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Low-Reynolds-Number Effect on Aerodynamic Characteristics of a NACA 0012 Airfoil

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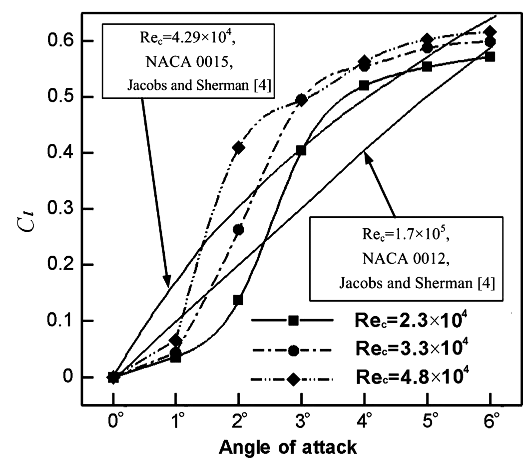
The boundary-layer properties and aerodynamic characteristics for the NACA 0012 airfoil were investigated at low Reynolds numbers ($Re_c = 2.3 \times 10^3$, 3.3×10^3, and 4.8×10^3) and low angles of attack ($\alpha = 0$ to 6°). Boundary-layer visualization and static pressure measurements were performed to show the abrupt increase of lift coefficients between $\alpha = 2$ and 3° in low-Reynolds-number cases. This nonlinear lift variation is due to the abrupt formation of the attached boundary layer. Moreover, the angle-of-attack range where the pressure drag coefficient is decreased was observed due to the pressure increase starting from the trailing edge. This demonstrated the different aerodynamic characteristics for below $Re_c = 5.0 \times 10^3$.

Nomenclature

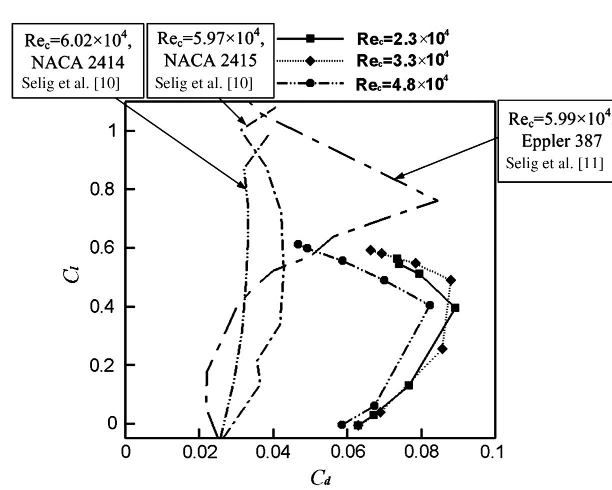
C	=	airfoil chord length
C_d	=	drag coefficient
C_l	=	lift coefficient
C_p	=	pressure coefficient
Re_c	=	Reynolds number based on airfoil chord length
x	=	freestream direction from airfoil leading edge
α	=	angle of attack

I. Introduction

THE flow properties in the low-Reynolds-number range, which are applicable to small-sized aerovehicles, wind turbines, propellers, and human-powered aerovehicles, have generally shown significant aerodynamic performance issues due to various boundary-layer events such as laminar separation [1–3]. In the subcritical region where laminar separation is dominant, the flow properties are ultimately influenced by Reynolds number, and unusual aerodynamic characteristics are observed [4]. Jacobs and Sherman [4] conducted wind-tunnel tests with various airfoils and suggested the Reynolds number effect Re_c from 4.0×10^4 to 3.3×10^6. Their results for Reynolds numbers over 1.0×10^5 showed the linear variation of lift coefficient, whereas lift coefficient showed the nonlinear pattern below $Re_c = 5.0 \times 10^4$ in the low angle-of-attack range. Such a nonlinear lift coefficient variation is clearly different from classical results, although its nonlinearity is small. An interest of flow properties in low Reynolds numbers has been raised due to the emergence of small-sized biomimetic flights



a) Lift coefficients



b) Drag polor in a NACA 0012 airfoil

Fig. 1 Lift coefficients and drag polar in a NACA 0012 airfoil.

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[5]. However, there are insufficient reliable data below $Re_c = 5.0 \times 10^4$. Accordingly, more refined results and physical understanding about the nonlinear variation of the lift coefficient are necessary to apply various flowfields.

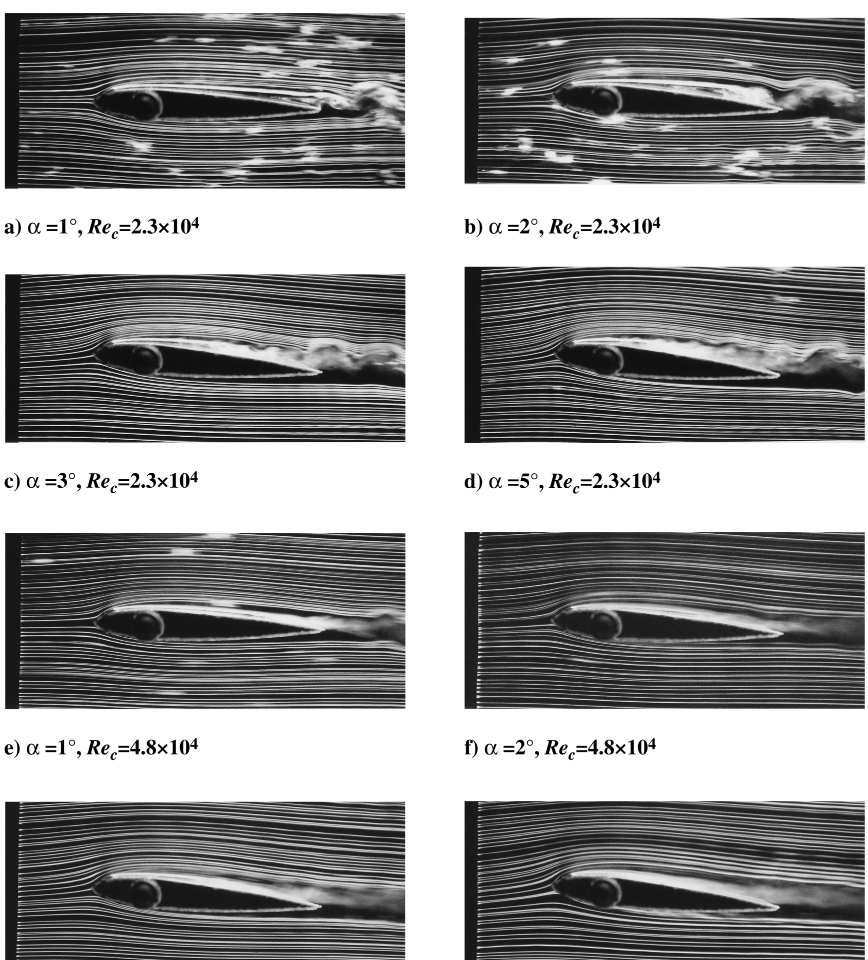
The objectives of this study are to gain physical knowledge about the aerodynamic characteristics in the range of $Re_c = 2.0 \times 10^4 \sim 5.0 \times 10^4$. In the subcritical region, because the boundary layer is a transitional regime, its properties are ambiguous and dramatically varied, depending on Reynolds number [6]. Therefore, more refined and systematic data are necessary for the understanding of phenomena, which is different from the classical pattern. Tests were performed for $Re_c = 2.3 \times 10^4$, 3.3×10^4, and 4.8×10^4 from $\alpha = 0$ to 6° with an interval of $\alpha = 1°$. The test conditions with narrow Reynolds number ranges were selected, because the boundary-layer properties are very sensitive with respect to the Reynolds number. Boundary-layer visualization and static pressure measurements were performed using a NACA 0012 airfoil having a 0.18 m chord length. The experimental apparatus is well described by Kim et al. [7]. The pressure on the airfoil surface was measured by 24 pressure holes and a pressure transducer (model 239, Setra). The pressure range of the pressure transducer was ± 0.25 inH_2O (about 60 Pa) and could measure very low pressure. Its sampling rate was 200 Hz, and the uncertainty pressure measurement was less than 3.5%.

II. Results and Discussion

Lift coefficients, calculated from the airfoil surface pressure, exhibit a linear increase up to $\alpha = 1°$, as shown in Fig. 1a and, in this region, the slopes of lift coefficients are between π and 2π. It is constantly increased up to the case of $Re_c = 1.7 \times 10^5$ (study of Jacobs and Sherman [4]). Lift coefficients between $\alpha = 1$ and 2° are dramatically increased in all Reynolds number cases, and the increase rate between $\alpha = 1$ and 2° significantly follows the increase of Reynolds number. However, from $\alpha = 2°$, the increase rate of the lift coefficients starts to decline with angle of attack, and the increase rate between $\alpha = 2$ and 3° is decreased with the Reynolds number increase. Thus, from $\alpha = 1$ to 6°, the lift coefficients are nonlinearly varied with the angle of attack, and their variations fitted by cubic spline are shown in Fig. 1a. Such a nonlinear lift coefficient variation was also observed in the study of Jacobs and Sherman [4] (Fig. 1a, NACA 0015, $Re_c = 4.29 \times 10^4$), even if its nonlinearity was small. Thus, the nonlinear variation of the lift coefficient is attributed to the low-Reynolds-number effect.

Figure 1b indicates the drag polar (pressure drag) variation with respect to the Reynolds number. In this figure, angle-of-attack ranges where the drag coefficients are decreased are observed for a given lift coefficient. These ranges are observed from $\alpha = 2$ to 6° ($Re_c = 4.8 \times 10^4$), from $\alpha = 3$ to 6° ($Re_c = 3.3 \times 10^4$), and from $\alpha = 3$ to 6° ($Re_c = 2.3 \times 10^4$). Thus, the drag coefficients start to be decreased at lower angles of attack in higher Reynolds numbers. At a constant lift coefficient, the drag coefficients are significantly decreased between $Re_c = 3.3 \times 10^4$ and 4.8×10^4. The decrease in drag coefficients is caused by the flow reattachment on the airfoil upper surface.

Figure 2 shows the boundary-layer visualization using the smoke-wire technique. For this process, a wire with a 0.1 mm diameter was installed at $0.06C$ behind the leading edge and at a distance of 1.0 mm above the airfoil surface. Under this experimental condition, besides buoyancy due to wire heating, the boundary-layer flow may experience a flow disturbance caused by the wire because the wire was installed inside the boundary layer. However, the Reynolds number



a) $\alpha = 1°$, $Re_c = 2.3 \times 10^4$ **b)** $\alpha = 2°$, $Re_c = 2.3 \times 10^4$

c) $\alpha = 3°$, $Re_c = 2.3 \times 10^4$ **d)** $\alpha = 5°$, $Re_c = 2.3 \times 10^4$

e) $\alpha = 1°$, $Re_c = 4.8 \times 10^4$ **f)** $\alpha = 2°$, $Re_c = 4.8 \times 10^4$

g) $\alpha = 3°$, $Re_c = 4.8 \times 10^4$ **h)** $\alpha = 5°$, $Re_c = 4.8 \times 10^4$

Fig. 2 Boundary-layer visualization in a NACA 0012 airfoil.

based on the wire diameter was favorably less than 30 in all cases [8]. This indicates that the flow disturbance caused by the wire could be neglected in this study, and its detail items were discussed by Kim and Chang [9].

In this study, the boundary-layer visualization elucidates the reason for the appropriate increase in lift coefficients. At $Re_c = 2.3 \times 10^4$, the boundary layers were similar between $\alpha = 1$ and $2°$ with respect to the formation of the attached boundary layer, whereas they showed a significant difference between $\alpha = 2$ and $3°$. That is, the boundary layer was well attached when the angle of attack became $\alpha = 3°$. This illustrates the rapid increase of lift coefficient in Fig. 1a, and it is applicable to the case of $Re_c = 4.8 \times 10^4$. However, the boundary layer started to be attached at lower angles of attack as the Reynolds number increased from $Re_c = 2.3 \times 10^4$ to 4.8×10^4. Accordingly, for $Re_c = 4.8 \times 10^4$, the lift coefficient was rapidly increased between $\alpha = 1$ and $2°$. As a result, the formation of the attached boundary layer is the main reason for the abrupt lift increase in the low-Reynolds-number range; moreover, the rapid increase of lift coefficient is attributed to the Reynolds number increase in the low angle-of-attack range.

At $Re_c = 4.8 \times 10^4$, as the angle of attack increases from $\alpha = 1$ to $6°$, the laminar separation point rapidly and nonlinearly moved from the trailing edge to the middle region of the airfoil. Simultaneously, the transitioned area seemed to be increased rapidly on the airfoil surface. For the low angle of attack in this study, the separation point moved rapidly from the trailing edge toward the middle region of the airfoil. However, for the high angle of attack, the separation point hardly moved around the leading edge. This was approximately confirmed by the boundary-layer visualization on the upper surface of the airfoil. As a result, the transition degree and the transitioned area in the boundary layers are nonlinearly increased with the angle of attack. Therefore, the transition from the laminar to the turbulent flow is an important flow phenomenon for the nonlinear variation of lift coefficients in the low-Reynolds-number range.

Figure 3 shows the pressure coefficients on the airfoil surface at angles of attack of $\alpha = 1 \sim 6°$. In Figs. 3b–3f, the solid lines indicate

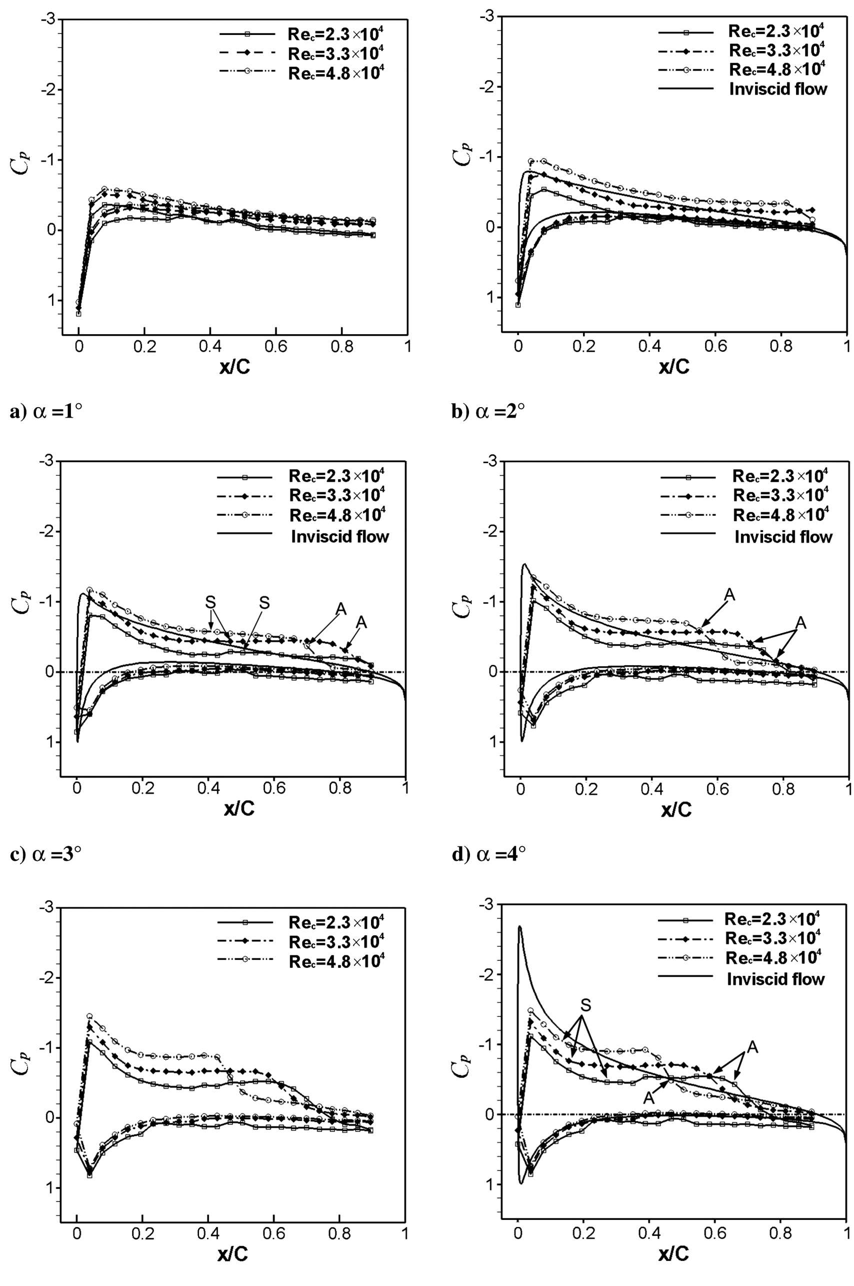


Fig. 3 Pressure coefficients in a NACA 0012 airfoil.

the pressure coefficients calculated under inviscid flow conditions using XFOIL. From about $\alpha = 1°$, the pressure coefficients on the upper surface show a constant variation from the middle position to the trailing edge, indicating laminar separation on the airfoil surface. The laminar separation is a principal factor in the increasing drag coefficient. However, starting from $Re_c = 4.8 \times 10^4$ at $\alpha = 2°$ (Fig. 3b), the increase in pressure coefficients is launched from the trailing edge. At this test condition, the drag coefficient starts to be decreased (Fig. 1b). This physical trend is enhanced with an increasing angle of attack, resulting in a decreased drag coefficient in all cases. On the other hand, for $Re_c = 2.3 \times 10^4$ and 3.3×10^4, the pressure coefficients observed over the trailing edge begin to be increased at $\alpha = 3°$. This indicates that, as the Reynolds number increases, the drag coefficients start to be decreased at a lower angle of attack. Actually, such a drag coefficient reduction is also observed in other types of airfoils in the low-Reynolds-number range [10,11]. Consequently, the pressure increase starting from the trailing edge plays an important role in drag decrement for the cases with low freestream velocities. Such a phenomena observed in the low-Reynolds-number range had been used to enhance the aerodynamic performance in low-speed airfoils [12], achieving lift enhancement and drag reduction.

The position at which the pressure coefficient after laminar separation increases on the upper surface of the airfoil is well known as a sign of reattachment. The reattachment point can be identified at a cross point between the pressure coefficient calculated under an inviscid flow condition and the pressure coefficient measured on the airfoil surface for a sufficiently large Reynolds number [13]. However, this does not correspond with the result in this paper due to the low-Reynolds-number effect. The "A" in Figs. 3c–3f shows the positions with maximum pressure fluctuations P_{rms} along the airfoil surface coordinate. A pressure coefficient is always increased, accompanied with a maximum pressure fluctuation. For $Re_c = 4.8 \times 10^4$ (Fig. 3f), the cross point between the calculated and measured pressure coefficients corresponds well with the A point around $x/C = 0.5$. The boundary-layer measurement suggested in the study of Kim et al. [7], who investigated the boundary layer under the same condition, does not indicate reattachment at $x/C = 0.5$ but rather the transition point in the boundary layer. Therefore, in this case, the boundary-layer development is not enough to characterize the pressure coefficient development due to low freestream velocity. For $Re_c = 2.3 \times 10^4$ and 3.3×10^4, and $\alpha = 6°$ (Fig. 3f), position A precedes the cross point, and this position appears to correspond with the transition point over the boundary layers shown by Kim et al. [7]. As a result, the cross point follows the boundary-layer transition in the low-Reynolds-number range.

III. Conclusions

The boundary-layer properties and aerodynamic characteristics for the NACA 0012 airfoil were investigated at low Reynolds numbers ($Re_c = 2.3 \times 10^4$, 3.3×10^4, and 4.8×10^4) and low angles of attack ($\alpha = 0 \sim 6°$). The lift coefficients are abruptly increased between $\alpha = 2°$ (1°) and $\alpha = 3°$ (2°) for $Re_c = 2.3 \times 10^4$ (4.8×10^4). It is due to the abrupt formation of the attached boundary layer with respect to the angle of attack, and it was demonstrated by boundary-layer visualization. Such an abrupt lift increment induces nonlinear variation with respect to the angle of attack, and the trend is significantly influenced by the Reynolds number, despite its small variation. The angle-of-attack range where the drag coefficient is decreased was observed due to the pressure increase starting from the trailing edge. As a result, the aerodynamic characteristics in the Reynolds number range below $Re_c = 5.0 \times 10^4$ are evidently different from the classical pattern and are significantly varied with the Reynolds number.

Acknowledgment

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References

[1] Lissaman, P. B. S., "Low-Reynolds-Number Airfoils," *Annual Review of Fluid Mechanics*, Vol. 15, No. 1, 1983, pp. 223–239. doi:10.1146/annurev.fl.15.010183.001255

[2] Carmichael, B. H., "Low Reynolds Number Airfoil Survey," NASA CR 165803, 1981.

[3] Lin, J. C. M., and Pauley, L. L., "Low-Reynolds-Numbers Separation on an Airfoil," *AIAA Journal*, Vol. 34, No. 8, 1996, pp. 1570–1577. doi:10.2514/3.13273

[4] Jacobs, E. N., and Sherman, A., "Airfoil Section Characteristics as Affected by Variations of the Reynolds Number," NACA TR 586, 1937.

[5] Muller, T. J., and DeLaurier, J. D., "Aerodynamics of Small Vehicles," *Annual Review of Fluid Mechanics*, Vol. 35, No. 1, 2003, pp. 89–111. doi:10.1146/annurev.fluid.35.101101.161102

[6] Huang, R. F., and Lin, C. L., "Vortex Shedding and Shear-Layer Instability of Wing at Low Reynolds Numbers," *AIAA Journal*, Vol. 33, No. 8, 1995, pp. 1398–1403. doi:10.2514/3.12561

[7] Kim, D. H., Yang, J. H., Chang, J. W., and Chung, J., "Boundary Layer and Near-Wake Measurements of NACA 0012 Airfoil at Low Reynolds Numbers," AIAA Paper 2009-1472, 2009.

[8] Batill, S. M., and Muller, T. J., "Visualization of Transition in the Flow over an Airfoil Using the Smoke-Wire Technique," *AIAA Journal*, Vol. 19, No. 3, 1981, pp. 340–345. doi:10.2514/3.50953

[9] Kim, D. H., and Chang, J. W., "Unsteady Boundary Layer for a Pitching Airfoil at Low Reynolds Numbers," *Journal of Mechanical Science and Technology*, Vol. 24, No. 1, 2010, pp. 429–440. doi:10.1007/s12206-009-1105-x

[10] Selig, M. S., Lyon, C. A., Giguere, P., Ninham, C. P., and Guglielmo, J. J., *Summary of Low-Speed Airfoil Data*, Vol. 2, SoarTech Publ., Virginia Beach, VA, 1996, pp. 95–99.

[11] Selig, M. S., Lyon, C. A., Giguere, P., Ninham, C. P., and Guglielmo, J. J., *Summary of Low-Speed Airfoil Data*, Vol. 3, SoarTech Publ., Virginia Beach, VA, 1998, p. 105.

[12] Somers, D. M., "Effects of Airfoil Thickness and Maximum Lift Coefficient on Roughness Sensitivity," Rept. NREL/SR-500-36336, National Renewable Energy Lab., Golden, CO, 2005.

[13] Yarusevych, S., Sullivan, P. E., and Kawall, J. G., "Coherent Structures in an Airfoil Boundary Layer and Wake at Low Reynolds Numbers," *Physics of Fluids*, Vol. 18, No. 4, 2006, Paper 044101. doi:10.1063/1.2187069