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Validation of LTRAN2-HI by Comparison with Unsteady Transonic Experiment

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Introduction

COMPUTATION of unsteady transonic flow about oscillating airfoils is possible through the use of LTRAN2, a computer code developed at NASA Ames Research Center by Ballhaus and Goorjian.[1] LTRAN2 solves the two-dimensional, nonlinear, small-disturbance equation, i.e.

$$(2kM_\infty^2/\delta^{2/3})\phi_{xt} = [(1-M_\infty^2)/\delta^{2/3}... \tag{1}$$

under the low reduced frequency assumption

$$k=\omega c/U_\infty \sim \delta^{2/3} \sim 1-M_\infty^2 \ll 1$$

Here ϕ is the disturbance velocity potential, M_∞ is the freestream Mach number, and δ is the airfoil thickness-to-chord ratio. For the purpose of flutter analysis, industrial users have indicated the need to perform accurate calculations in a frequency range up to $k=1.0$, a reduced frequency violating the "low-frequency" assumption. Therefore an objective of the present study is to extend the range of reduced frequency for improved LTRAN2 applicability. The modifications made to the code in this study involve the addition of high-frequency time-dependent terms in the calculation of the pressure coefficient as well as the wake and downstream boundary conditions. The low-frequency governing equation is retained, however.

Several other researchers[2-4] have performed similar modifications to LTRAN2, adding high-frequency terms to the boundary conditions of the numerical algorithm. Their results indicate that under subsonic flow conditions, improved agreement with linear theory in amplitudes and phase angles of lift and moment coefficients is obtained at higher frequencies with the modified code.[2] However, to truly demonstrate the merit of the modified code, calculations done under transonic flow conditions should be compared with experimental results. Hence this study was undertaken to modify the existing code LTRAN2 and to evaluate the effects of these changes by comparison with experimental data.

The experimental test case for comparison, performed by Davis and Malcolm,[5] is a NACA 64A010 airfoil, pitching about quarter chord, at a Mach number of 0.8 over a range of reduced frequencies up to 0.6. This case was chosen based on the following criteria: 1) the availability of good test data, 2) the presence of a moderate strength shock wave, 3) the absence of strong separation effects in the experiments.

Modified Boundary Conditions

The numerical boundary conditions and their modification to include high-frequency effects will now be discussed.

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Pressure Coefficient

An expression for the unsteady, small-disturbance pressure coefficient may be written

$$C_p = -2(\phi_x + k\phi_t) \tag{2}$$

Under the low-frequency assumption (original LTRAN2) the $k\phi_t$ term was omitted by an order of magnitude argument. LTRAN2-HI, a high-frequency extension of the code, now incorporates high-frequency effects in the calculation of C_p by employing Eq. (2).

Wake Condition

To ensure a continuity of pressure across the vortex sheet

$$[C_p]=0$$

which now implies

$$[\phi_x + k\phi_t]=0 \tag{3}$$

where [ ] denotes a jump across the wake. Formerly, vorticity in the wake propagated instantaneously downstream. The introduction of the $k\phi_t$ term in Eq. (3) provides a more accurate description of vorticity propagation in the wake at the freestream velocity.

Downstream Boundary Condition

The far downstream boundary condition (formerly $\phi_x=0$ as x approaches infinity) becomes

$$\phi_x + k\phi_t = 0 \qquad x\to\infty \tag{4}$$

This condition differs from the LTRAN2-NLR[2] downstream boundary condition where zeroth-order extrapolation ($\phi_x=0$) was retained. However, implementation of Eq. (4) maintains consistency with Eq. (3) at the point of intersection of the wake and downstream boundary conditions.

Airfoil Tangency Condition

A time-dependent term is included in the body boundary condition, thus eliminating the low-frequency assumption in the airfoil tangency condition. If $y=f(x,t)$ defines the body surface, then

$$\phi_y = f_x(x,t) + kf_t(x,t) \tag{5}$$

ensures flow tangency.

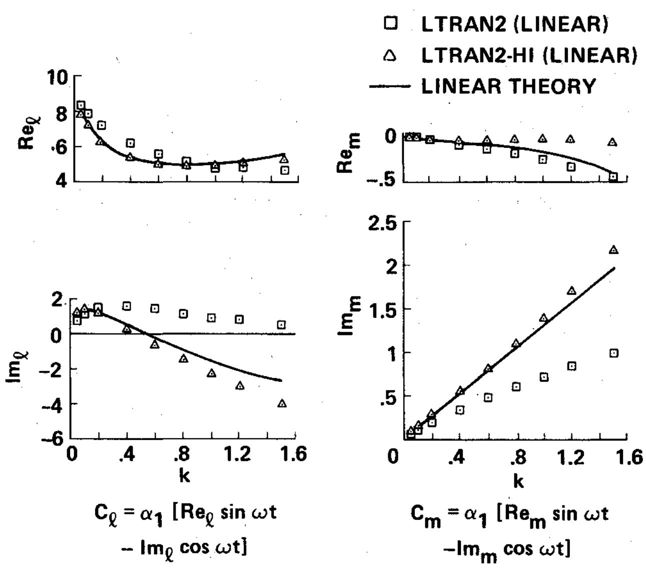

Fig. 1 Lift and quarter-chord moment coefficients vs reduced frequency for a pitching flat plate, $M_\infty=0.7$, $k=\omega c/U_\infty$, $\alpha=\alpha_0+\alpha_1 \sin\omega t$.

Although undocumented, Eq. (5) (including this time-dependent term) was used in all published "low-frequency" LTRAN2 calculations by Ballhaus and Goorjian.[1] Also, in the calculations presented here, Eq. (5) will be used by both LTRAN2 and LTRAN2-HI.

Calculated Results and Discussion

Linear Calculations

Computed results from LTRAN2 and LTRAN2-HI are first compared with exact linear theory results. This test serves to establish the capability of the modified code to provide accurate unsteady solutions in the linear domain. The linear theory results are solutions to the "all-frequency" unsteady, transonic small-disturbance equation (i.e., the governing equation includes a ϕ_{tt} term that is neglected in the LTRAN2, LTRAN2-HI codes). Figure 1 displays lift and moment coefficients vs reduced frequency for the case published in Ref. 2 (flat plate pitching 0.25 deg about quarter chord, $\alpha_0 = 0$ deg, $M_\infty = 0.7$). Note that the original LTRAN2 provides reasonably accurate results but only for reduced frequencies less than 0.2. With the exception of the real component of the moment coefficient, LTRAN2-HI gives a more accurate prediction of both lifts and moments over the entire range of reduced frequencies tested. The discrepancy seen in the moment comparison may be attributed to the omission of the ϕ_{tt} term in the governing equation of the codes. Results from Bland[6] verify that calculations from a LTRAN2-HI-type code compare more favorably, almost precisely, with a linear theory formulation also neglecting ϕ_{tt}. Owing to the relatively small magnitude of the real component of moment, LTRAN2-HI still provides the better agreement with linear theory moments in amplitude and phase.[7]

Nonlinear Experimental Comparisons

As stated previously, comparisons with experimental data[5] for a pitching (1 deg about quarter chord) NACA 64A010 airfoil were made at a transonic Mach number of 0.8. Figure 2 displays first harmonic comparisons of lift and moment coefficients vs reduced frequency. The high-frequency modification, in general, produces an improvement in the calculation of real and imaginary components of both lift and moment coefficients over the entire reduced frequency range. The greatest improvement is seen in the determination of the imaginary components where LTRAN2-HI, unlike the original code, captures the experimentally observed trends. Note in particular the successful prediction by LTRAN2-HI of the zero crossing in the imaginary component of the leading-edge moment corresponding to a critical transition from a phase lead to a phase lag. For these reasons, LTRAN2-HI is the recommended version of the code for use in transonic calculations.

The details of these calculations, the algorithmic developments for the modified boundary conditions, as well as additional comparisons with experimental results (unsteady surface pressures for the range of reduced frequencies given in Fig. 2) may be examined in Ref. 7.

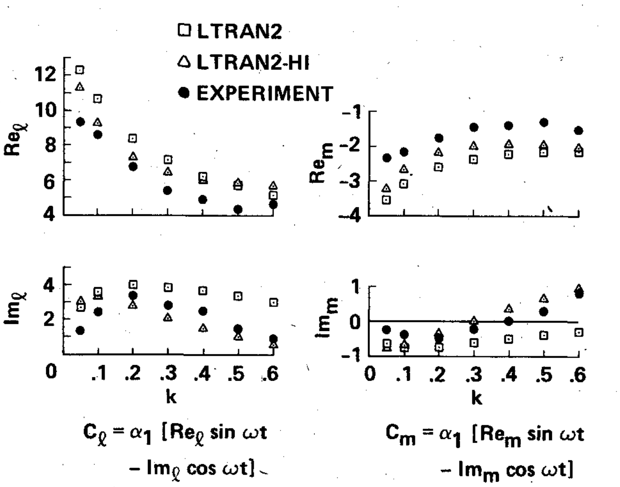

Fig. 2 Lift and leading-edge moment coefficients vs reduced frequency for a pitching NACA 64A010 airfoil, $M_\infty = 0.8$, $k = \omega c / U_\infty$, $\alpha = \alpha_0 + \alpha_1 \sin\omega t$.

Conclusions

LTRAN2-HI, a high-frequency extension of the NASA Ames unsteady, small-disturbance code LTRAN2, provides more accurate unsteady results, as evidenced by experimental comparisons. The modified code is a versatile tool capable of performing reasonably accurate inviscid calculations in both linear and nonlinear flow regimes. Results from the improved code may be obtained at no extra computational expense. LTRAN2-HI has now become the default option of the NASA Ames code LTRAN2.

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A Hybrid Shear Panel

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Introduction

SHEAR panels are used on airframe structures to model thin sheet metal that is attached to heavy stiffeners. The axial load is carried by the stiffeners, which are represented as rods. It is assumed that the sheet metal carries shear stresses at

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