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AERODYNAMIC HYSTERESIS OF OSCILLATING AIRFOIL

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Abstract: *In the aerodynamic calculations, the steady aerodynamic data, which contain the coefficients in form of a function dependent only on the angle of attack (AoA) are used. However, the airfoil aerodynamic characteristics are always unsteady in the real conditions at the same AoA can be different because of the time delay, which occurs in dynamic state. The unsteady approach can improve the aerodynamic calculation process of propellers and wind turbines in the yaw (in the crosswind) or helicopter rotors at high forward speed. This paper contains the results of wind tunnel test of the oscillating airfoil which demonstrate hysteresis properties of airfoil aerodynamics and the dependency of aerodynamic hysteresis on the angular frequency.*

Keywords: Oscillating airfoil, 2D airfoil, Aerodynamic hysteresis, Angular frequency, Dynamic stall.

1. Introduction

The unsteady behavior of airfoils has been known as a cause of the undesirable aerodynamic phenomenon in helicopter main rotors, wind turbine blades, aircraft propellers, and wings. It is directly related to the dynamic properties of airfoil sections when they perform rapid pitching and plunging motion against inflow direction.

This report presents, in graphical form, some experimental aerodynamic data from the wind tunnel test of oscillating airfoils at the same flow condition, but at various angular frequencies. Test results show that lift and drag characteristics of airfoil section feature typical hysteresis loop shape which depends clearly on the frequency of pitching motion.

2. Theoretical analysis

The static pre-stall data of airfoils used in the aircraft industry is usually obtained from wind tunnel tests when the AoA of the airfoil section increases very slowly to minimize the influence of the rotation on the measured data. In the range of small AoA, the flow through the airfoil can be described by potential flow model and the static lift curve can be considered as a linear. When the AoA of airfoil increases to high-enough value, the flow around airfoil behaves like a separated flow. The so-called "pre-stall data" appear only in a certain range limited by a stall angle. Below this stall angle, the airfoil dramatically stops producing lift.

Dynamic stall is the delay of stall existence at high AoA. It is characterized by the shedding and passage over the upper surface of the airfoil. The typical aspect of this phenomenon is the increase of stall coefficients and stall angle (McCroskey, 1981 and Åhlund, 2004). In some cases, the lift coefficient in the dynamic stall can increase for about 50 to 100 % in comparison with its static value (Sharma, 2010).

There are many studies on the dynamic stall of airfoils, and the focus of this paper is on the cases of dynamic changes. During dynamic changes, the stall phenomenon does not appear, because the AoA of airfoil section changes around a relatively small value α_o, which is much lower than the static stall angle (Fig. 1). An example of dynamic change is the harmonic oscillating blade section of non-pitching propellers or wind turbines in steady yaw (Guntur, Sorensen, Schreck and Bergami, 2016). The vortex-

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shedding shows different shapes when airfoil rotates up or down and the aerodynamic curves look like closed hysteresis loops (McCroskey, 1981).

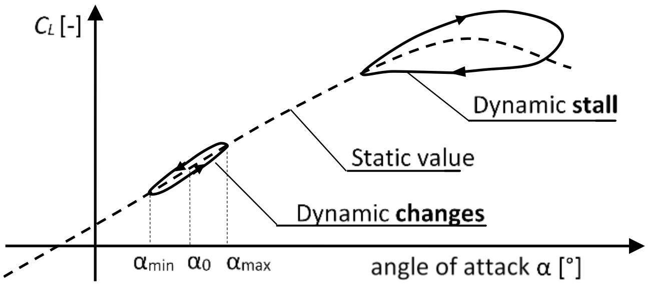


Fig. 1: Comparison of the dynamic stall and the dynamic change (Åhlund, 2004).

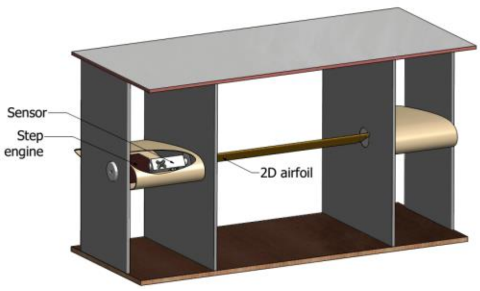
The AoA of airfoil section is changed from α_{min} to α_{max} and then returns to the minimum value with constant angular frequency ω. During one revolution of the rotor, the blade section operates harmonically with the oscillated movement. This movement can be described by the mean value α_o of the AoA with the amplitude $\Delta\alpha = (\alpha_{max} - \alpha_{min}) / 2$ and angular frequency ω. The static curve can be noted as a special case of the dynamic change in the same range of AoA when the angular frequency is zero.

$$\alpha = \alpha_0 + \Delta\alpha . \sin(\omega t) \tag{1}$$

The necessary condition of unsteady behavior on the airfoil is the non-zero angular frequency ω of the oscillating movement. The angular frequency ω can be estimated through the largest and smallest values of AoA $\omega = \Delta\alpha / \Omega$. If b is the chord of the airfoil and V is the onset flow velocity, the ratio between these two parameters defines reduced frequency $k = \omega\ b / (2\ V)$. In this paper, experimental results with different values ω are compared under the same test conditions.

3. Test setup

Test equipment used for the measurements of unsteady aerodynamic characteristics of wing section is shown in Fig. 2. Lift and drag forces acting on the airfoil section are measured by two two-component strain gauge balances, which are mounted on both ends of the airfoil section. The body of balance is milled from duralumin and each balance contains four strain gauges, which are connected to the full Wheatstone bridge with a total resistance of 700 **Ω**.



a) scheme of the test stand.

b) placement of test stand in the wind tunnel.

Fig. 2: Test set-up in wind tunnel.

The airfoil section has the same airfoil with chord $b = 58\ mm$ along the span $l = 60\ mm$. Both sides of the airfoil section are fixed and kept in position by sliding bearings, where the axis of rotation is at the 44 % of the chord (Tab. 1). One end can freely rotate while the second is fixed in the sensor. The position of this oscillating axis and the tested free flow velocity are limited by the holding moment of the stepper motor. Stepper motor is also used to generate the oscillation. This motor is connected to the NI stepper motion controller which has been programmed in LabVIEW software. At higher oscillating frequency, it is necessary to perform the correction for deviation of AoA at the boundary values. Symbol of rotating direction CCW indicates counterclockwise rotation, which is related to the side view of the test equipment. Measurement equipment is located in the open measurement section of a low-speed return-flow wind tunnel.

Tab. 1: Main parameters of test.

Test section size	600 mm x 58 mm x 10 mm	**Mean AoA α_o**	10 °
Wind velocity V	15 [m/s]	**Amplitude of AoA $\Delta\alpha$**	15 °
Maximum Re	128 000	**Mechanical tolerance**	± 0.45 °

4. Result and discussion

The AoA changes regularly around $\alpha_o = 10$ ° with an angular amplitude of $\Delta\alpha = 15$ °. The total AoA can be theoretically described by equation $\alpha = 10 + 15 \sin(\omega.t)$. The value of angular frequency ω is changed differently due to the speed regulation of electric stepper motor. In this paper, lift and drag coefficients of the measured section are compared in 5 various values of angular frequency ω. Both lift and drag data have been graphically displayed in Fig. 3.

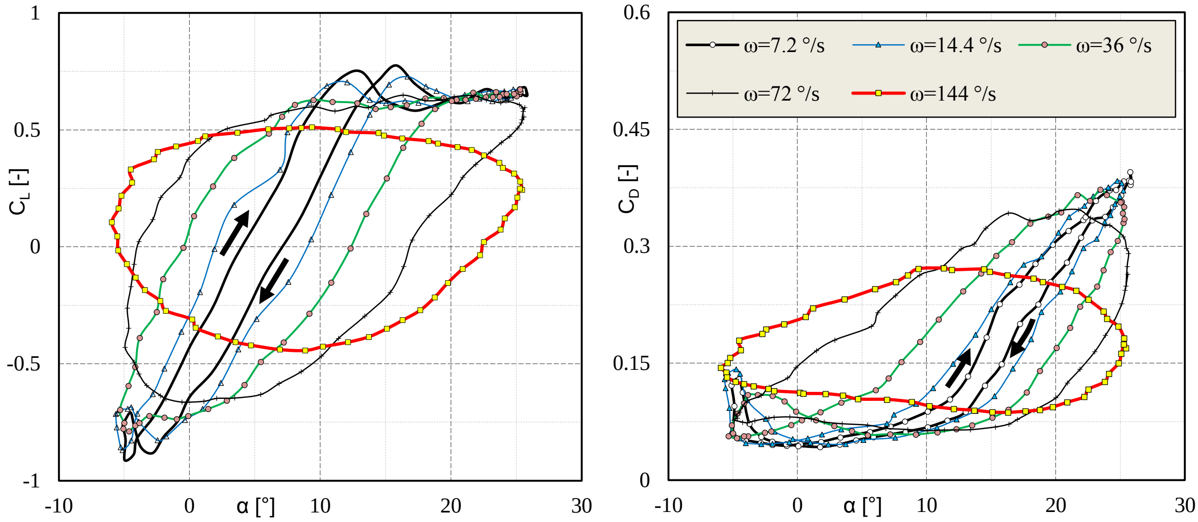


Fig. 3: The lift and drag characteristics with $\alpha = 0° \pm 15°$, direction CCW.

The real amplitude of the movement is slightly increased because of the mechanical tolerance of the system and deformation of measured airfoil due to aerodynamic and inertial forces. Furthermore, the stepper motor used has full-step of 1.8 ° and the motor shaft can be precisely positioned only in discrete positions, which are separated by this step. The real angle of the stepper motor at high loads must be calculated with an error of approximately 0.9 °. As a result of the cyclic motion, the AoA can increases for about 0.21 ° to 1.08 °.

Hysteresis share of aerodynamic curves

In every oscillating cycle, the lift curve is divided into two parts when values go up and down. The dependency of the lift coefficient on AoA when the AoA is increased from -15 ° to 15 ° can be described by the left part of the curve shown in Fig. 3 (arrow pointing up). At the beginning is the AoA decreased from 15 ° to -15 ° and the change of lift coefficient is shown in the right part of the curve (with a digit down). At the smallest frequency ($\omega = 7.2$ °/s), both parts of the lift curve have very similar shape. However, the first part (arrow pointing up) appears to be shifted to the left for a certain distance in comparison to the second part. With the ω increasing, the difference between both parts of the hysteresis loop becomes more apparent.

The dependency of the shape of the hysteresis on angular frequency

With the increased angular frequency ω, the “thickness” (distance between lower and upper part) of lift loop increases too, yet the height (distance between maximum and minimum value) of lift curve decreases (Fig. 4). Absolute value of lift coefficient decreases approximately to a half from C_L = -0.91 ÷ 0.78 for ω = 7.2 °/s to C_L = -0.44 ÷ 0.51 for ω = 144 °/s (red solid curve, Fig. 4). In this limiting case, the lift characteristic occurs an elliptic shape (red solid curve, Fig. 3).

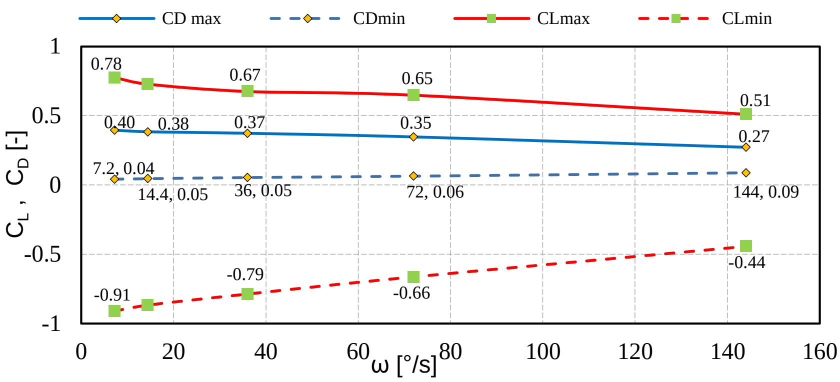


Fig. 4: The dependent of hysteresis shape on angular frequency.

The minimum value of drag coefficient increases proportionally with angular frequency. In limiting case, when ω = 144 °/s, the minimum drag coefficient is 2.5 times higher than for ω = 7.2 °/s and the maximum drag coefficient decreases for about 30 % (blue solid curve, Fig. 4). It is possible to confirm the hypothesis that aerodynamic coefficient of the oscillating wing section is related to the oscillation.

5. Conclusion

In the aerodynamic calculation of propellers or wind turbines in yaw, the oscillation of blade sections is usually ignored and only static data are used. Nonetheless, the blade element model and vortex theory show all blades of yawed propeller and wind turbines oscillate (Munduate, 2002) and the static data is not enough to calculate precisely the efficiency of such rotors. Therefore, a new method is proposed, in which the aerodynamic data must include the unsteady effect of oscillating movement. The value of the aerodynamic coefficient of current airfoil must be a function not only of the AoA but also of the angular frequency ω (represented by reduced frequency k). The experimental results can be used to perform interpolation to obtain aerodynamic coefficients, which include the effect of oscillating state $C_L, C_D = f(\alpha, \omega)$.

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