, the propeller thrust was recorded with the help of load cell at different engine speed (rpm). The engine rpm was varied using the throttle regulator to obtain different thrust values at different propeller rpm. Also, the airflow velocity across the propeller disk was measured using anemometer and other parameters like advance ratio, propeller actuator disk efficiency, thrust coefficient, power coefficient, etc. were also calculated to study their effects on the propeller performance.***

KeyWords: *Thrust coefficient, Power coefficient, Advance ratio, Speed Power coefficient, Propeller Actuator Disk Efficiency*

1. INTRODUCTION

Piston engines and turbines are the backbone of the aircraft industry because these engines provide necessary power to generate the required thrust to propel the aircraft at various attitude and altitude of flying operations. One of the kinds of engines is the turbo-prop engine in which propeller is an essential element to generate the thrust. The propeller may have two or more blades which are attached to a central hub. Propeller hub receives power from the engine to rotate the propeller whose rpm is variable by use of gear mechanism. Each blade of an airplane propeller is like a rotating wing and the propeller blades are like aerofoils and produce forces that create the thrust to pull, or push, the airplane through the air. There are different types of propulsive systems to generate thrust using different mechanisms, although they all function on Newton's Third Law of Motion and Bernoulli's equation. Because of the global objective to enhance the aircraft engine efficiency to achieve energy security in aviation industry, there has been a renewed interest in the use of more efficient propellers. It has been estimated that in the use of the prop-fan concept [1], a fuel savings of approximately 36% can be realized over the turbofan through proper propeller design. Propeller moves an aircraft through the air, and their performance depend upon the blade path, blade chord, and relative wind. The two types of motion are associated with the propeller blades: Rotational speed of the propeller and Forward speed of the airplane. The airplane's relative wind velocity (V_∞) and speed of the blade section due to rotation ($r\omega$), where ω is angular velocity, gives rise to the resultant speed of the airplane which is the vector sum of the rotational and relative wind speed as shown in fig1. If the chord line is at an angle of attack (α) with the free stream wind velocity (V_∞), then lift and drag are generated. This in turn produces thrust.
The propeller characteristics obtained from the wind tunnel tests are used for estimation of airplane performance. These characteristics are presented in terms

of certain parameters. The propeller performance is expressed using non-dimensional coefficients like power coefficient, thrust coefficient, torque coefficient, advance ratio and efficiency of the propeller [2].

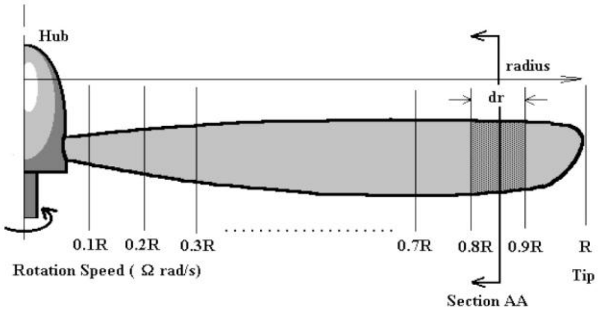

Figure 1- Radial Blade Element

The overall propeller thrust (T) and torque (Q) will be obtained by integrating the individual element performance from root to tip as shown in figure1.

$T=\sum \Delta T$ (for all elements), and $Q=\sum \Delta Q$ (for all elements)

The non-dimensional thrust coefficient (C_T), torque coefficient (C_Q), Power coefficient (C_P) and speed power coefficient (Cs) can then be calculated along with the advance ratio (J) at which they have been calculated.

$C_T = T / \rho n^2 D^4$ $C_Q = Q / \rho n^2 D^5$ $J = V_\infty / nD$

$C_P = P/\rho n^3 d^5$ $Cs = V (\rho / Pn^2)^{1/5}$

Where 'n' is the rotation speed of propeller in revs per second and D is the propeller diameter [3]. The efficiency of the propeller actuator disk under these flight conditions will then be η (propeller) = $JC_T / 2\Pi C_Q$

Airfoil development for propeller applications has been limited with the continual use of the Clark Y and RAF 6 series airfoil. The last major development in this area occurred with the development of the NACA16 series airfoil [4]. This airfoil has the characteristic "flat bottom", maximum thickness occurring at approximately the 50% point, and a small leading edge radius with many of the design characteristics dictated by manufacturing constraints. Therefore many propellers of today incorporate the Clark Y or RAE 6 airfoil series during the initial 50% of the blade transitioning to the NACA 16 series which has a high drag divergence Mach number in the outer segment of the propeller where the resultant Mach numbers can approach unity. The airfoil profile used for the propeller in the research is Clark Y. Clark Y is the name of a particular airfoil profile, widely used in general purpose aircraft designs, and much studied in aerodynamics over the years. The profile was designed in 1922 by Virginius E. Clark. The airfoil has a thickness of 11.7 percent and is flat on the lower surface from 30 percent of chord back. The flat bottom simplifies angle measurements on propellers, and makes for easy construction of wings on a flat surface.

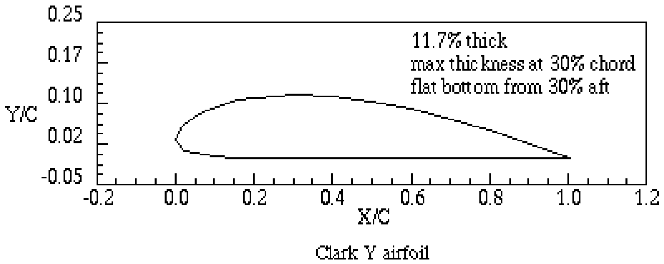

Figure 2- Clark Y airfoil configuration

A number of theories have been developed for analyzing the propeller performance and two important of them were momentum theory and blade element theory. The simple Rankine Froude momentum disc theory [5, 6] assumes that the propeller is replaced by a disc with an infinite number of blades producing a uniform change in the velocity of the stream passing through the disc. This theory is useful in calculating theoretical maximum efficiencies but does not deal in the details of the propeller configuration such as number of blades and blade thickness. These factors are considered in the blade element analysis [7, 8], the next degree of sophistication, which deals in the forward and rotational velocity components to determine the resultant velocity or the effective pitch angle and hence the angle of attack as seen by each airfoil section making up the propeller blade. The next order of development and accuracy come with the Goldstein lifting - line model [9] where the blade is replaced by a series of horse shoe vortices. The approximation of blade replacement by vortices is acceptable since most general aviation propellers have a relatively high aspect ratio. Also, the lifting line approach can utilize corrections for viscosity and compressibility but is accepted as an "approximate method" using the Goldstein factor. As the propeller configurations change to relatively small aspect ratio or large surface areas as in the pro-fan concept, advanced analytical methods must be used such as the Ludwig-Ginzel lifting surface model [10] to model the propeller flow field accurately. It is the purpose of the present effort to compare directly with experimental data the prediction results of vortex and lifting line theory to determine the ranges of applicability and levels of accuracy. In doing so, the current methods may be enhanced to provide increased accuracy in the prediction of propeller performance.

2. METHODOLOGY

2.1 Propeller test rig specifications and procedure

1. A pusher type fixed pitch propeller is attached to the shaft of a 2-stroke spark ignition engine which is used to drive a trike, a beamed structure as in figure 3.

2. An S- type load cell is mounted over the trike, by using an angular beam as shown in figure 4, which is used to convert the thrust force into electrical signals. Load cell consists of a sensing element and a strain gage. Sensing element is the main structural component which develops a strain in response to the load applied. Strain gage utilise the principle of change in resistance of a metal when elongated or contracted.
3. The 2-stroke spark ignition engine is then started to rotate the blades of the propeller which produces thrust to move the trike in forward direction at 15 degrees throttle.
4. The rotational speed (rpm) of the engine shaft is measured using a laser tachometer by pointing the laser at the centre of the rotating shaft and it can be varied using throttle.
5. Thus, variation in the rpm of propeller is plotted against the thrust produced by the propeller.
6. Also an anemometer is used to measure the forward velocity of the propeller.
7. Other graphs showing airscrew coefficients are also plotted for detailed analysis of the propeller performance.

Figure 3– Model

Figure 4 – Load cell attachments

2.2 Apparatus used

1. A propeller of Clark Y configuration of radius 68cm.
2. S-type Load cell of range 10,000 N with a least count of 1N.
3. A laser tachometer.
4. Anemometer for measuring velocity.
5. Yamaha RX100 98cc engine.

2.3 Engine Specifications:

- Indicated Shaft power = 8.4 kW or 11.5 H.P.
- Maximum number of revolutions per minute = 7500 rpm
- Maximum velocity produced by engine = 24 m/s or 53.68 mph

2.4 Catia Model

The propeller used in the project was designed by using the CatiaV5 software, and was fabricated accordingly.

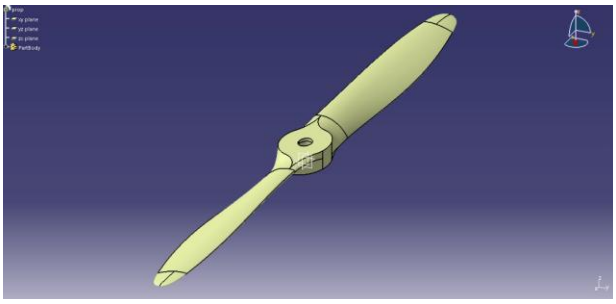

Figure 5- Isometric View.

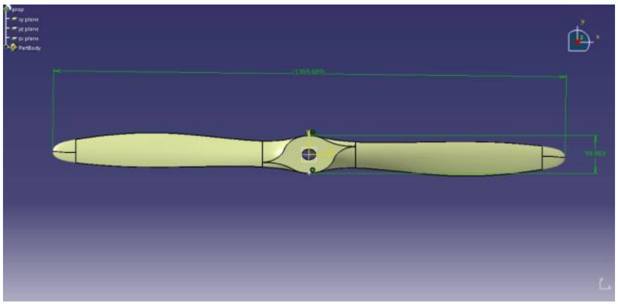

Figure 6- Top View with dimensions.

3. RESULT AND DISCUSSIONS

The characteristics of a propeller were studied carefully and the measurements of the propeller were taken. The airfoil of the propeller is of Clark Y configuration as it simplifies the angle measurements of the airfoil and was easy in construction. The thickness of Clark Y airfoil is 11.7% and is flat on the lower surface. The precision of the load cell is 1N. The components needed for the assembly of the load cell with the trike were fabricated and put together.

3.1 Experimental Values

Table 1. Experimental Observations

S. no.	Throttle Angle (Degrees)	RPM – Revolutions Per Minute	RPS – Revolutions Per Second	Thrust (N)	Forward Velocity (m/sec)
1	15	1700	28.33	33.20	5.50
2	30	2700	45.00	48.80	9.00
3	45	3550	59.16	58.90	12.00
4	60	3800	63.33	63.33	13.00
5	75	4000	66.67	69.90	13.70
6	90	4200	70.00	77.00	14.50

Table 2. Experimental Calculations

S. no.	Advance Ratio (J)	Thrust Coefficient (C_T)	Power Coefficient (C_P)	Speed Power Coefficient (C_S)	*Actuator Disk Efficiency (η), %
1	0.1427	0.009873	0.001758	0.5076	80.00
2	0.1470	0.005752	0.000971	0.5889	87.10
3	0.1491	0.004016	0.000661	0.6449	90.60
4	0.1509	0.003768	0.000623	0.6605	91.00
5	0.1511	0.003753	0.000621	0.6616	91.27
6	0.1523	0.003750	0.000625	0.6661	91.30

*The experimental propeller disk efficiency is calculated using the formula:

$$\eta = 2/ \{1+ [(2T/AV^2) +1]^{1/2}\}$$

A is the propeller area

3.2 Plots Showing Propeller Performance

The performance of a propeller is indicated by thrust coefficient (C_T), power coefficient (C_P) and Propeller efficiency (η). These parameters depend on advance ratio (J) and blade angle of the propeller. The following plots are used to study the performance parameters of a fixed pitch 2-blade propeller:

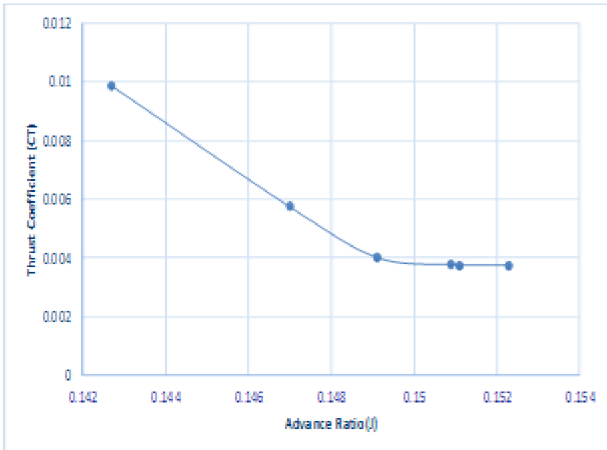

Figure 7(a) - Thrust Coefficient vs Advance Ratio

```The results explained in figure 7(a) states that the thrust coefficient is inversely proportional to the advance ratio. This is due to the fact that the thrust coefficient is inversely proportional to the square of rpm, and as rpm increases, thrust coefficient decreases considerably. Therefore at higher rpm the thrust delivered by the propeller increases, which is a desirable property when the aircraft is taking off.

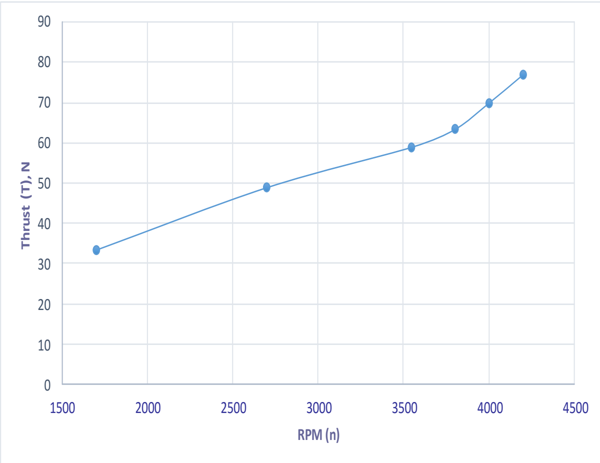


Figure 7(b) – Thrust vs RPM

The figure 7(b) shows that the thrust produced by the propeller is directly proportional to the rpm, thus at higher rpm, the thrust produced will be more. This brings us to a conclusion that for the aircraft to take-off, the rpm of the propeller should be high enough so that it delivers enough thrust and the aircraft takes off smoothly.

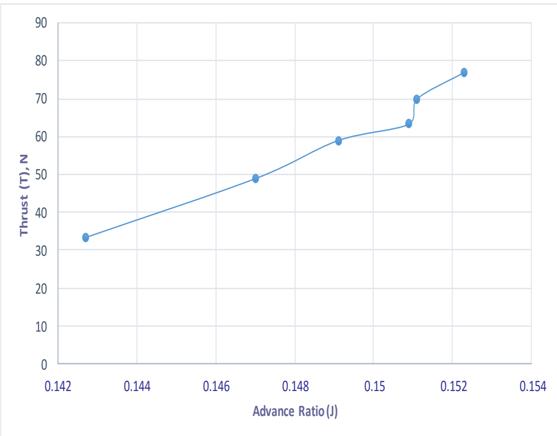


Figure 7(c) – Thrust vs Advance Ratio

This figure 7(c) shows that the thrust is directly proportional to the advance ratio and thus the aircraft advances more at higher thrust values, i.e. the aircraft moves greater distance at higher thrust, which is a straightforward physical aspect of any thrust producing engine.

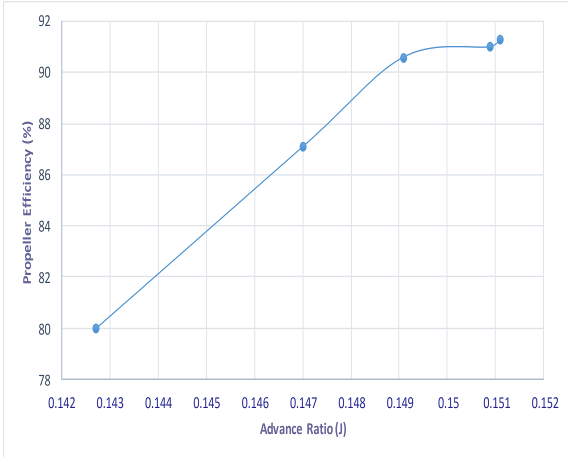


Figure 7(d) – Propeller Efficiency vs Advance Ratio

The figure 7(d) shows that the Propeller efficiency increases with increase in advance ratio. This means that the aircraft's velocity plays a key role in knowing how efficient an aircraft performs at a given velocity. During the initial stages of flight, the velocity is low, and so is the propeller efficiency, and as the velocity increases, the propeller efficiency increases. This brings us to a conclusion that the aircraft should always fly at relatively high speeds for lower fuel consumptions, and thus, fuel consumption during take-off is more as compared to fuel consumption during cruise.

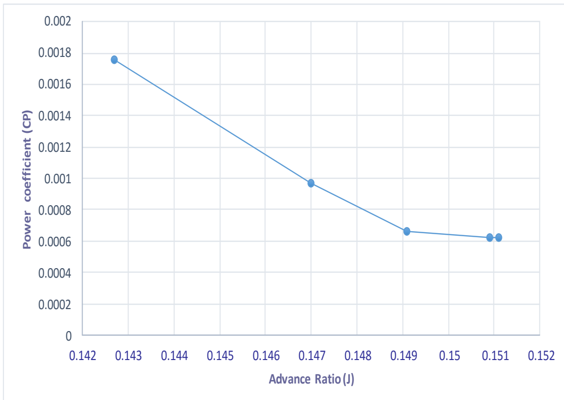


Figure 7(e) – Power Coefficient vs Advance Ratio

The results of figure 7(e) explained that power coefficient is inversely proportional to the advance ratio. This is due to the fact that the power coefficient is inversely proportional to the cube of rpm, and as rpm increases, power
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coefficient decreases considerably. Therefore at higher rpm the power delivered by the propeller increases, which is a desirable property when the aircraft is taking off.

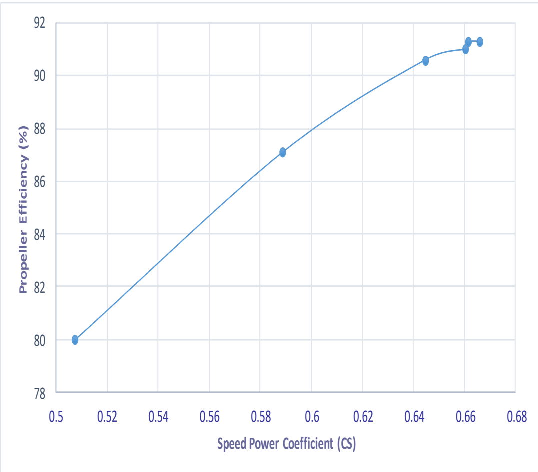

Fig 7(f): Propeller Efficiency vs Speed Power Coefficient

The figure 7(f) states that the Propeller efficiency increases with increase in speed power coefficient. This means that the aircraft's velocity plays a key role in knowing how efficient an aircraft performs at a given velocity. During the initial stages of flight, the velocity is low, and so is the propeller efficiency, and as the velocity increases, the propeller efficiency increases. This brings us to a conclusion that the aircraft should always fly at relatively high speeds for lower fuel consumptions, and thus, fuel consumption during take-off is more as compared to fuel consumption during cruise.

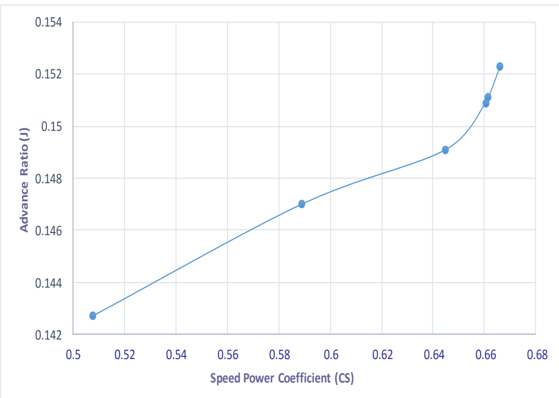

Figure 7(g) – Advance Ratio vs Speed Power Coefficient

The figure 7(g) between advance ratio and speed power coefficient is a linearly increasing curve, thus advance ratio is directly proportional to speed coefficient. This provides us with a simple conclusion that as the velocity of the aircraft increases, the advancement of the aircraft is more, i.e. it moves greater distances with higher speeds.

4. CONCLUSIONS & FUTURE SCOPE

Two-blade fixed pitch propeller of Clark-Y configuration has been studied in this paper and various graphs has been plotted evaluating the propeller performance. The results were as follows:

- The thrust coefficient is inversely proportional to the advance ratio. Therefore at higher rpm the thrust delivered by the propeller increases, which is a desirable property when the aircraft is taking off.
- For the aircraft to take-off, the rpm of the propeller should be high enough so that it delivers enough thrust and the aircraft takes off smoothly.
- The thrust is directly proportional to the advance ratio. Thus, the aircraft moves greater distance at higher thrust, which is a straightforward physical aspect of any thrust producing engine.
- The propeller actuator disk efficiency is directly proportional to the advance ratio and speed power coefficient. This brings us to a conclusion that the aircraft should always fly at relatively high speeds for lower fuel consumptions, and thus, fuel consumption during take-off is more as compared to fuel consumption during cruise.
- Advance ratio and speed power coefficient is a linearly increasing curve. Thus as the velocity of the aircraft increases, the advancement of the aircraft is more, i.e. it moves greater distances with higher speeds
- Power coefficient is inversely proportional to the advance ratio. Therefore at higher rpm the power delivered by the propeller increases, which is a desirable property when the aircraft is taking off.

The results concluded from the graphs were similar to those carried out by Weick n 1929 and others. These performance parameters were very useful in determining the performance of the propellers, and such propeller driven trikes can be used for small scale flights in rescue operations such as the earthquakes, landslides, etc. These flights will be very economical, easy to handle, easy to maintain and repair, and can be flown to remote locations as the size of the trike will be less.

Experiments using different propeller designs can be performed. Instead, a variable pitch propeller can be used which will give a wider frame and better knowledge of the performance parameters.

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