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Technical Notes

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Measurements in the Tip Vortex Roll-Up Region of an Oscillating Wing

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Introduction

NUMEROUS experimental and computational works[1–8] and references cited therein report various features of the flow characteristics of the trailing vortex behind a stationary wing. Evolution of the tip vortex, development of the axial and tangential velocities with the downstream distance, turbulent flow structures of the vortex, and so on are well documented. Although a vast amount of research effort has been devoted to the study of the tip vortex of a stationary wing, little attention has been given to the tip vortex of an oscillating wing practically encountered in rotor aerodynamics. Ramaprian and Zheng[9] recently carried out an experimental study using laser Doppler velocimetry to investigate the unsteady velocity and vorticity field associated with the evolving tip vortex in the near field of an oscillating rectangular NACA 0015 wing. The reduced frequency, defined by $\omega C/2U_\infty$ with ω being the circular frequency of oscillation, and the Reynolds number of their work were 0.1 and 1.8×10^5, respectively. The amplitude of oscillation was 5 deg. Their study provided detailed quantitative data of an oscillating wing tip vortex such as mean velocity, vorticity, movement of the vortex center, and circulation in the near field roll-up region. The purpose of the present work, similar to the work of Ramaprian and Zheng, is to investigate experimentally the tip vortex roll-up phenomena behind an oscillating rectangular wing. A notable difference, however, is a larger amplitude of oscillation of the present work. In this work the instantaneous angle of attack varies from 0 to 30 deg, and, hence, a massive flow separation occurs during a cycle of oscillation. Thus, the tip-vortex roll up from a separated flow could be explored. Special attention has been given to the change of circulation of the trailing vortex over a cycle of oscillation. Recent studies[10,11] revealed that the wake dynamics is better represented by the Strouhal number defined as fA/U_∞, where f is the frequency of oscillation and A is the maximum cross-stream excursion of the trailing edge. Contrary to the reduced frequency, the amplitude of oscillation is evidently a determining factor of this Strouhal number. The Strouhal number of the present work is 0.01, whereas that of Ramaprian and Zheng's work was 0.005. The wake is not propulsive for these small Strouhal numbers. The reduced frequency of the present work is 0.09, close to that of Ramaprian and Zheng.

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Experimental Setup and Procedure

Experiments were carried out in a closed-circuit wind tunnel with a square test cross section of 0.9×0.9 m^2 using a NACA 0012 rectangular wing model. The chord length C and the (half) span of the wing model were 15 and 60 cm, respectively. A dc motor drove the harmonic drive to produce sinusoidal oscillation about the quarter chord. Schematic of the experimental setup is given in Fig. 1. Both mean incidence α_0 and the amplitude of oscillation α_1 were set at 15 deg. The frequency of oscillation f was 0.54 Hz. Because the instantaneous angle of attack varies as $\alpha = \alpha_0 + \alpha_1 \sin 2\pi f t$, α ranges from 0 to 30 deg. The freestream velocity was 2.9 m/s, which resulted in the Strouhal number of 0.01 and the chord Reynolds number of $R_N = 3.4 \times 10^4$. Under these test conditions the freestream turbulence level was about 0.3%.

Dantec's StreamLine System and a triple hot-film (55R91) probe were employed to measure the three component velocities. Measurements were carried out for two downstream stations: $X/C = 0.5$ and 1.5. The measurement plane consisted of 25×25 data points: the distance between two neighboring data points was 5 mm. Ninety-two samples of velocity data, distributed evenly over one period of oscillation, were taken at a given probe position. For each phase angle 201 ensembles were used for averaging, which were sufficient to yield converged values. Because the present experiment required very long measurement time, the freestream velocity of a run could not be made exactly the same as that of previous run and was varied slightly for a set of measurement. The standard deviation of the freestream velocity variations was about 2.1%. Pitch and yaw tests of the three-component probe of the present work showed that when the velocity vector was within ±20 deg of the probe axis the velocity measurement uncertainties (at 20:1 odds) of the mean velocities (U, V, W) were about ±4.0, ±3.9, and ±3.8%, respectively. When the velocity vector was in the range from ±20 to ±30 deg, the uncertainties were about ±3.5, ±13.0, and ±8.8%. More details of the experimental setup and measurement can be found in Ref. 12.

Results and Discussion

The contours of the normalized axial component velocity (U/U_∞) for $\alpha = 11$ deg are presented in Fig. 2. The interval of the contour lines is 0.06, and the rectangle marked by the dashed line inside the figure is the projection of the wing planform to the cross-sectional plane. We see that the velocity gradient in the core region is much steeper during the pitch-up motion than during the pitch-down motion. The flow at $\alpha = 11$ deg during pitch-down was massively separated as was illustrated by the visualization pictures of Refs. 12 and 13, which resulted in a broader core size and milder velocity gradient. The vortex regions in all of the cases suffer from velocity deficit. The occurrence of velocity deficit in the vortex region was

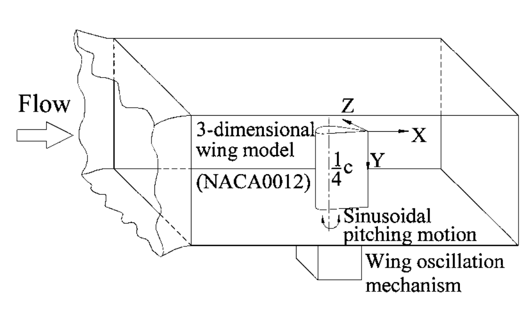


Fig. 1 Schematic of the test setup and the coordinate system.

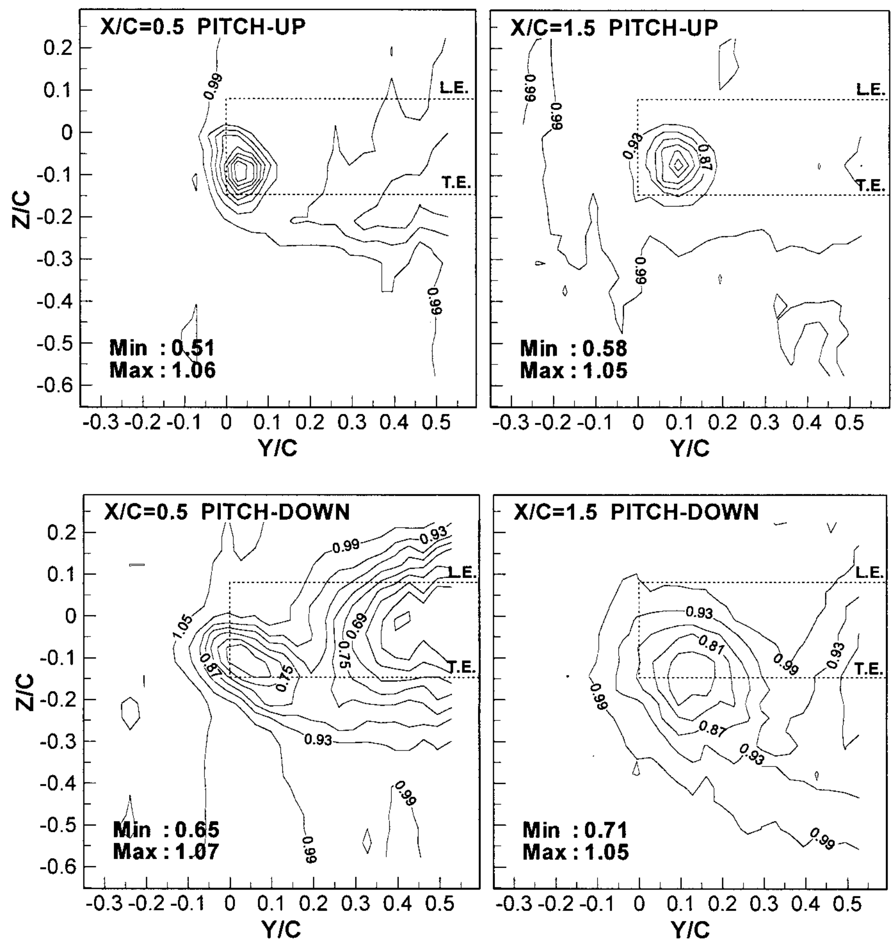


Fig. 2 Contours of normalized axial component of velocity (U/U_∞) at $\alpha = 11$ deg.

also observed in Ref. 9 for the case of pitch-up motion. However, they occasionally observed velocity excess at certain instantaneous angles of attack during the pitch-down motion. Many researchers reported velocity excess in the vortex core region in the near field. Chow et al.[8] observed a velocity excess as large as 1.77 times the freestream velocity just off the trailing edge in their stationary wing test. The Reynolds number and the aspect ratio of the wing in their work were 4.6×10^6 and 0.75, respectively. The Reynolds number and the aspect ratio of Ramaprian and Zheng[9] were 1.8×10^5 and 2.0, respectively. Thompson[14] observed axial velocity deficit in his towing tank test with a NACA 0012 wing of aspect ratio of 1.95 at Reynolds numbers of 3.4×10^4 and 6.8×10^4. We thus conjecture that the main cause of velocity deficit in the core region of the present work is caused by the low Reynolds number. Through the comparison of the velocity profiles at various angles of attack, it was shown that the velocity deficit increased with the angle of attack.[12] The velocity deficit region became broader, and the magnitude of the velocity deficit became smaller during pitch-down. This indicates that the flow during pitch-down leads to better mixing and hence less velocity deficit. The main portion of the flow during pitch-up remained attached to the wing resulting in a wake that was less turbulent and better organized, as was presented in Ref. 13. During the pitch-down motion, the flow was separated over the entire wing, and the tip vortex core became irregular and turbulent. The degree of flow separation and disturbance of the present work during pitch-down was much greater than that of Ramaprian and Zheng's study[9] because of a much larger amplitude of oscillation (or, equivalently the greater Strouhal number) and the lower Reynolds number.

Figure 3 displays tangential velocity profiles along the normal lines (to the wing surface) that pass through the vortex center at various angles of attack. The vortex center moves with the instantaneous angle of attack; a general trend is that the vortex center moves to the inboard from the wing tip and upward relative to the trailing edge as the angle of attack increases.[12] Because the velocity profiles of Fig. 3 are plotted for fixed Y coordinates of the vortex center at various incidences, only the vortex center motion in Z direction is noticeable from the plot. With the increase of the angle of attack, the Z coordinate of the center moves to the negative Z direction. The trailing edge, however, is at the farther left of the Z coordinate of the vortex center so that the relative motion of the vortex center to the trailing edge is in upward direction with the increase of the angle of attack. The tangential velocity distributions of Fig. 3 also show that the velocity profile inside the core is roughly linear at all angles of attack. For both pitch-up and pitch-down the peak tangential velocity increases with the angle of attack. The peak tangential velocities at various angles of attack during pitch-down are much smaller than during pitch-up. The size of the vortex core, however, is larger during pitch-down. These are again caused by the roll-up from separated flow where the flow is more diffusive. Variations of the peak velocity and the core size during a cycle of oscillation suggest that it would be of interest to look into the change of circulation over a period of oscillation, which will be discussed shortly. Before leaving the discussion of Fig. 3, we add a comment that a straightforward comparison of the velocity profiles at $X/C = 0.5$ with those at $X/C = 1.5$ can be misled. Because the wing oscillates, the mean velocity signal sensed at a given downstream station also oscillates but with a phase lag relative to the wing oscillation. Therefore, the velocity profiles at $X/C = 0.5$ and those at $X/C = 1.5$, even though these were measured at a given instantaneous angle of attack, do not properly match each other because of the phase lag or the convection time difference.

Variation of the vortex strength over one cycle of oscillation is given in Fig. 4. The data of Fig. 4a were evaluated from the measurement data. The angle of attack of Fig. 4a denotes the instantaneous angle of attack of the pitching wing. The circulation curve clearly demonstrates the hysteretic property between pitch-up and pitch-down. The circulation for both cases is seen to vary approximately linearly with the angle of attack over a wide range. The circulation

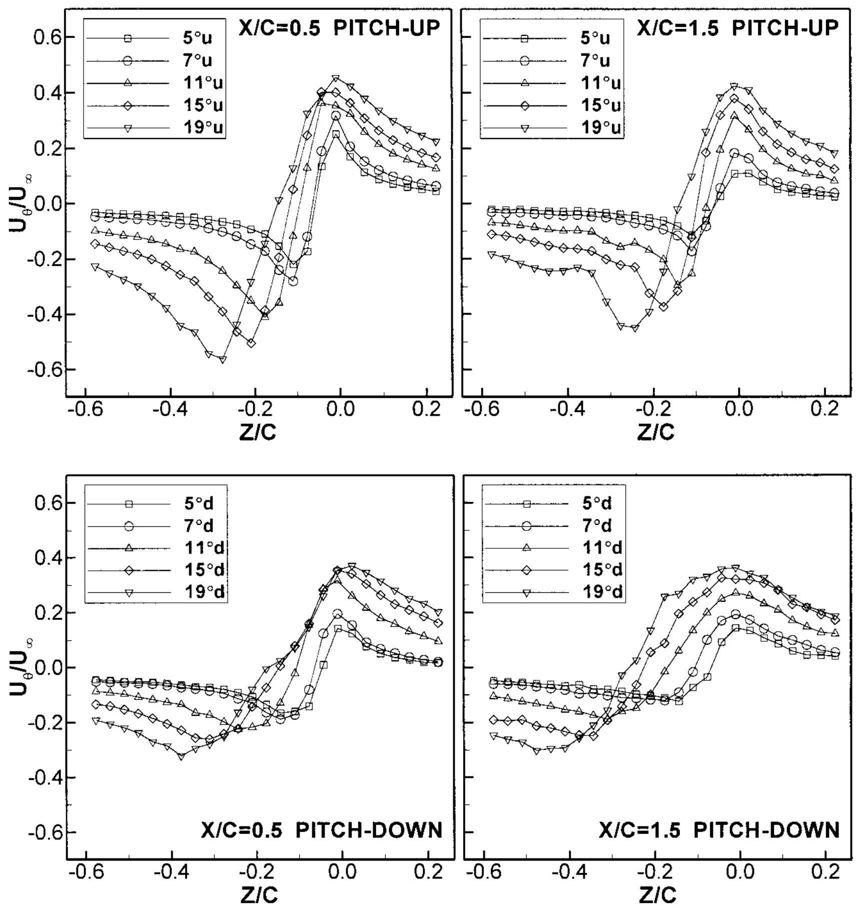
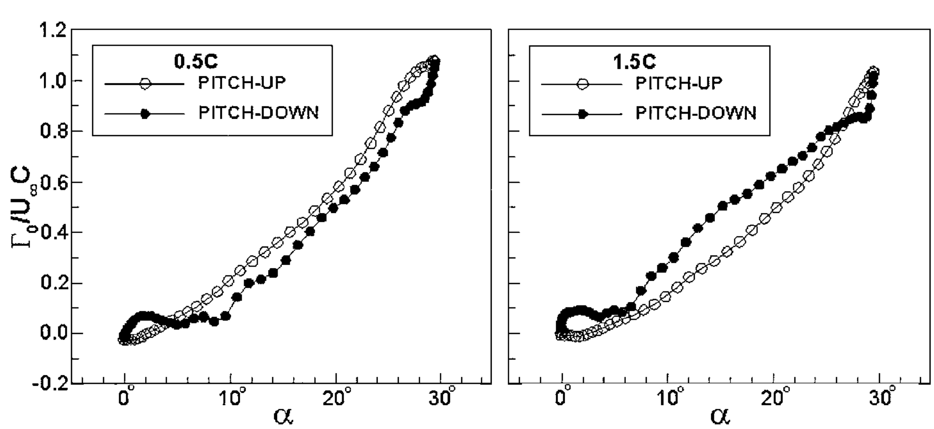
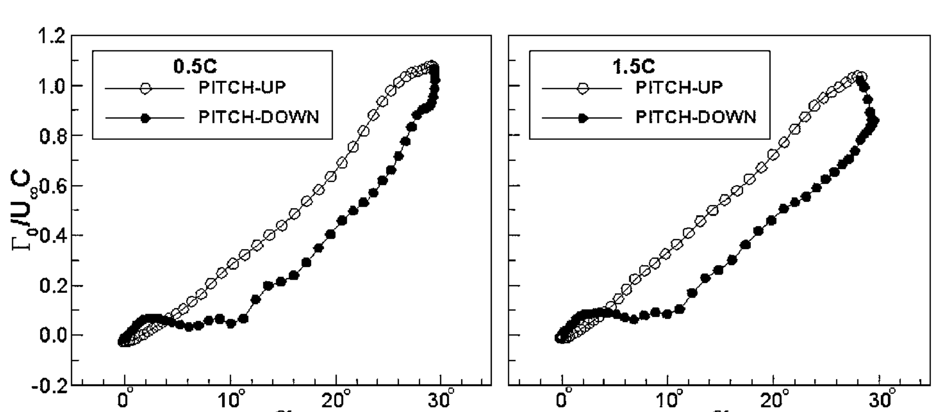


Fig. 3 Tangential velocity profiles at various angles of attack.



a) Measurement data



b) Compensated data

Fig. 4 Nondimensional circulation ($\Gamma_0/U_\infty C$) vs angle of attack.

is determined by the spanwise lift distribution, and the lift during pitch-up will be greater than that during pitch-down at a given angle of attack. The circulation curve for $0.5C$ illuminates this trend; the circulation during pitch-up is greater than that during pitch-down at a given angle of attack. However, the curve for $1.5C$ is contrary to this. This discrepancy can be explained if we take into account the fact that the velocity signal sensed at $1.5C$ reflects the data originated at an earlier phase angle of the wing oscillation. The true phase angles (hence, the true angles of attack) for the data for 0.5 and $1.5C$ are different from each other. For an adequate comparison we therefore need to take into account the phase lag of the present measurement. To compensate for the phase lag, we assumed that the convection velocity was approximately equal to the mean axial velocity in the tip vortex region at $0.5C$. We fitted the mean axial velocity data averaged over the vortex core region at several angles of attack into two straight lines, one for pitch-up and the other for pitch-down. The convection velocity at an angle of attack of interest was then obtained from these straight lines.

The phase lag compensated plot of the data is given in Fig. 4b. Obviously, at a given angle of attack the circulation during pitch-up is greater than that during pitch-down as expected. Figure 4b also points out that the rates of increase or decrease of the vortex strength per unit angle of attack are about the same for both pitch-up and pitch-down. This signifies that the rate of increase of the vortex strength per unit angle of attack remains the same even when the mean flow is massively separated. The value of circulation for $\alpha = 7$ deg during pitch-up from the phase lag compensated curve (Fig. 4b) is read to be about 0.23, which is in close agreement with the value of 0.28 (at $1.5C$) for $\alpha = 7$ deg of the stationary wing test.[12] Takahashi and McAlister[15] investigated the tip vortex in the near field of a stationary wing at $R_N = 1.02 \times 10^6$. The normalized circulation at large radius in their work was 0.33 at $\alpha = 11$ deg and $X/C = 1.6$. The value from the phase lag compensated curve (Fig. 4b) is about 0.37. This, in a way, ascertains that the flow during pitch-up is similar to that of the stationary wing in the present range of experiment. The circulation at various angles of attack for $X/C = 0.5$ and that for $X/C = 1.5$ are seen to be a little different from each other. However, these two can be said to be about the same if we take the measurement uncertainty into consideration. The uncertainties of circulation for $\alpha = 15$ deg during pitch-up were about ± 11.8, $\pm 9.5\%$ at 0.5 and $1.5C$, respectively.

Conclusion

Phase-averaged mean axial and tangential velocity profiles in the near field of the trailing vortex behind an oscillating wing were presented. These velocity profiles clearly demonstrated hysteretic behavior of the wake. The flow during the pitch-down motion was more disturbed and irregular so that it was more diffusive. The size of the vortex core was larger, and the peak tangential velocity and the axial velocity deficit were smaller during pitch-down than during pitch-up. The axial velocity within the vortex region was found to suffer from velocity deficit for both pitch-up and pitch-down cases. The hysteretic behavior of the wake was best illustrated in the plot showing the variation of the circulation over one cycle of oscillation. To adequately describe the change of circulation during a cycle of oscillation, the phase lag of the measurement signal was taken into account. The phase lag compensated variation of the vortex strength over one cycle of oscillation showed that the circulation at a given angle of attack was greater during pitch-up than during pitch-down. The rates of increase or decrease of the vortex strength per unit angle of attack, however, were found to be about the same for both pitch-up and pitch-down motion.

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Application of Acoustic Analogy to Automotive Engine-Cooling Fan Noise Prediction

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Nomenclature

c_0	= speed of sound
h	= blade surface equation $h = 0$, where $h > 0$ outside the blade
l_i	= force per unit area exerted on the fluid by the solid surface (in x_i direction)
l_r	= $l_i \hat{r}_i$, force per unit area exerted on the fluid in the radiation direction
M	= local Mach number
M_i	= local Mach number in x_i direction
M_r	= $M_i \hat{r}_i$, local Mach number in the radiation direction
N_{blade}	= number of blades
N_p	= number of singularity panels in potential flow solver
N_t	= number of time steps in potential flow solver
p'	= acoustic pressure
R	= fan radius
R_w	= wake radius
r	= $\lvert \boldsymbol{x} - \boldsymbol{y} \rvert$, where $\boldsymbol{y}$ is the source position
$\hat{r}_i$	= unit radiation vector, $(\boldsymbol{x} - \boldsymbol{y})/r$
S	= surface area of the actual body $h = 0$
t	= observer time

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