Transonic Aeroelastic Analyses of Wings Considering UViscous and Thickness Effects

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Abstract

The aeroelastic analyses for several wing models were performed using the transonic small-disturbance (TSD) equation, which is very efficient, to consider the aerodynamic nonlinearities in the transonic region. For more accurate aerodynamic analysis of airfoil and wing models with shock waves, the viscous equations based on the Green's lag-entrainment equation of boundary-layer effects were coupled with the TSD equation in the transonic region. Finally the aeroelastic characteristics of wing models were investigated through comparisons of the aeroelastic analysis results for wing models considering the change of a thickness of the airfoil section. Moreover, the results of the aeroelastic analysis using the coupled TSD equation with the viscous equations were compared with those using the TSD equation for several wing models.

Key Word : Aeroelasticity, Flutter, Transonic Flow, Viscosity, Thickness Effects

Introduction

Aeroelasticity is concerned with the interaction phenomena between the elastic motions of structures and the resulting aerodynamic forces. Such a mutual interaction can exist for flying aircrafts. There are many categories of aeroelastic phenomena according to physical features: flutter, divergence, gust response, buffeting, limit cycle oscillations (LCO), and so on. All of these should be considered in aircraft design because the structural flexibility for light materials in modern aircrafts is more susceptible to aeroelastic phenomena. Among the abovementioned categories, flutter is the most dangerous dynamic aeroelastic problem because flutter can result in complete structural failure in a few seconds.

The computational fluid dynamics (CFD) technique must be used due to aerodynamic nonlinearity such as moving shock to perform accurate aeroelastic analyses in transonic flow regions. Aeroelastic analysis using an efficient unsteady aerodynamic analysis such as the transonic small disturbance (TSD) equation, which is widely recognized as one of the most efficient aerodynamic theories among the conventional CFD-based approaches, can have strong computational advantages in various parametric studies [1]. For the past few decades, research on aeroelastic analysis for various aircraft models has been conducted using the TSD equation due to the efficient numerical computations. Particularly, Batina [2] improved the efficiency by applying a time-accurate approximate factorization (AF) algorithm to a solution of the three-dimensional unsteady TSD equation. When the aerodynamic analysis is performed for flows around strong

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shock waves, however, the TSD equation shows discrepancy with experimental data or numerical results of Navier-Stokes and Euler equations. That is a limitation of the potential theory such as the TSD equation due to assumptions deriving the equation as inviscid and isentropic flows. To predict accurately flows around strong shock waves using the TSD equation, various researches have been conducted. Batina [3] incorporated entropy and vorticity effects within the solution procedure of the TSD equation, and the aerodynamic results of the modified TSD equation were good agreement with Euler calculations. On the other hand, there are many researches incorporating the viscous effects with the TSD equations to predict accurately flows around strong shock waves. Rizzetta [4] and Howlett [5] computed unsteady transonic flows including viscous effects using two-dimensional TSD equations with the entrainment equation derived by Head [6] and the lag-entrainment equation derived by Green et al. [7]. Thereafter, Howlett [8] performed unsteady aerodynamic analyses including viscous effects for two- and three-dimensional flows and calculated unsteady flows with mild separation using an inverse boundary-layer method. The method is coupled with Euler equations by Zhang et al. [9]. Edwards [10] incorporated new interactive boundary-layer coupling method with Howlett's inverse solution procedure, and performed aeroelastic analyses for airfoils and wing models.

In this study, the aeroelastic analyses are performed using the TSD equation for wings which have different thickness in transonic region. Because wings with relative thick airfoil induce the strong shock waves, the interactive boundary-layer coupling method implemented by Howlett [8] and Zhang et al. [9] is coupled with the TSD equation for more accurate prediction of transonic flows with the strong shock waves. The aerodynamic results using the coupled TSD equation are compared with experimental data for wings with strong shock waves. Finally, the aeroelastic characteristics for the changes of the wing thickness are investigated.

Theoretical Background

TSD Equation

Although the Navier-Stokes equations are the most accurate aerodynamic equation, many flow features depend on a precise evaluation of the viscous and turbulent terms. If the viscous terms are removed from the Navier-Stokes equations, the equations become the Euler equations. Furthermore, if the flow around the aircraft wing is irrotational and the perturbation is small, the transonic small disturbance (TSD) theory can be applied to aerodynamic analysis. The three-dimensional unsteady TSD equation may be written in conservation law form as [3]:

$$\frac{\partial f_0}{\partial t}+\frac{\partial f_1}{\partial x}+\frac{\partial f_2}{\partial y}+\frac{\partial f_3}{\partial z}=0 \tag{1}$$

where

$$f_0=-A\phi_t-B\phi_x,\qquad f_1=E\phi_x+F\phi_x^2+G\phi_y^2,\qquad f_2=\phi_y\left(1+H\phi_x\right),\qquad f_3=\phi_z$$

The above equations are given in a physical coordinate system (x, y, z, t), and subscript x, y and z denote the derivative of the streamwise, span-wise, and vertical direction, respectively. The values of t and x, y, z are non-dimensionalized by U/c_r and c_r, respectively. The value of ϕ represents the disturbance velocity potential and all coefficients are defined in Ref. 3.

Viscous Equations

For more accurate results in the TSD equation for the transonic regime, viscous effects should be considered. The effects of a turbulent viscous boundary layer for attached flows are modeled in a quasi-steady manner by Green's lag-entrainment equations. The boundary layer equations for attached flows can be expressed as [4, 5]:

$$\frac{d\theta}{dx}=\frac{1}{2}C_f-\left(H+2-M_e^2\right)\theta\phi_{xx} \tag{2}$$

$$\theta\frac{d\bar{H}}{dx}=\left(C_E-\frac{1}{2}H_1C_f\right)\frac{d\bar{H}}{dH_1}+H_1\left(H+1\right)\frac{d\bar{H}}{dH_1}\theta\phi_{xx} \tag{3}$$

$$\theta\frac{dC_E}{dx}=F\left\{\frac{2.8}{H+H_1}\left[\left(C_\tau\right)_{EQO}-\lambda C_\tau^{1/2}\right]+\left(\frac{\theta}{U_e}\frac{dU_e}{dx}\right)_{EQ}\right\}-F\left(1+0.075M_e^2\frac{1+\frac{\gamma-1}{2}rM_e^2}{1+0.1M_e^2}\right)\theta\phi_{xx} \tag{4}$$

where Eq. (2) is simply derived from continuity and momentum equation. Head [16] derived the entrainment equation of Eq. (3), and Green et al [7] derived the lag-entrainment equation of Eq. (4) from the turbulent kinetic energy relations. In Eq. (4), the subscript e refers to the quantities at the boundary layer edge, and the subscripts EQ and EQO denote the equilibrium conditions and equilibrium conditions in the absence of secondary influences on the turbulence structure, respectively[5]. Each parameter is defined in Ref. 8.

For the separation flows, the effects of a turbulent viscous boundary layer are modeled by the inverse boundary-layer calculation. A perturbation mass flow parameter is introduced to solve the inverse boundary-layer equations [8]. In an inverse boundary layer calculation, the pressure or velocity at the boundary layer edge is solved from a given distribution of a boundary layer displacement thickness [9].

$$\frac{H\theta}{\bar{m}}\frac{d\bar{m}}{dx}=H\frac{d\theta}{dx}+R_1\theta\frac{d\bar{H}}{dx}+\left[\left(H+1\right)R_3+H\left(1-M_e^2\right)\right]\frac{\theta}{U_e}\frac{dU_e}{dx} \tag{5}$$

$$C_E=H_1\frac{d\theta}{dx}+H_1\left(1-M_e^2\right)\frac{\theta}{U_e}\frac{dU_e}{dx}+\theta\frac{dH_1}{d\bar{H}}\frac{d\bar{H}}{dx} \tag{6}$$

$$\frac{C_f}{2}=\frac{d\theta}{dx}+\left(H+2-M_e^2\right)\frac{\theta}{U_e}\frac{dU_e}{dx} \tag{7}$$

$$\theta\frac{dC_E}{dx}=F\left\{\frac{2.8}{H+H_1}\left[\left(C_\tau\right)_{EQO}^{1/2}-\lambda C_\tau^{1/2}\right]+\left(\frac{\theta}{U_e}\frac{dU_e}{dx}\right)_{EQ}-\left[1+0.075M_e^2\frac{R_1}{1+0.1M_e^2}\right]\frac{\theta}{U_e}\frac{dU_e}{dx}\right\} \tag{8}$$

The above equations require the closure conditions in Ref. 8. The various parameters in inverse boundary-layer equations are defined in Refs. 8 and 9. Numerical integration of the first order set of ordinary differential equations for the viscous equations is performed using a fourth-order Runge-Kutta method. The coupling between the TSD equation and the viscous equations is through the boundary conditions on wing and wake surfaces as follows:

$$\phi_z^{\pm}=f_x^{\pm}+f_x^{\pm}+\delta_x^{*\pm} \quad \text{; on wing surface}$$

$$\Delta\left(\phi_z\right)=\Delta\left(\delta_x^{*}\right) \quad \text{; on wake surface}$$

where superscript $\pm$ refers to the upper and lower surfaces, and the values of f and $\Delta(\ldots)$ denote the airfoil shape and the jump in the bracketed quantity, respectively.

Numerical Analysis Results

The aerodynamic analyses of two-dimensional airfoil and three-dimensional wing models were performed using the coupled TSD equation with the viscous equations considering the boundary-layer effects. The aerodynamic results were compared with experimental data in

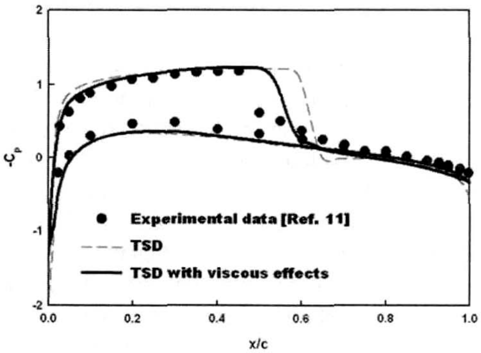


Fig. 1. Comparisons of steady pressure coefficients of the NACA 0012 airfoil

references to verify the aerodynamic analysis using the coupled TSD equation. Firstly, the two-dimensional aerodynamic analysis of the NACA 0012 airfoil was implemented. Figure 1 shows the comparison of steady aerodynamic coefficients between the TSD equation and the coupled TSD equation with the viscous equations. Moreover, the numerical steady aerodynamic coefficients were compared with experimental data in Ref. 11. In this case, the free-stream Mach number M is 0.775 and the angle-of-attack α_0 is 2.05°. For the viscous aerodynamic analysis using the coupled TSD equation, the Reynolds number Re is assumed 1.0×10^7.

The aerodynamic coefficients obtained from the coupled TSD equation with the viscous equations are more accurate than those calculated by the TSD equation compared with experimental data around the shock wave on the upper surface. The three-dimensional aerodynamic analyses of several wing models were implemented. The three-dimensional model is the F-5 wing model. The F-5 wing model has a full-span aspect ratio of 3.16, a taper ratio of 0.28, and a leading edge sweep angle of 31.9°. The section airfoil of the wing model is NACA 65A004.8. Figure 2 shows the comparisons of steady aerodynamic coefficients at 49% and 94% semi-spans between the TSD equation and the coupled TSD equation with the viscous equations. Moreover, the numerical steady aerodynamic coefficients were compared with experimental data in Ref. 12. In this case, the free-stream Mach number M is 0.946 and α_0 is -0.004°. For the viscous aerodynamic analysis using the coupled TSD equation, the Reynolds number Re is assumed 5.89×10^6. At each position of semi-span, the aerodynamic coefficients of the coupled TSD equation are more accurate than those of the TSD equation compared with experimental data. Moreover, as positions of semi-span get near the wing tip, the accuracy of the coupled TSD equation with the viscous equations is conspicuous around the shock wave.

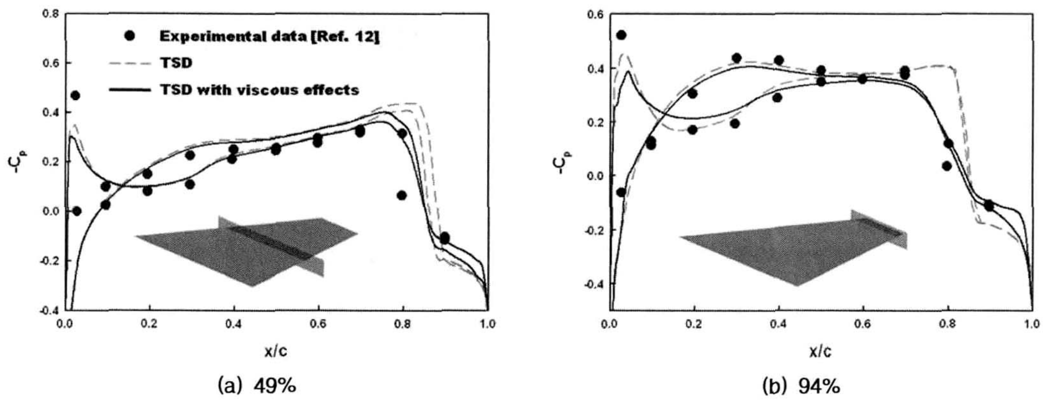
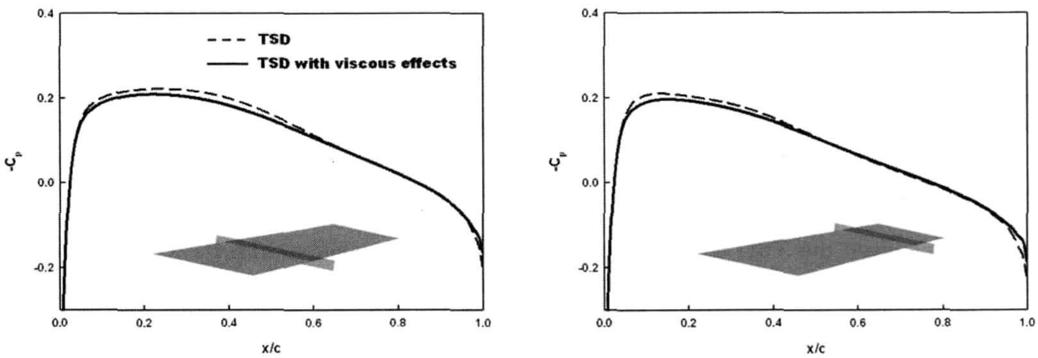


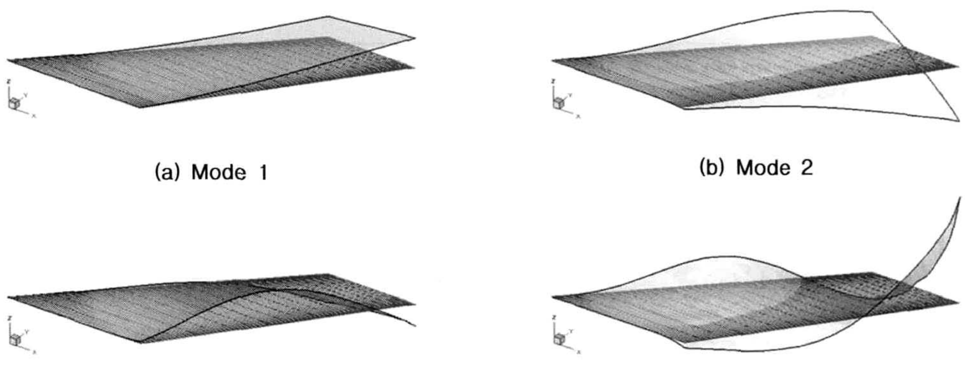
Fig. 2. Comparisons of steady pressure coefficients of the F-5 wing model

The aeroelastic analyses were performed as changing the thickness of the airfoil section of the three-dimensional wing mode at $M = 0.960$. The configuration of three-dimensional wing model is identical to the AGARD 445.6 wing model. To consider the changes of the thickness of wing models, two wing models are applied. Each three-dimensional wing model has the NACA 0006 and NACA 0012 airfoils, respectively. Figure 3 shows the comparisons of the aerodynamic coefficients of the wing model with 6% thickness between the TSD equation and the coupled TSD equation with the viscous equations at 40% and 80% semi-spans. For the aerodynamic analysis using the coupled TSD equation with the viscous equations, the Reynolds number Re is assumed 1.0×10^6. The dashed lines denote the aerodynamic coefficients with the TSD equation, and the solid lines indicate the aerodynamic coefficients with the coupled TSD equation. At all positions of semi-spans, the aerodynamic coefficients show approximate agreement between the TSD equation and the coupled TSD equation with the viscous equations because of absence of shock waves. For the aeroelastic analyses of using the modal approach, the four elastic modes are used. Each aeroelastic analysis for four wing model is applied the same mode data. The mode shapes represent the first bending mode, first torsion mode, second bending mode, and second torsion mode. The modes have sequential natural frequencies of 9.6 Hz, 38.17 Hz, 48.35 Hz, and 91.54 Hz, respectively. The splined mode shapes into the aerodynamic grids are showed in Fig. 4. The density of the free-flow in present aeroelastic analysis is 0.0634 kg/m^3. Figure 5 shows the comparisons of the first modal displacements between the TSD equation and the coupled TSD equation for the wing models with 6% and 12% airfoil sections.



(a) 40% (b) 80%

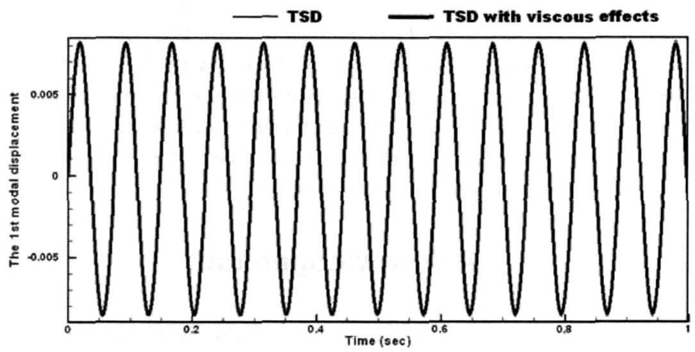
Fig. 3. Comparisons of steady pressure coefficients of the wing model with 6% thickness



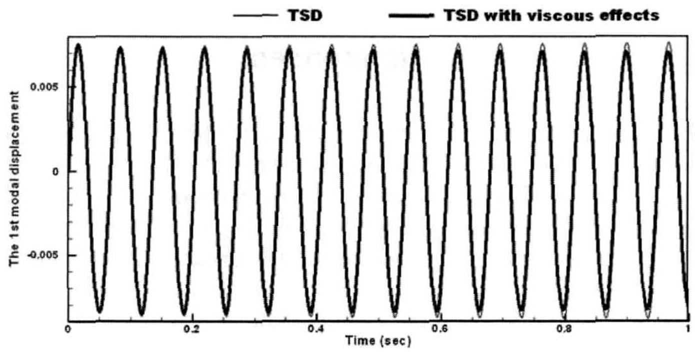
(a) Mode 1 (b) Mode 2

(c) Mode 3 (d) Mode 4

Fig. 4. Splined elastic mode shapes into the aerodynamic grids



(a) 6% thickness wing model at V = 291 m/s



(b) 12% thickness wing model at V = 326 m/s

Fig. 5. Comparisons of first modal displacements between the TSD equation and the coupled TSD equation at M = 0.960

The thin lines denote the first modal displacements using the TSD equation, and the thick lines indicate the firs modal displacement using the coupled TSD equation. For the wing model with 6% thickness which has absence of the shock wave, the flutter speed using the TSD equation is almost identical to that using the coupled TSD equation with the viscous equations as the flutter speed is 292 m/s. In this case, the aerodynamic characteristics are similar between the TSD equation and the coupled TSD equation. On the other hand, for the wing model with 12% thickness, the flutter speed using the TSD equation is 324 m/s, and that using the coupled TSD equation with the viscous equations is 328 m/s. In this case, although the aerodynamic results between the TSD equation and the coupled TSD equation show conspicuous difference around the shock waves, the aeroelastic results show little difference.

Conclusion

In the present study, the TSD equation was coupled with the viscous equations for more accurate aerodynamic analysis of the models with shock waves in transonic region. The aerodynamic analyses of airfoil and wing models were implemented using the coupled TSD equation with the viscous equations. For F-5 wing and NACA 0012 models which have the shock wave, the aerodynamic analyses using the coupled TSD equation showed more accurate results than those using the TSD equation compared with experimental data from the literature in the transonic region. Finally the aeroelastic characteristics of wing models were investigated through comparisons of the aeroelastic analysis results for wing models with 6% and 12% airfoil thickness at free-stream Mach number 0.960. The aeroelastic analyses using the TSD equation were compared with those using the coupled TSD equation with the viscous equations for the wing models with 6% and 12% thickness. For the wing model with 6% thickness, the flutter speeds between the TSD equation and the coupled TSD equation were identical as like the aerodynamic results did not show difference. However, for the wing model with 12% thickness, although the aerodynamic results showed conspicuous difference between the TSD equation and the coupled TSD equation, the flutter speed showed little difference.

Acknowledgement

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