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Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Prediction of Transonic Buffet Onset for Airfoils with Separation Bubble Using Steady Approaches

Injae Chung*
Agency for Defense Development, Taejon 305-600, Republic of Korea
Duckjoo Lee†
Korea Advanced Institute of Science and Technology, Taejon 305-701, Republic of Korea
and
Taekyu Reu‡ and Duckkon Ko‡
Agency for Defense Development, Taejon 305-600, Republic of Korea

Introduction

BECAUSE the flight envelope of transonic aircraft is restricted when a certain degree of buffet occurs, the prediction of the buffet onset boundary is quite important. To predict the buffet onset boundary, several wind-tunnel test methods[1] have been developed. However, they are not suitable for the first step in design of transonic aircraft due to high expenditure of time and cost. For this reason, to predict the buffet onset theoretically, several methods[1] have been developed instead of wind-tunnel tests.

As a first step, it is useful to examine the case of airfoil flow models to analyze the dominant physical features of transonic buffet. Such flow models were suggested by Pearcey et al.[2] and were classified into two broad categories, as models A and B. Model A is for conventional airfoils, which have a tendency toward separation bubble formation due to the shock. Model B is for supercritical airfoils, which have tendency toward rear boundary-layer separation due to the shock. To predict the transonic buffet onset for both model A and B airfoils, generally, two different theoretical approaches have been considered. One approach is a steady approaching method based on the boundary-layer theory. The other approach is an unsteady approaching method based on Navier–Stokes solver. The steady approaching method was suggested by Thomas[3] and has successfully been used to predict the transonic buffet onset for model B airfoils (see Ref. 4). In this flow model, the flow is assumed to be steady for the buffet onset. Because Thomas's method[3] is based on boundary-layer theory, it is only applicable for the case of airfoils with rear separation (model B airfoils). On the other hand, in the case of airfoils with shock-induced separation bubble (model A airfoils), the buffet onset cannot be predicted by Thomas's method because the boundary-layer assumption is no longer valid in the separation bubble. Thus, so far no theoretical steady approaching method has been developed to predict the buffet onset for model A airfoils. To predict the transonic buffet onset for model A airfoils, a new steady approaching method is proposed in this Note. The basis of the new method is to apply the method of kink analysis to the curve plots calculated from a steady Navier–Stokes solver. This kink is caused by the shock-induced separation bubble and can be identified as buffet onset.[5] The accuracy of present method is verified in this Note by comparison with results of two-dimensional transonic buffet wind-tunnel test.

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*Senior Researcher, 3rd R&D Center, Yusong P.O. Box 35-3; Kraft1961@hitel.net. Member AIAA.
†Professor, Department of Aerospace Engineering, 373-1, Kusong-dong, Yusong-Ku. Member AIAA.
‡Senior Researcher, 3rd R&D Center, Yusong P.O. Box 35-3.

Approach

The steady Navier–Stokes solver based on the DADI[6] scheme computation is performed on the conventional NACA 0012 airfoil (model A) with the assumption of steady flow for the buffet onset as suggested by Thomas.[3] The Baldwin–Lomax[7] algebraic turbulence model is used here. A C-type grid of 275×65 points covering the computational domain that extends to 10 chord lengths from the airfoil is used. Flow conditions are Mach number 0.7–0.8, angle of attack 0–5 deg, and Reynolds number based on chord length 6.0×10^6. Local time stepping was used in the steady calculation to accelerate convergence to steady state, which is reached when the lift coefficient is 0.1% of its final value with at least four orders of magnitude of residual reduction. To predict the transonic buffet onset for the NACA 0012 airfoil from the calculated curve plots, the method of kink analysis in the various aerodynamic curves is examined. In addition, an existing unsteady approaching method[8] based on unsteady Navier–Stokes solver has been examined to verify the accuracy of the present method. In this calculation, a second-order time-accurate computation was used with time steps of 0.0005.

Results and Discussion

The accuracy of numerical method based on the steady Navier–Stokes solver with the Baldwin–Lomax turbulence model has been examined by other researchers, for example, in Ref. 9. In this Note, results from one test case are presented and compared with experimental data.[10] Figure 1a shows the surface pressure coefficient distributions for this case along with experimental data. The overall agreement is good except near the shock. The location of shock is predicted slightly downstream of the experimentally observed location of shock. This discrepancy is due to the limitations of Baldwin–Lomax turbulence model in the shock–boundary-layer interaction. As noted by Holst,[9] the normal shock behavior in the transonic flows is quite sensitive to the choice of turbulence model. However, when the known sensitivity of other turbulence models is considered, the overall quality of the results is believed to be acceptable for this mild shock-induced separation. However, for the cases with a large region of shock-induced separation, the location of shock is predicted farther downstream of the experimentally observed shock location, with a corresponding underprediction of displacement thickness behind shock. Such cases are beyond the scope of prediction of buffet onset because only steady states with attached flow or mild separation bubble are considered in this study.

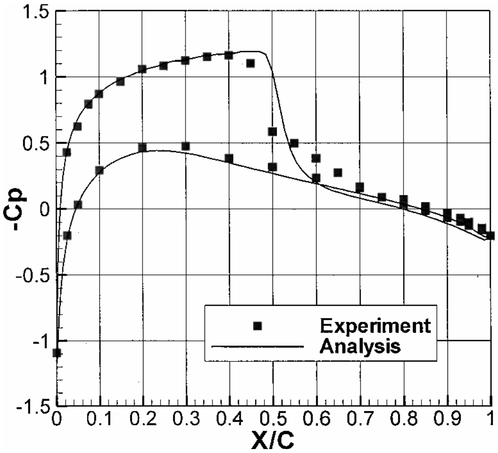

Fig. 1a Surface pressure coefficient distribution, Mach = 0.778, *Re* = 6.0 × 10⁶, and angle of attack = 2.03 deg.

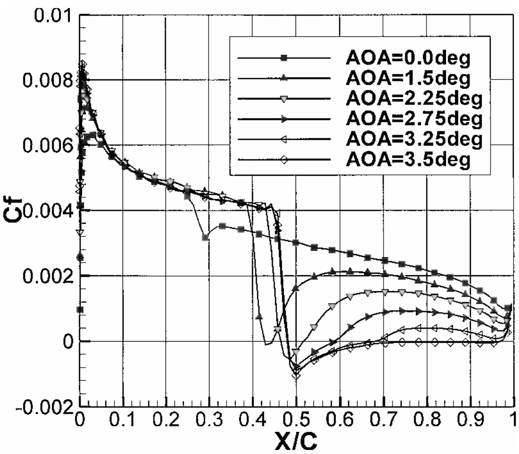

Fig. 1b Upper surface skin friction coefficient distribution, Mach = 0.76 and *Re* = 6.0 × 10⁶.

Because the present method is based on kink analysis, the most important factor required is whether the separation bubble, which causes the kink in the particular aerodynamic curves, exists in the NACA 0012 airfoil flow at given flow conditions. The effect of the separation bubble is clearly seen in the skin-friction coefficient curve in Fig. 1b. The validity of these calculations has not been quantitatively examined in this Note because no experimental skin-friction data are available to compare with the computed results. The purpose of the presentation of Fig. 1b is to show that the NACA 0012 airfoil is model A-type airfoil at given flow conditions. In these calculations, shock-induced separation bubble formation is noticed at 1.5-deg angle of attack. Also, the shock is seen to move rearward with extension of bubble length as angle of attack increases. As shown in Fig. 1b, observe that separation bubble burst occurs suddenly at around 3.25-deg angle of attack. This suggests buffet onset, but cannot be verified by Thomas's 90% chord criterion.[4] Thus, it is apparent that, for the case of the airfoil with separation bubble dominant, buffet onset prediction is not possible by Thomas's method.

Figure 2a shows the lift curves. As angle of attack increases beyond the linear range, the shock moves backward and becomes strong enough to cause the separation bubble. When the separation bubble extends rapidly from the shock to the trailing edge, the slope of lift curve is drastically reduced. This is recognized as buffet onset. Pearcey and Holder[5] showed experimentally that the distinct slope change (or kink) in the lift curve coincided with buffet onset as measured with a strain gauge on a two-dimensional airfoil. In these curves, the distinct slope changes can be found at higher Mach number, as shown in Fig. 2a. However, the distinct slope changes are not shown clearly at relatively low Mach numbers because the effects of weak shock movement represent a small variation of lift

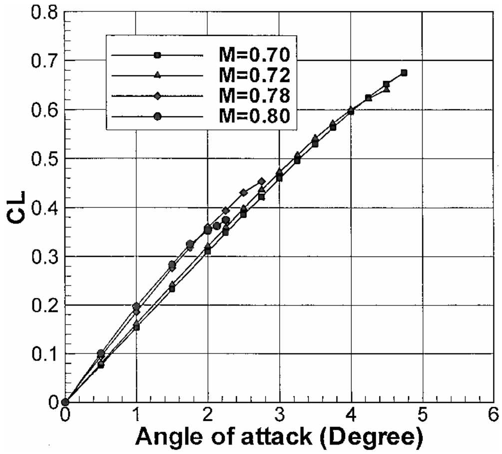

Fig. 2a Lift coefficient curve, *Re* = 6.0 × 10⁶.

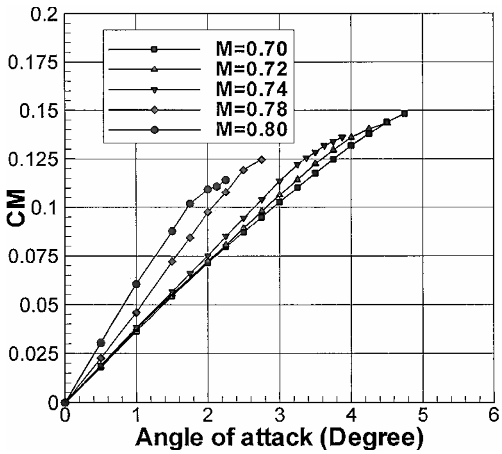

Fig. 2b Pitching moment coefficient curve, *Re* = 6.0 × 10⁶.

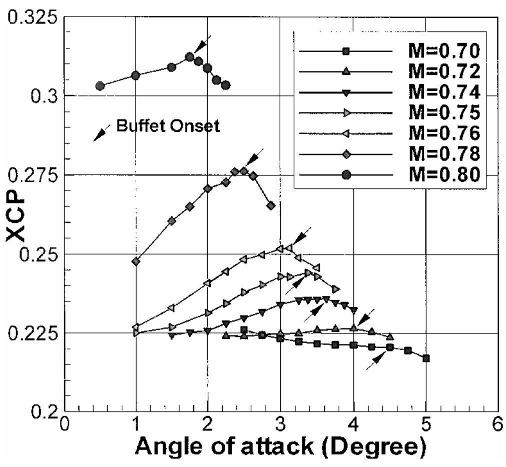

Fig. 2c Center of pressure variation curve, *Re* = 6.0 × 10⁶.

curve, in general. It is difficult to predict the buffet onset by kink analysis in the lift curves at a certain flow conditions. Thus, alternative methods are required, which correspond to the method of kink analysis in the lift curves, to find the points of more distinct slope change in the particular aerodynamic curves. The pitching moment and center of pressure variation curves are considered in this study as alternative methods. In the lift curves, some cases show a slight oscillation (within 0.5–1% of mean value) at the higher angle of attack after the kink. Because only steady states are considered in this study, these small oscillations after the kinks are not of primary concern. Furthermore, these kinks do not affect the trend in the curves for kink analysis. From the engineering application viewpoint these

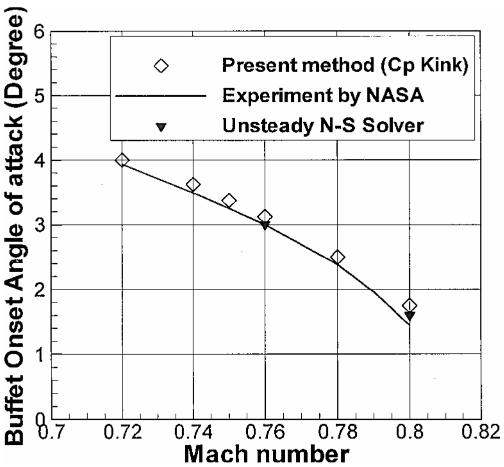

Fig. 3 Comparison of buffet onset, $Re = 6.0 \times 10^6$.

oscillations are small enough so that steady state may be assumed to estimate the mean value.

As an alternative method, a frequently used method is analysis of pitching moment curve deviation[6] as shown in Fig. 2b. The pitching moment is referenced at the leading edge. Figure 2b shows more obvious slope changes in the curves than those in the lift curves. The variation of pitching moment is sensitive due to the length between the reference point and the point in the separated region. As the separated region moves aft with movement of the shock, this effect is accentuated.

The movement of the shock wave with variation in angle of attack causes changes in the position of the center of pressure. Note that the center of pressure curves show noticeable kinks, as shown in Fig. 2c, compared with other curves. This occurs because the effect of shock movement causes a relatively small variation of lift in general, but it causes drastic variation on position of center of pressure. Furthermore, this effect is accentuated when shock-induced separation exists. These kink points coincided with those in the lift curves and pitching moment curves, as shown in Figs. 2a–2c. Therefore, the kink points in the center of pressure curves can be recognized as buffet onset points.

The predicted results of transonic buffet onset for the NACA 0012 airfoil are shown in Fig. 3 along with those of two-dimensional buffet wind-tunnel test.[10] Figure 3 shows that the predicted results of the present method are very close to the experimental predictions, except for results at the higher mach number. These discrepancies at higher Mach number are due to the difference between the shock locations predicted by experiments and computations. A more advanced turbulence model may alleviate this problem. Unsteady prediction is carried out for the cases of Mach numbers 0.76 and 0.80. Buffet onset is predicted almost exactly as shown in Fig. 3. However, this prediction requires very long computing time and large memory.

Conclusions

The new theoretical steady approaching method developed is useful to predict the buffet onset for an airfoil with shock-induced separation bubble (model A airfoil) when compared with the two-dimensional buffet wind-tunnel test. Among the various aerodynamic curves, the center of pressure curve shows the most distinct kink point even at relatively low Mach number with high angle of attack and good agreement with unsteady wind-tunnel test results. Therefore, it can be suggested that the kink of the center of pressure vs angle-of-attack curve can be used as a reliable indicator of buffet onset on a model A airfoil for the steady experimental method. In addition, in comparison with the results of unsteady prediction method, which requires more computational time and memory, the present method is shown to be accurate for transonic buffet onset prediction from the engineering application viewpoint. Because the present method applies the kink analysis method to curves calculated from steady Navier–Stokes solver, it can be applicable even to the three-dimensional full configuration of aircraft.

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Characteristics of Compressible Concave-Corner Flows

Kung-Ming Chung*
National Cheng-Kung University,
Tainan 711, Taiwan, Republic of China

Nomenclature

C_p	=	pressure coefficient, $(p_w - p_\infty)/q_\infty$
M_∞	=	freestream Mach number
p	=	static pressure
q_∞	=	dynamic pressure
x	=	coordinate along the surface of the corner
$x*$	=	x/δ_0
x_u^*, x_d^*	=	normalized upstream and downstream influence region
α	=	concave-corner angle, deg
δ_0	=	incoming boundary-layer thickness
η	=	convex-corner angle, deg
ξ	=	interaction region, $(x_d^* - x_u^*)$

Introduction

IMPROVEMENT of aircraft performance is always one of the major goals for the aerodynamists.[1] Bolonki and Gilyard[2] have indicated that the deflected control surfaces could be used in combination to provide the variable camber control within the operational flight envelope. The active modification of the control surfaces could potentially play a role in performance optimization for an aircraft. At transonic speeds the benefits of variable camber using a simple trailing-edge control surface system can approach more than

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*Research Fellow, Aerospace Science and Technology Research Center, 2500 Section 1, Chung-Cheng S. Rd, Kueijen. Senior Member AIAA.