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Analysis of Distribution of Thrust, Torque and Efficiency of a Constant Chord, Constant Pitch C.R.P. Fan by H.E.S. Method

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Abstract**—**For the first time since 1940 and presentation of theodorson's theory, distribution of thrust, torque and efficiency along the blade of a counter rotating propeller axial fan was studied with a novel method in this research. A constant chord, constant pitch symmetric fan was investigated with Reynolds Stress Turbulence method in this project and H.E.S. method was utilized to obtain distribution profiles from C.F.D. tests outcome. C.F.D. test results were validated by estimation from Playlic's analytical method. Final results proved ability of H.E.S. method to obtain distribution profiles from C.F.D test results and demonstrated interesting facts about effects of solidity and differences between distributions in front and rear section.

Keywords**—**C.F.D Test, Counter Rotating Propeller, H.E.S. Method, R.S.M. Method

I. Introduction

USUALLY single rotating propeller's analytical methods are used to design and analyze counter rotating propellers and counter rotating fans. These methods are not accurate enough to gain exact data for vibration and fatigue analysis. But there are three special methods for design and analysis of counter rotating propellers so far. First method, developed by Ginzel,[2] makes no presumption about the distribution of span wise circulation across the blade. It is restricted to the use of aerodynamics that results from propellers, which were built in accordance with the structural constraints existed at the time the theory was developed. This structural restriction was applied in 1943 and is not pertinent with respect to the current state of technology. For example, with the advent of composite materials and high strength alloy metals, the structural assumptions that Ginzel based his method on are no longer valid.

Other methods for the design of counter-rotating propellers include SBAC method and a theoretical model developed at United Technologies Research Center (UTRC). SBAC method is computationally very cumbersome as it is a design-by-analysis method and requires data interpolation and cross referencing. UTRC method requires extensive computer time and memory [9].

In another method, Naiman uses a modified strip theory in which approximations for the interference relations from the front and aft propeller disks are assumed such that the interference calculations are functions of each propeller disk independently. Naiman uses sectional aerodynamic characteristics as a basis for his derivations, and hence allows the use of various families of airfoils and different structural constraints. Sectional circulation to determine the interference relations is also utilized by Naiman, and therefore the method is adaptable to change technology.

Another counter-rotating propeller calculation method investigted was Lock and Theodorsen [7]. As described by Davidson, this method uses an interpolation scheme between both propeller disks for the interference of one disk upon the other, and requires the use of the circulation of the entire configuration as an input for calculation of the interference relations. Similar to Nairnan's method, Davidson's approach is easily expanded to off-design analysis [6].

Since Ginzel's method was considered unacceptable, as were SBAC and UTRC methods for ease of use and applicability to design, the methods of Naiman and Davidson were chosen for further development and investigation. The results of computer-generated designs for these two theoretical models were compared to determine which model was superior for reasons of accuracy, computational efficiency and further development. The results of the comparison of the two methods by Playle have shown that the Lock and Thedorsen method, given by Davidson, was more accurate. Davidson's approach yielded realistic designs of counter-rotating propeller configurations in terms of planform and performance values and was adaptable to further development. In addition, inclusion of drag and compressibility shown in this work were the most useful modifications using this theoretical approach. Davidson's method was also found to be adaptable to include off-design analysis, disk spacing, blade weep, and different angular velocities on each propeller disk.

II. Counter Rotating Propellers Design and Analysis

The main advantage of counter-rotating propellers stems from the swirl velocity losses of the front propeller disk being recovered by the aft propeller disk. The front disk imparts a tangential velocity to the air as it passes through the front

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propeller disk plane. This swirl velocity acts as an additional angular velocity for the aft disk, without the power plant having to drive the aft disk at a higher angular velocity. Fig. 1 and 2 show the velocity diagrams for the front and aft disk, respectively. It may be noted that a tangential interference velocity is recognized by the front disk, but is typically an order-of-magnitude smaller than other interference velocities and therefore neglected, resulting in a first order theory for the design and analysis of counter- rotating propellers.

Airfoil data, such as lift, drag, and angle of attack are specified for each radial location along the propeller blade. This is done through the use of airfoil data banks, utilizing either tabulated data or empirical formulations that yield airfoil lift and drag as functions of angle of attack and Mach number. The airfoil data used in the calculations during the design process was selected to maximize the lift-to-drag ratio of the airfoil used at each radial location dong the blade. In regions near the hub, where the propeller blade quickly transitions from an airfoil to a right circular cylinder, a different approach has been taken. To accommodate this transition, the chord length is linearly interpolated from that calculated to a structurally feasible cylinder at the hub. The design procedure involves calculations, which include division by the lift coefficient, to determine chord length. Since the lift coefficient of a circular cylinder is zero, it may be noted in the development of the theoretical model that it is necessary to maintain a finite-lift coefficient to insure arriving at positive values of the blade chord.

Once the airfoil data have been specified, a comparison scheme is initiated whereby the power input to the propeller and the power absorbed by the propeller are matched. This iteration scheme begins with an assumed value for the propeller efficiency, which need not be accurate since q will be changed by the iteration process. From the assumed propeller efficiency Betz's coefficient is calculated, which is the parameter through which the iteration process is conducted. Davidson has derived Betz's coefficient using calculus of optimization as [9]:

$$b_k=4(1-\eta) \qquad (1)$$

Calculation of the rearward helical displacement velocity may be accomplished by the expression [4]:

$$w^2=2p/\rho[(1+0.2M_\infty^2)^{3.5}-1] \qquad (2)$$

where M_∞ is infinite stream mach number and p is bladesnumber. Using the experimental values of circulation by Theodorsen as a function of r/R and $(V+ w)/nD$, the circulation $K(x)$ can be found for each radial location as noted in Fig 3.

The present method for designing and analyzing counter-rotating propeller configurations is two dimensional by virtue of the strip-analysis approach. However, the propeller is primary a three-dimensional flow phenomena, and therefore a method to include the difference between two and three-dimensional flow is required.

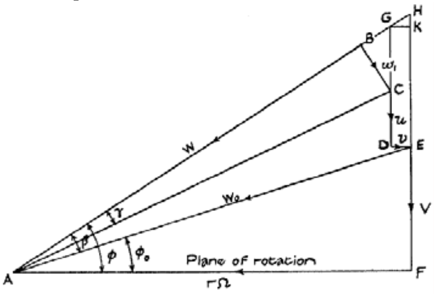

Fig. 1 Velocity diagram for front propeller disk [1]

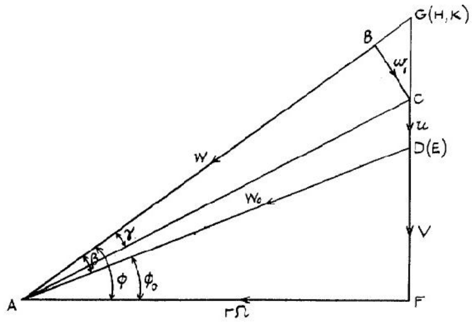

Fig. 2 Velocity diagram for back propeller disk [1]

Davidson derived a version of Lock's tip-loss factor for specific application to counter-rotating propellers, which is a well behaved function that is different from a single-rotation propeller. A reformulation for Lock's tip-loss factor that includes drag has been derived and takes the form [4]:

$$X_0= qs/(2p-qrs) \qquad (3)$$

Where:

$$p=\frac{1/2}{cos\Phi_0}\left(sin\Phi_0+\frac{C_D}{C_L}cos\Phi_0\right) \qquad (4)$$

$$q=\frac{1}{sin\Phi_0} \quad r=cos^2\Phi_0-sin^2\Phi_0 \qquad (5)$$

$$s=(J/\pi x)/[K(x)sin\Phi_0] \qquad (6)$$

Where Φ_0 is element pitch angle and J is advance ratio. The solidity-lift coefficient for each radial location on each disk is then given by:

$$\sigma C_L=\left[\frac{\frac{1}{2}}{b_k}\left(sin\Phi_0+\frac{C_D}{C_L}cos\Phi_0\right)cos\Phi_0-\frac{C_D}{C_L}\right]+\left[\frac{1}{2sin\Phi_0}\left(\frac{1}{X_0}+cos^2\Phi_0-sin^2\Phi_0\right)\right] \qquad (7)$$

With the value of C_D/C_L arrived at through use of the airfoil data banks. Having calculated the solidity-lift coefficient, the differential power coefficients, which are measures of the power absorbed by each propeller disk, can be computed by [3]:

$$\frac{dC_p}{dx} = \frac{\pi^4}{4}(sec^2\Phi_0 x^4 \sigma C_L(sin\Phi_0 + \frac{C_D}{C_L}cos\Phi_0 \quad (8)$$

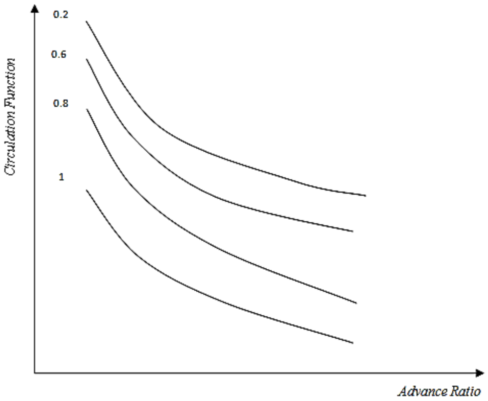

Fig. 3 circulation function for dual-rotation propeller, four blades, front and back propeller disk

Equation (6) is integrated to find the total power coefficient for the power absorbed by both the front and aft propeller disk. The power absorbed IS compared to the power input to the propeller by the power plant, which is dictated by the available horsepower of the power plant specified in power coefficient form by:

$$C_P = 350SHP/\rho n^3 D^5 \quad (9)$$

If the two values of the power coefficient do not match within a given tolerance, Betz's coefficient is adjusted and the power absorbed is recalculated following the outlined procedure. The adjustment made to Betz's coefficient represents alterations in the planform of the propeller blade, and thus propeller blade loading. Should the power absorbed be lower or higher than the power input, Betz's coefficient is increased or decreased, respectively. The iteration process is continued until the power absorbed by the propeller is within a predetermined percentage of the power input to the propeller.The condition of the power absorbed by the propeller being equal to the power input, defines the optimum propeller for the given flight conditions since the configuration was designed using the maximum lift-to-drag ratio for the chosen airfoil at each radial location. Also, since the form of Btz's coefficient has been determined through calculus of optimization and used as the iteration parameter, the resulting design is considered to be the optimum counter-rotating propeller for the input condition.The physical geometry of the propeller is calculated axe the solidity-lift coefficient radial distribution has been defined through the above iteration process. By iterating between the resultant interference velocities and the resultant total velocity, both the interference and total velocities can be found by the following expressions:

$$W_F = r\Omega_F sec\Phi_0 \cos(\Phi_F - \Phi_0) + u_F sin\Phi_F \quad (10)$$

$$W_B = r\Omega_B sec\Phi_0 \cos(\Phi_F - \Phi_0) + u_B sin\Phi_B + v_B cos\Phi_0 \quad (11)$$

$$u_F = X_0\omega_{1B} cos\Phi_0 \quad (12)$$

$$u_B = X_0\omega_{1f} cos\Phi_0 \quad (13)$$

$$v_B = 2X_0\omega_{1f} sin\Phi_0 \quad (14)$$

Where:

$$\omega_1 = \Phi C_L W/4X_0 sin\Phi_0 \quad (15)$$

The differential thrust and torque are functions of the resultant velocities and calculated by the following expressions[2]:

$$\frac{dT}{dr} = \pi\rho r\sigma C_L W^2(\ cos\Phi_0 - \frac{C_D}{C_L}sin\Phi_0\ ) \quad (16)$$

$$\frac{dQ}{dr} = \pi\rho r^2\sigma C_L W^2(\ sin\Phi_0 - \frac{C_D}{C_L}\ cos\Phi_0\ ) \quad (17)$$

Integration of Eqs. (16) and (17) results in values of thrust and torque, hence the thrust coefficient, torque coefficient, and efficiency, i.e.,

$$C_T = \frac{T}{\rho n^2 D^4} \quad (18)$$

$$C_Q = \frac{Q}{\rho n^2 D^5} \quad (19)$$

$$C_P = 2\pi C_Q \quad (20)$$

$$\eta = C_T J/C_P \quad (21)$$

At this point, the radial values of the blade planform and twist distribution for each propeller disk can be calculated from:

$$Chord = 2\pi\rho r\sigma C_L/(No.Blades)C_L \quad (22)$$

$$\beta = \Phi_0 + B + \alpha \quad (23)$$

Where:

$$B_F = \left(\frac{\sigma C_{L_F}}{4X_0 sin\Phi_0}\right)(1 + X_0 cos^2\Phi_0) \quad (24)$$

$$B_B = \left(\frac{\sigma C_{L_B}}{4X_0 sin\Phi_0}\right)(1 + X_0 cos^2\Phi_0 - 2sin^2\Phi_0) \quad (25)$$

It is noted that the values for angle of attack were selected through the iteration process. In the present method, which uses the airfoil data banks, the numerical routine has used values for angle of attack that correspond to maximum lift to drag ratios at each radial location for each propeller disk.

As previously discussed, there exists a difficulty in the calculation of chord lengths in the region near the hub. In this segment of the blade, the structural requirements force the airfoil to take on the characteristics of a circular cylinder. As a result, the solidity-lift coefficient may take on negative values as the shank region of the propeller is approached because of large values of C_D and relatively small values of C_L.AS noted in Eq. *(51,* for large values of C_D/C_L, the numerator becomes negative. Examination of Eq. *(20)* indicates that for negative solidity-lift coefficients, the chord length would also result in a negative value. In the present study, it was determined that the most acceptable means to calculate chord length in the vicinity of the hub region would be through a linear interpolation of the chord length from the radial location, where the slope of the planform goes positive to a value of zero at *r/R=0.*

Once the chord length has been calculated, a new value for the solidity-lift coefficient must be found to complete the calculations for the radial variation of thrust and torque:

$$\sigma C_L = (No.Blades)(Chord)C_L/D\pi x \qquad (26)$$

By this present approach, any possibility of negative chord lengths in the region of the hub during the numerical design procedure is eliminated.

III. H. E.S. Method

Horizontal Element Separation method is a pre and post processing technique to be used for aerial and marine propeller-fans in order to obtain distribution profiles across the blade span [5]. In this method, span will be separated to horizontal elements with equal advance ratio across each element. Advance ratio could be calculated from [3]:

$$J = \frac{V+\omega}{nD} \qquad (27)$$

This method allows analyzers to use C.F.D. tests outcomes as blade element theory's input, in a reversed concept. Having thrust and resistance force from C.F.D. test, torque of each element would come from [5]:

$$Q = R_{real} L_c \qquad (28)$$

Where[5]:

$$L_c = \frac{0.5\rho V^2 S}{R_{real}} \int_{l_0}^{l} (C_l \sin\left(\frac{V_a}{rl} + \gamma + a\right) - C_d \cos\left(\frac{V_a}{rl} + \gamma + a\right))dr \qquad (29)$$

IV. C.F.D. Test's Validation

Due to compliments of interference velocities, it is not possible to determine exact thrust and torque of a constant chord and constant pitch fan but in this project and in order to validate C.F.D. tests, we estimated a possible range of thrust for each section by the analytical method of Lock and compared the results with this acceptable range.

TABLE I
Validation of C.F.D. Test

Section	Max. Thrust	Min. Thrust	Thrust
Front	35.00	28.00	29.09
Back	15.00	8.00	11.13

V. Results

A constant chord, constant pitch, symmetric counter rotating fan was analyzed in this project. This fan has a diameter of 40 Cm and radial velocity of 6 m/s with NACA 2412 airfoil cross section. Front section's referential element's angle of attack had been set for 6 degree and rear's set for 4 degree. In order to investigate effects of solidity in distribution profiles 4, 8 and 12 blades were considered for this fan in several tests. Constant chord and pitch fans are easy to design and model but they are harder than regular fans to analyze.

Results showed thrust distribution in front and rear blades [Fig. 4]. After post processing resistance force values, torque profiles were drown for front and rear blades[Fig.5], having thrust and torque of each element, efficiency distribution profiles were also drown for front and rear section[fig.6].

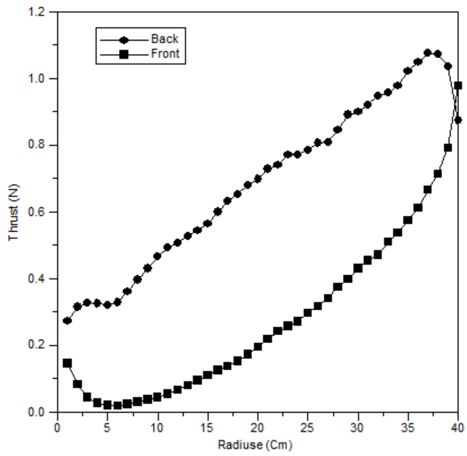

Fig. 4 Thrust distribution on blades

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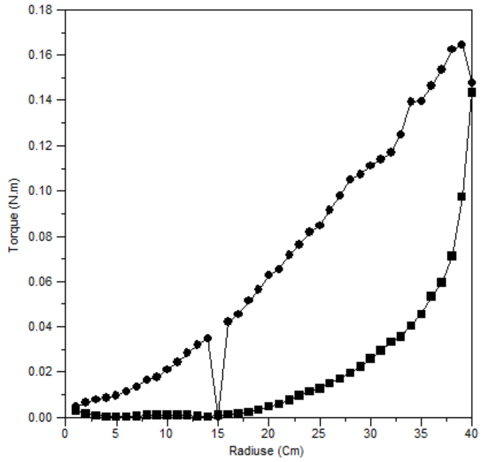

Fig. 5 Torque distribution on blades

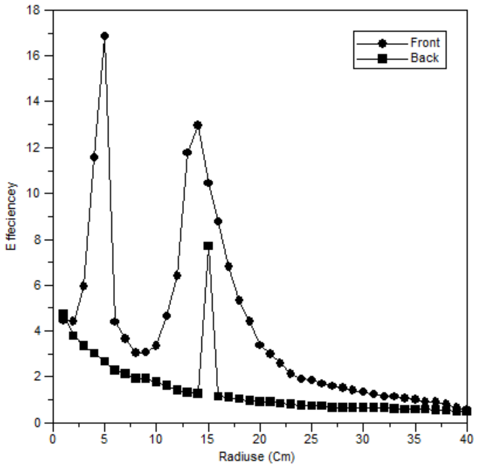

Fig. 6 efficiency distribution on blades

VI. Conclusion

A constant chord, constant pitch, counter rotating fan was tested in C.F.D. environment in this research. H.E.S. method proved its ability to draw distribution profiles for a counter rotating propeller fan. Comparison between slope and shape of each profile in front and rear sections shows significant facts about effects of tip vortex and induced angels on distribution profiles. This data also could be used as input for codes of calculation of induced velocities and distribution functions as authors' article declared in Aero2011 conference in Tehran[5]. Results of this project will also be a significant asset in vibration and fatigue analysis of C.R.P. fans.

References

[1] C.N.H Lock, A graphical method of calculation the performance of an airscrew, 1935, British A.R.C. report and memoranda 1675.

[2] G. Bull and G. Bennett, propulsive efficiency and aircraft drag determined from steady state flight test data, Mississippi state university department of aerospace engineering, society of automotive engineers, 1985.

[3] S. Slavik, preliminary determination of propeller aerodynamic characteristics for small aero planes, Actapolytechnica, VOl.44, No.2.2004.

[4] E.P. Hartman and D. Biermann, the aerodynamic characteristics of full scale propellers having 2, 3 and 4 blades of Clark Y and R.A.F. airfoil sections, 1938, technical report No.640 N.A.C.A.

[5] M. Abbaszadeh, R. Shabani, M. Shahrooz, P. Nikpur, presentation of horizontal element separation for analyzing aerial propellers, 2011, 10th Iranian aerospace society conference.

[6] T. Kokturk, design and performance analysis of a revirsable axial flow fan, 2005 M.S. Thesis university of east Mediterranea, departeman of mechanical engineering.

[7] T. Teodorson, The theory of propellers determination of the circulation function and the mass coefficient for dual rotating propellers, 1939, N.A.C.A report No. 775.

[8] W.f. wolfe, S. Stuart. C.F.D calculations of s809 aerodynamic characteristics, AIAA-97-0937.