A PIV Study of Flow Patterns Over Stationary and Pitch-Oscillating Airfoils with Blowing Jet

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Abstract

A particle image velocimetry (PIV) technique was employed to investigate the effects of blowing jet on the flow characteristics over stationary and pitch-oscillating airfoils. The Reynolds number was 7.84×10^5 based on the chord length. It was found that for stationary airfoil cases, continuous and pulsating blowing jets successfully reduced separated wake region at high angles of attack. A comparison study of two different types of jet blowing indicated that pulsating jet is more effective than continuous jet for flow separation control. Pulsating leading-edge blowing postpones flow separation and increased stall angle of attack by $2° \sim 3°$. For pitch-oscillating airfoil cases, the PIV results showed that blowing jet efficiently delays the separation onset point during pitch-up stroke, whereas it does not prevent flow separation during pitch-down stroke, even at angles of attack smaller than static ones.

Key Word : Pitch-Oscillating Airfoil, Flow Pattern, Blowing Jet, Flow Separation Control

Introduction

The onset of flow separation has a deleterious effect on the airfoil performance compared to that obtained with fully attached flow. Particularly, the dynamic stall phenomenon is hard to predict and can cause fatal results to aircraft by producing abrupt changes in aerodynamic forces and moments. Thus, elimination or suppression of flow separation would increase lift and reduce drag, improving the aerodynamic performance of airfoils. The use of passive and active flow control devices may offer further gains in airfoil performance. The flow control technology is believed by many researchers to be one of the promising solutions for satisfying increased criteria of reducing vehicle weight and structural complexity, enhancing maneuverability, combat survivability, and stealth capability. Recent development of advanced micro sensors and actuators using new materials such as MEMS and piezo-ceramics also accelerated the flow control technology. A number of different flow control approaches have been investigated to reduce flow separation. Recently, researchers have been successful in improving flight conditions with the use of synthetic jets[1-3]. The use of plasma actuator and synthetic jet actuators has been proved to be very effective in reducing flow separation[4-6]. However, such flow control mechanisms have been very useful in laboratory but still incredulous for practical flight applications. For example, piezo-electric synthetic jet actuator based on cavity designs are most efficient at the resonance frequency of piezo, and therefore, are limited by the natural frequency of the cavity. Furthermore, the root mean square velocity drops off sharply away from the preferred frequencies[7, 8].

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Therefore, it is a fact that only a few conventional techniques have been successfully applied by aircraft manufacturers for the delay of separation. Although active flow control concepts have limitations on actual applications, these concepts are likely to see much future interest for achieving better airfoil performance.

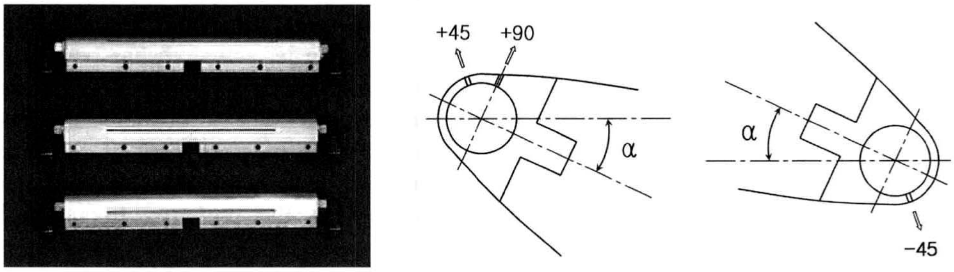
The purpose of the present paper is to extend the understanding of the effects of continuous and pulsating blowing jet on the flow characteristics for stationary and pitch-oscillating airfoils. Particularly, to understand the very complicated unsteady flow involved, a detailed knowledge of the flow field has crucial importance. A blowing jet actuator using compressed air was fabricated and applied to separation control of an airfoil. The influences of different parameters of blowing jet(jet type, jet slot location and jet orientation) on the flow patterns over the airfoil were analyzed. Exchangeable leading-edge and trailing-edge blocks were used to change the jet slot location. Jet velocity was varied by changing the feeding pressure level. This experimental study is based on the analysis of flow patterns obtained from a particle image velocimetry (PIV) technique. Experiments are conducted to further understand the fundamental physics behind the active flow control mechanism. Particularly, many efforts have been reported on the control of separation over conventional NACA series airfoils such as NACA 0012 and NACA 0015. Herein we report the control effectiveness of blowing jet on an elliptic airfoil that has not received much attention so far. Elliptic airfoils are symmetric about both the chord line and the mid-section. They are good candidates for marine vehicles and versatile air vehicles. Also elliptic airfoils have been of fundamental interest in fluid mechanics because they have mathematically defined configuration and are widely used in practice. Because elliptic airfoil has a unique geometric configuration, it exhibits different aerodynamic characteristics from those of conventional airfoils.

Experimental Set-up and Techniques

Test Model and Jet Actuator

The airfoil used for this study was a two-dimensional elliptic airfoil. It had a 400 mm chord, 1,500 mm span and 12.5% maximum thickness-to-chord ratio $(t/c)_{max}$. The airfoil had an interior plenum with two-dimensional jet slot. Three sets of jet slot blocks, which were used for changing the jet slot location, are shown in Fig. 1a. A flow system was designed to provide air for the leading-edge or trailing-edge injection which allowed adjustment of both flow rate and jet angle using replaceable jet slot blocks. The slot was 1 mm wide and 100 mm long. The leading-edge and trailing-edge jet slot blocks were fitted to the center portion of the model wing. The jet slot was oriented to 45° and 90° from the chord-line respectively at the leading-edge, and -45° at the trailing-edge(Fig 1b). Only one jet slot, leading-edge or trailing-edge slot, was used for each experiment.

The air for the blowing jets was provided by a commercially available air compressor that was capable of providing enough flow-rate to operate blowing jets. The jet exit velocity and the jet flow rate was found to be almost linearly dependent with the valve inlet pressure. The hot



(a) Jet slot blocks (b) Jet orientation

Fig. 1. Jet slot blocks and jet orientation

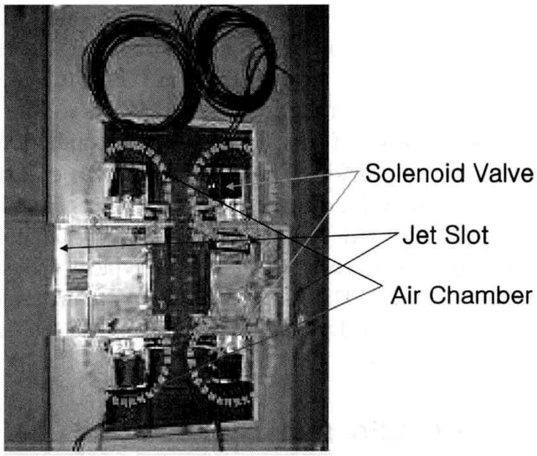


Fig. 2. Compressed air jet actuator

-wire measurements were used to determine the jet exit flow rate. Pulsating jets were generated by fast switching solenoid valves, which only had two states of open and closed conditions. Four valves connected to a common inlet manifold were used(Fig. 2). A maximum pulsation frequency of 40 Hz at 50% duty cycle was possible. Valve control was achieved using a digital I/O card connected to a PC. The pulsating jet was fluctuated as a square wave, and tests were conducted at frequency of 0 Hz for continuous blowing and 40 Hz for pulsating one. The magnitude of the non-dimensional jet excitation frequency($f^+=f_j c/U_\infty$)was 1.6.

Measuring Techniques and Test Conditions

Qualitative flow patterns were obtained by a PIV system. The PIV setup consisted of a double oscillator Nd-YAG laser with pulse energy of 200 mJ. A 12 bit CCD camera with 2,048×2,048 pixels resolution was used for capturing the images. Uniform seeding was obtained using DEHS(Di-Ethyl- Hexyl-Sebacat; $C_{26}H_{50}O_4$) inserted upstream of the airfoil. In order to obtain the vector fields, the post-processing of recorded images was undertaken with a commercial PIV software incorporating and adaptive correlation technique. The mean velocity vector field was obtained by averaging 30 instantaneous flow fields. Fig. 3 shows the experimental setup for the PIV measurements.

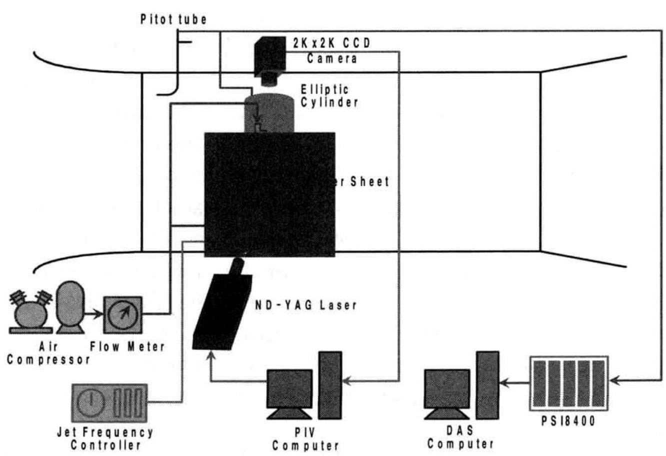


Fig. 3. Schematic of PIV system

The present experiments have been carried out in a subsonic wind tunnel located at the Korea Air Force Academy. The facility is a continuous, closed-loop, subsonic wind tunnel having a test section of 2.45 m high, 3.5 m wide and 8.7 m long. The turbulent intensity is less than 0.05% for the available test section speed range from 5 to 92 m/s. The results presented in this paper were obtained for a flow velocity of U_∞=30 m/s, corresponding to a Reynolds number of 7.84×10^5 based on the chord length of airfoil. The mean effective jet exit velocity, $V_{j,rms}$, was 60 m/s, which was twice of free stream velocity, and hence it corresponded to 2% of jet momentum coefficient $\{C_\mu=2h/c(V_{j,rms}/U_\infty)^2]$. The reduced frequency($k=\pi f_a c/U_\infty$) for airfoil oscillation was k=0.1. The value was chosen because it corresponded to a typical full scale rotor[9]. Meanwhile, pitch-oscillating frequency(f_a) was 1.5 Hz, and the free stream velocity was 19 m/s. All experimental conditions were controlled by TCS(Tunnel control system) and an external PC which was linked to the airfoil actuator system.

Results and Discussions

Flow Patterns over a Static Airfoil without and with Blowing Jet

To illustrate the effectiveness of the blowing jet on the airfoil performance, flow patterns over the airfoil were acquired at various angles of attack by PIV technique. The PIV results can show the differences of the flow patterns with and without blowing jet. Only the results of flow patterns for continuous and pulsating jet at the leading-edge are presented in this paper. In the following figures, LE and TE denote the slot positions at the leading-edge and the trailing-edge, respectively. CB and PB represent continuous and pulsating blowings, and the numbers in legend means jet orientations. For example, LE_90_PB corresponds to leading-edge pulsating jet with 90° jet orientation. Flow patterns when jet actuator was not operated are shown in the first column of Fig. 4. Those of jet actuator operated with continuous jet(LE_90_CB) and pulsating jet(LE_90_PB) are shown in second and third columns of Fig. 4, respectively. The flow runs from left to right. The gray code represents iso-velocity contours. The dark region between free stream and the airfoil surface shows separated flow region.

For the regime of pre-stall (α=10°), the flow is attached to the surface and only a small separated flow region can be seen near the trailing-edge(Fig. 4-1a). Comparison of Fig. 4-1a and Fig. 4-3a shows no detectable change in flow patterns between with and without blowing. However, development of a quarter chord sized separated bubble is seen at the leading-edge region for the continuous blowing case(Fig. 4-2a). At α=12°, the separated flow region is expanded toward the leading-edge(Fig. 4-1b). This enlarged separated region disappeared by the blowing jet effect(Fig. 4-2b and Fig. 4-3b). When the incidence angle was further increased to α=14° and α=16°, near the stall regime, the existence of recirculation zone associated with the separated flow for no blowing cases was observed in Fig. 4-1c and Fig. 4-1d . When the blowing jet is applied, reattachment of flow takes place and this separated flow region is reduced(Fig. 4-2c, d and Fig. 4-3c, d). That is, the flow pattern changes along the entire range over the airfoil from the leading-edge separated region to the weakened trailing-edge separated region via leading-edge blowing jet. Thus the blowing jet can suppress the flow separation effectively.

For a higher angles of attack of post stall regime (α=18°), a large scale of separated flow region is observed. The flow remains attached near the leading-edge due to the entrainment process of the higher momentum outer flow; however, the flow loses its momentum at the downstream of the airfoil and the adverse pressure gradient starts to build up, which results in flow separation(Fig. 4-1e). In this regime, flow reattachment is not observed in either of continuous nor pulsating blowing jet cases. Only a slightly reduced separated region can be seen(Fig. 4-2e & 4-3e).

Fig. 5 compares the effect of jet location(LE vs TE), jet type(CB vs PB) and jet orientation (α_j=90°, 45° at LE & -45° at TE) on the flow patterns for massively separated regime (α=17°).

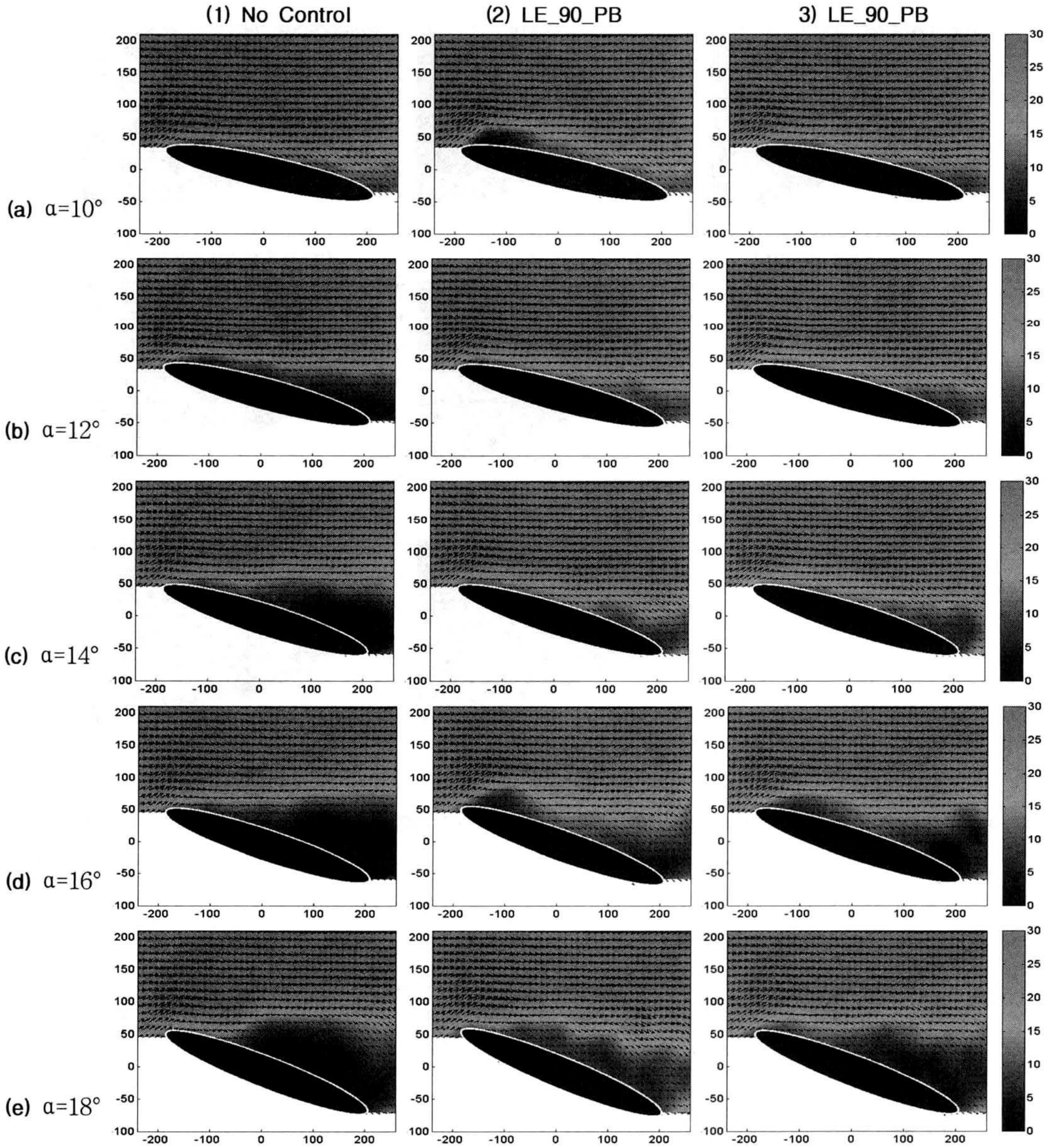


Fig. 4. Comparison of PIV flow patterns with and without jet blowing for stationary airfoil

The reduced separated flow regions can be seen with blowing jet, regardless of jet location, jet type and jet orientation, except for LE_45_CB case in which a separation bubble forms near the leading-edge region. The continuous jet adds only higher momentum flow into the lower momentum boundary layer, whereas the pulsating jet assists the natural amplification of small perturbations and by this mean promoting the entrainment of the high momentum fluid from the outer layer stream into the region of separated flow having lower momentum[10]. Therefore, pulsating jet is constantly adding energy into the flow which, in turn, enables to overcome the adverse pressure gradient. Comparison of Fig. 5a-3~Fig. 5b-3 and Fig. 5c-3 indicates that there is no discernible difference in flow patterns between leading-edge and trailing-edge blowings. This result does not coincidence with the previous research effort that showed better effectiveness of the actuators for separation control when they were placed close to separation point[2].

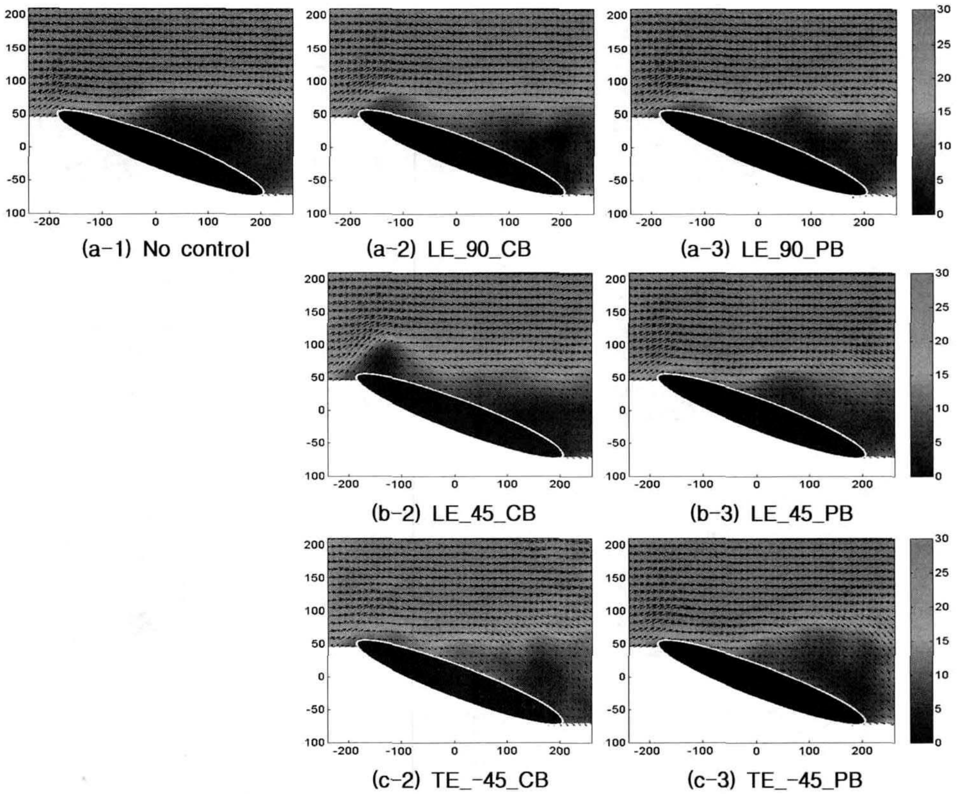
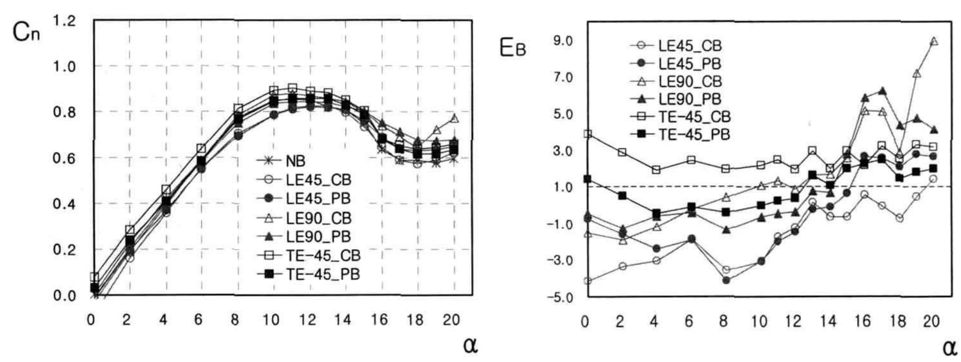


Fig. 5. Comparison of PIV flow patterns for various jet location, type and orientation at α=17°



(a) normal force coefficient (b) blowing effectiveness

Fig. 6. Variation of C_n and EB for various jet location, type and orientation[11]

Fig. 6 shows the variation of normal force coefficient(C_n) and blowing effectiveness(E_B) obtained for different jet locations and jet orientations for continuous and pulsating blowing cases at the same test condition[11]. As shown in Fig. 6a, the blowing effect on C_n results are different at pre-stall and post-stall regimes. For example, C_n increased when pulsating blowing jet is applied at the leading-edge. The maximum C_n value increased by up to 17.2% at α=16°. On the contrary, C_n decreased by -4.8% at α=4°. The increment due to blowing jet is more pronounced at higher angles of attack, i.e., α=16°, 17°, and 18°, as compared with the cases having angles of attack lower than stall angle. When comparing the results of Fig. 4 with those of Fig. 6a, a reduced separated flow region is observed for blowing jet cases. The suction peak near the leading-edge was re-established, and the normal force was recovered, which indicates stall suppression. Unlike the leading-edge blowing, the trailing-edge blowing brings about normal force that is maintained throughout most of angles of attack. However, the C_n values are not significantly affected.

Fig. 6b also shows variation of blowing effectiveness(E_B) with the changes in angle of attack for various types of blowing. The blowing effectiveness is defined as $E_B=\Delta C_n/C_\mu$, where ΔC_n is the ratio of normal force increment by blowing, and C_μ is the jet momentum coefficient[12]. Thus, blowing jet is effective when E_B is larger than 1. As shown in Fig. 6b, at pre-stall regime, the blowing jets are not effective in increasing normal force, except the trailing-edge blowing. However, near and post-stall regimes, it becomes effective regardless of its location. Particularly, LE_90_PB shows higher blowing effectiveness(E_B=4.24~6.23) than other ones even at high angles of attack. Comparing the blowing effects of jet location, the leading-edge blowing produces a big difference of E_B values between pre-stall and post-stall regimes, whereas the trailing-edge blowing shows relatively constant blowing effectiveness (E_B=1.92~3.85) at most of incidence angles. Consequently, pulsating leading-edge blowing is considered as an efficient technique for improving the performance of airfoils at high angles of attack, and it works effectively in the fully separated region. The stall angle is postponed from 14° to 16° when pulsating jet is applied. These results are coincidence with other researchers' works[10, 11].

Flow Patterns over a Pitch-Oscillating Airfoil without and with Jet

In this section, some selected PIV flow patterns of pitch-oscillating airfoil are presented. These PIV flow patterns are phase-averaged data, i.e., 30 single images were taken and averaged at each phase angle. The airfoil model oscillated in pitch about its half chord with the oscillation amplitude of ±10° starting from the mean incidence angle of 15°, which was the static stall angle[11]. Fig. 7 shows the comparison of flow patterns over the airfoil in pitching motion from 5° to 25° with and without blowing jet for a reduced frequency(k) of 0.10. In the first column of Fig. 7(Fig. 7-1a through 7-1e), no blowing case shows the formation of a quarter-chord-sized leading-edge vortex at 16° incidence. The leading-edge vortex grows in size as the airfoil continues to pitch up over 20°(Fig. 7-1c). The vortex eventually lifts off from the surface and shed into the wake as the angle of attack increased(Fig 7-1e). These flow patterns are well documented at a previous investigation[13]. Comparison of Fig. 4-1a~Fig. 4-1e (stationary airfoil) and Fig. 7-1a~Fig. 7-1e (oscillating airfoil) indicates that flow separation was delayed about 4°~5° during pitch-up stroke for the oscillation case.

The change in flow patterns of dynamic airfoil due to blowing jet can be observed in Fig. 7 and Fig. 8. Comparison of Fig. 7-1 and Fig. 7-2~Fig. 7-3 shows blowing jet effectively suppressed flow separation and resulted in the reduction of separated wake region. Particularly, pulsating jet at the leading-edge imposed the flow to be attached to the airfoil surface, even at high angles of attack(Fig. 7-3a~Fig. 7-3c). When compared to Fig. 7-1a~Fig. 7-1c, flow separation was delayed by 3° to 4° with the leading-edge pulsating jet. Thus the pulsating jet at the leading-edge is also effective in suppressing dynamic stall. When the incidence angle further increased over 22°, blowing jet reduced separated flow region, even though the suppression effect can not expected anymore. The reduction of separated wake region was insignificant for both continuous and pulsating blowing at the leading-edge(Fig. 7-2d, e & Fig.7-3d, e). Furthermore, trailing-edge blowing has no effect on the control of separated flow(not shown). According to Greenblat and Wygnanski's similar study about NACA airfoil series(NACA 0012, NACA 0015, $Re_c=2.4\times10^5$, k=0.05), they reported that strong jet momentum($C_\mu \geq 0.10$) is needed to remove the dynamic stall vortex completely[14]. Thus, a weak jet momentum, such as present test condition(C_μ=0.02) has somewhat limited capability to control the highly separated flow, resulting in strong circulatory flow induced by the boundary layer separation at the leading-edge. However, the optimal jet strength was not proposed consistently because the results varied with airfoil shape and flow condition. For example, Amity et al[15] showed that reduced jet momentum was also possible to control the separated flow for the case of higher jet frequency($f^+=f_j c/U_\infty$=3~10).

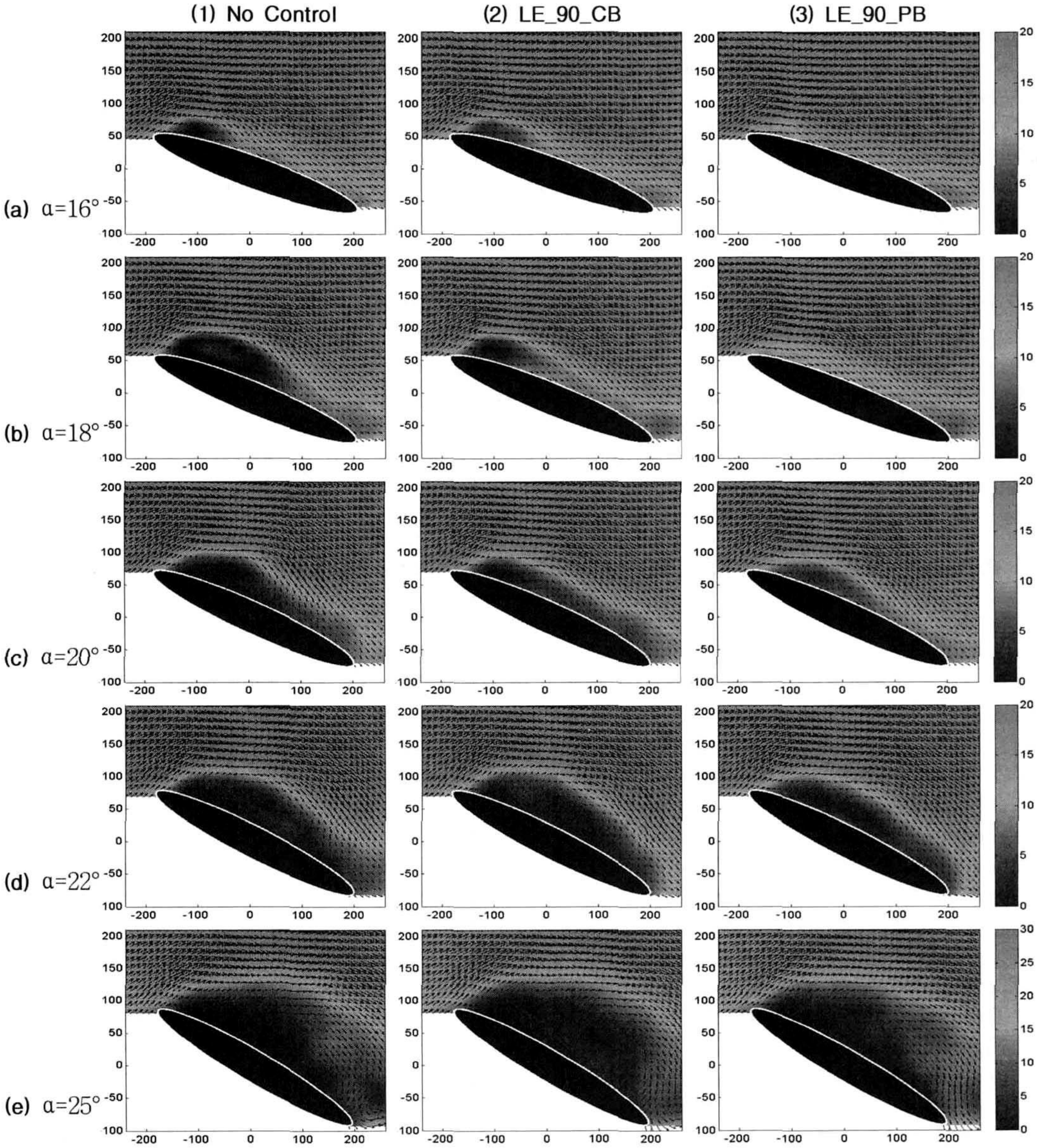


Fig. 7. Comparison of PIV flow patterns for pitch-oscillating airfoil with and without jet blowing during pitch-up stroke

Fig. 8 compares the effect on flow patterns with and without blowing jet for various angles of attack during pitch-down stroke. For no-blowing jet case (Fig. 8-1a to Fig. 8-1c), the flow patterns do not change much as the angle of attack varies, compared to those of pitch-up phase, even at low incidence angles. However, the flow patterns do not exhibit strong recirculation found in the results of pitch-up stroke. When the angle of attack further decreases, reduction of separated wake region can be seen(not shown). Finally, flow reattachment is observed close to 5° incidence. Thus, strong hysteresis effect occurs during the pitch-down stroke. This hysteresis of pitch-oscillating airfoil is caused by different flow patterns between pitch-up and pitch-down strokes. The attached flow pattern is maintained during most of pitch-up stroke, whereas flow experiences separation during most of pitch-down stroke.

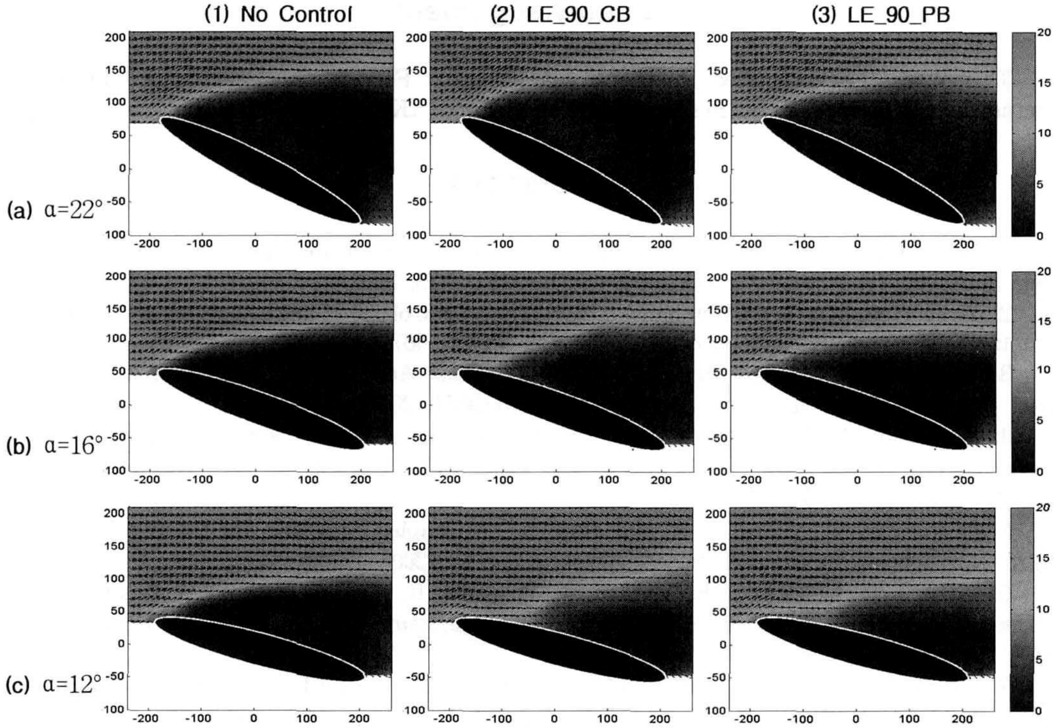


Fig. 8. Comparison of PIV flow patterns for pitch-oscillating airfoil with and without jet blowing during pitch-down stroke

As seen from the comparison of Fig. 8-1a~Fig. 8-1b, Fig. 8-2a~Fig. 8-2b and Fig. 8-3a~Fig. 8-3b, no particular change on flow patterns by blowing jet was observed in contrast to pitch-up stroke. During pitch-down stroke, where the strong turbulent separated wake region is maintained, there is insignificant effect on the suppression of separated flow by blowing jet. However, elimination of turbulent wake region near the leading-edge by blowing jet can be observed by decreasing incidence angle lower than static stall angle (Fig. 8-2c & Fig. 8-3c). Especially, pulsating blowing at the leading-edge forces the boundary layer separation point to move downstream of the airfoil. That indicates the possibility of alleviation of hysteresis by blowing jet during pitch-down stroke.

Conclusions

For the purpose of suppression of flow separation, the viability of blowing jet as an active flow control device was investigated. A series of low-speed wind tunnel test were carried out on both stationary and pitch-oscillating airfoil fitted with blowing jet slots.

For the case of a stationary airfoil, the measured flow patterns indicated that both continuous and pulsating blowing jets have an effect of suppressing flow separation, resulting in the reduction of separated wake region. The decrease in the wake region was more pronounced at higher incidences, whereas the effectiveness of jet blowing was reduced at lower incidences. Leading-edge pulsating blowing with 90° was found to be the most effective in controlling flow separation than other types of blowing jet configurations tested in this present research.

For the pitch-oscillating airfoil, PIV flow patterns showed the main features of the dynamic stall process: development, growth and shedding of dynamic stall vortex. The flow patterns of phase-averaged PIV showed that pulsating blowing jet is more effective for controlling separation than continuous one. During pitch-up stroke, elimination of the thick wake by the imposed blowing jet was observed. However, a large region of wake flow still existed during pitch-down stroke, even at lower angles of attack than static stall.

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