Investigation of the parameters of a Constant pitch aircraft propeller

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Investigation into the Parameters of Constant Pitch Aircraft Propeller using Blade Element Momentum theory.

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Abstract

Propeller driven aircraft remain a common sight in aeronautics with extensive research on their behavior and characteristics of flow over blade sections. There are multiple propeller characteristics that can greatly influence the performance of a propeller. In this paper an investigation was conducted on the effects of propeller geometrical parameters Such as diameter, chord, pitch angle, and number of blades, on various engine speeds. Utilizing BEM theory to measure propellers performance. Results were derived using a mathematical solver GNU OCTAVE. Refinement of the BEM theory is discussed in accounting for losses near the tips of the blades represented by the Prandtle tip loss correction factor, and the effect of including a twist along the blade profile.

This paper provides useful data for propeller geometrical design. Therefore contributes to more efficient propeller designs.

1. Introduction

Airplane propellers remain in wide use in the aeronautic industry, with extensive research in operation and development being published each year. A propeller is one of the most predominant design features when designing an aircraft, it provides the mean for gripping the air, generating thrust pulling the aircraft forward and drastically influence the system efficiency. Designing a propeller usually focuses on optimizing efficiency for cruise speed without considerable losses in other flight modes such as take-off and climbing. For a fixed pitch propeller the efficiency between the flight modes of take-off, climbing and cruise can differ considerably, but the aircraft should be able to operate across a wide range of flight conditions [ ].

Modelling in high speed rotating flow fields is a complex analytical problem, due to its inherently unsteady flow characteristics [ ]. Advances in computer processing speeds, memory capacity and user interface have allowed numerical solutions in computational fluid dynamics to grow rapidly. But solutions for such complex fields is difficult not to mention its high cost rendering it unsuitable for early stage designs. For conceptual design low order engineering codes are still preferred. One of such codes is Glaurt blade element momentum theory (BEMT), which has been used extensively in modelling a flow around a rotating propeller, for its convenience, ease of application, low computer cost and acceptable results.

A propeller geometrical features can affect its efficiency greatly, and therefore define the application in which it can be used. Variation in these features can affect the flow envelope around a rotating propeller.

Although, this topic have been researched extensively, but the literature is scarce and sometimes contradictory. The aim of this paper is to provide direct and clear data regarding the influence of a propeller geometrical features on efficiency using numerical methods. Though contribute to more efficient fixed pitch propeller designs.

2. Theory

There exists a number of methods for designing and optimizing rotor blades. 'Classical blade element' methods model the rotor when the flow is fully developed and attached 'on design' while empirical methods such as found in the Hamilton Standard "Red book" model propeller performance over wide range of conditions. For this paper the former method will be chosen for the reasons discussed in the introduction.

The Glaurt blade element momentum theory (BEMT) traces back to the original work of Ranking and Froude [ ].

2.1 Momentum Theory

In the momentum theory, Ranking modelled the propeller as an actuator disc, which produces a uniformly distributed acceleration of air, created by a differential of pressure directly before and behind the disc [ ]. Air is assumed to be a perfect fluid with no viscosity or compressibility effect. And the boundary lines are assumed to enclose the entire affected streamlines of air.

From the fig ( ) the streamline velocity is denoted by V_∞, the velocity increases to V_d at the disk. The acceleration imparted by the disk to the air by v_i resulting in a final velocity of V_s at the slipstream. Applying conservation of linear momentum the thrust developed can be evaluated as:

$$dT = 2\pi\rho V_D(V_\infty - V_e)rdr$$

By considering, the differential thrust as the resultant of the differential pressure before and after the disk multiplied by its area, and applying the Bernoulli equation to the flow the air velocity at the actuator V_d can be found to be:

$$V_D = \frac{V_e+V_\infty}{2}$$

Then, Ranking momentum theory calculate the ideal efficiency of a propeller as:

$$\eta = \frac{2V_\infty}{V_\infty+v_i} \qquad (1)$$

This distinctly shows that the efficiency will increase as v_i approaches zero, but since the developed thrust is directly proportional to the induced velocity; for a fixed streamline area as v_i approaches zero thrust diminishes to zero rendering the design inefficient.

Momentum theory while helpful neglects several important parameters that limits its application such as: aerodynamic drag, energy losses due to slipstream rotation and losses due to the periodic thrust variation caused by a finite number of blades. This is where we turn to Glaurt blade element theory, though with many simplifications, this method makes many assumptions, it is still presented in many propeller and helicopter design texts [ ] [ ].

2.2 Blade Element theory

In Drzewiecki blade-element theory the blade is segmented to various segments “elements”. The airflow around each element is assumed to be 2-dimensional; therefore unaffected by the other segments of the blade. BE theory estimates the performance of a blade by calculating the aerodynamic forces acting on it. Namely differential thrust and torque. The efficiency of the blade can be found by integrating these forces along the span of the blade.

Complete knowledge of aerofoil flow characteristics and test data are essential for such analysis to be accurate

The fore mentioned equations for differential thrust and torque are:

$$dT = \frac{1}{2}\rho V^2 (C_L \cos \emptyset - C_D \sin \emptyset) b.N.dr$$

$$dQ = \frac{1}{2}\rho V^2 r[(C_L \sin \emptyset) + (C_D \cos \emptyset)] b.r.N\,dr$$

These differential equations will be integrated across the span of the blade to obtain the overall thrust and torque, which will be substituted by the non-dimensionless coefficients denoted as coefficient of thrust (C_L) and coefficient of torque (C_Q). where the efficiency of the blade will be calculated using equation:

$$\eta = \frac{j}{2\pi} \times \frac{C_T}{C_Q}$$

2.3 Improved blade element method

2.3.1 Prandtle tip correction

One the main assumption in the simple blade element theory is modelling the propeller as an ideal actuator disc with infinite number of blades. Resulting in an overestimate of the blade efficiency. This is dealt with by incorporating prandtle tip correction factor in the momentum theory section.

$$F = \frac{2}{\pi}.\cos^{-1}(-f) \qquad f = \frac{N}{2}.\frac{R-r}{r.\sin(\emptyset)}$$

2.3.2 Blade twist

Twisting the blade with a defined angle from the hub to root of the blade will maintain constant circulation [ ] that will have positive effects on the generated thrust across the blade as to keep the angle of attack within a certain threshold, erecting a favourable position.

3. Implementation

In this work, the for mentioned equation were solved simultaneously using iterative techniques, developing a code that first uses a comprehensive list of aerodynamic coefficients namely c_l and c_d derived using panel method solvers (X-Foil). Second uses a special code for obtaining accurate estimates of inflow factors “a & b” and last its internal mathematics incorporates sins and cosines instead of using small angle approximation for more accurate results.

4. Results and Discussion

The model was ran with the different variation demonstrated in table 1 , and the results were found as follows:

4.1 Effect of propeller chord line

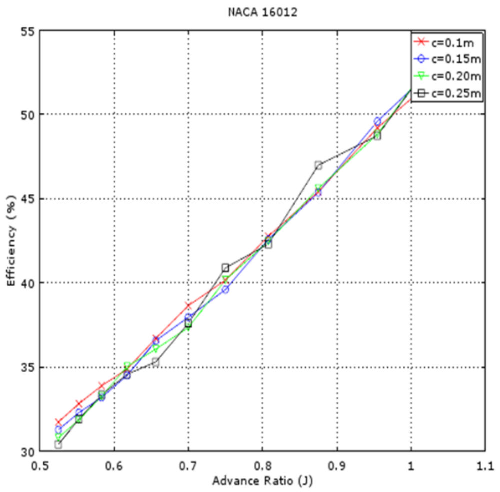

Figure 1Figure (1): Effect of chord line variation on efficiency of NACA 16012

All the results were plotted as efficiency (η) versus advance ratio (J) to investigate the effect of each design parameter on efficiency, also study the effect of Prandtl factor and blade twist on propeller efficiency for the selected cross section airfoil shape NACA 16012. As it can be seen; obviously, from Fig (1), that a continuous linear trend of efficiency with the advance ratio (as that the case encountered in all results) also from the graph, the propeller of smaller chord length achieve the higher efficiencies. A shift is noted (nearly at J≥0.8) where the opposite holds true, where the propeller of bigger chord lengths seems to have the higher efficiencies. This could be due to variation of inflow angle (ᴓ) and (φ) the angle between lift coefficient and the resultant, from low advance ration to high ones, where the efficiency is in the form of $\eta = \frac{tan\theta}{\tan(\theta+\varphi)}$.

4.2 Effect of propeller blades number

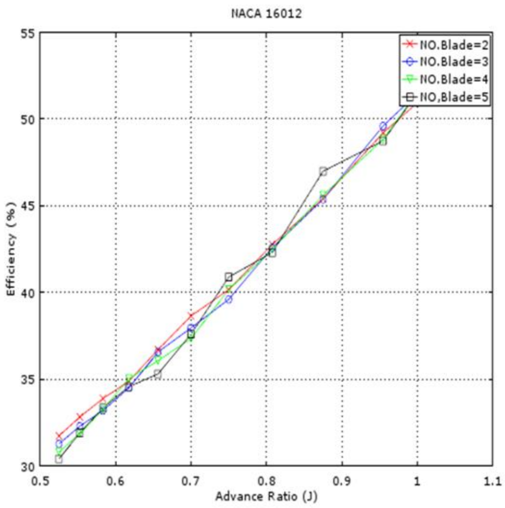

Figure (2): Effect of blades number on efficiency of NACA 16012

The trend of curves in Fig (2), due to varying blades number looks like that obtained due to chord line variation, where efficiency rise with the higher advance ratio, propellers with lower number of blades attain higher efficiency at low advance ratio. Where in the other hand, at high advance ratio, propeller of higher number of blades achieve higher efficiencies. It can be seen that at high advance ratios, efficiency is governed mostly by the total blade width of the annulus represented by (cB). However increasing blades number would increase the torque required by the engine and thus increase power consumption and result decrease propeller efficiency.

4.3Effect of propeller pitch angle setting

In Fig (3), a linear trend exist of efficiency with the advance ratio, where maximum efficiency attained by β=35^0, and decrease as pitch angle increase. That reduction in propeller efficiency as pitch angle increase could result from constrain angle of attack (α) at high values, causing a poor C_L/C_D fraction to be yielded, and thus a drop in efficiency occur.

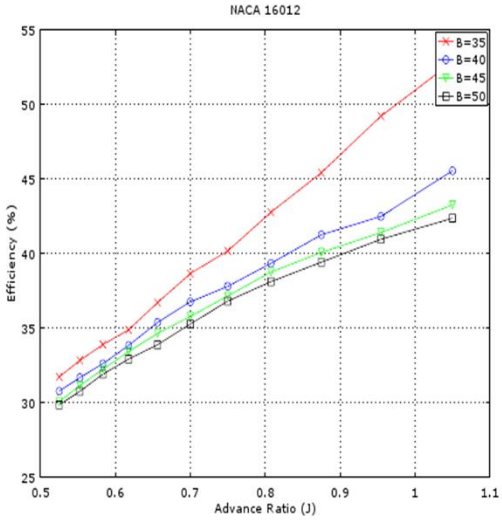

Figure (3): Effect of different pitch angle setting on efficiency for NACA 16012

4.4 Effect of propeller diameter

The graph in Fig (4), shows that all of curves are nearly collinear to some degree in which efficiency increase as advance ratio increase; also from the graph, propellers of longer diameter have the lower efficiency, and shorter propeller have the higher efficiency. It is

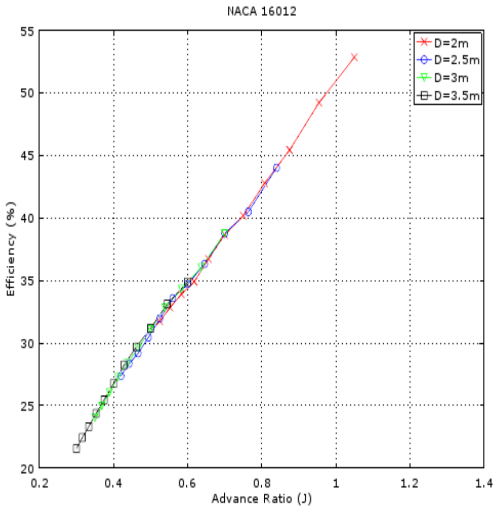

Figure (4): Effect of different propeller diameter on efficiency for NACA 16012

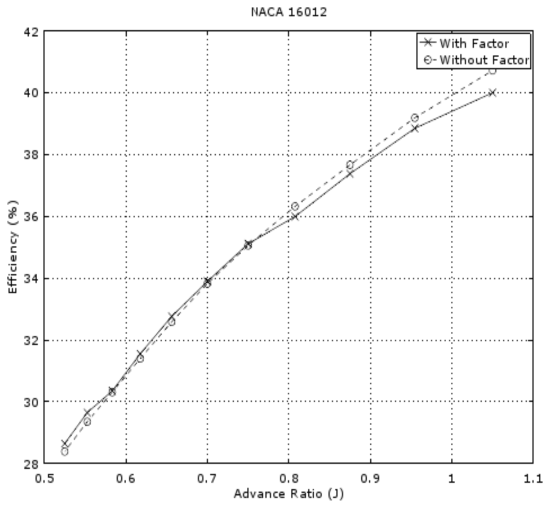

Figure (5): Effect of Prandtl correction factor for NACA 16012

evident that increasing propeller size due to increase its diameter would increase the contact surface area of airfoil with incoming air, causing more thrust produced along the blade. However, that increase in propeller size requires more torque by the engine to drive this large propeller, resulting in a drop in efficiency. In other words, increasing propeller diameter will make a better operation performance, but it will reduce propeller efficiency.

4.5 Effect of Prandtl tip loss correction factor on propeller efficiency

The graph of the Fig (6), shows a general drop in efficiency, and an overlapping region appear at $J \leq 0.75$ with a slightly increase in efficiency. The effect on induced velocity in the propeller plane is most pronounced near the tips of the blades. The original BEMT does not consider the influence of vortices shed from the blade tips into the slipstream on the induced velocity field. These tip vortices create multiple helical structures in the wake, and play a major role in the induced velocity distribution along the propeller; thus reducing the resulting forces in the vicinity of the tip. Prandtl factor was used to correct the the induced velocity field, and compensate for this deficiency in BEMT.

4.6 Effect of twisting the propeller blades

It can be seen distinctly from Fig (7), that blades with built in twist experience a

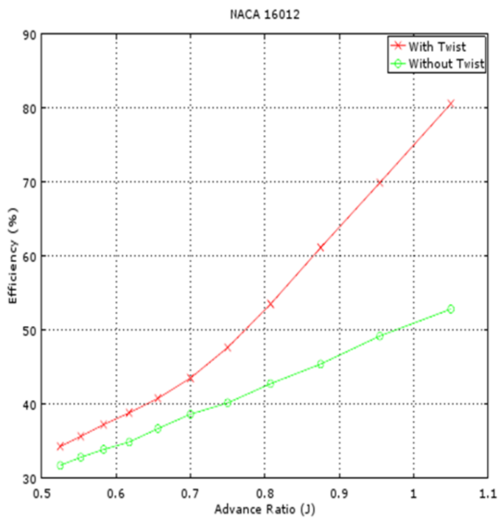

Figure (6): Effect of twisting propeller blades of NACA 16012

considerable rise in efficiency with increasing advance ratio compared with blades without twist for the same operating conditions. Twisting the blade will ensure angle of attack to maintain small as minimum as possible which provide greater lift over drag; in other world, higher C_L/C_D can obtained due twist, and thus constant circulation around the airfoil section that in turn will result in steady thrust across the blade.

5. Conclusion

In this paper, a study was made into the various parameters of a propeller showing that at low advance ratio a propeller with low chord will increase the efficiency, while at high advance ratios a propeller with high chord will increase the efficiency. Increase blade length (diameter) lead to more thrust produced along a blade. Also that increase yield a drop in propeller efficiency as the blade length increase the thrust generated increases, but in the other hand, torque required to produce that thrust is greatly increase more than that thrust. The blade orientation effect is found to be that at low pitch angles the propeller will have higher efficiency than at higher pitch angles. Number of blades effect on efficiency is marginal where a propeller with a higher number of blades will do slightly better achieving a small increase in efficiency, provided consideration were made to maintain the same solidity. Since, there are no alternate means to calculate the torque, thrust and efficiency the results shown are not validated, hence more extensive study can be made to further understand the effects of propeller parameters on its performance.