Paper

Int'l J. of Aeronautical & Space Sci. 18(1), 1–7 (2017)
DOI: doi.org/10.5139/IJASS.2017.18.1.1

IJASS
International Journal of Aeronautical and Space Sciences

Prediction of Transonic Buffet Onset for a Supercritical Airfoil with Shock-Boundary Layer Interactions Using Navier-Stokes Solver

Injae Chung*

Agency for Defense Development, Daejeon 34186, Republic of Korea

Abstract

To predict the transonic buffet onset for a supercritical airfoil with shock-boundary layer interactions, a practical steady approach has been proposed. In this study, it is assumed that the airfoil flow is steady even when buffet onset occurs. Steady Navier-Stokes computations are performed on the supercritical airfoil. Using the aerodynamic parameters calculated from Navier-Stokes solver, various steady approaches for predicting buffet onset are discussed. Among the various steady approaches considered in this study, Thomas' criterion based on Navier-Stokes computation has shown to be the most appropriate indicator of identifying the buffet onset for a supercritical airfoil with shock-boundary layer interactions. Good agreements have been obtained compared with the results of unsteady transonic wind tunnel tests. The present method is shown to be reliable and useful for transonic buffet onset for a supercritical airfoil with shock-boundary layer interactions in terms of practical engineering viewpoint.

Key words: Transonic Buffet Onset, Shock-Boundary layer Interactions, Supercritical Airfoil, Thomas' Criterion

1. Introduction

To predict the transonic buffet onset theoretically, several methods have been developed instead of expensive wind tunnel tests for the early design stage of the transonic aircraft. Considering the inherent complexity of the transonic buffet phenomena, the simplified flow models are required for the theoretical approaches. For this purpose, two-dimensional airfoil flow models were suggested based on the dominant features of shock-boundary layer interactions investigated from wind tunnel tests. These flow models are classified into two broad categories as model A and B[1]. The model A flow is for mainly thin or conventional airfoil having tendency of shock induced separation bubble. The model B flow is for mainly thick or supercritical airfoil having tendency of shock induced rear separation. These flow models have been used to predict the transonic buffet onset for the airfoils, which may prove to be useful in early design stage of the aircraft.

To predict the transonic buffet onset for both model A and B airfoils theoretically, various approaches have been developed. Typical approach is a steady approach based on the classical boundary layer theory. This steady approach was suggested by Thomas[2]. In this flow model, the flow was assumed to be steady for the buffet onset prediction. This method has been used to predict the transonic buffet onset for airfoils, which may prove to be useful in early design stage of aircrafts. In this method, the buffet onset is defined, for a given Mach number, in terms of the angle of attack or the lift coefficient when a separation point of turbulent boundary layer, moving from the trailing edge, reaches 90% of the airfoil chord length from the leading edge. The criterion of 90% location of rear separation had been established by comparing the calculation with experimental results. However, for the case of complex shock- boundary layer interactions, such as shock induced separation bubble, the applications of this method based on the boundary layer theory are often restricted, since the boundary layer assumption is theoretically no longer valid in the separation bubble. Thus this method can be used for the case of airfoils with pure rear separation (Model B airfoils). On the other hand in the case

* Researcher, Corresponding author: ijchung@add.re.kr

Received: March30, 2016 Revised: February 17, 2017 Accepted: February 17, 2017

http://ijass.org pISSN: 2093-274x eISSN: 2093-2480

of airfoils with shock induced separation bubble dominant (Model A airfoils), the buffet onset cannot be predicted by Thomas' method.

Recently, the problem of buffet onset prediction for a supercritical airfoil with shock-boundary layer interactions has been very important with the introduction of long range airliner or HALE UAV(High Altitude Long Endurance Unmanned Aerial Vehicle). These aircrafts are characterized by high aspect ratio wing with supercritical airfoils, also emphasizing the buffet alleviation design particularly. Therefore, a practical approach is needed to predict the transonic buffet onset for supercritical airfoils with shock-boundary layer interactions in the early design stage of high speed aircraft. In this study, in order to achieve practical prediction results of a supercritical airfoil with shock-boundary layer interactions, instead of computations based on classical boundary layer theory, the steady Navier-Stokes computations have been performed with the assumption of steady flow for buffet onset as Thomas suggested. Using the aerodynamic parameters calculated from Navier-Stokes solver, various steady approaches for predicting buffet onset are discussed. Compared with each other, the most appropriate indicator of identifying the buffet onset for a supercritical airfoil is suggested. The results given by the present method are also compared with the results of two-dimensional wind tunnel transonic buffet test for verification.

2. Numerical method

To compute the transonic flow over a supercritical airfoil, the thin-layer form of compressible Navier-Stokes solver expressed in strong conservation-law form is solved using an implicit finite volume method. The numerical algorithm adopted is the upwind Roe's FDS scheme for calculating inviscid flux[3]. To increase the accuracy of the solution, TVD scheme based on MUSCL type approach with the minmod flux limiter is applied[4]. The DADI scheme is used for the time integration. To treat the turbulent flow, the two-layer algebraic eddy viscosity turbulence model by Baldwin-Lomax is chosen in favor of computational robustness[5].

For the verification of numerical method used in this study steady solutions have been computed for the transonic flow over RAE2822 supercritical airfoil. This airfoil has a maximum thickness of 12.1% of chord and a leading-edge radius of 0.827% of chord[6]. For this verification, a C-type grid of 369×65 points covering the computing region size of 10 chord length from airfoil in each direction was used. The minimum normal size of grid is 1×10^{-5} chord length scale. The first y+ value on grid spacing off the airfoil surface is approximately 1.0. This grid was also generated by the algebraic grid generation technique. Fig. 1 shows the grid system used in this verification. A local time stepping was used in the steady calculation to accelerate convergence to the steady state. A steady state was defined to be reached when the lift coefficient reached 0.1% of its final value with at least four orders of magnitude of residual reduction. Turbulent flow was initiated at the airfoil leading edge (x/c=0.). Fig. 2 shows the code validation for pressure distribution of RAE2822 airfoil at Mach number 0.734 with the angle of attack 2.54 degree and Reynolds number 6.5×10^{6}. The overall agreement is good except for near the leading edge and the shock interaction region. Upper surface skin friction is compared for the case at Mach number 0.734 with the angle of attack 2.54 degree and Reynolds number 6.5×10^{6} in Fig. 3. Skin friction distributions are based on the free stream condition. In this case, the Baldwin-Lomax turbulence model gives good agreement in the skin friction distributions. It is also found that the turbulence model predicts weak separation at the trailing edge as shown in Fig. 3

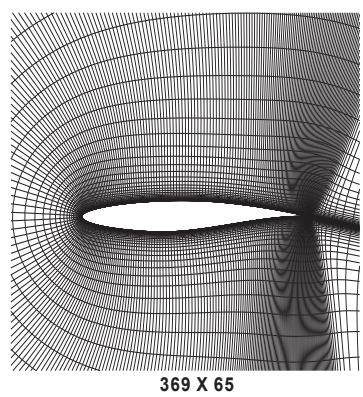

Fig. 1. RAE2822 Airfoil Computation Grid

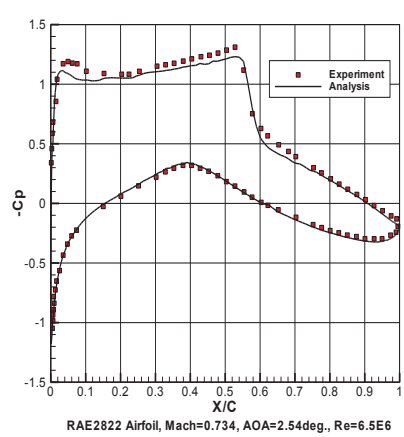

Fig. 2. RAE2822 Airfoil Surface Pressure Distribution

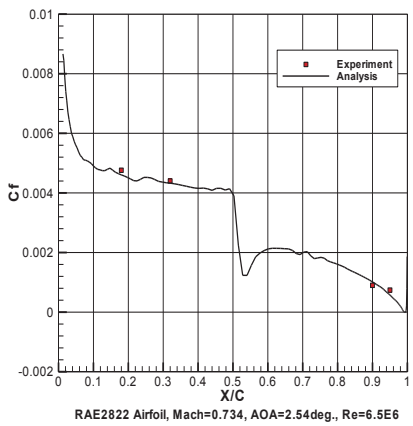

Fig. 3. RAE2822 Airfoil Upper Surface Skin Friction Distribution

3. Prediction of Buffet Onset for BGK No.1 Airfoil

The steady Navier-Stokes computations have been performed for the transonic flow over BGK No.1 supercritical airfoil to predict the buffet onset based on steady approach.

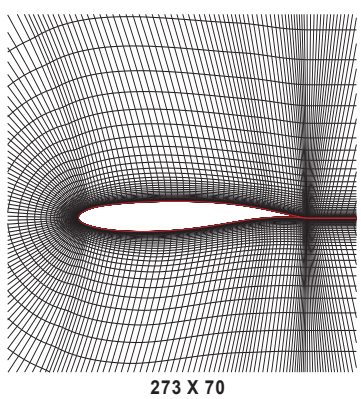

Fig. 4. BGK No.1 Airfoil Computation Grid

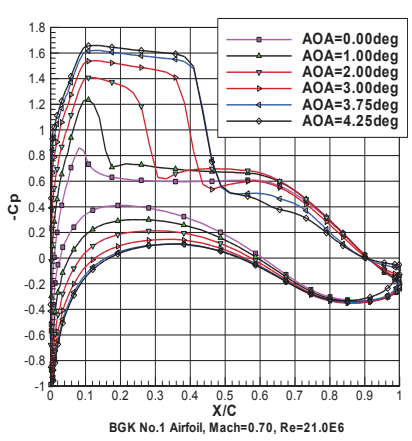

Fig. 5. BGK No.1 Airfoil Surface Pressure Distribution

This airfoil designed by Garabedian and Korn has a shock free distribution at design Mach number and lift coefficient of 0.75 and 0.63[7]. All computations have been made for comparison with experimental buffet data. For BGK No.1 supercritical airfoil, flow conditions are Mach number 0.6~0.8, angle of attack 0~8 deg. and Reynolds number based on chord length is 2.1×10^7. For the present computation, the grid used is a similar C-grid topology to the case of RAE2822 airfoil, which is also generated by the algebraic grid generation technique. The prepared 273×70 C-grid for BGK No. 1 supercritical airfoil is shown in Fig. 4. In these steady calculations, a local time stepping was used to accelerate convergence to the steady state. A steady state was defined to be reached when the lift coefficient reached 0.1% of its final value with at least four orders of magnitude of residual reduction. All the calculations presented here were performed by assuming the flow to be fully turbulent on the surface. Fig. 5 shows how the pressure distribution for the BGK No.1 airfoil evolved with increasing angle of attack. In these curves, sets of pressure distributions show clearly the characteristic rear loading and flat upper surface pressure distribution of this airfoil. Also evident is the rearward shift of the shock as angle of attack is increased. In contrast to the conventional airfoil, the pressure distributions of the BGK No.1 airfoil show a strong pressure rise between the shock and the trailing edge. Such pressure distributions lead to typical rear separation of the boundary layer.

3.1 Buffet onset prediction by aerodynamic loads changes

The most frequently used steady approaching method of prediction of transonic buffet onset is to apply the method of kink analysis to curve plots of various aerodynamic characteristics. The method of kink analysis is based on Pearcey and Holder's concept of mean aerodynamic loads changes, which is the earliest concept of deriving buffet boundaries from the results of normal static wind tunnel tests[8]. In the transonic airfoil flow, if the pressure on the airfoil upper surface changes as result of flow separation due to shock on the airfoil upper surface, the lower surface flow must adjust itself to produce a similar change in pressure, because the wake cannot support a pressure difference across it generally. This condition for maintaining the pressure compatibility means a rapid drop of airfoil circulation which represents mean aerodynamic loads changes. The method of kink analysis takes into account the deviation from linear behavior (or called as kink), which is represented by mean aerodynamic loads changes when buffet occurs, in the curves of particular aerodynamic quantities plotted versus

either angle of attack or Mach number. The first kink point in these curves is recognized as the buffet onset[8].

In this paper, the applicability of kink analysis method to the prediction of transonic buffet onset for BGK No.1 airfoil has been examined using the aerodynamic parameters calculated from steady Navier-Stokes solver. Fig. 6 shows the lift coefficients versus angle of attack of BGK No.1 airfoil at Reynolds number 2.1×10^7 with the variation of Mach number. In these curves, the distinct slope changes (kinks) cannot be found at Mach numbers near or less than the design value. With increasing angle of attack beyond the linear range the separation point moves forward from the trailing edge, the slope of lift curve is gradually reduced without the distinct slope changes. As examined in other study, the steep chord wise pressure gradients on the conventional airfoil (NACA0012) mean that small displacements of the shock correspond to appreciable lift changes and substantial variation in shock strength[9]. However, because of the flat upper surface, the supercritical airfoil has a correspondingly flat upper surface pressure distribution that allows the shock to move chord wise with comparatively little change in lift. For free stream Mach numbers greater than design Mach number, a maximum value of lift coefficient cannot be observed. Instead, the lift curve increases initially with angle of attack but gradually taper off without reaching a maximum value. These trends in the lift curves cannot be verified quantitatively in this study since no experimental data available for comparison. However, it can be qualitatively acceptable since the similar trends are observed in the experimental lift curves for the other supercritical airfoils[10].

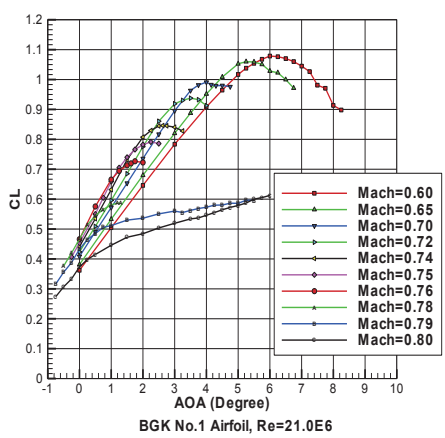

Fig. 6. BGK No.1 Airfoil Lift Curves

Figure 7 shows the center of pressure versus angle of attack of BGK No.1 airfoil with variation of Mach number. For the case of A type flow model, as discussed in other study, the variation of center of pressure curves showed to provide the clearest kink indicator of transonic buffet onset, among the various aerodynamic parameters considered[9]. However, the distinct slope changes (kinks) cannot be found in these curves for the same reason with the case of lift curve. Based on these results, it is apparent that for the case of the airfoil with shock induced rear separation dominant (model B airfoil), buffet onset prediction cannot be verified by kink analysis method.

3.2 Buffet onset prediction by alternative method

As an alternative indicator for buffet onset, a commonly used indicator is the divergence of the pressure measured near the airfoil trailing edge. As described above, as a result of the shock-boundary layer interaction on the airfoil upper surface, the lower airfoil surface flow must adjust itself to produce a similar change in pressure unless the flow would locally supersonic flow. This condition for change(divergence) of trailing edge pressure is known to be corresponding to those for a rapid drop in the circulation(aerodynamic load) and to onset of buffet. Pearcey and Holder showed experimentally that the divergence in trailing edge pressure in the transonic

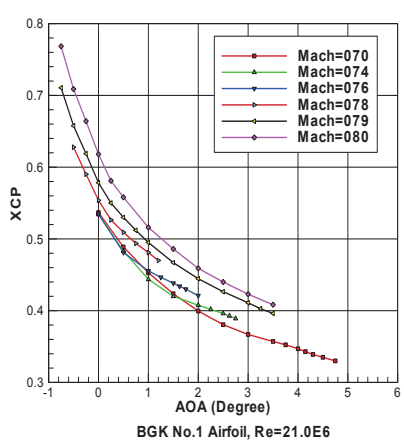

Fig. 7. BGK No.1 Airfoil Variation of Center of Pressure

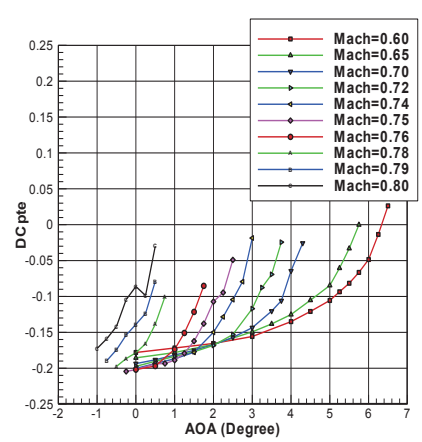

Fig. 8. BGK No.1 Airfoil Trailing Edge Pressure Deviations

airfoil flow coincided with a rapid drop in the lift coefficient and the buffet onset[8].

Figure 8 shows the trailing edge pressure deviation with increasing the angle of attack. From these curves in Fig. 8, buffet severity can be represented by the trailing edge pressure deviation(ΔCpte). For this alternative method, there is no exact deviation criterion for the buffet onset of specified airfoil, in this paper the buffet onset is defined for the BGK No.1 airfoil as the angle of attack at which the measured trailing edge pressure coefficient has diverged by 0.05 (ΔCpte =0.05) from its trend in attached flow. This criterion has been used in predicting the buffet onset for either model A or model B airfoils, and found to be acceptably accurate[8]. Based on numerical results for the trailing edge pressure deviation, it can be found that for higher Mach numbers, much larger changes in trailing pressure deviation occur than at Mach numbers near or less than the design Mach number. For much higher Mach numbers, the calculations of the trailing edge pressure deviation become difficult and are not accurate.

In the transonic airfoil flow, the shock wave normally moves smoothly rearward as increasing angle of attack, and the shock strengthens as it moves down stream and eventually becomes sufficiently strong to separate the boundary layer. But this progression is disturbed when the separation region extends from shock to the trailing edge. Simultaneously, the shock generally moves upstream to maintain compatibility of the pressure rise across the shock and the separated flow.

This reversal in the shock movement is sometimes useful in detecting the buffet onset because they occur almost simultaneously with the divergence in trailing edge pressure. Thus the points of reversal in the shock movement are recognized as buffet onset points[8].

The Fig. 9 shows the effects of angle of attack on shock position at Mach numbers below and above the design value. The motion of the shock with angle of attack is quite different from these two cases. For Mach numbers near or less than the design value the shock initially moves downstream with increasing angle of attack to a maximum downstream position before moving slowly back upstream or, in some cases, remain more or less stationary. In this case buffet onset is defined as shock turning point given by angle of attack corresponding max x/c point in the Fig. 9. For higher Mach numbers, although the calculations of the shock location become difficult and are not accurate, only upstream motion of the shock is detected.

3.3 Buffet onset prediction by Thomas' method

Figure 10 shows skin friction coefficient distribution on the upper surface of BGK No.1 airfoil with respect to angle of attack at Mach number 0.7, Reynolds number 2.1×10^7. The separation point is clearly seen in skin friction coefficient curve plot, given by $C_f = 0$. In these computations, it can be seen trailing edge separation occurs when angle of attack reaches a certain value and moves upstream with increasing angle of attack. This phenomenon modifies the effective shape of the airfoil and results in loss of lift and increase of drag. The purpose of the presentation of Fig. 10 is to show that the BGK No.1 airfoil is model B type airfoil that is shock induced rear separation dominant airfoil at given flow conditions. With increasing angle of attack, the separation point will move forward from the trailing edge, until it finally reaches the shock wave. In these calculations, existence of shock induced separation bubble formation is noticed at 4.25 degree of angle of attack. However, the distinct slope changes (kinks) which indicate the buffet onset cannot be found at corresponding angle of attack in the lift curves(Fig. 6) or center of pressure curves(Fig. 7). Thus for flow model

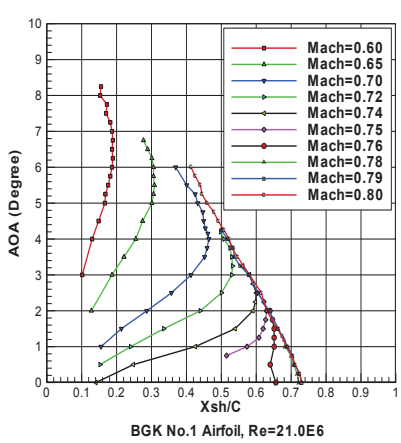

Fig. 9. BGK No.1 Airfoil Shock Movement

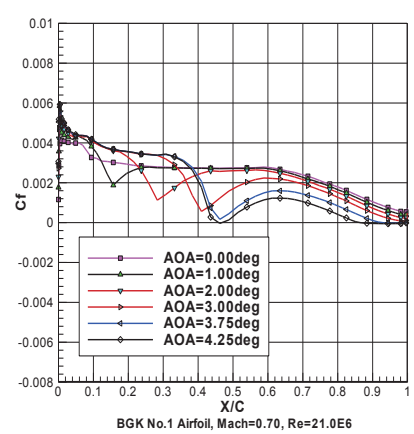

Fig. 10. BGK No.1 Airfoil Skin Friction Distributions

B, it is often ignored the eventual existence of a turbulent separation bubble at the foot of the shock wave for the prediction of buffet onset.

In this study, the point of buffet onset for BGK No.1 airfoil is predicted in terms of the angle of attack when a separation point as given by C_f=0 in Fig. 10, reaches 90% of the airfoil chord from leading edge for a given Mach number as Thomas suggested. The corresponding buffet onset C_L can be found in the Fig. 9.

4. Comparison with Experimental Results

Figure 11 shows comparison between predicted buffet onset results for BGK No.1 airfoil and the experimental buffet onset results in the lift coefficient at buffet onset-Mach number diagram. The predicted results of transonic buffet onset for BGK No.1 airfoil are based on the Thomas and alternative methods. For the alternatives methods based on the trailing edge pressure deviation(ΔCpte) and shock turning point, it can be possible to predict the buffet onset for BGK No.1 airfoil at the Mach numbers near or less than design value. For higher Mach numbers, the predictions of buffet onset become difficult and are not accurate.

The method used for determining the experimental buffet onset is to observe the analog signal from a force element of one of the sidewall balances supporting the model and to note the flow conditions when oscillations first appear[11].

As a characteristic of supercritical airfoils, the buffet onset boundaries are practically flat for free stream Mach numbers more or less than design Mach number, while the buffet onset boundaries decrease rapidly for free stream Mach numbers greater than design Mach number. It is evident from this figure that the predicted results of Thomas method (criterion on 90% chord) based on Navier-Stokes solver show

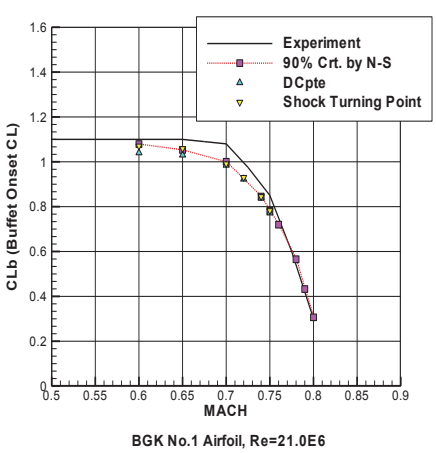

Fig. 11. Comparison with Experiment for BGK No.1 Airfoil

the good results compared with the unsteady experimental buffet onset characteristics of BGK No.1 airfoil, while those of buffet onset based on the alternative method show restricted results within range of below the design Mach numbers.

5. Concluding Remarks

In this study, to achieve realistic prediction results of transonic buffet onset for a supercritical airfoil with shock-boundary layer interactions, a practical steady approach has been proposed. Since the present method is to apply the Thomas' method to the friction coefficients curve plots calculated from steady Navier-Stokes solver, it can be applicable even to the supercritical airfoil with shock boundary interaction such as shock induced separation bubble. The present method proposed in this study has shown to be reliable for the computational buffet onset predictions in the early design stage of an aircraft and can reduce the amount of expensive model testing.

The major conclusions can be drawn from the present studies as follows.

1) It has been found the aerodynamic curves obtained from steady Navier-Stokes solver computation do not show the noticeable kink points for identifying the transonic buffet onset for the supercritical airfoil with shock-boundary layer interactions. The method of kink analysis for prediction of transonic buffet onset cannot be applied to the supercritical airfoil such as the one investigated in this study.

2) Compared with the results of wind tunnel test, the Thomas method based on steady Navier-Stokes solver is shown to be reliable and useful for transonic buffet onset prediction for the supercritical airfoil with shock-boundary layer interactions. Even for the case of the eventual existence of a turbulent separation bubble at the foot of the shock wave, the present method proves to be useful.

References

[1] Pearcey, H. H., "A Method for the Prediction of the Onset of Buffeting and Other Separation Effects from Wind-Tunnel Tests on Rigid Models", AGARD Report 223, 1958.

[2] Thomas, F., "The Determination of the Buffet Boundaries of Aerofoils in the Transonic Regimes", *Aircraft Research Association Library Translation*, No. 19, 1969.

[3] Roe, P. L., "Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes", *Journal of Computational Physics*, Vol. 43, No. 2, 1981, pp. 357-372.

[4] Van Leer, B., "Towards the Ultimate Conservative Difference

Scheme. V. A Second Order Sequel to Godunov's Method", *Journal of Computational Physics*, Vol. 32, 1979, pp. 101-136

[5] Baldwin, B. S. and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows", AIAA Paper 78-257, 1978.

[6] Cook, P. H., McDonald, M. A. and Firman, M. C. P. M. C. P., "Aerofoil RAE2822 Pressure Distributions and Boundary Layer Wake Measurements", AGARD AR-138, 1979.

[7] Garabedian, P. R. and Korn, D. G., "Analysis of Transonic Airfoils", *Communications on Pure and Applied Mathematics*, Vol. 24, No. 6, 1971, pp. 841-851.

[8] Pearcey, H. H. and Holder, D. W., "Simple Method for the Prediction of Wing Buffeting Resulting from Bubble Type Separation", NPL Aero Report 1024, 1962.

[9] Chung, I., Lee, D., Reu, T. and Ko, D., "Prediction of Transonic Buffet Onset for Airfoils with Separation Bubble Using Steady Approaches", *Journal of Aircraft*, Vol. 40, No.4, 2003, pp. 795-797.

[10] Lee, B. H. and Ohman, L. H., "Unsteady Pressure and Force During Transonic Buffeting of a Supercritical Airfoil", *Journal of Aircraft*, Vol. 21, No. 6, 1984, pp. 439-441.

[11] Ohman, L. H., Kacprzynski, J. J. and Brown, D., "Some Results from Tests in the NAE High Reynolds Number Two-Dimensional Test Facility on Shockless and Other Airfoils", *Canadian Aeronautical and Space Journal*, Vol. 19, 1973, pp. 297-312.