Two Complementary Approaches to Transonic Potential Flow About Oscillating Airfoils

H. Schippers* and M. H. L. Hounjet†
National Aerospace Laboratory, Amsterdam, The Netherlands

Results of two-dimensional (2D) unsteady transonic full-potential flow calculations for AGARD standard aeroelastic configurations are presented and compared with experimental data. Two complementary methods have been applied: 1) the time-integration TULIPS method, and 2) the time-linearized FTRANC method. The calculations have been performed for the NACA 64A010 (Ames) airfoil and for the supercritical NLR 7301 airfoil, both undergoing sinusoidal pitching oscillations. The results of both methods are in good agreement, and the comparison with experimental data is fair.

Introduction

AT the National Aerospace Laboratory (NLR), continuous attempts are being made to improve the accuracy of computational methods for unsteady airloads in transonic flow. Having already various transonic small-pertubation (TSP) methods available, recently two full-potential methods have been developed for two-dimensional (2D) unsteady transonic flow about oscillating thick blunt-nosed airfoils in which the time parameter is used in different ways: 1) the time-accurate integration method, TULIPS (Transonic Unsteady Lifting Inviscid Potential-Flow Simulation), and 2) the time-linearized method, FTRANC (Full-Potential Transonic Analysis on C-type Grids). Each of these methods is subject to various kinds of modeling errors, which have a different influence on the numerical results. For moderate frequencies, it can be shown that the time-integration methods yields more accurate results; for low frequencies, the results of the time-linearized method are more accurate. In this way, the methods are complementary in the frequency range. When the numerical results of these methods compare well, they may be considered from a numerical point of view as being reliable. The purpose of this paper is twofold: 1) to introduce and to describe the aforementioned methods, and 2) to supply high-quality calculated, full-potential aerodynamic data for two airfoils in transonic flow that are recommended as standard aeroelastic configurations by AGARD. Finally, it is demonstrated that results of these full-potential methods compare satisfactorily with experimental data.

Computational Methods

The TULIPS and FTRANC computational methods solve the unsteady full-potential equation on a boundary-conforming C-type grid. The time-accurate integration method, TULIPS, was developed at NLR to provide high-quality solutions that can be used to establish the limits of applicability of the transonic small-perturbation methods and of the time-linearized method, FTRANC. The latter method solves the unsteady full-potential flow about a harmonically oscillating airfoil by calculating a mean steady potential and its first harmonic component.

Description of TULIPS

TULIPS, the time-integration method, is based on the numerical integration of the unsteady full-potential equation. The equation is discretized in space by applying a fully conservative finite-difference scheme utilizing Godunov flux splitting to maintain stability in the supersonic flow region. The present scheme yields numerical solutions with sharp compression shocks and rules out expansion shocks. The application of the Godunov flux splitting has been discussed in detail in Ref. 1. After the spatial differencing has been carried out, there results a large system of ordinary differential equations, which is integrated in time applying a first-order fractional step method. The obtained velocity potential contains an integration error of $O(\Delta t/k)$, i.e., for a fixed time step Δt, the contribution of the time-integration errors increases as the reduced frequency k decreases.

At the outer boundary of the C-type grid, a first-order boundary differential equation is applied, which has been derived in Ref. 2, following the approach of Bayliss and Turkel.[3] This numerical boundary condition simulates the radiation of energy out of the computational domain and toward infinity.

Description of FTRANC

FTRANC, the time-linearized method, solves the transonic flow about an oscillating airfoil. The velocity potential is decomposed into a mean steady potential and its first harmonic component, which are determined from appropriate differential equations and boundary conditions. The higher harmonic components are neglected. In time-linearized methods, it is usual to define the mean steady potential by the steady potential at the mean position, as was applied in Refs. 4 and 5. This choice suffices if the nonlinear effects are small, as occurs for subsonic flow at low Mach numbers, for supersonic flow at high Mach numbers, and for transonic flow with a small shock trajectory. When nonlinear effects become more important, the steady potential at the mean position is no longer appropriate for the accurate calculation of the first harmonic components. In particular, it cannot represent flows with large shock excursions, which would result in an erroneous calculation of the first harmonics. It appears that the time-linearized approach fails for these types of flow. In this paper, however, it is established that it still can give reasonable results for genuine nonlinear transonic flow, provided the mean steady potential is defined as a weighted average of

---

Presented as Paper 86-1821 at the AIAA 4th Applied Aerodynamics Conference, San Diego, CA, June 9–11, 1986; received Nov. 7, 1986; revision received Aug. 10, 1987.

*Senior Research Scientist, Informatics Division, Mathematical Models and Methods Department.

†Senior Research Scientist, Fluid Dynamics Division, Department of Aeroelasticity.

steady potentials at N different amplitudes α_ℓ, given by

$$\alpha_\ell = \alpha^0 + \Delta\alpha \sin(2\pi\ell/N), \quad \ell = 1,\ldots, N \tag{1}$$

The steady potentials, denoted by φ_ℓ, follow from solving N steady potential-flow problems governed by

$$\nabla \cdot \rho[\varphi]\nabla\varphi = 0 \tag{2}$$

with boundary condition

$$\nabla\varphi \cdot \boldsymbol{n}_\ell = 0 \tag{3}$$

Then, the mean steady potential is defined as

$$\varphi^0(x, y) = \frac{1}{N}\sum_{\ell=1}^{N} \varphi_\ell(x, y) \tag{4}$$

which can be considered as an approximation to the mean steady potential that would have been obtained for reduced frequency $k = 0$. In general, this potential differs from the potential at the mean position because Eqs. (2) and (3) are not satisfied there.

Next, the unsteady full-potential equation is time-linearized about φ^0. This yields a linear second-order hyperbolic equation for the disturbance potential ψ, which is resolved into a harmonic series

$$\psi(x, y, t) = \psi^0(x, y) + \psi^1(x, y)e^{it} + \psi^2(x, y)e^{2it} + \cdots \tag{5}$$

The disturbance potential ψ^1 can be considered as an approximation to the first harmonic component of the velocity potential. The thus obtained solution is free of numerical integration errors but still contains a truncation error due to taking the mean steady potential at reduced frequency $k = 0$ instead of the actual value of k, which is expected to be of $O(k)$.

The differential equations are discretized using the finite-volume method of Ref. 6. For the capture of shocks, Engquist-Osher flux splitting is applied. The nonlinear equations for the mean steady flowfield are solved by using a Newton procedure and a two-level method. The extent of the grid is reduced by using a field panel method on a coarse grid to obtain nonreflective far-field boundary conditions on the fine grid. This two-level method has been described in detail in Ref. 6.

Comparison of Numerical Results

Results of unsteady transonic calculations are presented for two AGARD standard configurations: 1) the NACA 64A010 (Ames) airfoil at $M_\infty = 0.796$, $\bar{\alpha} = -0.1$ deg, $\Delta\alpha = 1$ deg, and 2) the NLR 7301 airfoil at $M_\infty = 0.721$, $\bar{\alpha} = -0.19$ deg, and $\Delta\alpha = 0.5$ deg. The geometries have been taken from Ref. 7. The unsteady motion of the NACA 64A010 airfoil is pitching about the quarter-chord position, while the motion of the NLR 7301 airfoil is pitching about the 0.4 chord position. More results have been generated and compared for thick blunted airfoils in subsonic flow for values of $\bar{\alpha}$ up to 20 deg and for values of k up to 1, which proved to be in excellent agreement. These results are not included here.

The unsteady TULIPS results have been obtained using 600 time steps per cycle of oscillation. The unsteady FTRANC results are based on a mean steady flowfield constructed by averaging five steady flowfields at angles of attack $\alpha = \bar{\alpha}$, $\bar{\alpha} \pm \frac{1}{2}\Delta\alpha$, and $\bar{\alpha} \pm \Delta\alpha$. The calculations are carried out on a 104×24 C-type grid (72 segments on the airfoil) extending about 10–15 chords away from the airfoil. Such a small extent is sufficient because appropriate far-field boundary conditions are applied.

NACA 64A010 Airfoil

Figures 1 and 2 show results of calculations at the reduced frequencies of $k = 0.05$ and 0.2, respectively. A good overall agreement can be observed. Small but significant differences appear at the shock trajectory, particularly in the mean steady pressure distribution and in the real part of the first harmonic component. Inspection of the figures reveals that the shock locations deviate more as the frequency increases. This could be expected because the mean steady flowfield of FTRANC, being the same for all unsteady calculations, refers to the reduced frequency $k = 0$ (i.e., quasisteady flow). Table 1 gives the comparison of the unsteady lift and moment coefficients at $k = 0.05$, 0.01, and 0.20. The correlation is satisfactory.

NLR 7301 airfoil

In Fig. 3, the results of both methods are given for the NLR 7301 airfoil pitching about 0.4 chord in its supercritical design condition: $k = 0.068$. Qualitatively, the TULIPS and FTRANC results agree. In the subsonic region on the lower side, the results are in good agreement, but in the supersonic region on the upper side the results differ significantly. The cause is probably FTRANC, which cannot predict the shock excursions accurately enough. In Table 2, the unsteady lift and moment coefficients are presented at $k = 0.068$ and 0.181. It appears that the real parts of the lift coefficient are in good agreement, particularly for the low-frequency case $k = 0.068$. However, the other coefficients deviate substantially.

Reliability

The satisfactory correlation for the NACA 64A010 airfoil shows that both methods are equally well able to calculate unsteady transonic flow, which is dominated by the effect of shock displacement. Such a type of flow leads to a shock doublet in the unsteady pressure distribution, which is calculated by both methods with obviously similar results. The resemblance improves as the frequency decreases, which could be expected because the results of FTRANC involve trunca-

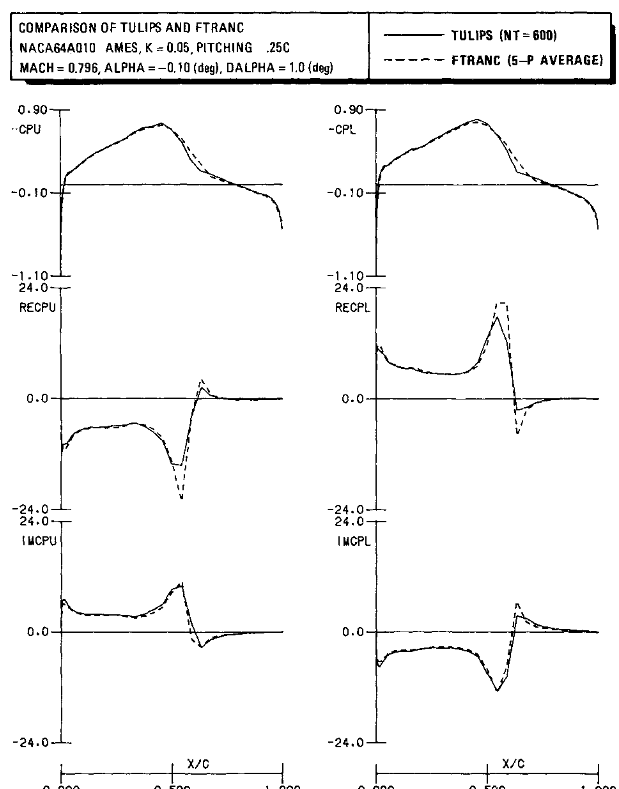

Fig. 1 Comparison of calculated distributions of pressure coefficients of the NACA 64A010 (Ames) airfoil for reduced frequency $k = 0.05$.

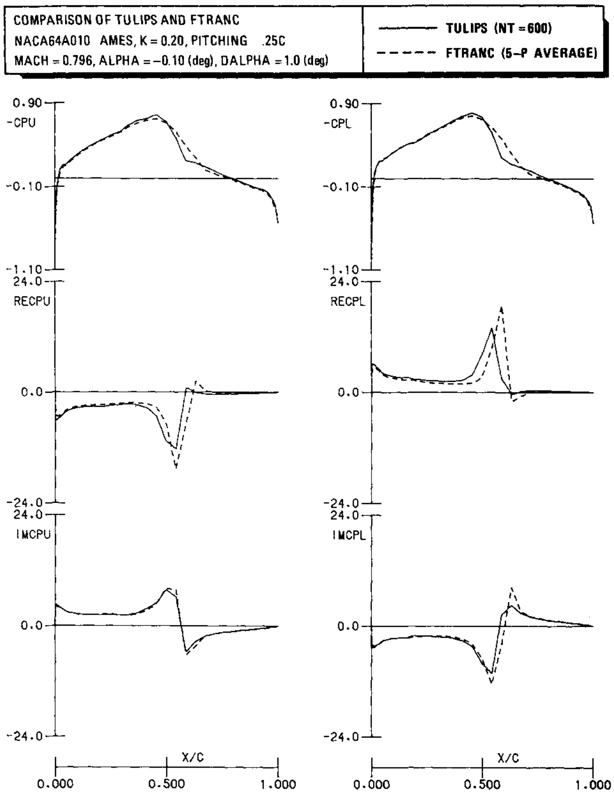

Fig. 2 Comparison of calculated distributions of pressure coefficients of the NACA 64A010 (Ames) airfoil for reduced frequency $k = 0.20$.

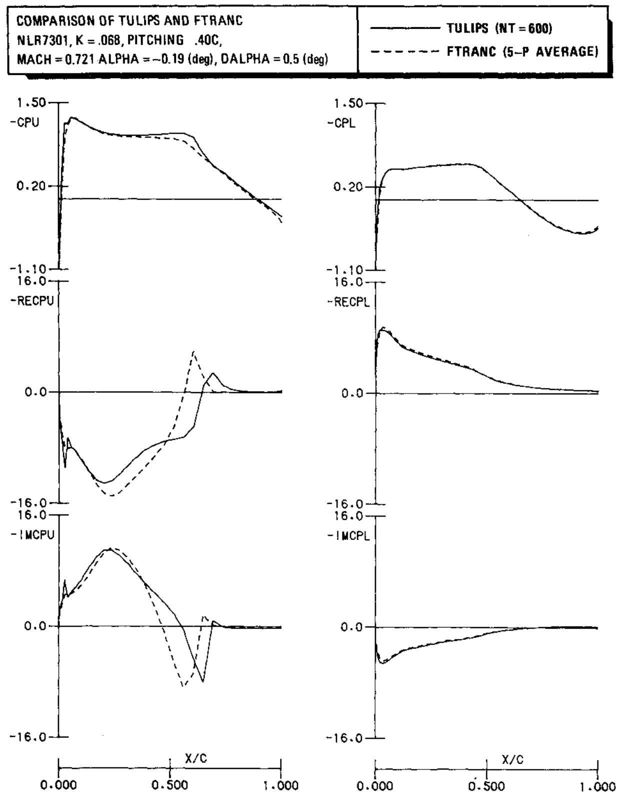

Fig. 3 Comparison of calculated distributions of pressure coefficients of the NLR 7301 airfoil at supercritical conditions for reduced frequency $k = 0.068$.

Table 1 Comparison of first harmonic components of lift and moment coefficients, NACA 64A010 (Ames) airfoil

k	Method	k'	k''	m'	m''
0.05	TULIPS	3.02	−1.80	0.47	−0.16
	FTRANC	3.14	−1.62	0.49	−0.11
0.10	TULIPS	2.36	−1.34	0.38	0.00
	FTRANC	2.26	−1.32	0.41	0.01
0.20	TULIPS	1.74	−0.85	0.39	0.18
	FTRANC	1.67	−0.85	0.44	0.19

Table 2 Comparison of first harmonic components of lift and moment coefficients, NLR 7301 airfoil

k	Method	k'	k''	m'	m''
0.068	TULIPS	2.74	−1.42	0.14	0.20
	FTRANC	2.73	−1.19	0:03	0.24
0.181	TULIPS	1.78	−1.00	0.30	0.31
	FTRANC	1.84	−0.85	0.24	0.43

tion errors, due to taking the mean steady flow at reduced frequency $k = 0$ instead of the actual value of k. For the NLR 7301 airfoil, the correlation is less satisfactory. It appears that, at the supercritical design conditions, the flow is dominated by strongly nonlinear effects, such as considerable changes in the pressure distribution in the supersonic region at the upper side of the airfoil. It is likely that these nonlinear effects cannot be modeled accurately by the time-linearized FTRANC method. On the other hand, the time-integration TULIPS method has no limitations to cope with this type of nonlinear flow. Therefore, having observed a satisfactory resemblance for the NACA 64A010 airfoil, it is plausible to state that TULIPS yields also reliable results for the flow about the NLR 7301 airfoil at its supercritical design conditions.

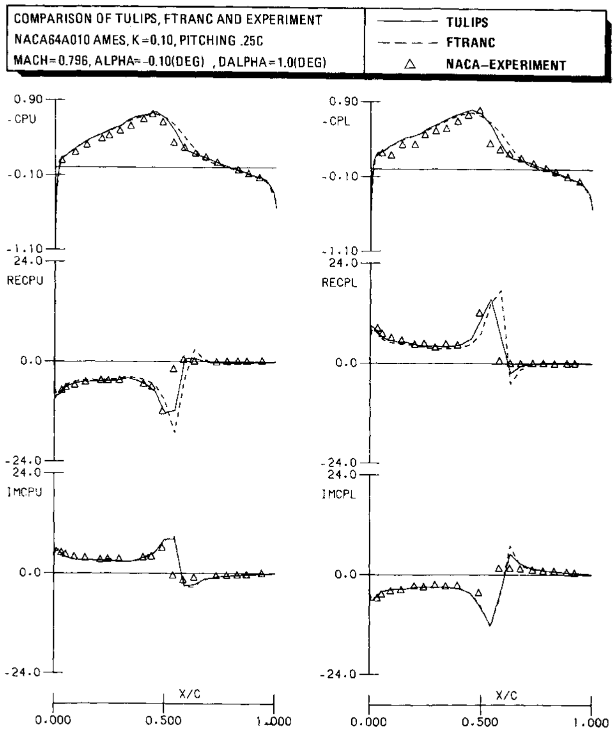

Fig. 4 Comparison of experimental and calculated distributions of pressure coefficients of the NACA 64A010 (Ames) airfoil for reduced frequency $k = 0.10$.

Comparison of Calculated Full-Potential Results and Experimental Data

Having investigated the accuracy of TULIPS and FTRANC, it is interesting to see how the results of these codes compare with experimental data.

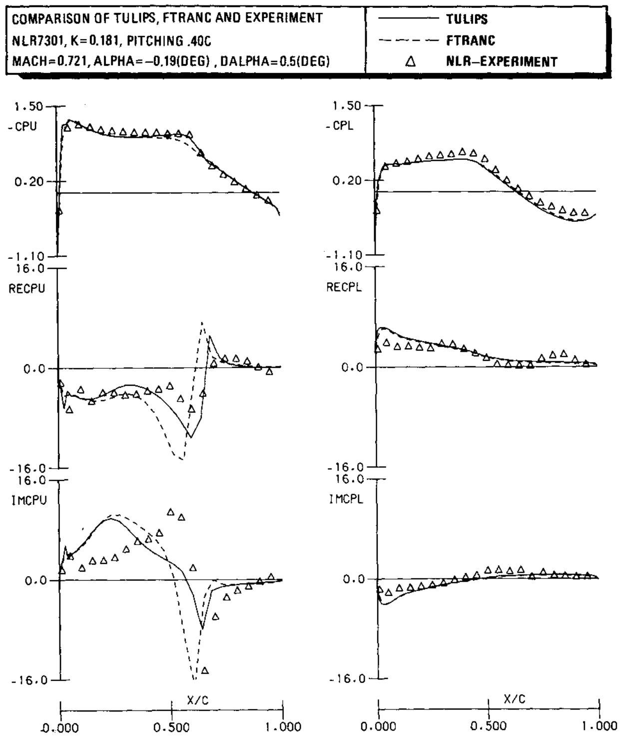

Fig. 5 Comparison of experimental and calculated distributions of pressure coefficients of the NLR 7301 airfoil at supercritical conditions for reduced frequency $k = 0.181$.

NACA 64A010 Airfoil

Figure 4 shows a comparison of calculated and measured[7] mean steady and first harmonic pressure coefficients at $k = 0.10$ at the upper and lower sides. Except for peak values, the agreement between theories and experiment is fair.

NLR 7301 Airfoil

Figure 5 compares calculated and measured mean steady and first harmonic pressure coefficients at the upper and lower sides at $k = 0.168$. Except for the first harmonic pressure coefficients at the upper side, the correlation is reasonable. At the shock trajectory, the TULIPS results have a better correlation with respect to the mean steady pressure coefficients. The poorer agreement for the unsteady pressures at the upper side is probably due to wind-tunnel wall interference. This interference is not observed in the steady data because, in the experiments, Mach number and incidence were tuned to compensate for steady wall interference. This steady compensation, however, seems insufficient for the unsteady data and might even have an adverse effect on the comparison.

Conclusions

The application of the time-integration TULIPS method and the time-linearized FTRANC method to transonic flow permits the following conclusions:

1) For the NACA 64A010 airfoil, good agreement has been observed between the TULIPS and FTRANC results. Therefore, the calculated results are highly reliable and are considered as valuable contributions to the database being set up for these configurations.

2) For the supercritical NLR 7301 airfoil in its transonic design conditions, the agreement between the TULIPS and FTRANC results is less satisfactory. It is likely that this case exceeds the range of applicability of the FTRANC time-linearized method.

3) Calculated results of the unsteady full-potential methods compare reasonably well with the experimental data for the NACA 64A010 airfoil in transonic flow. For the supercritical NLR 7301 airfoil, this is true for the mean steady data and the subsonic unsteady data at the lower side. The unsteady data at the upper side deviates substantially. Unsteady wind tunnel wall interference effects seem to contribute much to this.

Acknowledgment

This investigation has been carried out partly under Contract 1902 with the Netherlands Agency for Aerospace Programs.

References

[1]Schippers, H., "Numerical Treatment of Shocks in Unsteady Potential Flow Computation," NLR MP 85044 U, 1985.

[2]Van der Vooren, J. and Schippers, H., "Implicit Finite-Difference Methods for the Calculation of Unsteady Transonic Potential Flow About 2D-Airfoils—A Discussion," NLR MP 83063 U, 1983.

[3]Bayliss, A. and Turkel, E., "Far Field Boundary Conditions for Compressible Flows," *Journal of Computational Physics*, Vol. 48, No. 2, 1982, pp. 182–199.

[4]Weatherhill, W.H. and Ehlers, F.E., "Analysis of Transonic Flow About Harmonically Oscillating Airfoils," AIAA Paper 80-0149, 1980.

[5]Hounjet, M.H.L., "Calculation of Unsteady Transonic Flows with Shocks by Field Panel Methods," *AIAA Journal*, Vol. 20, June 1982, pp. 857–859.

[6]Hounjet, M.H.L., "FTRAN3S and FTRAN3: Methods to Calculate Steady and Time-Linearized Unsteady Transonic Potential Flow About Wings," NLR TR 87020 L, 1977.

[7]Bland, S.R., "AGARD 2-D Aeroelastic Configurations," AGARD AR 156, 1979.