Application of Panel Methods to External Stores at Supersonic Speeds

J. D. Waskiewicz* and J. E. DeJongh*
Flight Dynamics Laboratory, WPAFB, Ohio
and
A. Cenko†
Grumman Aerospace Company, Bethpage, New York

The capability of aerodynamic panel method technology to provide accurate aerodynamic predictions of store proximity and mutual interference effects has been investigated using the simple aerodynamic flowfield generated by a flat plate at angle of attack. Force and moment data have been compared against experimental results for two store models at Mach numbers of 1.5 and 1.9. Model configurations consisting of tangent ogive and winged stores were traversed through a flat plate flowfield at distances ranging from 1 to 6 store diameters below the plate. As expected, the study shows that the PANAIR code, which employs higher-order singularities and allows a more exact geometric representation, gives the best results.

Nomenclature

C_N = normal force coefficient
C_M = pitching moment coefficient
C_p = pressure coefficient
h = distance below the flat plate, in.
M = freestream Mach number
u = nondimensionalized x—perturbation velocity
x,z = Cartesian coordinates
X_s = distance from store nose to flat plate leading edge, in.
α = angle of attack
α_c = compressibility axis angle
β = shock angle
μ = Mach angle, $\sin^{-1}(1/M)$

Introduction

ALTHOUGH the problem of external store interference has been of interest for many years, cost-effective and systematic methods for predicting separation and achieving optimum aerodynamic integration are just coming of age.[1] Development of such methods for purely subsonic or purely supersonic flows have had the most attention[2,3] and favorable application of these procedures[4-6] has demonstrated their effectiveness for establishing weapon system design criteria.

Another requirement in the design of aircraft-weapon combinations is the need for detailed simulation of the geometric shapes involved. Prediction techniques must be able to represent geometries and flow phenomena associated with such configuration details (e.g., inlets, canards, conformally carried weapons) and must be able to account for mutual interference effects between the various components. Early linearized panel method programs[3,7] had severe geometry restrictions, especially at supersonic Mach numbers, and did not fully account for mutual interference. A higher-order panel method (PANAIR) developed by Boeing is free from any such restrictions as demonstrated by excellent correlations in several test cases involving realistic geometries.[8-10]

Presented as Paper 81-1653 at the AIAA Aircraft Systems and Technology Conference, Dayton, Ohio, Aug. 11-13, 1981; submitted Sept. 30, 1981; revision received April 15, 1982.

*Aerospace Engineer. Member AIAA.
†Senior Engineer. Member AIAA.

Also, this method's capability to predict mutual interference between an aircraft and a separated weapon has been examined[11] in conjunction with a Flight Dynamics Laboratory (FDL) test program[12] to assess the importance of various weapon aerodynamic technologies on weapon carriage and separation at high-speed flight conditions. In this study, the predicted aerodynamic flowfield characteristics were compared against experimental test results generated by the FDL program. Results of this effort demonstrated the unique capability and versatility of the PANAIR code to analyze complex vehicle-weapon combinations. For subsonic and low supersonic Mach numbers, where nonlinear effects were small, the method gave excellent correlation with experimental data. At the higher supersonic Mach numbers, results indicated that even though the calculations did not match the measured data in the highly nonlinear region, the theoretical method could still reflect the proper characteristics. Based upon these results it was felt that the real flowfield beneath the aircraft must have been very complex, with strong disturbances that were not amenable to linear theory analysis. It is clear that further study is needed to make a more thorough analysis of proximity and mutual interference effects. To facilitate this effort, an FDL wind tunnel test was conducted to obtain force and moment data on various store models being traversed through the flowfield produced by a flat plate at angle of attack. This test was performed in the Trisonic Gasdynamics Facility (TGF) at Wright-Patterson AFB for Mach numbers ranging from 1.5 to 2.3. These data were used to evaluate the effectiveness of various panel methods in predicting proximity effects.

Three linear panel methods chosen for study were Woodward I,[7] Woodward II (USSAEROB),[13] and the PANAIR Pilot Code.[14] Calculated values from these codes are compared to the experimental data in order to provide some insight into the capabilities of each code.

Geometric Representation

Two store geometries used to examine the interference phenomena were the planar wing weapon (PWW) and ogive cylinder (generic) stores shown in Fig. 1. Force and moment comparisons were made for the stores in the flat plate flowfield. Traverses were made at three different h locations below the plate, as illustrated in Fig. 2, for Mach numbers of 1.5 and 1.9. The plate and store were both at $\alpha = 4$ deg relative to the freestream at all heights and Mach numbers.

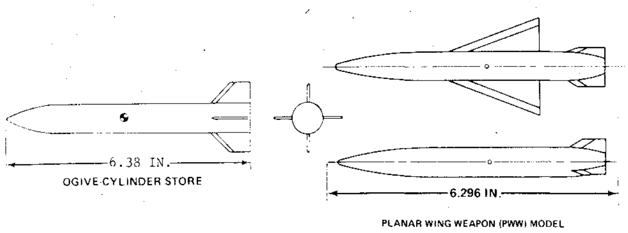

Fig. 1 Store model geometries.

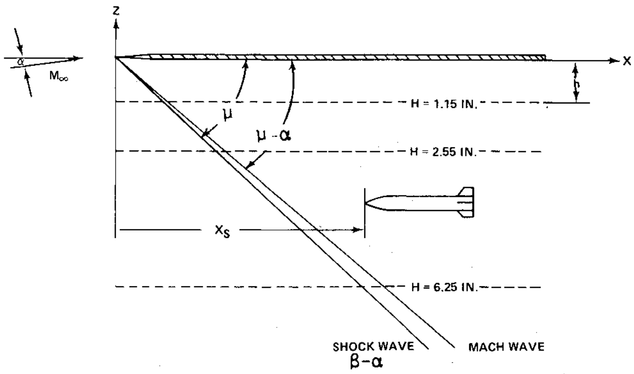

Fig. 2 Locations at which data are compared.

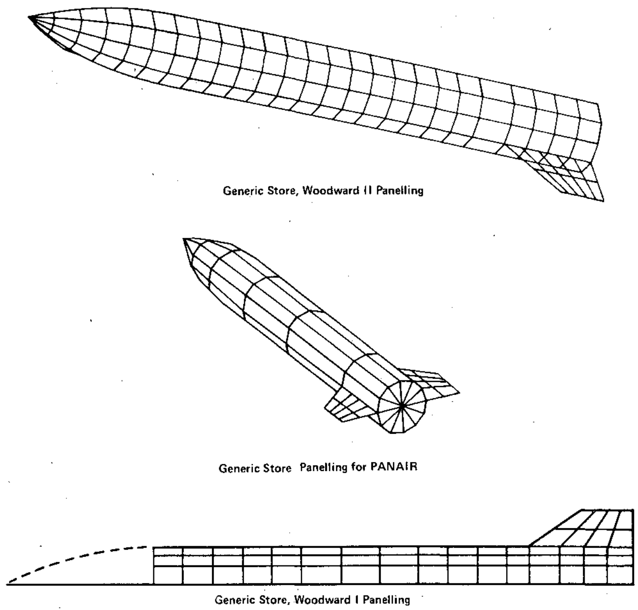

Fig. 3 Ogive-cylinder (generic) panelling.

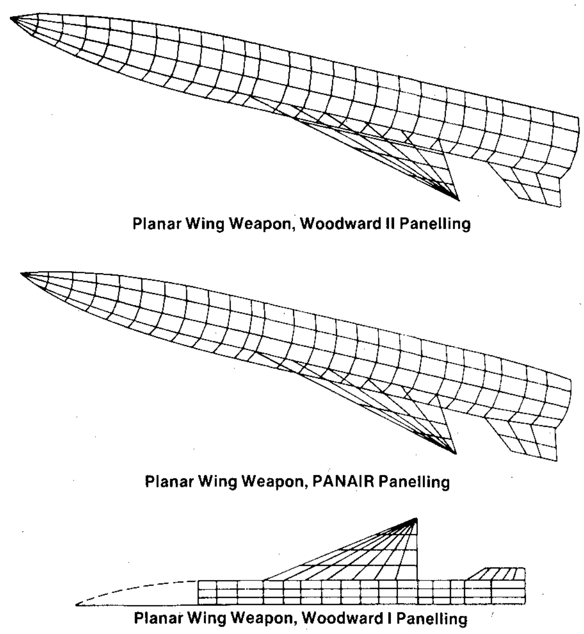

Fig. 4 Planar wing weapon (PWW) panelling.

The major difference between the three panel methods is the amount of geometric complexity the codes can represent. The Woodward I code is the most restrictive, since the body panelling has to have a constant cross section, with variations in body geometry represented by a source model which does not interact with the wing surfaces. Furthermore, the wing and tail surfaces cannot have any dihedral. The Woodward II code is considerably less restrictive, permitting arbitrary body geometries as well as wing and tail dihedral. However, the body cross sections have to be constant in regions of wing and tail intersection to prevent gaps in panelling from appearing. Furthermore, arbitrary changes in body cross section can produce internal reflections[9,15] which degrade the solution. The PANAIR code has no inherent geometric restrictions; however, representing highly complex geometric shapes is time consuming and probably beyond the scope of linear theory analysis.[16]

Figures 3 and 4 show the panelling of the generic and PWW stores for the three codes. As may be seen from these figures, the Woodward II and PANAIR representations are similar for the two stores, with the principal difference occurring in the tail region of the PWW store. The Woodward I representations differ considerably from those for Woodward II and PANAIR. The principal difficulty in the Woodward I representations is the inability to panel the nose, since no interference is calculated for the nose source model.

The PANAIR representation for the generic store is identical to that used in Ref. 16. The PANAIR PWW representation is similar to that for the generic; composite source-doublet panels on the body, and linearized zero thickness doublet panels on wing and tail. Forces and moments for the PANAIR code were calculated using the isentropic C_p formulations, while the two Woodward codes used the nonlinear C_p formulation for the body and the linear for wings and tails.

Nonlinear Effects

Before discussing results of the store traverse comparisons, some information regarding the calculation procedures used in these codes should be provided. First, the Woodward methods calculate a solution based upon a linearization about the x axis, which is assumed to be the longitudinal axis of the configuration. In contrast, PANAIR calculates a solution based upon a linearization about a compressibility axis.[17] This axis can be chosen arbitrarily, but best results are obtained when it is aligned with the configuration angle of attack ($\alpha_c = \alpha$). The result of this difference in procedure is that the PANAIR calculations will be performed along Mach lines equal to $\alpha_c \pm \mu$ while the Woodward calculations will ignore the compressibility axis. For the present experimental conditions, a shock wave was produced by the plate leading edge. Linear theory calculates disturbances propagating along Mach waves rather than shock waves. Therefore calculations made using linear theory methods will be displaced from the experimental data which correspond to the shock wave off the plate leading edge. This displacement would be in the opposite direction from that produced by the Woodward methods' linearization about the x axis (Fig. 2). For the experimental conditions used in this study, the two linearizing assumptions in the Woodward methods fortuitously cancel each other while the PANAIR results are displaced (Fig. 5). If the disturbances were to have been caused by an expansion fan, PANAIR would be in better agreement with the experiment.

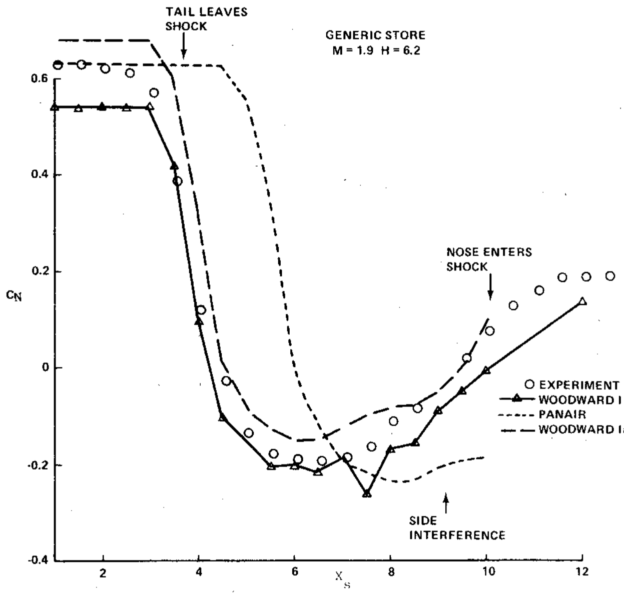

Fig. 5 Linear solution displacement due to Mach wave angle.

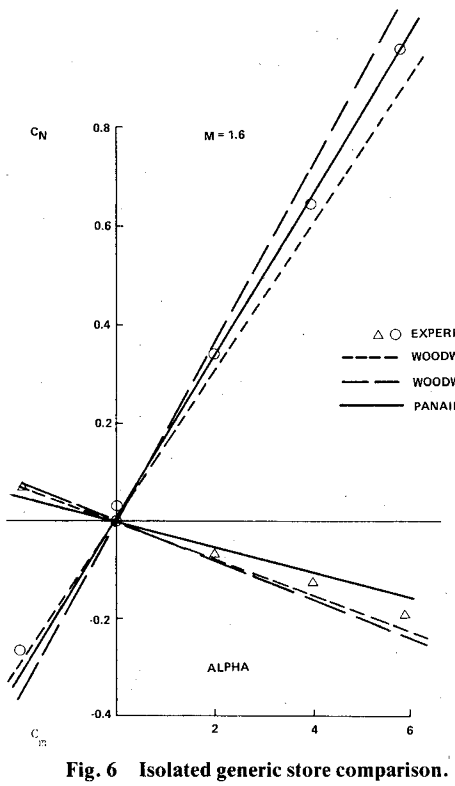

Fig. 6 Isolated generic store comparison.

Although the PANAIR code could be run at a compressibility axis of 0 deg, to bring the results of all three methods together, this would sacrifice accuracy in the force and moment calculations. An easier correction[16] is to shift the PANAIR results by an amount determined by the difference between the shock and Mach angle. Consequently, all PANAIR results, subsequent to Fig. 5, have been appropriately shifted, while results from the Woodward techniques are presented without change.

The PANAIR code, in addition to using higher-order singularities, allows the user a choice of boundary condition options. Velocity boundary conditions were used in all the comparisons shown. Since then, unpublished work by Melnik and Mason[18] has provided strong evidence that the mass flux boundary condition formulation is incomplete.

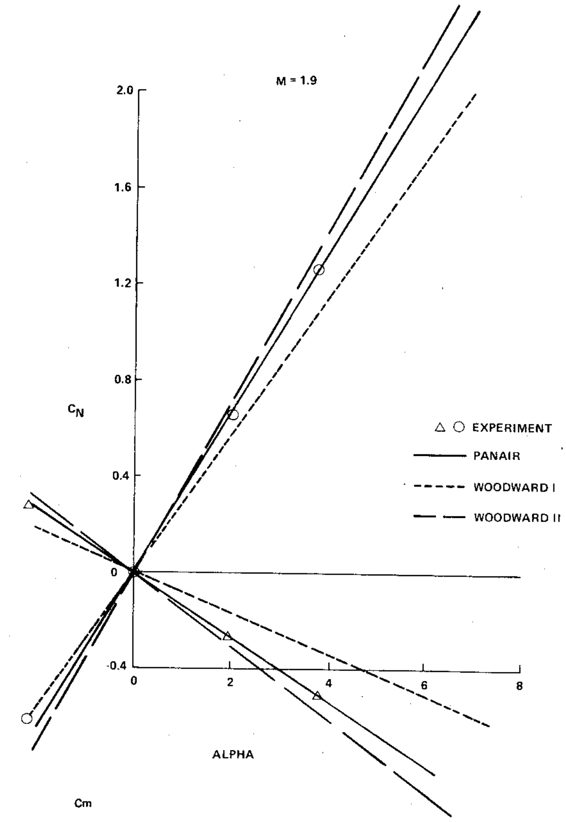

Fig. 7 Isolated planar wing weapon comparison.

Results

Figures 6 and 7 present force and moment prediction comparisons from all three methods on the isolated generic and PWW stores. The PANAIR code seems to give the best normal force predictions, while the Woodward I code consistently underpredicts and the Woodward II code overpredicts. This was not surprising, since the PANAIR code, which uses higher-order singularities and more exact geometric representation, should outperform the two Woodward codes. The large difference between the Woodward codes might be attributable[19] to the use of linearly varying wing singularities in the Woodward II code as opposed to constant in the Woodward I code. Furthermore, the Woodward II code accounted for dihedral whereas the Woodward I did not. The large variation in the predictions of all three codes can be attributed to the differences in geometric representation, Figs. 3 and 4. The ability of the PANAIR code to faithfully represent the geometries of these stores is considered one of its principal advantages. PANAIR also appears to do the best job in predicting the moments for the three stores.

Figures 8 and 9 present the generic store traverses at 6.25 in. for Mach numbers of 1.5 and 1.9. All three codes agree well with the experiment from upstream to the location where the nose enters the shock. Since aft of this position the store should be in an $\alpha = 0$ deg flowfield, and therefore have zero normal force and moment, test-theory disagreement in this region can be attributed to side interference, which theoretically will occur along Mach lines instead of curved shock waves (see Fig. 10).

Figures 11 and 12 present the generic store traverse at 2.55 in. for $M = 1.5$ and 1.9. For these cases the store was subject to vertical interference caused by the nose shock wave reflecting from the wedge. All three codes show a position dependent oscillation at $M = 1.5$. At $M = 1.9$, only the PANAIR code shows the position dependent oscillations. To determine whether panel density affected the solution, the

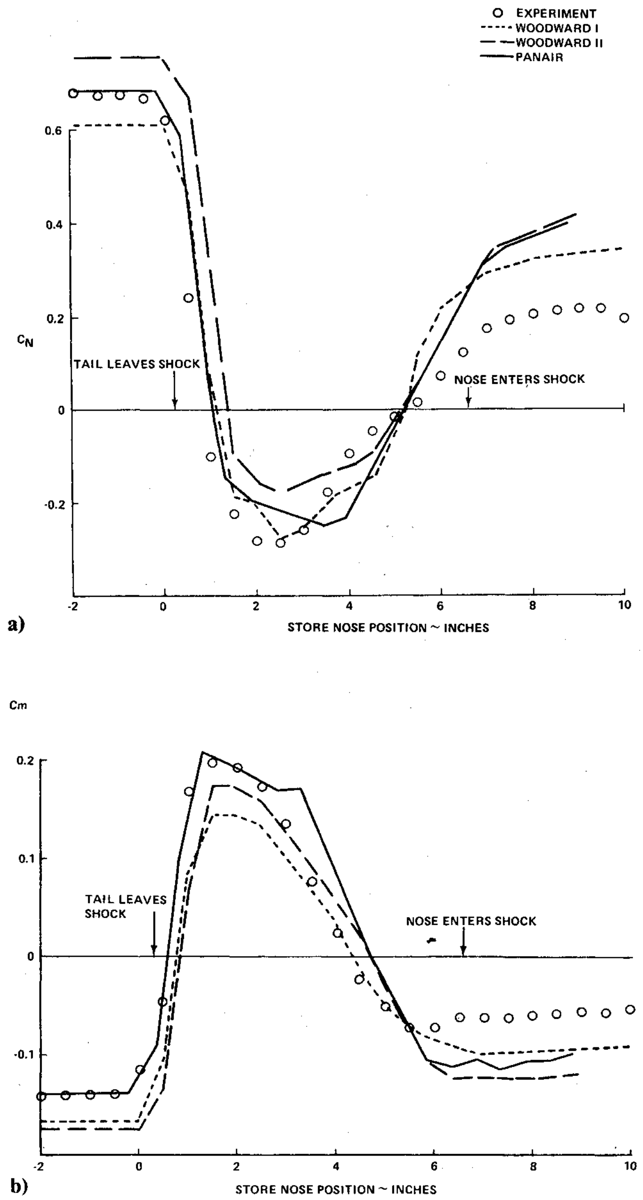

Fig. 8 a) Generic store normal force comparison. b) Generic store moment comparison, $M=1.5$, $h=6.2$.

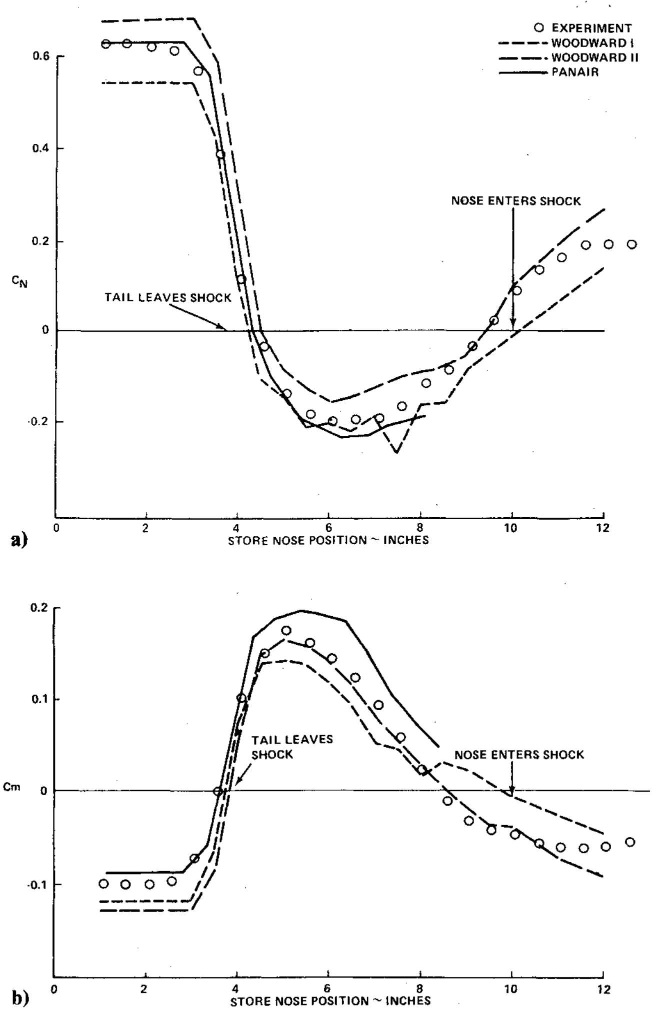

Fig. 9 a) Generic store normal force comparison. b) Generic store moment comparison, $M=1.9$, $h=6.2$.

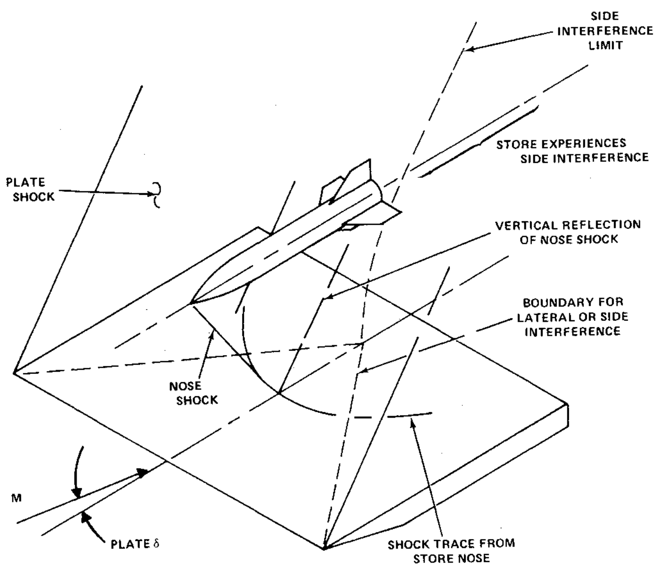

Fig. 10 Possible flowfield interferences.

PANAIR model was repanelled with four times the number of panels, giving it the same panel density as the Woodward II representation, Fig. 3. This showed no improvement (Figs. 11a and 11b) in eliminating the oscillatory behavior. Also, changing the panelling on the flat plate had no perceptible effect.

Results for the $h=1.15$-in. traverse exhibited similar oscillatory behavior. The magnitude of the oscillation is greater, however, owing to the smaller distance between the plate and store (i.e., reflections are greater in number and strength). It appears that linear theory cannot adequately predict shock reflection effects.

Figures 13 and 14 present the PWW store results for $M=1.9$ at $h=6.25$ and 2.55 in. Although the correlation shown by the three codes for these cases is unexciting, it must be pointed out that the upstream normal force and moment disagree with their freestream values by 10% (Fig. 7). If the predictions were lined up to match the upstream values the correlation for the Woodward II and PANAIR codes would substantially improve. The Woodward I code's lack of correlation can be attributed to the nose representation which affects half the traverse. Note that at the $h=2.55$-in. traverse, the oscillations in the PANAIR results are considerably less for the PWW store. This might be due to the fact that the PWW nose is considerably more slender than that of the generic store.

Results for the $h=1.15$-in. traverse, as well as for two other store geometries, are available in Ref. 20.

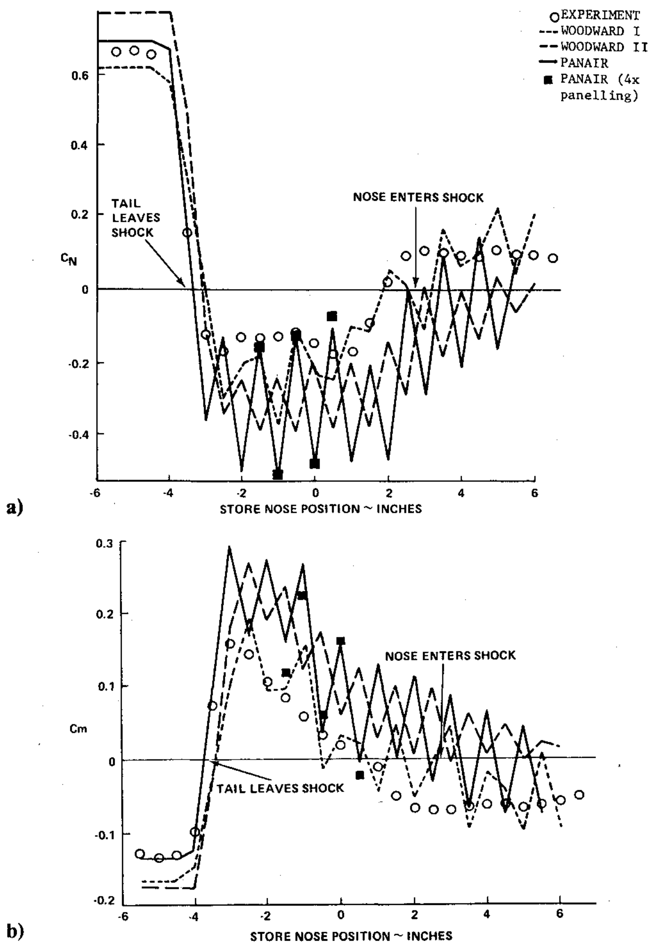

Fig. 11 a) Generic store normal force comparison. b) Generic store moment comparison, $M=1.5$, $h=2.45$.

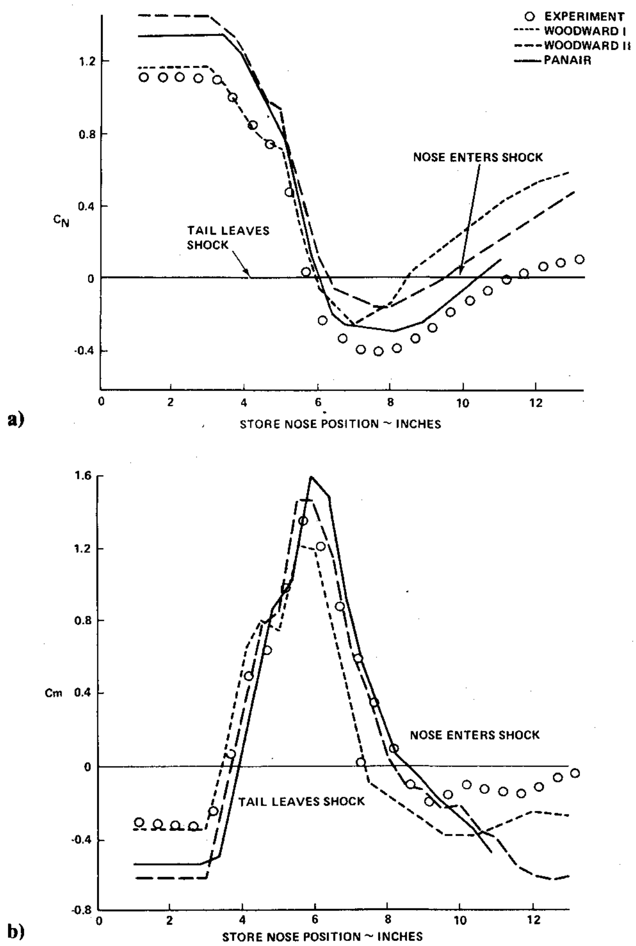

Fig. 13 a) PWW normal force comparison. b) PWW moment comparison, $M=1.9$, $h=6.2$.

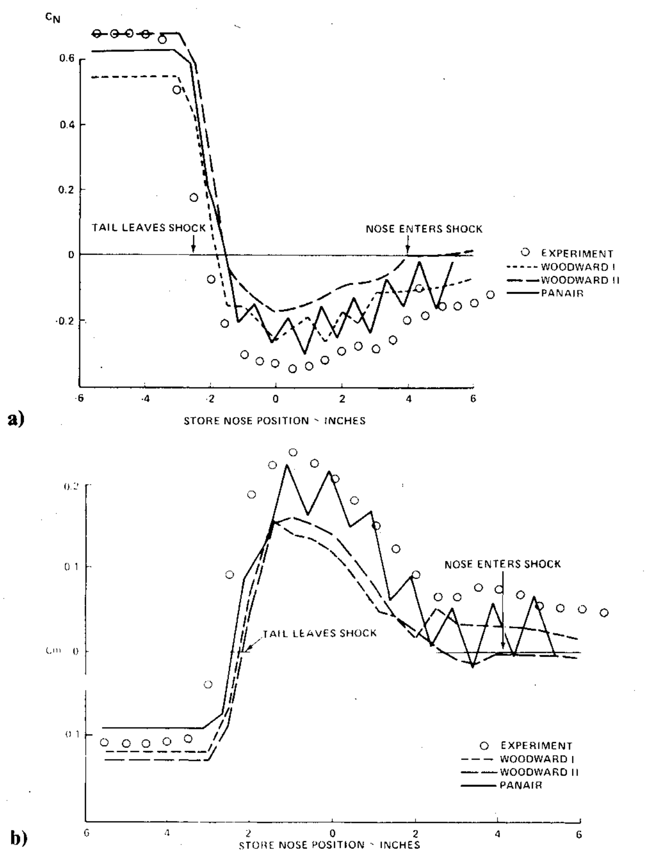

Fig. 12 a) Generic store normal force comparison. b) Generic store moment comparison, $M=1.9$, $h=2.5$.

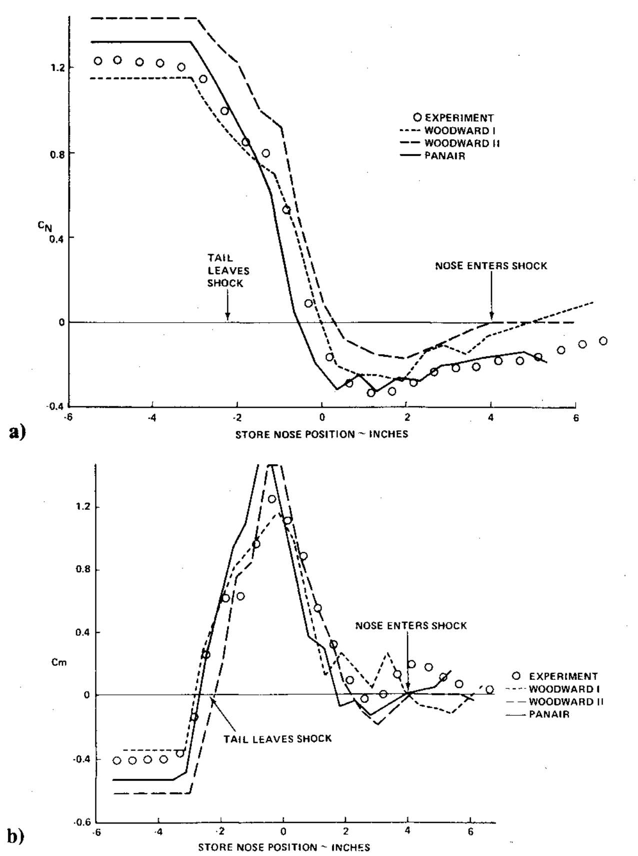

Fig. 14 a) PWW normal force comparison. b) PWW moment comparison, $M=1.9$, $h=2.5$.

Concluding Remarks

Three panelling methods were used to make predictions of store aerodynamic characteristics in the flowfield of a flat plate at angle of attack. The results show relatively good agreement between the predictions and experimental data for traverse heights where the shock from the store nose does not reflect back on the store. Results indicate that predictions made by the linear methods are subject to oscillatory behavior at the closer traverses owing to Mach wave reflection effects which are a function of the freestream Mach number and distance between the plate and stores. The region close to the flat plate is characterized by strong mutual interference effect and the present analysis has demonstrated the inability of the theoretical methods to simulate this complex phenomenon using simple linear theory. The PANAIR code, which has the capability of exact geometric representation, and higher-order mathematical singularities, appears to be superior to the two Woodward codes in regions where linear theory is applicable.

References

[1] Shankar, V. and Malmuth, N., "Computational and Simplified Analytical Treatment of Transonic Wing-Fusel-Pylon-Store Interactions," AIAA Paper 80-0127, Jan. 1980.

[2] Dillenius, M.F.E., Goodwin, F.K., and Nielsen, J.N., "Extension of the Method of Predicting Six-Degree-of Freedom Store Separation Trajectories at Speeds Up to the Critical Speed to Include a Fuselage with Noncircular Cross Section, Theoretical Method and Comparisons with Experiment," Vol. I, AFFDL-TR-74-130, March 1974.

[3] Dillenius, M.F.E., Goodwin, K.F., and Nielsen, J.N., "Prediction of Supersonic Store Separation Characteristics, Theoretical Methods and Comparisons with Experiment," Vol. I, AFFDL-TR-76-41, May 1976.

[4] Spahr, H.R., "Theoretical Store Separation Analyses of a Prototype Store," *Journal of Aircraft,* Vol. 12, Oct. 1975, pp. 807-811.

[5] Spahr, H.R., "Theoretical Store Separation Analyses of a Prototype Store and Comparison with a Flight Drop Test," AIAA Paper 74-776, Aug. 1974.

[6] Spahr, H.R., Everett, R.N., and Kryvoruka, J.K., "A Multifaceted Store Separation Analysis," *Proceedings of the AIAA 9th Aerodynamic Testing Conference,* June 1976, pp. 292-300.

[7] Woodward, F.A., Tinoco, E.N., and Larsen, J.W., "Analysis and Design of Supersonic Wing-Body Combinations, Including Flow Properties in the Near Field," NASA CR-73106, 1967.

[8] Ehlers, F.E., Epton, M.A., Johnson, F.T., Magnus, A.E., and Rubbert, P.E., "An Improved Higher-Order Panel Method for Linearized Supersonic Flow," AIAA Paper 78-13, Jan. 1978.

[9] Tinoco, E.N., Freeman, L.M., and Johnson, F.T., "Application of a Higher Order Panel Method to Realistic Supersonic Configurations," AIAA Paper 79-0274, Jan. 1979.

[10] Thomas, J.L. and Miller, D.S., "Numerical Comparisons of Panel Methods at Subsonic and Supersonic Speeds," AIAA Paper 79-0404, Jan. 1979.

[11] Cenko, A., Tinoco, E.N., Dyer, R.D., and DeJongh, J., "PANAIR Applications to Weapon Carriage and Separation," AIAA Paper 80-0187, Jan. 1980.

[12] Vore, D.A., "Wind Tunnel Test of Advanced Configurations and Various Weapons for Mach Numbers 0.6 to 1.6," AEDC TSR 79-P69, Nov. 1979.

[13] Woodward, F.A., "An Improved Method for the Aerodynamic Analysis of Wing-Body-Tail Configurations in Subsonic and Supersonic Flow," NASA CR- 2228, May 1973.

[14] Ehlers, F.E., Epton, M.E., Johnson, F.T., Magnus, A.E., and Rubbert, P.E., "A Higher Order Panel Method for Linearized Supersonic Flow," NASA CR 3062, Nov. 1978.

[15] Woodward, F.A and Landrum, E.J., "The Supersonic Triplet—A New Aerodynamic Panel Singularity with Directional Properties," AIAA Paper 79-0273, Jan. 1979.

[16] Cenko, A. and Tinoco, E.N., "PANAIR—Weapons, Carriage and Separation," AFFDL-TR-79-3142, Sept. 1979.

[17] Magnus, A.E. and Epton, M.E., "PANAIR—A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flows about Arbitrary Configurations using a Higher Order Panel Method, Vol. I, Theory Document," NASA CR 3251, April 1980.

[18] Mason, W., "Mass Flux Boundary Conditions in PANAIR," Grumman Inter-Office Memorandum, Feb. 1982.

[19] Cenko, A., "Advances in Supersonic Configuration Design Methods," *Journal of Aircraft,* Vol. 17, Feb. 1980, pp. 119-126.

[20] Cenko, A., Tessitore, F., and Meyer, R., "Prediction of Aerodynamic Characteristics for Weapon Separation, Part I, Theory and Applications," AFWAL-TR-3025, April 1982.