Turbulent intensity effect on low Reynolds number airfoil wake

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INTRODUCTION

The flow around an airfoil at a chord Reynolds number $Re_c < 10^5$ is of interest in connection with a variety of engineering applications including the design of micro air vehicles and wind turbines. Hence, it is not surprising that the airfoil flow at small Re_c has attracted a surge attention of researchers. Previous investigations found that at $Re_c > 10^4$ the separated shear layer reattaches on the airfoil surface, which enhances the airfoil lift. In contrast, at $Re_c < 10^4$ the separated shear layer does not reattach to the airfoil surface, adversely affecting the lift. Investigations on the aerodynamics of airfoils at $Re_c < 10^4$ are very few. There is also a lack of data in the literature on how the turbulence level (T_u) of the oncoming flow affects the aerodynamics of the airfoil particularly at $Re_c < 10^4$. The objective of this work was (i) to investigate the effect of T_u on the force and the wake of a NACA0012 airfoil at $Re_c = 5.3\times10^3$ and 2×10^4 and (ii) to classify Re_c-dependent flow structures based on maximum lift ($C_{L,\max}$) and on inherent features of the shear/boundary layer.

EXPERIMENTS

Experiments were performed in a closed-loop water tunnel, with a test section of 0.3 m (width) × 0.6 m (height) × 2.4 m (length). The water speed in the test section ranges from 0.05 m/s to 4 m/s. A NACA0012 airfoil, with a span length of $s = 0.27$ m and a chord length of $c = 0.1$ m, was used as the test model and mounted horizontally in the test section. A grid placed at the upstream side of the airfoil model was used to generate turbulence in the free-stream. A variation in T_u from 0.6% to 6.0% was achieved by changing the distance between the grid and airfoil. While the lift and drag coefficients (C_D and C_L) of the airfoil were measured using a load cell, the flow field was estimated using particle image velocimetry techniques. Furthermore, a LIF flow visualization system was used to visualize the airfoil wake and shear layer behaviors. $C_{L,\max}$ data from the literature are collected to classify Re_c-dependent flow structures.

RESULTS AND DISCUSSION

Four Re_c regimes are identified for the first time, based on the characteristics of $C_{L,\max}$ dependence on Re_c, i.e., ultra-low ($< 10^4$), low ($10^4 \sim 3\times10^5$), moderate ($3\times10^5 \sim 5\times10^6$) and high ($> 5\times10^6$), see Fig. 1. Each of them involves different flow patterns and stall types which are mostly connected to the shear/boundary layer behaviors. While the shear layer is laminar in the ultra-low Re_c regime, shear layer transition followed by a reattachment occurs in both low and moderate Re_c regimes. The low Re_c regime corresponds to a relatively longer separation bubble than the moderate Re_c regime. The boundary layer transits in the high Re_c regime and no reattachment occurs. Attention is given largely to the first two regimes in this work.

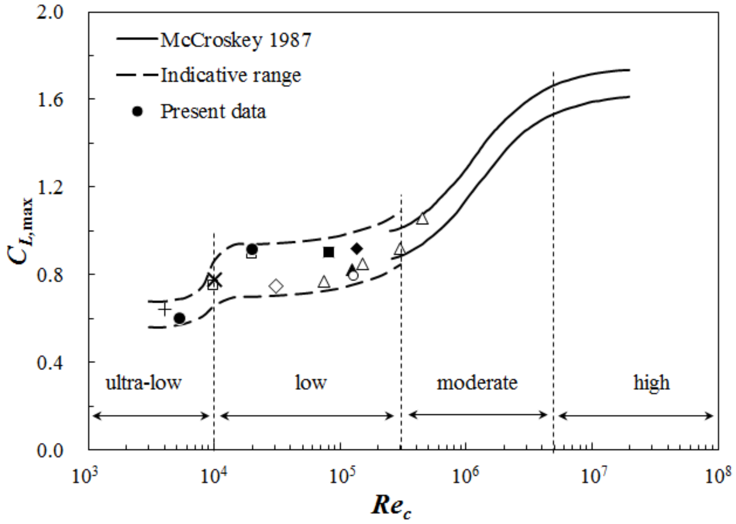

Fig. 1 Dependence of $C_{L\max}$ on Re_c of NACA 0012 airfoils. (+Sunada *et al.* (2002); ■ Chen and Choa (1999); × Akbari and Price (2003); ◆ Lee and Gerontakos (2004); ▲ Wong and Kontis (2007); ◇ Schlüter (2009); ☐ Cleaver *et al.* (2011); ○ Grager *et al.* (2011); △ Sant and Ayuso (2013))

Fig. 2 illustrates that at $Re_c = 5.3\times10^3$ (ultra-low regime) the airfoil stall is absent for T_u = 0.6% but occurs for T_u = 2.6% and 6.0%, resulting in a marked difference in C_L and a considerably improved lift-to-drag (C_L/C_D) ratio. The maximum C_L can be increased by 52%, while the maximum C_L/C_D can be improved by 45%.

LIF flow visualization photographs shown in Fig. 3 reveal that the increased T_u results in a postponement of the boundary layer separation (Figs. 3a, d), and occurrence of transition in the shear layer (Figs. 3b, e). The latter brings a successful reattachment of shear layer, responsible for the improved the lift.

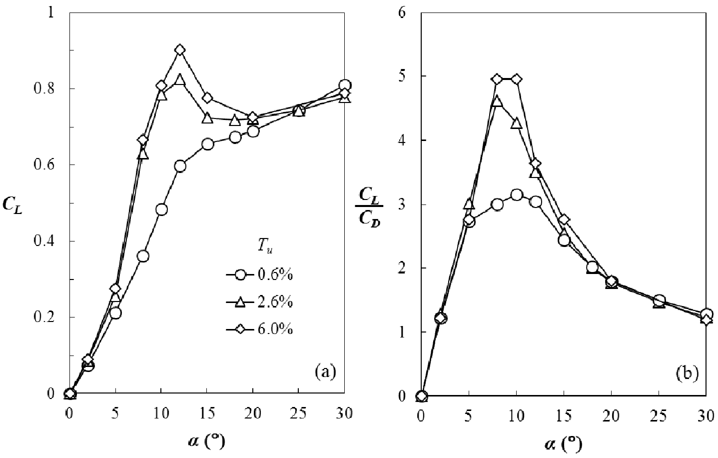

Fig. 2. Dependence on α of C_L (a), C_L/C_D (b) at different T_u. $Re_c = 5.3\times10^3$. Where α is the angle of attack

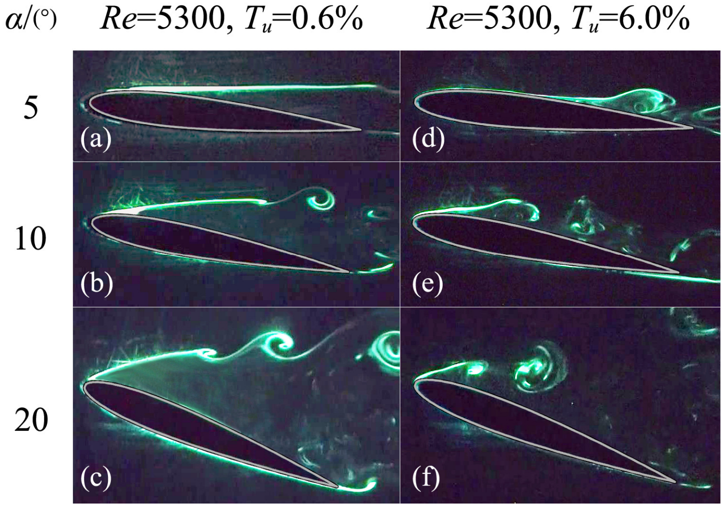

Fig. 3 Typical photographs captured in LIF flow visualization for various α.

CONCLUSIONS

The work leads to the following conclusions:

(1) Four Re_c regimes are identified on the basis of $C_{L,\max}$ and Boundary/shear layer characteristics, i.e., ultra-low, low, moderate and high Re_c regimes.

(2) A remarkable influence of T_u is observed at $Re_c = 5.3\times10^3$ (ultra-low Re_c regime), increasing C_L and C_L/C_D by 52% and 45%, respectively. Stall does not occur at T_u = 0.6% but does at T_u = 2.6% and 6.0%.

(3) The critical Reynolds number $Re_{c,\mathrm{cr}}$ that divides the ultra-low and low Re_c regimes decreases from 1×10^4 to less than 5.3×10^3 as T_u increases from 0.6% to 6.0%.

(4) While increasing T_u delays the separation of the boundary layer due to the enhanced mixing ability, increasing Re_c shows an opposite effect, promoting the separation.

Keywords: low Reynolds number, turbulent intensity, airfoil wake, lift force, stall