AIAA JOURNAL
Vol. 39, No. 7, July 2001

Technical Notes

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Stall Control with Local Surface Buzzing on a NACA 0012 Airfoil

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Introduction

THE stall control on a rotating blade or an airfoil has become one of the major topics for many researchers in aeronautical engineering. So far, the various techniques, such as slatted and slotted airfoils,[1] leading-edge oscillating flap,[2] and oscillatory surface blowing airfoils,[3,4] have been explored and reported to be effective in stall control. The periodic excitation investigated by Seifert et al.[3,4] proved to be more effective than steady one applied to many kinds of airfoils with various parameters including Reynolds numbers, added momentum, frequency, and locations of blowing. Bar-Sever[5] has shown that the periodically forcing wire which induces the transverse velocity fluctuations into a separated shear layer can be an effective control method. Miau and Chen[6] installed a vertically oscillating fence on a flat plate and found that the vortices shed from the fence enhance the momentum transfer between freestream and turbulent boundary layer to promote reattachment. The vibrating ribbon or the oscillating flap that has an angular motion with a hinge also can improve the stall characteristics because it directly influences velocity profiles and enhances the mixing.[7]

Whereas the earlier researchers have concentrated on oscillating flaps or oscillatory blowing on the airfoil surface to induce the streamwise velocity perturbations u', the present method uses the motion of the buzzing rod vertical to the flow direction, producing the only velocity perturbations vertical to the freestream direction v'. Moreover, the present method can be considered as the oscillatory trip strip with varying height as well as frequency. In other words, when the buzzing rod is fixed at a certain height, the effect of present method is similar to the trip strip with a given height at that location. Our objective is to investigate the effect of the motion of the buzzing rod with various flow conditions on the improvements of aerodynamic performances and the related mechanisms at low Reynolds number.

Experimental Setup

The experiments were conducted in a closed-return, low-speed wind tunnel in Seoul National University having a turbulence intensity of less than 0.3%. A NACA 0012 airfoil of 0.4-m chord and 0.6-m span with 47 pressure taps was tested for a chord Reynolds number in the range $2 \times 10^5 \sim 4 \times 10^5$. Figure 1 describes the mechanism of the present method, "local surface buzzing." The cams with an eccentricity were installed on outer surfaces of two splitter plates, and a buzzing rod was mounted between each cam's grooves so that the rotation of cams caused the rod to move up and down. The amplitude of buzzing rod was 2.6 mm (1.3 mm high from the baseline airfoil surface), and the frequency range was in the range $0 \sim 55$ Hz, resulting in a maximum velocity for the buzzing rod of about $0.05U_\infty$. The location of buzzing rod was placed at $0.1 < x/c < 0.12$ so that the reduced frequency ($F^+ \equiv f(0.88c)/U_\infty$) was in the range $0 \sim 2.11$ at $Re = 2 \times 10^5$.

The time-averaged surface pressures and the wake survey method are used for measuring lift and drag in the baseline and the controlled airfoil. The uncertainty of pressure coefficients was less than ± 0.05 except for the case of the location of suction peak at poststall angles where there was a maximum uncertainty of ± 0.3. Consequently, the lift coefficient had a maximum uncertainty of ± 0.015, but most of the results presented here had an uncertainty considerably less than this value. The uncertainties of freestream velocity and reduced frequency were 0.1 and 0.6 %, respectively.

Results and Discussion

For the representative result of this study, the section lift coefficients vs angle of attack for the various buzzing frequencies at $Re = 2 \times 10^5$ are plotted in Fig. 2. The lift distributions at prestall angles show no improvements like the results of oscillating wire[5] and the vibrating ribbon technique.[7] As an angle of attack increases where the separation occurs near the leading edge, the control effect begins to work. The lift coefficients at poststall angles increase with increasing the reduced frequency and exhibit milder stall characteristics with a delayed stall angle of 1 deg at $F^+ = 1.94$.

The time-average pressure distributions at $\alpha = 14$ deg for various frequencies are presented in Fig. 3. The flat pressure distribution on the baseline airfoil indicates the flow separation near leading edge, whereas the suction peak is discerned in the controlled cases. As the reduced frequency increases, the values of suction peak keep increasing with the shifted separation location to about $0.8c$ at $F^+ = 1.94$. The constant pressure plateau right after location of the buzzing rod indicates that the local separated bubble region is produced by the discontinuity in the surface contour. Figure 4 provides the effect of buzzing frequency on the lift increase ratio compared with the baseline lift C_{lo} at various poststall angles. Though data scattering makes it difficult to determine the optimum frequency, the lift seems to keep increasing with the best improvement of 24% at $\alpha = 14$ deg and $F^+ = 1.94$. Because of the limited experimental

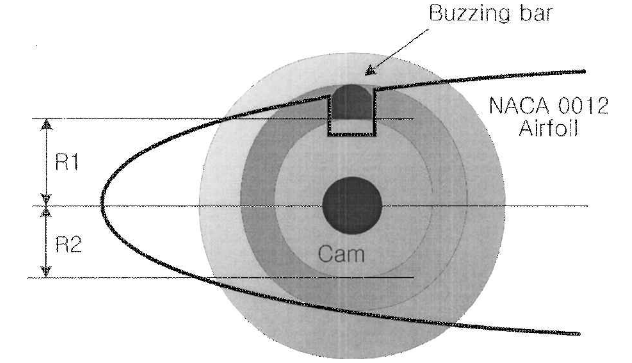

Fig. 1 Mechanism of the local surface buzzing at the maximum displacement amplitude.

Received 4 April 2000; revision received 21 September 2000; accepted for publication 24 October 2000.

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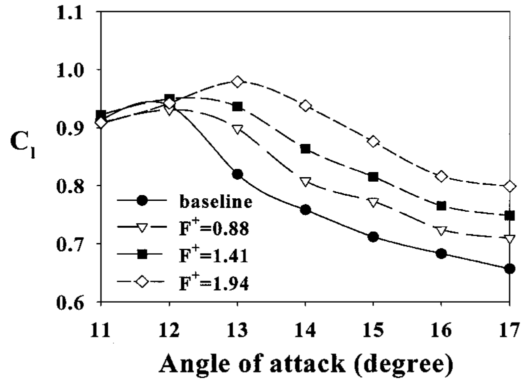

Fig. 2 Comparison of the lift coefficient curves for various buzzing frequencies at $Re = 2 \times 10^5$.

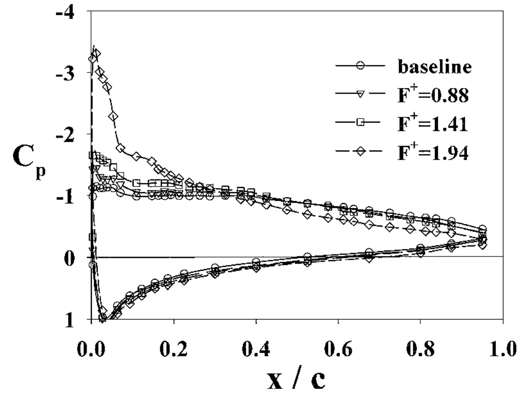

Fig. 3 Comparison of pressure distributions with increasing buzzing frequency at $\alpha = 14$ deg and $Re = 2 \times 10^5$.

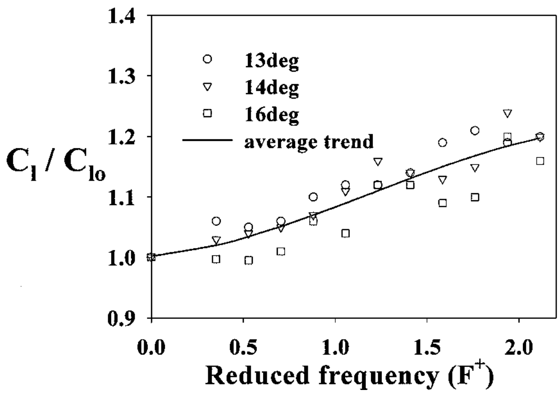

Fig. 4 Effect of buzzing frequency on lift coefficient at $\alpha = 13$, 14, and 16 deg and $Re = 2 \times 10^5$.

conditions, we could not conduct the experiments for higher frequencies, but this result implies that the effect of the present method on lift variation with respect to buzzing frequency is similar at all poststall angles. In the previous studies including periodic blowing and the vibrating ribbon method, the optimum reduced frequency in view of the lift was in the range $F^+ = 1.0 \sim 3.0$, which depends on many parameters such as control method, location of actuator, airfoil model, value of added momentum, and so on.[8] The effect of buzzing on the drag was also studied, revealing that the best drag reduction of about 60% occurs at 13 deg with decreasing influence at higher angles of attack.

The results of oil surface flow visualization are provided in Fig. 5 at 14 deg and $Re = 4 \times 10^5$. There is a laminar separation bubble ranging approximately at $x/c < 0.03$ in both cases, followed by the turbulent separation occurred at $x/c \approx 0.2$ in the baseline airfoil. In the controlled airfoil a series of vortices with scales proportional to the protrudent displacement of buzzing rod from the baseline surface contour are produced. These vortices are getting stronger and larger as convected along the surface followed by contacting to the surface at a certain location ($x/c \approx 0.3$), which means the flow is reattached. The oil surface pattern, which shows that the gap width of a series of black lines is getting larger, indicates that the scale of vortices is gradually larger and reattaches as the flow moves downstream. The aforementioned separated bubble region ranging right after the buzzing rod is related with this phenomenon, and its length is the distance required for the vortical flow to reattach. After all, the separation location is shifted to $x/c \approx 0.9$ in the controlled airfoil.

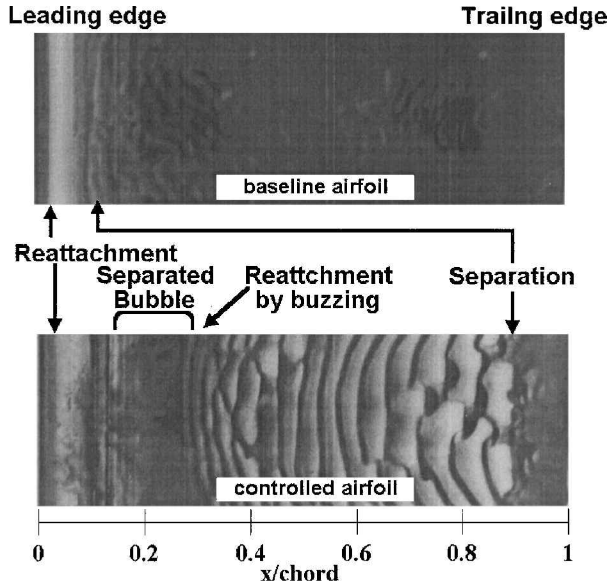

Fig. 5 Visualization of surface flow on the upper surface with and without buzzing at $\alpha = 14$ deg and $Re = 4 \times 10^5$.

Reynolds-number effects were studied in the range $2 \times 10^5 \sim 4 \times 10^5$. There is no significant change in aerodynamic characteristics except that the angle of the best improvement is slightly delayed with increasing Reynolds number, which indicates that the present method is most effective right after stall angle at this Reynolds-numbers range.

Conclusions

The effects of local surface buzzing vertical to the flow direction near the leading edge on an airfoil were investigated at low Reynolds numbers. The results showed that the aerodynamic characteristics including poststall lift and drag have been improved with milder stalling feature. The locally introduced unsteady disturbances by the present method caused the separated boundary layer to reattach to the surface by intensifying turbulence activity to enhance mixing and entrainment, which can be deduced from the result of oil surface visualization and pressure distributions. Further study for applying this to a real situation will be needed by considering higher Reynolds numbers as well as higher frequencies including the power-spectrum analysis and velocity measurements in the flowfield.

Acknowledgment

The authors wish to acknowledge the financial support of the Korea Research Foundation made in the program year of 1998 (98-018-E00171).

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Effect of Ribs on Suddenly Expanded Flows

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Nomenclature

D	=	duct diameter
L	=	duct length
P_a	=	ambient pressure
P_b	=	base pressure
P_t	=	total pressure at the center of enlarged duct exit
P_w	=	duct wall pressure
P_0	=	settling chamber pressure
S	=	rib aspect ratio, defined as width/height of rib
X	=	axial distance along duct

Introduction

SUDDENLY expanded flowfields find application in many interesting problems of practical importance, such as combustors and combustion chambers, propulsion systems, parallel diffusers, and so on. The need for controlling such flowfields has motivated studies of these flows. Passive control mechanisms have always attracted scientists because they give the desired result without the need for separate mechanisms, as in the case of active control. There is a vast amount of information about suddenly expanded flow problems in the literature, describing the mechanisms governing the base flows.[1–17] One study that has direct relevance to the present study is that of Anasu and Rathakrishnan,[18] who studied the flow through a convergent axisymmetric duct with annular rectangular cavities at specified intervals. They concluded that the introduction of secondary circulation by cavities reduces the oscillatory nature of the flow in the enlarged duct, thereby enabling the flow to develop smoothly from the base pressure to the atmospheric pressure at which the expanded jet was discharged. Subsequently, Rathakrishnan et al.[19] extended the study to cover a range of aspect ratios and concluded that the cavity is of considerable effect in the enlarged duct and that the effect is more pronounced for longer ducts than for shorter ducts. However, these investigations were only for subsonic Mach numbers. Further, when passive controls in the form of a cavity are employed for flow control, there is a possibility of the cavity behaving like a closed cavity, thereby becoming ineffective as a control device. Therefore, it was felt that it may prove to be advantageous over cavities if the control is in the form of annular ribs. The idea of using projections instead of cavities as passive controls motivated the present study, wherein the secondary vortices generated by the projections were expected to yield a better wall pressure distribution. The goal of this work was to find the optimum geometry of ribs for the minimum possible base pressure, over a range of Mach numbers from low subsonic levels to sonic.

Received 21 October 1999; revision received 21 February 2001; accepted for publication 26 February 2001.

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Experimental Setup

The experimental model consisted of a nozzle and an enlarged duct, as shown schematically in cross section in Fig. 1. The first diameter of duct length downstream of the nozzle exit consists of straight wall to keep the recirculating region near the base clean. After completing all of the measurements with one aspect ratio (width w/height h) of the ribs, the annular rib heights were machined to give the next desired aspect ratio. Three aspect ratios, 3:3, 3:2, and 3:1, were tested in the present study. The other parameters of the present investigation were the model area ratio, defined as the ratio of duct area to that of the nozzle exit, the length-to-diameter ratio of the enlarged duct, L/D, and the primary pressure ratio P_0/P_a. The model area ratio used was 6.25 in all cases. The L/D ratio was varied from 1 to 6 in steps of 1. The primary pressure ratios used were 1.141, 1.295, 1.550, 1.707, and 2.458, which corresponded to nozzle exit Mach numbers of 0.44, 0.62, 0.82, 0.91, and 1.0, respectively. Because these Mach numbers are calculated with isentropic relations, neglecting friction, the author feels that it is more appropriate to use the pressure ratio rather than the Mach number in the analysis. Hence, P_0/P_a is retained as a pertinent parameter. The measurements include the stagnation pressure of the settling chamber, the base pressure, and the wall pressure distribution along the length of the duct. To account for the pressure loss, the total pressure at the exit of the duct was also measured by positioning a total pressure probe at the center of the duct exit plane. All of the pressures were measured using mercury manometers, and the measurements were found to be repeatable to within $\pm 3\%$ and accurate to within $\pm 5\%$.

Results and Discussion

All measured pressures have been nondimensionalized with the back pressure P_a. The lengths are nondimensionalized with the ductinner diameter D. Because the prime objectives in this study are to control the base pressure, to have smooth development of flow without oscillations in the duct, and to minimize the total pressure loss, the results are analyzed with these features in mind.

The base pressure variation with duct L/D for a pressure ratio of 2.458 for several passive control geometries is presented in Fig. 2. It is seen that the annular ribs with aspect ratio 3:1 result in base pressures that are appreciably lower than those for the expansion without passive control. Further, it is seen that with the 3:1 rib the minimum base pressure occurs for L/D around 4, and for a further increase of L/D the base pressure seems to be not influenced by L/D. For aspect ratios of 3:2 and 3:3, even though the base pressures, which are much lower than those obtained with the plain duct for L/D values less than 3, for higher values of L/D, the base pressure increases with increasing L/D, resulting in values much higher than those for the plain duct. From the results for pressure ratio 1.141 it is also found that the rib aspect ratio 3:1 results in minimum base pressure at L/D around 4.

The effect of the primary pressure ratio on the base pressure is shown for the passive control geometry with aspect geometry 3:1 in Fig. 3. The strong influence of the stagnation pressure on the base pressure is evident. The nature of the variation of base pressure with duct L/D for rib aspect ratio 3:1 is similar to that reported by Rathakrishnan et al.,[19] for passive control in the form of annular grooves, and by Rathakrishnan and Sreekanth,[10] for flow in pipes with sudden enlargement. The physical reason for the base pressure attaining a minimum for rib aspect ratio 3:1 may be the following: the shear layer that expands from the nozzle exit attaches to the enlarged duct wall downstream of the base. Depending on the reattachment length and the nozzle exit Mach number, the primary vortex that is formed at the base influences the base pressure. The strength of the primary vortex dictates the level of low pressure at the base region. Because of this low-pressure region, flow is induced from the wall region downstream of the reattachment point toward the base region. The extra mass that enters the base region is ejected to the main flow via shear layer entrainment, and this cycle continues. This ejection of mass was called "jet pump" action by Wick.[1] The flow of fluid into the base region reduces the primary vortex strength, thereby increasing the base pressure above the level it would attain if no fluid from the boundary layer downstream of the reattachment point entered the base region. That is, the ribs prevent the flow