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Design of a Constant Chord Single-Rotating Propeller using Lock and Goldstein Techniques

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Abstract**—**Design of a constant chord propeller is presented in this paper in order to reduce propeller's design procedure's costs. The design process was based on Lock and Goldstein's techniques of propeller design and analysis. In order to calculate optimum chord of propeller, chord of a referential element is generalized as whole blades chord. The design outcome which named CS-X-1 is modeled & analyzed by CFD methods using K-ε: R.N.G turbulence model. Convergence of results of two codes proved that outcome results of design process are reliable. Design result is a two-blade propeller with a total diameter of 1.1 meter, radial velocity of 3000 R.P.M, efficiency above .75 and power coefficient near 1.05.

Keywords**—**Single rotating propeller, Design, C.F.D. test, constant chord

I. INTRODUCTION

FIRST analytic method for estimation of propeller performance was based on graphical calculations. Regards to C.N.H. Lock initial theory presented in British report and memoranda number 1623 in 1935[1]. Then in 1939 Creiger's experimental studies in NACA showed that graphical methodsare accurate in a 10 percent accuracy order[2]. In 1943 Theodorson's efforts presented accurate experimental values for circulation functions and definition of mass coefficient which was a valuable assist in more accurate estimation of propellers performance[7]. Since mid 60's main interest of propeller profession scientists was computational calculations for design and analysis of propellers but Blade element theories remains popular due to their low costs and realizibility till now.Nowadays, because of costs of propeller design, most of aircrafts use "generally designed propellers". These propellers have been designed for a certain working regime including specific rotational and axial speed. And because of slight difference between propellers optimum working regime and aircraft's flight regime real efficiency of installed propeller onthis aircrafts is far less than optimum design efficiency[4]. This variance between real and design efficiency is most remarkable in light aircrafts such as UAVs hovercrafts and ground effect aircrafts because of their particular design regime.

Main reason of the large efficiency drop is the difference between propellers design advance ratio and propellers real advance ratio. [fig.1] shows sharp efficiency drop around design point of a sample propeller.

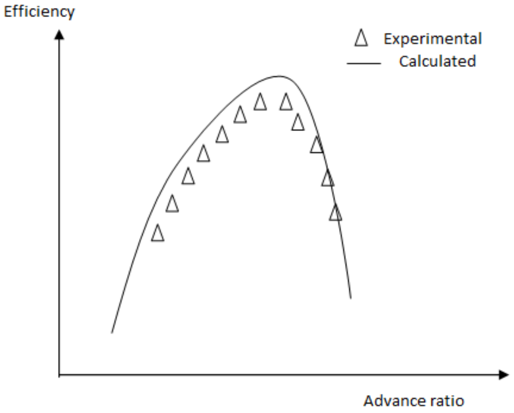

Fig.1 Efficiency drop in different advance ratios[3]

In this research design and performance of a constant chord propeller studied in to reduce design procedure costs.So specific design of propellers will be possible and result a significant improvement in economic and performance of propellers use in aircrafts. Famous Lock and Goldstein were utilized and modified in order topresenting a regular and specific design procedure.

II. DESIGN PROCESS

Design procedure of the constant chord propeller is based on Lock and Goldstein techniques of propellers design and analysis. Initial data for this design procedure are: shaft horse power, estimated propeller disk revolution per second, flight altitude, cruise speed and airfoil data bank.There are many considerations such as aerodynamic or structural concerns to choose a proper airfoil for propeller design. But in aspect of performance, main parameter is Cl/Cd which expected to acquire maximum values in low angles of attack[8].In this design process, aftera general estimation of propeller disk diameter and propeller's blade radius, specifications of a referential element of propeller will be located in 0.7 of radius of blade estimated by a complete curse of Lock and Goldstein analytic techniques. Then chord of this referential element will be generalized as a whole blade chord. And then specifications of other elements will be calculated. All initial estimations will be corrected during design process. Propeller disk diameter could be calculated by fallowing equation after choosing a proper advance ratio from design charts[7]:

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$$\lambda = \frac{V + \omega}{nD} \tag{1}$$

Where v is extreme velocity speed, n is disck reveloution per second, D is disk’s diameter and reward helical displacement velocity will become from[4]:

$$\omega^2 = \frac{2p}{\rho[(1 + 0.2\, M_\infty^2)^{3.5} - 1]} \tag{2}$$

For resultant velocity[1]:

$$W = W_0 \cos(\gamma_i) = \sqrt{{V_a}^2 + (\pi r n_s)^2} \cos(\gamma_i) \tag{3}$$

Which γ is induced angleAnd total angel of the real incoming flow[1]:

$$\phi = \phi_0 + \gamma + \alpha \tag{4}$$

And[1]:

$$V_a \tan \phi_0 = n_s r \tag{5}$$

Here $\phi_0$is blade pitch angle. Lock tip loss factor utilized in order to calculating induced velocity and induced angle. Lock tip loss factor is corresponded to blade geometry and advance ratio. It can be calculated by[3]:

$$X_0 = \frac{\sigma C_l}{4 \tan \gamma_i \sin \phi} \tag{6}$$

Also this factor stated in[3]:

$$X_0 = \frac{1}{a_x \sqrt{\gamma_i} + b_x \gamma_i} \tag{7}$$

Where[3]:

$$\begin{aligned} a_x &= 0.3254\lambda^2 + 0.3529\lambda + 0.4449 \\ b_x &= 0.8213\lambda^2 - 0.0854\lambda + 0.0628 \end{aligned} \tag{8}$$

Power coefficient in an experimental equation stated as[3]:

$$C_p = \frac{550\, SHP}{\rho n^3 D^5} \tag{9}$$

And also as a function of blade geometry[7]:

$$\frac{dC_p}{d\,x} = \frac{\pi^4}{4} (\sec^2 x) \sigma Cl \left(\sin \varphi_0 + \frac{c_d}{c_l} \cos \varphi_0 \right) \tag{10}$$

Utilizing above equation gives a good approximate value of propeller’s blade section solidity. By blade section’s solidity, element’s chord finally comes from[8]:

$$Ch = \frac{2\pi r \sigma}{No.Blades} \tag{11}$$

After calculating blade geometry، trust and torque values can be calculated from[1]:

$$\begin{aligned} T &= L \sin\varphi_0 - D \cos\varphi_0 \\ Q &= L \cos\varphi_0 + D \sin\varphi_0 \end{aligned} \tag{12}$$

And also non-dimensional coefficients for propeller performance and trust coefficient can be calculated from[3]:

$$C_T = \frac{T}{D^4 \rho n^2} \tag{13}$$

And torque coefficient[3]:

$$C_Q = \frac{Q}{\rho n^2 D^5} \tag{14}$$

And finally efficiency will be defined as ratio of beneficial energy to total input energy[3]:

$$\eta = \frac{T.V}{2\pi.\, n_s.\, Q} \tag{15}$$

III. DESIGN OUTCOME

After defining design method a real design procedure will be completed to study outcomes of a single rotating constant chord propeller. Since all performance parameters in distribution profiles depend on blade’s element area ، so it is important to predict parameters behavior when element’s area is constant along span wise. This impotency is due to performance or structural or vibration concerns. Here design input was assumed as a real light weight aircraft such as a sport aircraft, UAV or WIG aircraft by shaft horse power about 50, cruise speed equal to 200 km/h which is flying near sea altitude.Design result is a two-blade propeller with a total diameter of 1.1 meter, radial velocity of 3000 R.P.M, efficiency above .75 and power coefficient near 1.05. In this design distribution profiles of total incoming velocity [fig.2], trust [fig.3], resistance force [fig.4], trust coefficient [fig.5] and efficiency [fig.6] showed ascendant behavior while profile of power coefficient [fig.7] was falling.

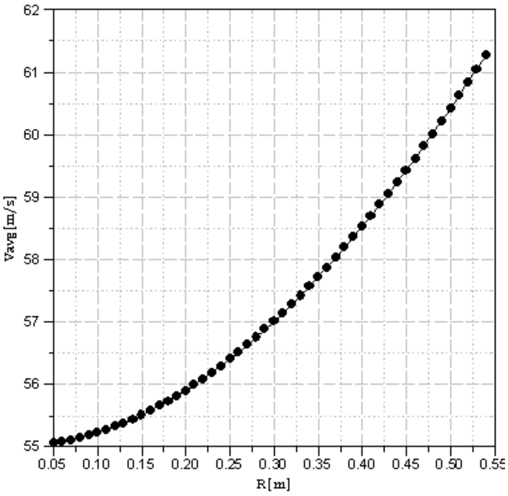

Fig. 2 Total velocity distribution

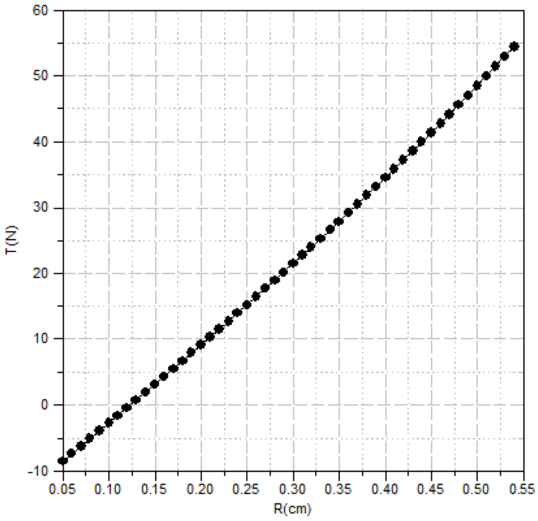

Fig. 3 Trust distribution

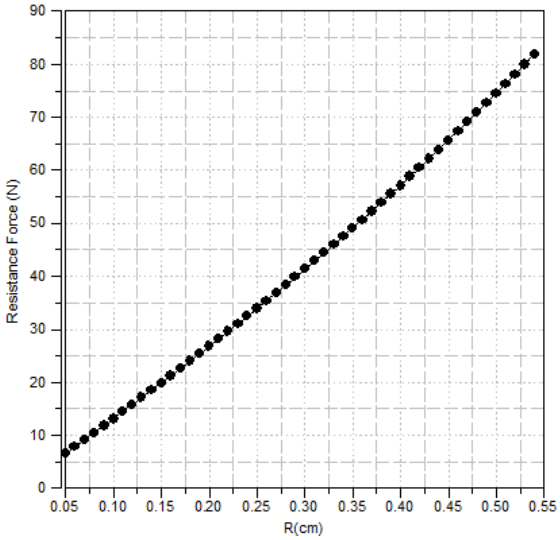

Fig. 4-Resistance force distribution

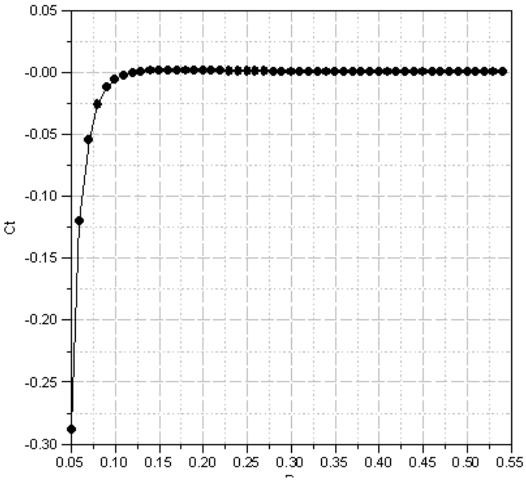

Fig.5 Trust coefficient distribution

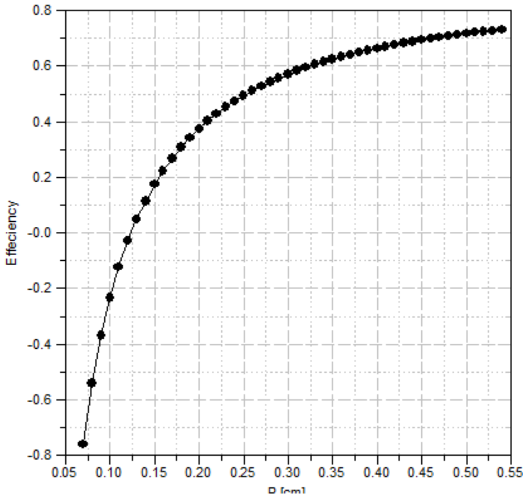

Fig. 6Efficiency distribution

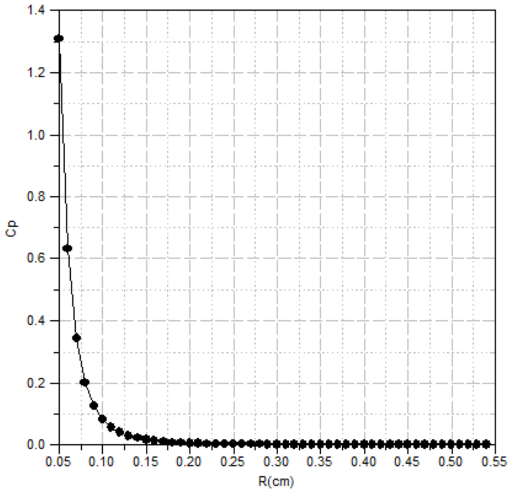

Fig.7. Power coefficient

IV. C.F.D. TESTS

Blade element theory passed through many experiences since initial presentation, hard tasks such as experimental tests or functional design. This theory was proved as a reliable one. But in this research due to importance of results for farther utilization, design outcomes were validated by comparing with C.F.D. tests.

Usually only available data from turbulence solution in propeller cases are speed and pressure measures and initial force values. In this research a pre and post processing method named horizontal element separation would be utilized to gain more information about C.F.D tests output such as torque distribution profiles and efficiency.

In H.E.S. method، blade span separates into several similar horizontal elements. Just due to blade element theory this elements must have equal advance ratio along each element span. C.F.D. software's like Fluent or C.F.X. can report forces in coordinate system axis. And Element torque can be written by[5]:

$$\qquad (16)$$

Where[5]:

$$L_c = \frac{\int_{l_0}^{l} R_{Real} dL}{R_{Real}} \qquad (17)$$

And after situation of resistance force it could be written as[5]:

$$L, \qquad (18)$$

According previous investigations advice's k-epsilon: R.N.G. turbulence model was chosen for C.F.D. test in this research. An un-structured triangular mesh was chosen for model [fig.10] and blade span divided in to 10 equal elements due to H.E.S. method.

C.F.D test results showed a close match with design outcomes. Trust [fig.8] and torque [fig.9] distributions also showed similar behavior with design results. In these profiles a major drop due to tip vortex effects could be seen. Comparing blade's front and back static pressure contours [fig11] also showed an acceptable pressure distribution along blade's span wise.

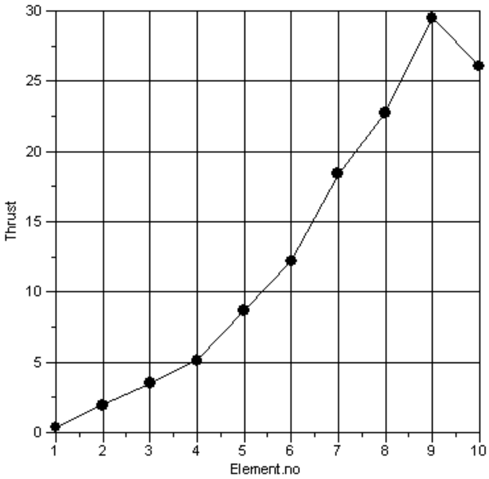

Fig. 8- Trust distribution due to C.F.D. test

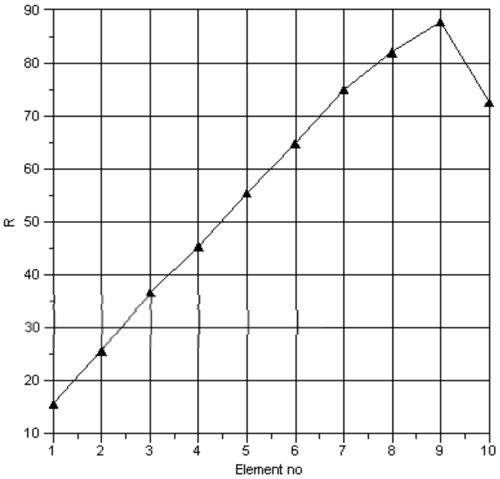

Fig. 9-Resistance force due to C.F.D. test

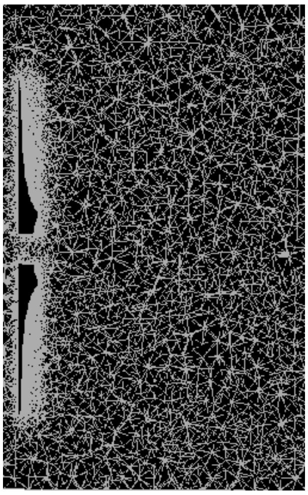

Fig.10 Un-structured mesh around model

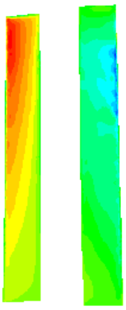

Fig.11 pressure contours on blade sides

TABLE I
COMPARTION OF C.F.D. AND DESIGN OUTCOME

Parameter source	**Trust**	**torque**	**Efficiency**
Design result	250	16	75
C.F.D. test	235	16.5	65

V. CONCLUSION

This research proved that problem of efficiency drop in generally designed propellers could be solved by using constant chord propellers design. Generalizing lock’s referential element’s chord also showed an acceptable effect on propellers performance. Design result had an efficiency around .75 which is high value in in propeller design and this efficiency proved that an acceptable design for a constant chord propeller will have the same aero dynamical performance as a variable chord one. However using a constant chord propeller may have structural benefits to.

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