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THE EFFECT OF ACOUSTICS ON FLOW PASSING A HIGH-AOA AIRFOIL

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In this paper a study is presented of the separated flow properties and corresponding aerodynamic behaviors of a high-AOA, NACA 63_3-018 airfoil under internal acoustically pulsing excitation in a subsonic wind tunnel. The measurements by means of pitot-static pressure tube and hot-wire anemometer include the boundary layer velocity profiles, boundary layer velocity energy spectra and velocity defect profiles in the wake. Results indicate that the acoustic excitation technique is able to alter the flow properties and thus to improve the aerodynamic performance, especially when the airfoil is fully stalled at high AOA. After the flow is effectively excited, the developed boundary layer delays its separation from the surface. The most effective excitation frequency is found to be equal to the shear layer instability frequency when the airfoil is around at the post-stall angle; however, it becomes of the vortex shedding frequency of the wake when the airfoil's AOA is increased beyond the stall. Data also show that the higher the pulsing acoustic level is, the better the flow properties are improved.

1. INTRODUCTION

During the course of combat, take-off and landing of an aircraft, a wing-stall phenomenon may occur when the aircraft is flying at a high angle of attack (AOA). This is due primarily to the occurrence of flow separation over a large portion of the wing surface. As a result, aerodynamic lift is lost and drag increased dramatically. It is therefore of great interest to alleviate this problem by introducing some means of control to suppress or delay such flow separation, thus improving the aerodynamic performance in the post-stall region. With the existence of an adverse pressure gradient in a viscous boundary layer flow, the boundary layer which contains less energy may break away, or separate, from the wall as it flows downstream. In order to keep the flow remaining attached to the surface, the boundary layer must have sufficient energy to overcome the adverse pressure gradient when it occurred. Thus, the basic idea of the flow control herewith is to energize the boundary layer and therefore suppress the flow separation.

There are many techniques such as vortex generators, roughness trips, blowing and suction, heating elements, etc., which have been considered as devices to control the flow separation problems. Whenever a control device is employed, the concerns of energy requirement, structural arrangement and space constraints then become important issues. The induced drag due to the introduction of such a device may come into play as well. Thus, in practical application, the operational conditions of conventional control devices are limited by the above drawbacks.

The acoustic wave used in the present paper is a pressure disturbance that transforms its energy into the airstream. The usage of this acoustic excitation in controlling a

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boundary layer flow has been well recognized for many decades. However, the active control of the separated flow by acoustics to improve the aerodynamic performance is only a recently undertaken technique. A detailed experimental study should be carried out fully to understand the mechanism of its interaction between the acoustic excitation and the separated flow. In early 1984, Schubauer and Skramstad [10] successfully applied acoustic waves to influence the boundary layer transition processes. After that, both Blevins [2] and Peterka and Richardson [9] investigated the effectiveness of the external acoustic excitation technique on shedding vortices behind circular cylinders. Their experimental results showed that when the excitation frequency f_e was near the shear layer instability frequency f_t or the shedding vortex instability frequency f_s, the characteristics of the flow structures could be altered easily. The application of the external acoustic excitation technique for controlling the separated flow on airfoils has been utilized by several researchers. Among them, Collins and Zelenevitz [3], Ahuja and Burrin [1] and Zaman *et al*. [10] separately applied acoustic waves externally to an airfoil where the flow was naturally separated. They found that the introduced acoustic waves, at some specific frequencies, could effectively influence the flow to cause a partial re-attachment of the separated flow so that the airfoil aerodynamic performance was improved. The other similar but different forcing method is called the internal acoustic excitation technique, in which the acoustic waves are emitted internally from a slot of the model surface to excite the separated flow over a post-stall airfoil. This technique has been intensively studied by Chang *et al*. [4], Hsiao *et al*. [5–7] and Lu and Ma [8]. They indicated that, as far as the better aerodynamic performance of an airfoil at high angles of attack is concerned, the internal excitation technique has more advantages over the external one.

Hence, the main purpose of this paper is further to examine the effectiveness of the internal acoustically pulsing excitation technique on the separated flow properties and its relevant aerodynamic performance of an airfoil at high angles of attack. Pulsing acoustic fluctuations injected from a forcing slot are used to excite the flow field. The measurements for analyses include boundary layer velocity profiles, fluctuating velocity energy spectra in the shear layer and velocity defect profiles in the wake.

2. EXPERIMENTAL FACILITIES

The experiment is conducted in an open-circuited, suction wind tunnel with a 90×120 cm test section. A contraction section with a contraction ratio of 9:1 and five fine-meshed screens is used for managing the freestream turbulence intensity. The flow is driven by a 200 hp motor with a set of rotary vanes for the speed control. The airstream velocity in the test section varies between 3 and 35 m/s. An airfoil model of 30 cm in chord and 60 cm in span with a NACA 63_3-018 cross-section is used for pressure and velocity measurements. As shown in Figure 1, the model is vertically mounted in the test section and restricted at both ends by flat steel plates. A narrow slot of 0.6 mm in width and 40 cm in length at 1.25% chord from the leading edge is manufactured to eject the acoustically pulsing velocity fluctuations. The acoustic fluctuations are generated by a loudspeaker, funnelled into the interior of the model, and then emitted into the flow through the narrow slot. The loudspeaker is driven by a power amplifier with a variable-frequency function generator. Information regarding the velocity field is taken by a pitot-static tube for the mean velocity measurements, and by a constant-temperature hot-wire anemometer with a single-wire probe constructed of a 5 μm diameter platinum wire for the streamwise fluctuating velocity measurements. In addition, a spectrum analyzer is used to obtain the frequency spectra of the velocity fluctuations. For the Cartesian co-ordinate system used for the

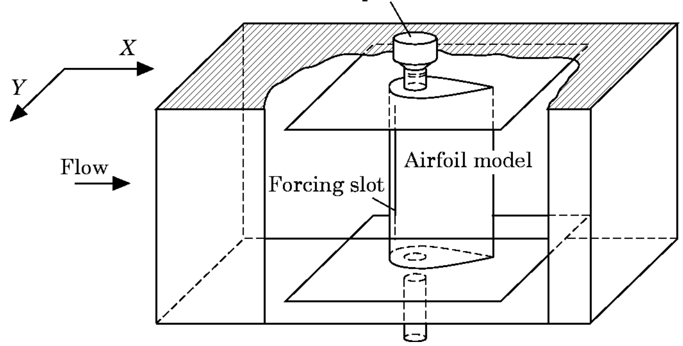

Figure 1. The arrangement of the airfoil model in the test section.

measurements, the X-direction denotes the streamwise direction from the leading edge of the airfoil and Y-direction the transverse direction to the freestream from the airfoil surface.

3. RESULTS AND DISCUSSION

In many studies concerning acoustic control on separated flows, the sound wave was believed to be an effective excitation source. Therefore, the sound pressure level (SPL) was habitually taken as a forcing amplitude parameter. However, in recent investigations by Chang *et al*. [4] and Hsiao *et al*. [7], both sound pressure level and velocity fluctuation, respectively, measured at the slot exit, were taken as the reference forcing parameters. Their experimental results indicate that the maximum acoustic velocity fluctuation which corresponds to some SPLs bears only a small percentage of the total forcing disturbance. Thus, the velocity fluctuation created by the periodic acoustic pulsing of fluid around the slot is recognized as the major disturbance source for the internal excitation technique. In order to avoid confusion with the velocity measurements of the flow field, the maximum velocity fluctuation, denoted by V'_{max}, generated due to acoustic pulsing right at the slot exit, is adopted as the reference parameter of excitation level in the present study. A detailed discussion can be found in Chang *et al*. [4].

3.1. ENERGY SPECTRA OF VELOCITY IN LOW POST-STALL REGION

Since the stall angle of the airfoil model used is about 17° at the operating Reynolds numbers, the angles of attack between 18° and 24° are thus categorized as in the low post-stall region. The leading-edged, separated boundary layer in such post-stall region is expected to be easily re-attached to the surface after the acoustics is internally introduced, as obtained by Hsiao *et al*. [5]. In comparison with the resulting flow for both excited and unexcited cases, some basic measurements of the flow field are first investigated for the typical 20° angle of attack case. A single hot wire is traversed perpendicularly to the freestream at 10% chord to measure the streamwise velocity fluctuations for the Reynolds number of 1.2×10^5. The fluctuating velocity signals in the separated shear layer region are directly fed into the spectrum analyzer. The effect of acoustic excitation in terms of the excitation frequency on fluctuating velocity spectral energy distributions in the shear layer region is depicted in Figure 2. For the cases of 50 and 100 Hz shown in Figures 2(a) and (b), both energy spectra obviously become concentrated at the excitation frequency and its harmonics, respectively, as compared to the case without excitation. For the

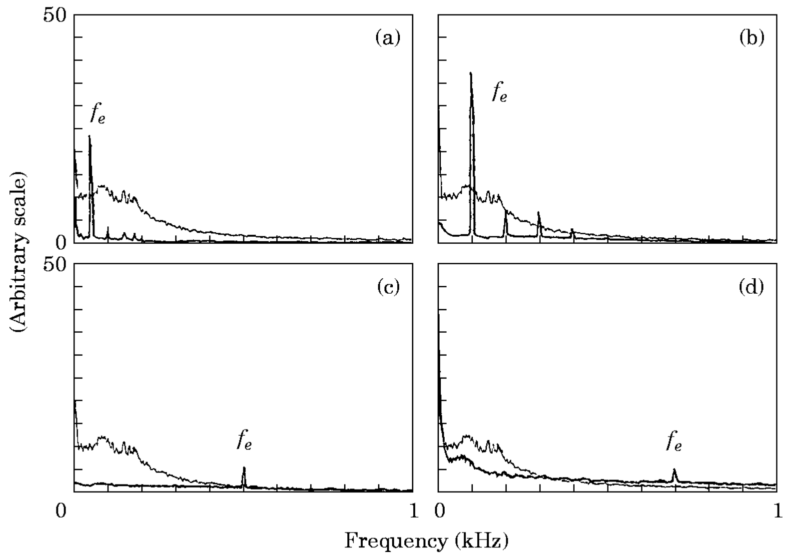

Figure 2. Typical velocity energy spectra in the shear layer region at 10% chord for AOA $= 20°$, $Re = 1.2 \times 10^5$ and various excitation frequencies. (a) $f_e = 50$ Hz; (b) $f_e = 100$ Hz; (c) $f_e = 500$ Hz; (d) $f_e = 700$ Hz. - - - - , Before excitation; ——, after excitation.

unexcited case, the natural shear layer instability measured is about 100 Hz, indicating that the forcing frequencies of 100 Hz and 50 Hz being used match the shear layer instability frequency and its subharmonic. Hence, this demonstrates the case of most effective excitation when the excitation frequency equals the shear layer instability frequency (Figure 2(a)), or of less effective excitation when the excitation frequency equals its subharmonic (Figure 2(b)). However, when the separated flow is subjected to 500 Hz or 700 Hz excitation in Figures 2(c) or (d), which are not within the shear layer instability frequency range, the excited energy spectra do not give rise to a forcing peak around the shear layer instability frequency. Instead, a peak appears corresponding to the excitation frequency in the energy spectra, indicating that these two cases correspond to the ineffective excitation as compared with the previous effective excitation cases.

In Figure 3 is shown a series of energy spectra under effective excitation, $f_e = 100$ Hz, by traversing the hot-wire probe perpendicularly to the freestream at 10% chord. The figure clearly illustrates that the component energy of the peak frequency decays with the distance moving away from the surface, showing that the internal acoustic excitation prevails as a local effect. This substantiates the results proposed by Hsiao *et al*. [5] that the acoustic excitation only influences the flow field locally around the forcing slot, which may then engulf the freestream mass into the separated shear layer region so as to produce the boundary layer re-attachment.

3.2. EXCITATION EFFECT ON BOUNDARY LAYER VELOCITY PROFILE

Another way of determining the effectiveness of excitation on the flow field is to compare the boundary layer velocity profiles at the upper surface of the airfoil under various forcing conditions. The mean velocity measurements are conducted over the airfoil by employing a pitot-tube traversing at seven chordwise locations, from 10% chord to the end of the airfoil with an increment of 10% chord. Because the flow is reversed in the separated region near the airfoil's surface, the results from the pitot-tube measurements in this region are not accurate but simply used for qualitative comparison. The boundary layer velocity profiles are measured at 20° angle of attack with and without excitation. In addition, the excitation amplitude and frequency are taken as the control parameters, which will be discussed as follows.

Before excitation is applied at 20° angle of attack, the airfoil is fully stalled and the flow is separated from the leading edge of the airfoil. However, when the flow is excitated at various acoustic frequencies, the variations of the boundary velocity profiles presented in Figure 4 indicate that the leading-edged flow separation is suppressed when the effective excitation frequency of 100 Hz is used, as compared to the other cases. That is, in this beneficial excitation case, the upper surface's boundary becomes thicker but remains attached until at about 35% chord and then separates from the surface afterwards. As a consequence, a low pressure region on the upper surface and a narrower wake region downstream of the airfoil will be obtained. It thus causes an increase in lift and a reduction in drag, as has been obtained by Chang *et al*. [4]. Moreover, under an excitation frequency of 500 Hz, the boundary layer velocity profile remains attached until at about 15% chord. However, excitation at 700 Hz shows no significant influence on the velocity profiles, due to an inappropriate excitation frequency being used. The excitation results in the boundary layer velocity profiles agree with those of the excited velocity energy spectra as discussed in the previous section. It can be concluded that under effective excitation, when the forcing frequency matches the shear layer instability frequency, the separated shear layer becomes energetic and is re-attached to the surface due to the violent mixing and momentum transport caused by the acoustic pulsing excitation interacting with the flow.

In Figure 5 are depicted comparisons of the boundary layer profiles in terms of the excitation level, V'_{max}, at the excitation frequency of 100 Hz. It is found that the location

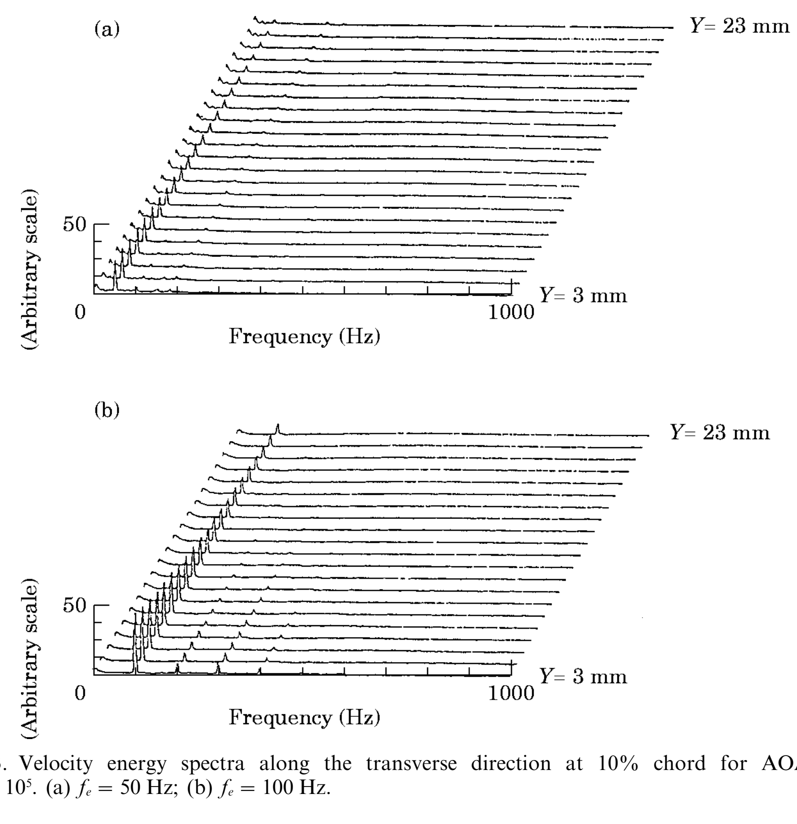

Figure 3. Velocity energy spectra along the transverse direction at 10% chord for AOA = 20° and $Re = 1.2 \times 10^5$. (a) $f_e = 50$ Hz; (b) $f_e = 100$ Hz.

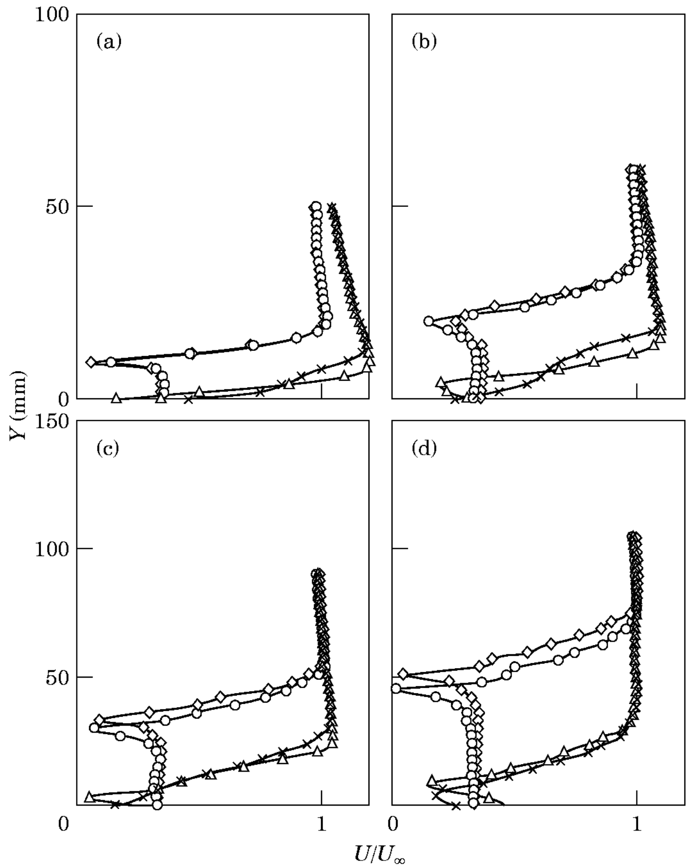

Figure 4. Comparisons of boundary layer profiles for AOA = 20°, $Re = 1.2 \times 10^5$ and $V'_{max} = 4.6$ m/s. (a) $x/c = 0.1$; (b) $x/c = 0.2$; (c) $x/c = 0.3$; (d) $x/c = 0.4$. ○, natural; ×, $f_e = 100$ Hz; △, $f_e = 500$ Hz; ◇, $f_e = 700$ Hz.

of flow re-attachment moves downstream with the increase of the excitation level. This demonstrates that the pulsing amplitude V'_{max} is also a governing parameter for modifying the separated flow properties. Moreover, the results of the boundary layer thickness, δ, corresponding to the above velocity profiles, are plotted in Figure 6. Here, the boundary layer thickness is defined as the distance from the airfoil's surface to the location at which the boundary velocity equals 99% of the freestream velocity. This figure clearly presents the fact that forcing at the shear layer instability frequency of 100 Hz has developed less boundary layer thickness and thus delayed the flow being separated, indicating that it is the most effective frequency. It is also shown that the higher the excitation level used the better is the excitation effectiveness obtained.

3.3. Excitation effect on wake defect profile

The wake defect profiles at $Re = 1.2 \times 10^5$ for angles of attack of 20° are measured by traversing a pitot-tube perpendicularly to the freestream at 200% chord from the trailing edge of the airfoil. In Figure 7(a) is shown the comparison of the wake defect profiles when the flow is unexcited or excited at various forcing frequencies. The results clearly exhibit a narrower wake region under the effective excitation condition, $f_e = 100$ Hz. This is due to the tendency of the boundary layer to re-attach to the wall surface, which results in a significant reduction in drag. The wake defect profiles with a beneficial forcing frequency of 100 Hz at various excitation levels are shown in Figure 7(b). It is noted that the higher the excitation level is, the narrower the wake defect will be. Thus, a narrowest wake with smallest velocity defect is observed at the maximum excitation level; hence, the least drag is expected.

By inspecting the aerodynamic properties before and after excitation as obtained, it is concluded that, when the flow is excited with a periodic pulsing fluctuations close to the shear layer instability frequency, the separated flow can be excited to produce the re-attachment. Thus, a double advantage of higher lift and lower drag assures a better aerodynamic performance through the use of the periodic pulsing excitation technique in the low post-stall conditions, as has also been obtained by Chang *et al*. [4] and Hsiao *et al*. [5, 7].

3.4. ENERGY SPECTRA OF VELOCITY FLUCTUATIONS IN HIGH POST-STALL REGION

According to the above discussion, the separated boundary layer in a low-stalled angle of attack (18°–24°) can be excited to be re-attached to the airfoil surface under effective excitation. However, if the angle of attack is inceased to 24° or higher, the forcing effectiveness becomes degenerative due to an increased adverse pressure gradient developed over the upper surface of the airfoil. The separated boundary layer from the leading edge

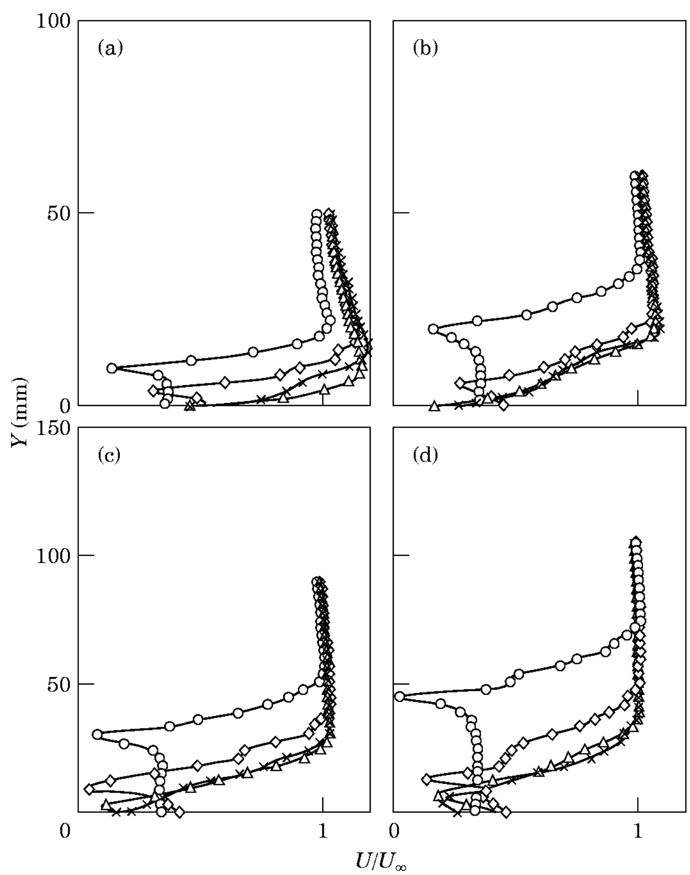

Figure 5. Comparisons of boundary layer profiles for AOA = 20°, $Re = 1.2 \times 10^5$ and $f_e = 100$ Hz. (a) $x/c = 0.1$; (b) $x/c = 0.2$; (c) $x/c = 0.3$; (d) $x/c = 0.4$. ○, natural; ×, $V'_{max} = 4.6$ m/s; △ $V'_{max} = 4.2$ m/s; ◇, $V'_{max} = 3.8$ m/s.

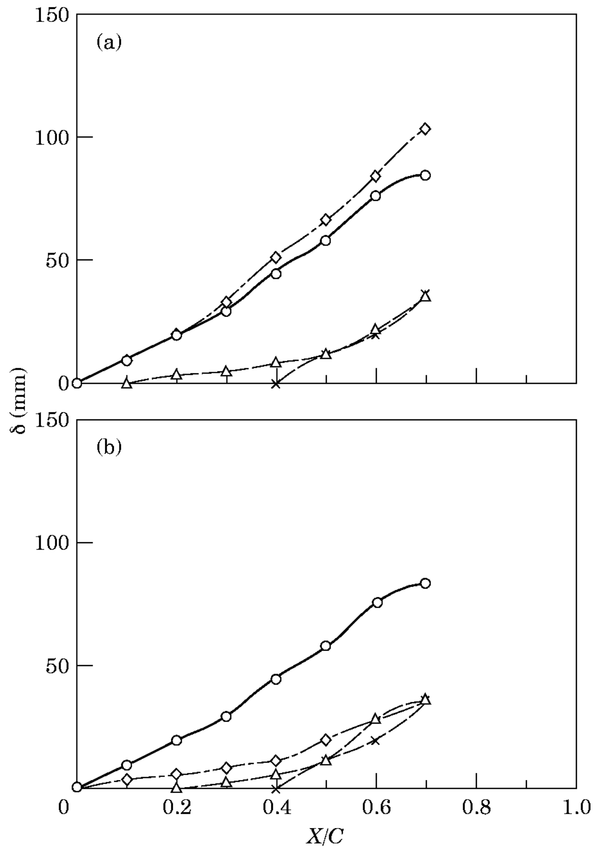

Figure 6. Comparisons of boundary layer thickness before and after excitation from Figures 4 and 5. (a) $V'_{max} = 4.6$ m/s: ○, natural; ×, $f_e = 100$ Hz; △, $f_e = 500$ Hz; ◇, $f_e = 700$ Hz. (b) $f_e = 100$ Hz: ○, natural; ×, $V'_{max} = 4.6$ m/s; △, $V'_{max} = 4.2$ m/s; ◇, $V'_{max} = 3.8$ m/s.

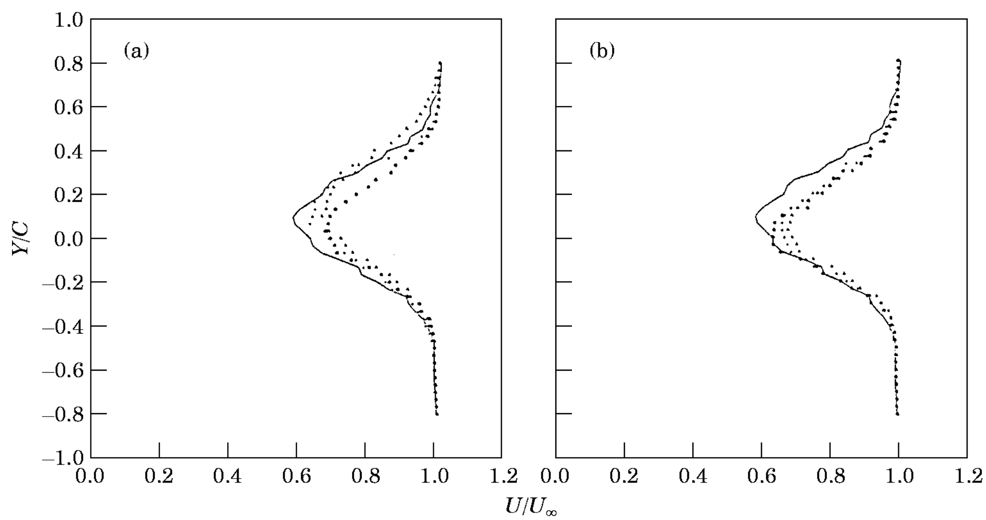

Figure 7. Comparisons of wake defect profiles before and after excitation for AOA = 20° and $Re = 1.2 \times 10^5$ in terms of (a) excitation frequency and (b) excitation level, $f_e = 100$ Hz. (a) ——, Natural, $C_d = 0.289$; ○, $f_e = 100$ Hz, $C_d = 0.224$; ×, $f_e = 500$ Hz, $C_d = 0.262$; △, $f_e = 700$ Hz, $C_d = 0.275$. (b) ——, Natural, $C_d = 0.289$; ○, $V'_{max} = 3.5$ m/s, $C_d = 0.243$; ×, $V'_{max} = 4.2$ m/s, $C_d = 0.239$; △, $V'_{max} = 4.6$ m/s, $C_d = 0.224$.

then would hardly be re-attached to the airfoil's surface. Referring to the experimental results of Hsiao *et al*. [7], as shown in Figure 8, the lift is increased in the high post-stall region when the acoustic excitation frequency matches the vortex shedding frequency in the wake. Moreover, the frequency band for effective excitation becomes narrower with the increase of the angle of attack. In order to examine the control effectiveness of pulsing excitation in such a condition, a high post-stall airfoil will be subjected to low frequency forcing.

The flow structures over airfoil surface and in the wake are measured using a hot-wire anemometer depict the energy spectra of the upper surface's velocity fluctuations at 25% chord, 50% chord and 75% chord, respectively, for three excitation frequencies at 30° angle of attack, are deposited in Figures 9(a)–(c). Without excitation, the natural shedding frequency is 6.25 Hz in the wake. Inspecting these curves in Figure 9, we can find that excitation applied at the vortex shedding frequency of 6.25 Hz would concentrate the vortical energy at the applied frequency and its harmonic. However, when the flow is excited at 50 Hz, which matches the subharmonic of the shear layer instability frequency, the natural shedding vortices are suppressed and a weaker energy peak appears at the forcing frequency.

Thus, the creation of weaker natural shedding vortices is delayed by forcing the wake flow with a frequency far from the vortex shedding instability frequency. It is then concluded that the pulsing perturbations have the ability to synchronize the vortex shedding and to increase the strength of shedding vortices from the airfoil when the

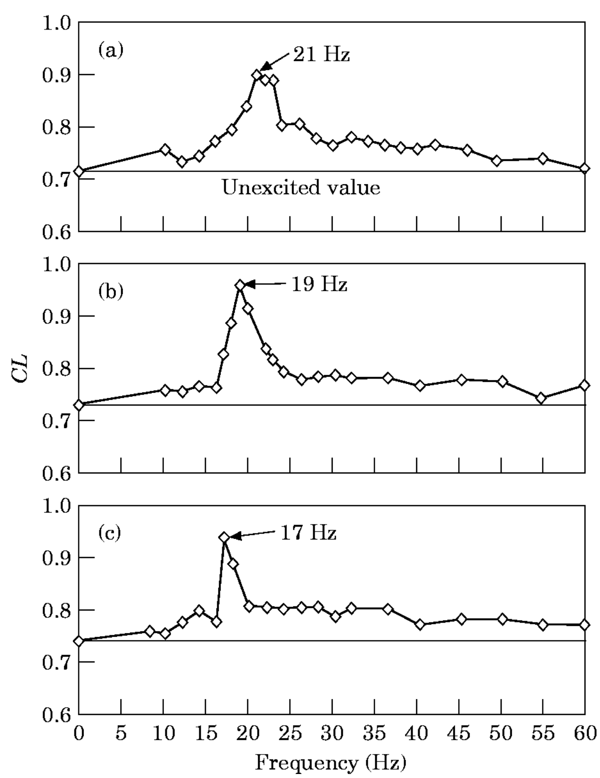

Figure 8. Comparisons of the lift coefficient with excitation frequency [7] at high post-stall angles. (a) AOA = 26°; (b) AOA = 28°; (c) AOA = 30°.

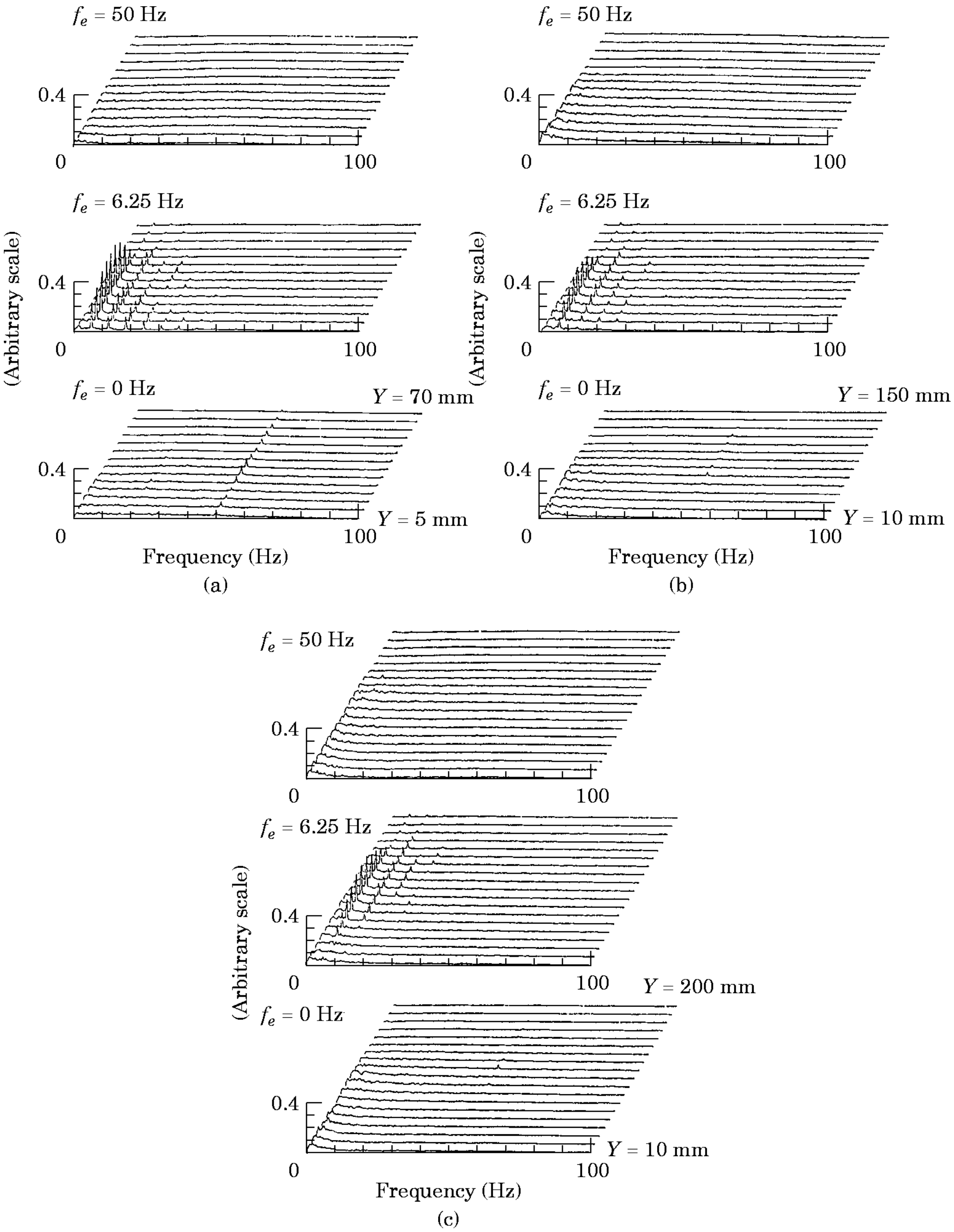

Figure 9. Velocity energy spectra along the transverse direction for AOA = 30° and $Re = 1.2 \times 10^5$ at (a) $x/c = 0.25$, (b) $x/c = 0.5$ and (c) $x/c = 0.75$.

excitation frequency is close to the natural shedding instability frequency. At 30° angle of attack, the iso-velocity component energy contour at the dominant vortex shedding frequency of 6.25 Hz under a 6.25 Hz excitation is given in Figure 10. An examination of this result reveals that the variation of shedding vortex energy and the location of this vortex core coincide with the result from the flow visualization as obtained by Chang *et al*. [4]. Once again, enhancement of the vortex shedding process is verified in the high post-stall region.

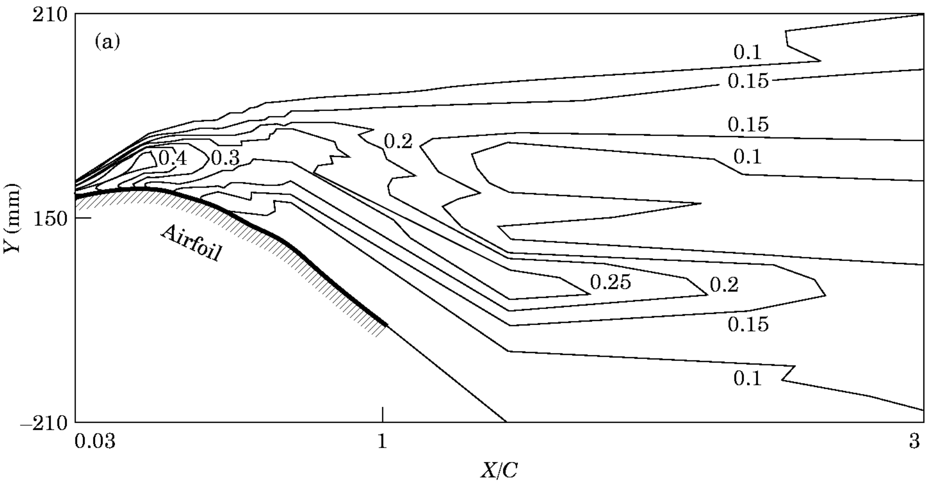

Figure 10. The iso-velocity component energy contour for AOA = 30°, $Re = 1.2 \times 10^5$ and $f_e = 6.25$ Hz.

4. CONCLUDING REMARKS

In this paper the effects of internal acoustic pulsing excitation on the improvement of post-stall aerodynamic performance about an airfoil at high angles of attack are studied by means of velocity measurements and velocity energy spectral analysis in a low speed wind tunnel. The experimental results show the following.

(1) The shear layer instability frequency, which increases with increasing Reynolds number, is easily excited by a periodic pulsing fluctuation at the same frequency.

(2) For the low post-stall angle airfoil performance (AOA = 18°–24°), the leading-edged flow separation is suppressed by excitation of a frequency near the shear layer instability frequency. Thus, the stall angle of attack is delayed and the airfoil stalled performance is improved. Moreover, the pulsing amplitude is also demonstrated to be an important parameter for modifying the separated flow.

(3) In the high post-stall region (AOA = 24° or higher), since the wake behind the flow separation tends to form a vortical flow structure, usually called the von Kármán vortex street, the most effective forcing frequency for improving the aerodynamic properties is to match the vortex shedding frequency in the wake.

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