AERODYNAMICS ANALYSIS OF CYCLOIDAL ROTOR

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Abstract

An improved aerodynamics model for cycloidal propellers based on Leishman-Beddoes(LB) dynamical stall model is presented in this paper. The validations are made between the experimental data and the results from presented model. The validations proved that the presented model is applicable for cycloidal propeller performance evaluation under hovering status. Based on the analysis with the calculation results, some of the mechanisms about how the efficiency of cycloidal propeller could be improved are revealed.

1 Introduction

Cylcoidal rotor is a rotor system that the blades rotate around an axis parallel to its span wise direction [1-3], usually used by cyclogyros, LTAs and boats. The pitch angle of each blade varies cyclically by an eccentric such that the blades experiences positive angles of attack at both the top and bottom positions of the azimuth cycle. The resulting time-varying lift and drag forces produced by each blade can be resolved into the vertical and horizontal direction. Varying the amplitude and phase of the cyclic blade pitch can change the magnitude and direction of the net thrust vector produced by the cyloidal rotor.

The flow on the blades is strongly unsteady when the cycloidal propeller rotates, thus it is very difficult to predict the aerodynamics performance. There are two categories of aerodynamics computation model for the cycloidal propeller, CFD and theoretical-experimental method. With a CFD tool, we can make a good understanding of flow field around the cycloidal rotor, and it is helpful for more efficient design. However, a problem caused by using CFD is its long computation time, and thus is not very suitable for the preliminary design and optimization. This is why the theoretical-experimental method is needed.

Mcnabb model [4] is one of the most famous theoretical-experimental aerodynamics force model for the cycloidal propeller. The lift computation is based on the Theordorson oscillating airfoil theory and the blade element theory. The zero-lifting drag in the steady flow is used as the value in the unsteady flow. And the induced drag of the blade is calculated with a formula, which includes a modified Oswald Efficiency factor derived from the experimental data. Then the thrust and power can be calculated. However, the Mcnabb model does not consider the effects of fluid viscosity, the flow separation and the shed vortex on the leading edge of the blade, thus it is only suitable for the cycloidal propeller in which blades experience low reduced frequency and small angle of attack.

In this study, a new aerodynamics force computation model for cycloidal propeller is presented. The model is based on the state-space based Leishman-Beddoes model[6-9], which can consider the effects of the airfoil and the flow separation, thus the precision of the zero-lifting drag is improved. Based on the analysis, some mechanisms about the aerodynamics of the cyclorotor are revealed.

2 The aerodynamics model based on LB dynamic stall model

The primary parameters of cycloidal rotor include airfoil, disc diameter, blade span, number of blades, chord, offset distance and offset azimuth angle. Fig.1. is a sketch map of cyclocopter with four cycloidal rotors[5].

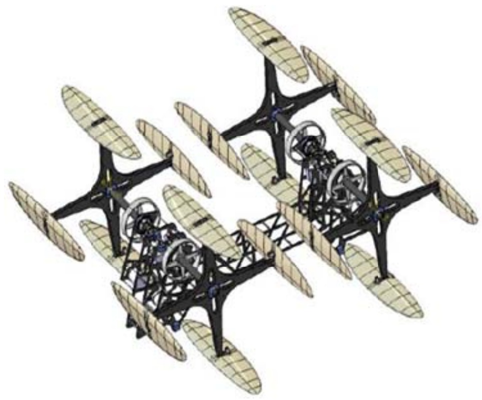


Figure 1. The cyclocopter with four cycloidal rotors

2.1. LB dynamic stall model

The underlying mechanism of the LB model is the indicial aerodynamic responses - changes in aerodynamic forces with respect to a step change in aerofoil pitch angle or pitch rate. For an arbitrary continuous motion, the corresponding total aerodynamic response is found by using this approach in conjunction with the superposition principle [9]. The details of LB dynamic stall model are introduced in the reference [6-9].

2.2. Methodology

The presented aerodynamics model is derived from the Mcnabb model[4]. The Leishman-Beddoes dynamic stall model [5-8] is introduced, so that the blade element lift and drag can be evaluated with high accuracy and the onset of flow separation also can be predicted. A local coordinate system is attached to each blade, LB dynamic stall model and blade element theory are used to calculate blade force at each time step within each cycle, then these force components are transformed into global coordinate system and added up to get the instantaneous thrust of cycloidal rotor ,

$$A = \sqrt{(A_Z)^2 + (A_X)^2} \qquad (1)$$

and power,

$$P = \sum_{\theta=0^o}^{360^o} \sum_{N} (D * V_t) \qquad (2)$$

Where A_Z , A_X is vertical and horizontal thrust respectively, D is blade drag, V_t is the blade tangential speed, N is the blade number, θ is the azimuth angle.

Compare the induced velocity with the given initial value when a periodic calculation is finished, if the difference between two values is less than the predefined error, stop the iteration; else use the dichotomy method to get a new induced velocity until it converged.

The proposed model needs two constants that appear in the equations about induced velocity and induced drag coefficient [4]. Using helicopter momentum theory, the induced velocity of the air through the cycloidal rotor is given by the following equation,

$$V_{induced} = \sqrt{\frac{Thrust}{2 * \rho * Const * A}} \qquad (3)$$

and induced drag coefficient is:

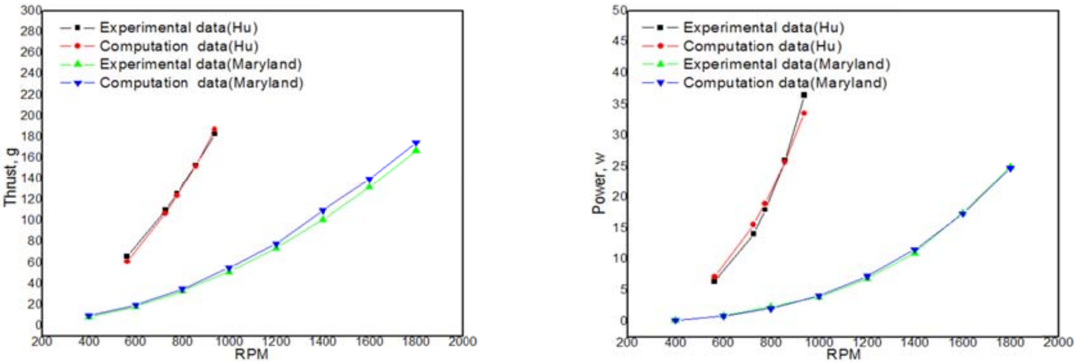
$$C_D = C_{D0} + \frac{{C_L}^2}{\pi * AR * Eff} \qquad (4)$$

Where ρ is the air density, A is the projected area, C_{D0} is zero-lift drag, AR is the aspect ratio, Eff is the Oswald efficiency.

The constants Const and Oswald factor Eff are set to be 0.26~0.55, and 0.6~1.5 respectively according to statistics data from experimental results. The experimental data and the results from proposed model match well, thus the high accuracy of the proposed model can be proved.

2.3. Validation

The comparison between analysis and experiment [1,2] is shown in Fig2. It can be seen that the computation results of the thrust and power coincide with experimental data well. Therefore the proposed model and the constants presented above are applicable for cycloidal propeller performance prediction under hovering status.



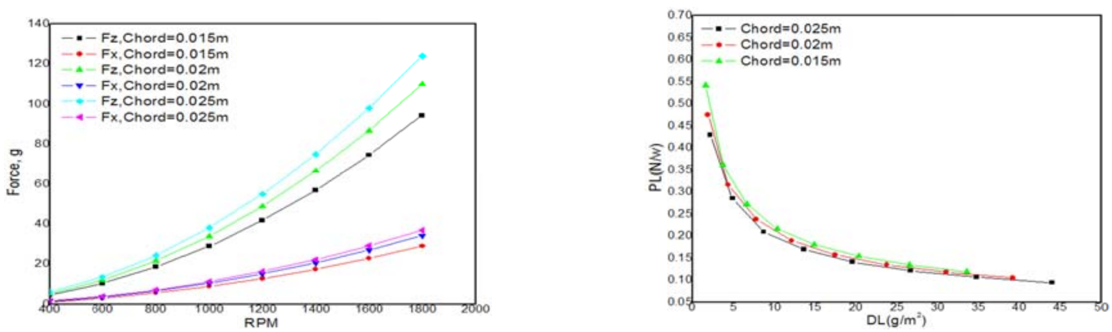
(a) The thrust vs. RPM (b) The power vs. RPM

Fig.2 The comparison between analysis and experiment

3. Computations and Analysis

All computations are based on 4-bladed cyclorotor. According to the computation results, the effects of several parameters, such as shape of rotor disc, blade pitching amplitude and blade chord, on the hovering performance are investigated.

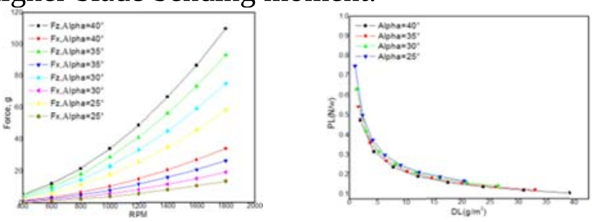
Fig.2. shows the performance of cyclorotor with blade chord length of 0.015m 0.02m and 0.025m. Computation results indicate that the larger the chord, the higher the lift. However, the power loading decreases a little bit as the chord length increases. But for the same thrust, the rotation speed of cyclorotor with shorter chord will be significantly higher than that with longer chord. This results in much higher centrifugal force acting on the blade which causes higher bending moments and also results in much higher forces imposed on the control mechanism which will reduce the mechanical efficiency.



(a) The thrust vs. RPM (b)The power –loading vs. disc-loading

Fig 2 The performance of cyclorotor with different blade chord length

The effects of variations in blade pitching amplitude are shown in Fig.3. Comparisons are made for blade pitch amplitude of 25°，30°，35°and 40°. From the results, it can be seen that the best efficiency was achieved for 25°pitching amplitude, followed by 30°，35°and 40°respectively. It also can be seen that at the same RPM, the cyclorotor produces larger force as the pitching amplitude increases. Since higher pitch angle causes higher AOA and hence higher blade lift forces. For a single pitching blade with high aspect ratio travels forward, it will stall before the pitching amplitude reaches 20°. But the blades remain un-stalled on cyclorotor at such a large pitch angle as 40°. From the computation it is found that the induced downwash velocity experienced by the blade is comparable to tangential velocity. Therefore, even though the pitch angle is very high, the large induced downwash decreased the effective blade angles of attack. This prevents the blade from stall. However, for a given thrust, smaller blade pitching amplitude needs much higher rotating speed. This causes higher mechanical loss which may lead to a lower total efficiency. Higher rotation speed also introduces higher blade bending moment.



(a) The thrust vs. RPM (b)The power –Loading vs. disc-loading

Fig 3 The performance of cyclorotor with different blade pitching amplitude

4 Conclusions

An aerodynamics analysis model based on LB dynamic model is presented. The high accuracy proves that this model is applicable for cycorotor performance prediction under hovering status.

The computation results show that:

a). The larger the blade chord, the higher the thrust. But the efficiency varies a little bit as the chord increases. For a given thrust, larger blade chord is preferred.

b). The induced downwash in the cycloidal rotor cage is comparable to the blade tangential velocity, thus the blades remained un-stalled at such a large pitch angle as 40°. And the results indicate that the larger the pitching amplitude, the larger the thrust, but the small pitching angle has better efficiency. Since for the same thrust, smaller blade pitching amplitude needs higher rotating speed and thus results in higher mechanical loss, the optimization that involves aerodynamics, structure and mechanical analysis shall be made to find the best pitching angle.

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