AIAA 80-0187R

PAN AIR Applications to Weapons Carriage and Separation

A. Cenko*
Grumman Aerospace Company, Bethpage, N.Y.
E. N. Tinoco†
Boeing Military Airplane Company, Seattle, Wash.
and
R. D. Dyer‡ and J. DeJongh‡
Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio

The PAN AIR technology has been used to analyze the complex flow phenomena associated with aircraft/weapons carriage and mutual interference during separation. Force, moment, and flowfield characteristics have been compared with experimental results for a fighter aircraft and a tangent ogive store. These comparisons were made for both the aircraft and store alone, as well as for the aircraft with the store in various separated conditions. The study has demonstrated the PAN AIR pilot code's unique capabilities to analyze complex aircraft and weapon configurations at both subsonic and supersonic speeds.

Nomenclature

c	= chord length
C_D	= drag coefficient
C_L	= lift coefficient
C_P	= pressure coefficient
C_M	= pitching moment coefficient
M	= freestream Mach number
$\hat{n}$	= surface unit normal vector
$\bar{v}$	= perturbation velocity
$\bar{V}$	= freestream velocity
$\bar{w}$	= perturbation mass flux vector
x, y, z	= Cartesian coordinates
α	= angle of attack
β	= $\sqrt{1-M^2}$
σ	= source strength
ϕ	= perturbation potential
ϕ_x, ϕ_y, ϕ_z	= gradient of perturbation potential

Subscripts

0	= zero lift
∞	= freestream
ℓ	= lower panel surface

I. Introduction

ADVANCED weapons and carriage techniques have become integral items in the design process for fighter aircraft. In this type of analysis, the capability of simulating detailed and complete geometric shapes is an absolute requirement. The individual aircraft and weapon configurations are generally complex and nonslender in shape. Also, the relative sizes and locations of weapon and aircraft are such that extreme detail is required in describing the geometry in the vicinity of the weapon so that adequate resolution is achieved of the small-scale (relative to the aircraft) aerodynamic phenomena.

The aerodynamic prediction method must be able to represent the geometries and flow phenomena associated with such configuration details as inlets, canards, conformally carried weapons, and mutual interference effects between the various components. The linearized panel method programs[1,2] presently in use for this purpose have severe geometric restrictions, especially for supersonic Mach numbers. A higher order panel method called PAN AIR (Panel Aerodynamics), currently under development at Boeing under joint NASA, Air Force, and Navy sponsorship, does not suffer from any such restrictions. It has demonstrated in pilot code form[3] excellent correlation for several test cases involving realistic geometries.[4-6] However, the method's capability to predict mutual interference between an aircraft and weapon had not been previously validated.

The Air Force Flight Dynamics Laboratory (AFFDL) currently has a program to assess the impact of various aircraft weapon aerodynamic technologies on weapon carriage and separation at high-speed flight conditions. From this program, both pressure and force space-grid and captive trajectory data[7] were generated for various weapon configurations at the Arnold Engineering Development Center (AEDC) 4 ft transonic wind tunnel.

As part of this program, a study was conducted to validate the effectiveness of PAN AIR technology in analyzing the complex flowfields associated with aircraft weapons carriage and mutual interference during separation. This was to be accomplished by comparing predicted aerodynamic and flowfield characteristics with the experimental test results generated by the AFFDL program. The PAN AIR pilot code was used for all aerodynamic predictions.

Two configuration geometries were examined. These were a fighter aircraft with a canard and horizontal tail, shown in Fig. 1, and a tangent ogive store shown in Fig. 2. This generic store is identical to the configuration used in the development of Ref. 2.

Several test conditions were selected as representative of the test program. These include off-body pressures at four z and three y locations, as illustrated in Fig. 3, for the aircraft alone and the aircraft with two generic stores mounted tangentially. Force and moment comparisons were performed for the aircraft alone, aircraft with generic stores mounted tangentially, generic store alone, and generic in the presence of the aircraft. These comparisons were done for both subsonic and supersonic Mach numbers. Highlights of this study are presented in this paper. Further details are given in Ref. 8.

The remainder of this paper is organized as follows: Sec. II discusses the application of the method to the weapon carriage aircraft. Comparison of results are shown for force and off-body pressure data. Section III presents comparisons

Presented as Paper 80-0187 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16, 1980; submitted Jan. 25, 1980; revision received June 9, 1980.

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

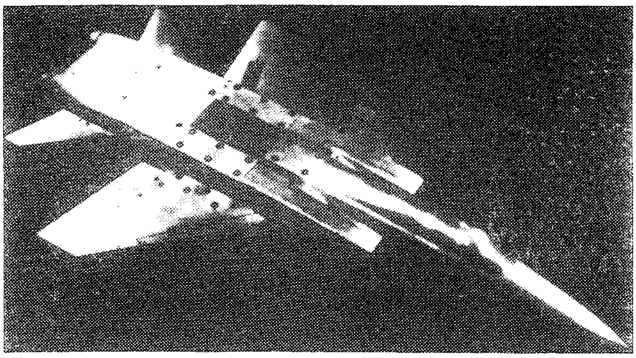

Fig. 1 Weapons carriage aircraft.

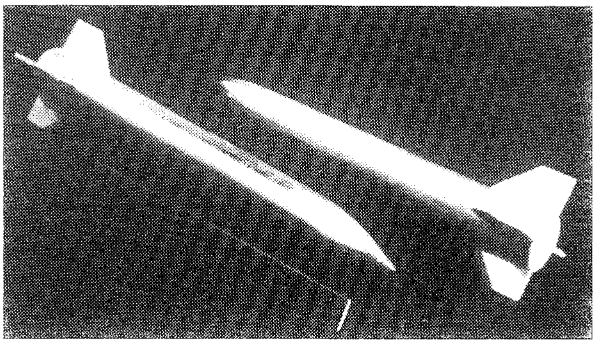

Fig. 2 Generic store.

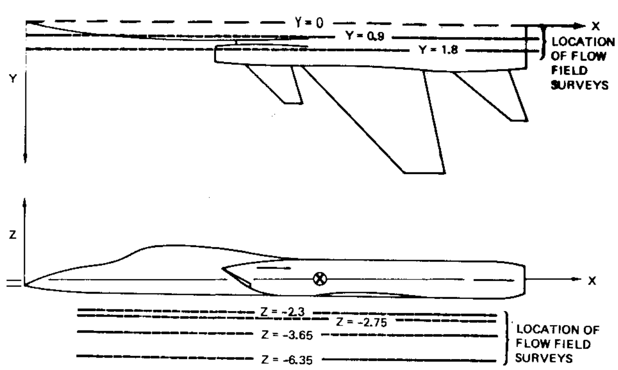

Fig. 3 Data comparison locations.

for the generic store, and Sec. IV illustrates the application of the method to weapons, carriage, and separation. The conclusions are presented in Sec. V.

II. Weapons Carriage Aircraft Analysis

The weapons carriage aircraft, shown in Figs. 1 and 3, is representative of an advanced supersonic attack aircraft. The configuration featured multiple lifting surfaces (wing, tail, and canard), in order to evaluate the effects of these features on weapon separation characteristics. The twin-engine layout with side-mounted inlets results in a box-like fuselage cross section which is not very amenable to solution using lower order methods.[1,2] The deficiencies of the lower order methods were overcome by use of a higher order panel method developed by Ehlers, Epton, Johnson, Magnus, and Rubbert.[4] A description of the method is available in Refs. 3-5, 8, and 9. The PAN AIR pilot code, which was used for the numerical development and validation of the method, produced the results presented.

Description of the Method

The method is intended to solve a variety of boundary value problems in steady subsonic or supersonic inviscid flow. The solutions are governed by the classic Prandtl-Glauert equation for linearized compressible flow:

$$\beta^2 \phi_{xx} + \phi_{yy} + \phi_{zz} = 0; \qquad \beta^2 = 1 - M_\infty^2 \tag{1}$$

The configuration is represented by a distribution of source and doublet singularities. These singularities, each of which is a solution to Eq. (1), may be placed on the actual configuration surface or may be used to represent components such as wings in linearized "thin wing" fashion by a single surface. A panel method is used for the solution. Here the configuration surface is divided into networks. A network is defined as a smooth portion of the configuration which has subsequently been divided into panels, each panel representing some source and doublet distribution. A linear source and quadratic doublet distribution over the panels is defined in terms of the values of the singularities at the centers of each panel and neighboring panels by a system of spline-type polynomials. Boundary conditions are applied at discrete points associated with each network. Each network is logically independent in that it contributes as many equations as unknowns to the overall boundary value problem. The required integrals are evaluated in closed form, and a resulting set of linear equations is solved for the required singularity strength parameters. Once this is accomplished, the potential and velocity fields are known. The pressure field can then be calculated from an appropriate pressure-velocity relationship, and forces and moments calculated by surface pressure integration.

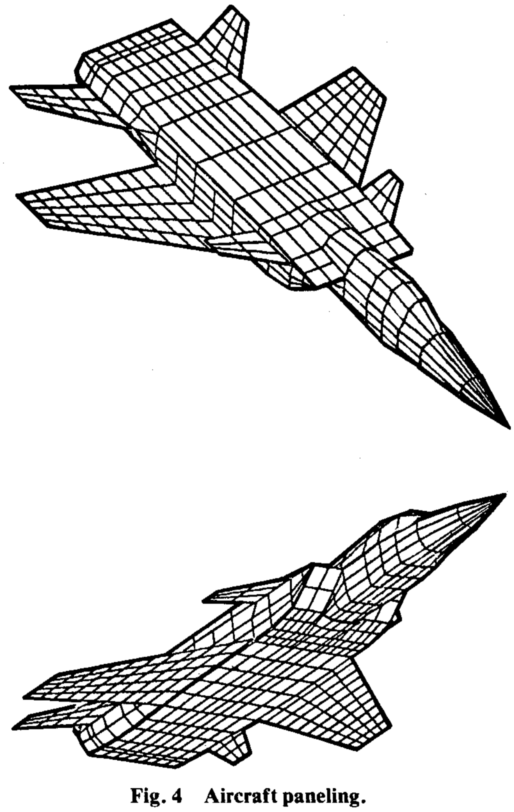

Fig. 4 Aircraft paneling.

Configuration Modeling

The paneling scheme for the aircraft employed in the PAN AIR pilot code is shown in Fig. 4. The wake paneling, shed from the canard, wing, tail, and fuselage, is not shown for clarity. The method will take advantage of symmetry so only half of the paneling was actually input. The figure illustrates some of the capabilities of the PAN AIR technology. The canopy, inlet, and the resulting fuselage cross sections are faithfully represented. Modeling simplifications, where deemed adequate and cost effective, have been incorporated into the analysis representation. These simplifications include the linearized "thin wing" representation for the canard, wing, and horizontal tail and the simple treatment of the inlet and diverter. The linearized wing representation is generally valid for thin wings which are not blended into the body and are relatively planar.

The inlet and diverter simplification was previously used in Ref. 5. Here the inlet and diverter were modeled by consolidating the inlet and diverter and placing a "barrier" over the resulting face. Inlet spillage can be controlled by specifying the inlet mass flow in subsonic flow, and in supersonic flow for Mach numbers for which the barrier is subinclined, i.e., inclined behind the Mach cone from its forward surface. When the barrier is superinclined, i.e., inclined ahead of the Mach cone, initial conditions are specified on the interior side of the barrier with the result that the incoming flow is captured by the sources on the barrier. If desired, the diverter spillage can also be specified along the appropriate panels. This type of modeling is deemed quite cost effective in that it adequately simulates the effects of these features without getting into excessive and perhaps meaningless detail. The diverter flow is highly viscous dominated, while the internal inlet flow is strongly dependent on shock-wave formation caused by the inlet ramp. These detailed flow characteristics are clearly out of the realm of inviscid linear compressible flow theory.

The total aircraft configuration, including the wakes and body closure, was represented by 443 panels on one side of the plane of symmetry. Surface panel density was varied to concentrate the paneling in regions deemed most appropriate. As a consequence, relatively sparse paneling is used on the upper portions of the fuselage or to represent the canard and tail. Denser paneling is found on the wing and the lower portions of the fuselage, in particular on the bottom portion of the inlet. Analysis had shown that a strong compression emanates from this region in supersonic flow, necessitating the denser paneling.

The boundary conditions imposed for the aircraft solution are illustrated in Fig. 5. Details of these specific boundary conditions are discussed in Ref. 8. The indirect mass flux impermeability conditions were imposed on the configuration surface. Wing thickness was not simulated. Inlet mass flow was specified for the solutions at Mach number 0.6 and 1.2. Superinclined initial conditions were specified on the inlet barrier for the solution at Mach 1.96.

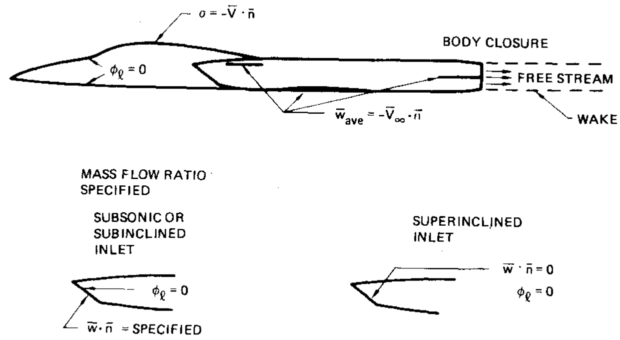

Fig. 5 Boundary conditions.

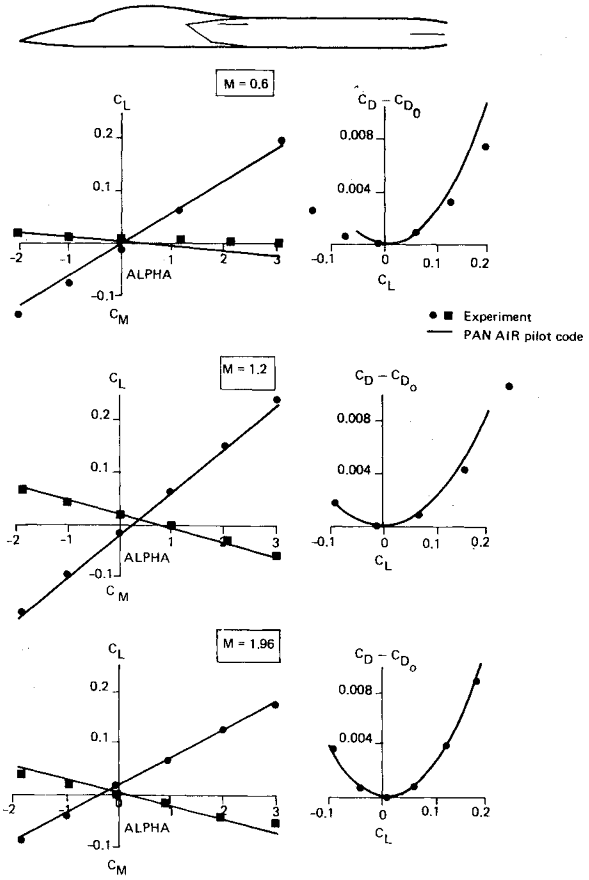

Fig. 6 Aircraft alone forces and moments.

Weapons Carriage Aircraft Results

Comparison of computed force and moment results with experimental data is shown in Fig. 6. Comparisons are made for Mach numbers 0.6, 1.2, and 1.96. The drag comparison in all cases is shown as $C_D - C_{D0}$, where C_{D0} is the configuration drag at $C_L = 0$. This representation was chosen because it gives the best indication of the PAN AIR pilot code's ability to predict drag due to lift, and its simplification in making the comparisons since wave and viscous drag can be neglected. For all cases, there is excellent correlation for lift and acceptable correlation for the drag and moment. The disagreement for drag due to lift at Mach numbers 0.6 and 1.2 is attributed to the inability of the pilot code to account for the leading-edge thrust developed by the linearized lifting surfaces. This is common to all panel methods, as described in Refs. 10-12. Including the full theoretical leading-edge thrust will not completely rectify the discrepancy, since the full theoretical value is rarely realized in real flow.

Comparisons of off-body flowfield pressures are shown in Fig. 7. Here, computed and measured pressure distributions along a line positioned below the aircraft are shown for Mach numbers 0.6, 1.2, and 1.96. Comparisons at 11 other positions are presented in Ref. 8. For subsonic and low supersonic Mach numbers, where nonlinear effects are small, the correlation is very good. At the higher supersonic Mach numbers results indicate that some correction is necessary to account for curved Mach line and local Mach number propagation effects.

As one moves further away from the body, there was an apparent phase shift in the off-body pressure predicted by the PAN AIR pilot code relative to the test data. This phase shift was most noticeable for the $M = 1.96$, $z = -6.35$ condition. This phase shift can be attributed to the fact that linear theory assumes disturbances propagate along straight Mach lines determined only by the freestream Mach number, whereas the disturbances actually propagate along curved Mach waves according to the local Mach number. This discrepancy is therefore greatest in regions of large compression, where the local Mach number differs significantly from freestream.

As a quick fix, the theoretical local Mach number at the aircraft location which causes the compression wave was used to compute where the disturbance would actually hit the off-body plane in question. The off-body pressure locations were then shifted by the difference between the location of the Mach lines determined by the freestream and local Mach number. This considerably improved test/theory correlation as shown in Fig. 8.

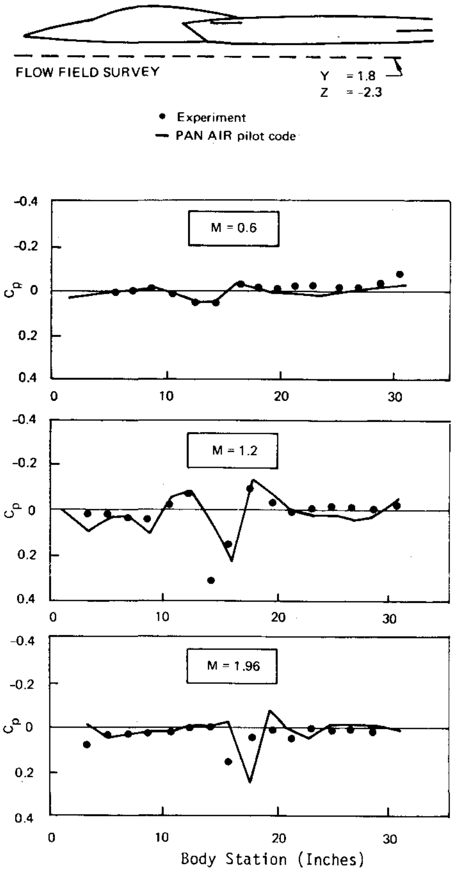

Fig. 7 Off-body points.

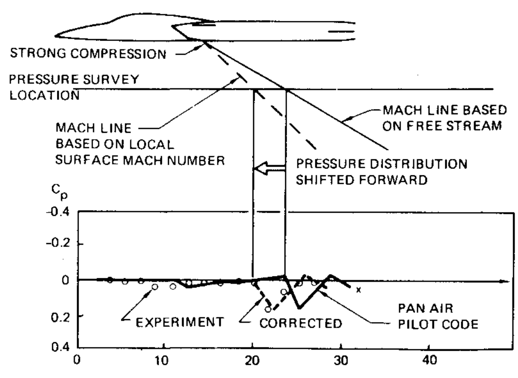

Fig. 8 Local Mach line corrections.

III. Generic Store Analysis

The weapon store shown in Fig. 2 is a simple tangent ogive cylinder with cruciform fins. This generic store is identical to the configuration used in the development of Ref. 2. It should be noted that any weapon geometry compatible with linear compressible flow theory would be acceptable for this analysis.

Store Modeling

The paneling scheme used for modeling the generic store is shown in Fig. 9. The vertical fin could not be modeled in the pilot code in cases in which the fin would lie entirely in the plane of symmetry. The resulting image fin, when symmetry is taken into account, would also lie in the same space, resulting in a singular matrix. In order to model the vertical fin in these cases a "thick wing" representation would have been necessary. The PAN AIR production code will allow the modeling of a "thin" vertical fin in the plane of symmetry. A total of 64 panels, including the base and wakes, were used to

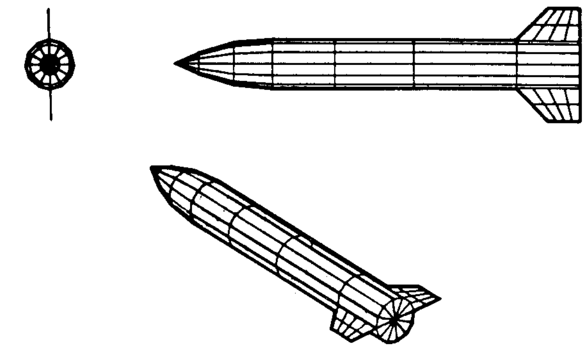

Fig. 9 Generic store paneling.

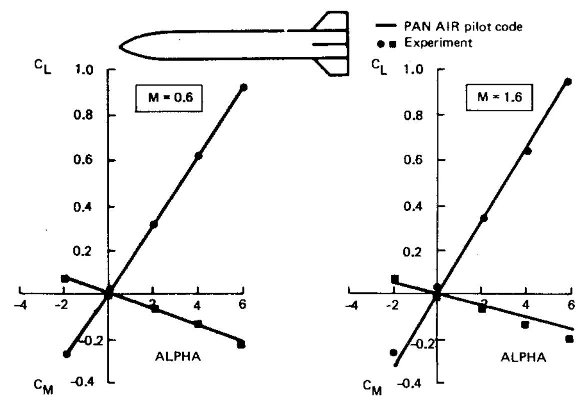

Fig. 10 Generic store alone forces and moments.

represent the generic weapon on one side of the plane of symmetry. The included cone angle of approximately 50 deg of the nose of the generic store proved to be too blunt for use of mass flux boundary conditions at supersonic Mach numbers. Instead, velocity impermeability boundary conditions[3,8] were used on the store body for analysis at supersonic Mach numbers, while mass flux impermeability conditions were used for analysis at subsonic Mach numbers.

Store Alone Results

Lift and moment comparisons are shown for the generic store at Mach numbers of 0.6 and 1.6 in Fig. 10. Excellent correlation between computed results and experimental data is seen for both Mach numbers.

IV. Weapon Carriage and Separation

Once the isolated weapon and aircraft computational models had been developed, the task of analyzing the combined models was undertaken. Two types of combinations typical of carriage and separation cases were analyzed. The carriage case consisted of the aircraft with two generic weapons. The separation case consisted of the carriage aircraft with one store still attached, and with the second store separated at various positions in the vicinity of the aircraft.

Weapon Carriage Analysis

For the carriage case, two generic stores were carried in tandem mounted tangentially to the bottom of the aircraft fuselage. This presented a problem in modeling in that the second store was immersed in the wake of the first. It would have been possible to model the two weapons separately with the wake of the first flowing around the second. However, deflecting the wake around the second store when both weapons are tangent to the aircraft fuselage would have resulted in very complex paneling. Also such a modeling, while mathematically correct, would be ignoring the highly viscous effects between the base of the first store and the nose

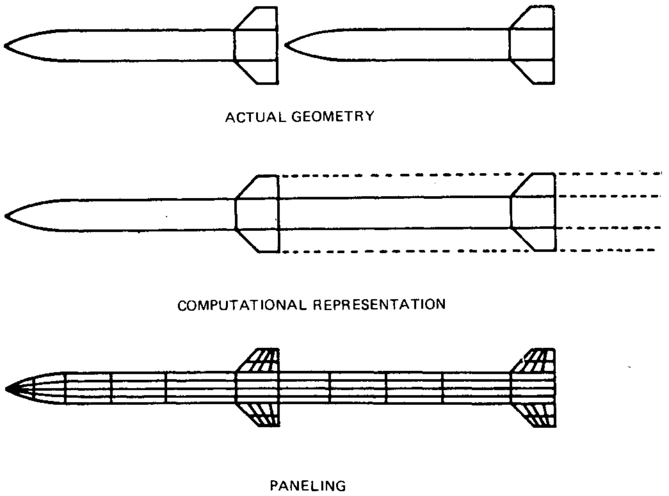

Fig. 11 Tandem weapon representation.

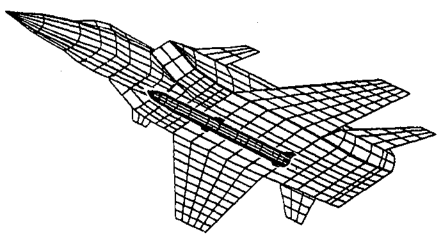

Fig. 12 Aircraft with tandem generic stores.

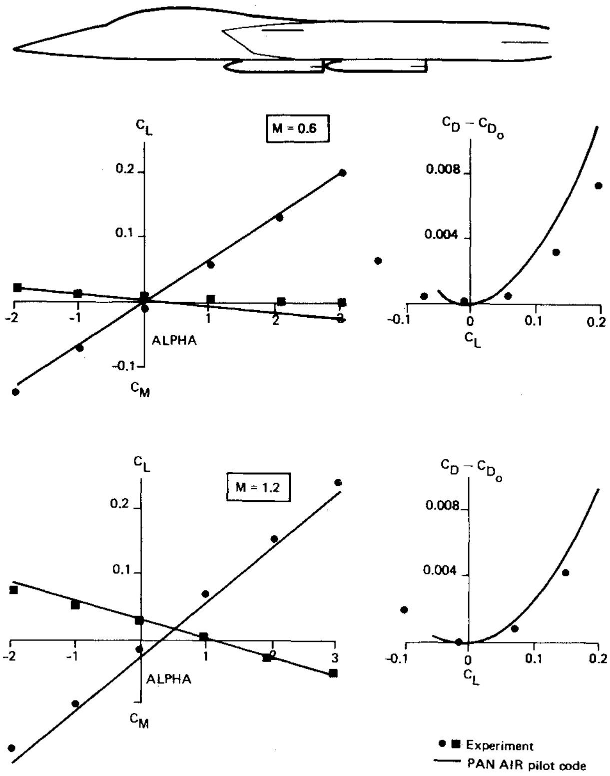

Fig. 13 Forces and moments on aircraft with generic stores.

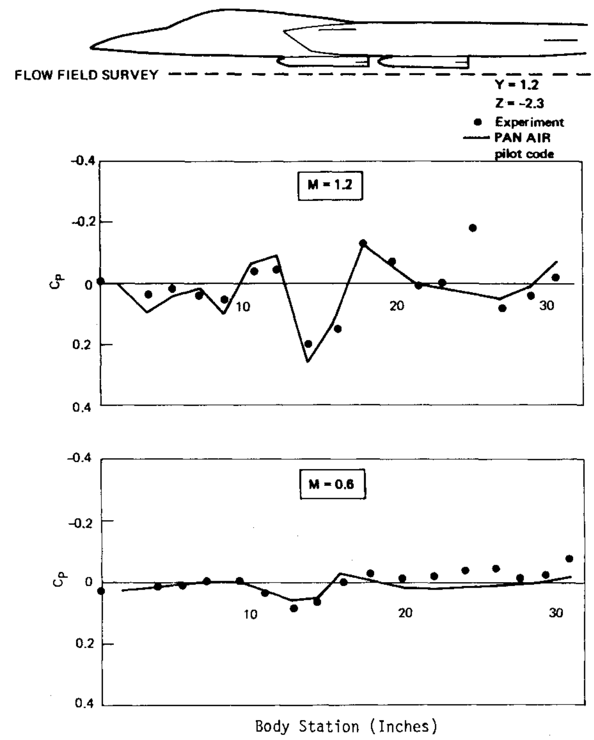

Fig. 14 Off-body pressures on aircraft with stores.

of the second. In fact, the nose of the second store would be seeing essentially freestream flow. Modeling the tandem stores as separate entities is not deemed reasonable.

A simple, but effective, modeling was chosen in which the two bodies were merged as illustrated in Fig. 11. Here it was assumed that the viscous effects fill in the space between the base of the first weapon and the nose of the second. The wakes from the fins of the first weapon are simply brought straight back and intersect the fins of the second. The second pair of fins, in turn, shed their wakes in the same plane. One drawback to this model is that the second pair of fins carry little if any lift. This is because the wakes tend to constrain the flow parallel to the second pair of fins. It would be possible to deflect the wake either above or below the second fin, but the effect is not considered significant enough to justify the added complexity. The paneling representation of the aircraft with the tangentially mounted stores is shown in Fig. 12.

Forces and moment comparisons for the carriage configuration are shown in Fig. 13. Computed results are compared with experimental data for Mach numbers 0.60 and 1.20. The overall correlation is considered good. The effect of adding the stores to the basic aircraft configuration resulted in a very minimal change in lift, drag due to lift, and pitching moment in both the experimental data and the predicted results. The drag due to lift discrepancies are due to the lack of properly accounting for the leading-edge thrust as previously discussed in Sec. II. Comparisons for the off-body flowfield pressures at $M = 0.6$ and 1.2 are shown in Fig. 14. Computed pressure coefficients are compared with experimental data along a line at a constant y and z location beneath the carriage combination. Comparisons at an additional 10 locations are presented in Ref. 8. Overall correlation is considered quite good considering the complexity of the configuration.

Weapon Separation Analysis

The separation analysis consisted of calculating the forces and moments on the store in several locations in the vicinity of the carriage aircraft. This analysis included the mutual interference effects of aircraft on weapons, weapons on aircraft, etc. A typical paneling of the aircraft with one store still attached and the other store in flight is shown in Fig. 15. Note that the exact spacial relationships between the weapon and the carriage aircraft can be simulated, including the weapon being at a different angle of attack from the aircraft. The total number of panels including wakes and body closure panels to represent this combination was 571.

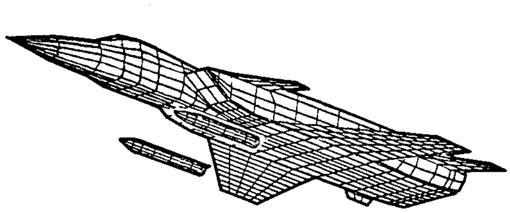

Fig. 15 Store separation paneling.

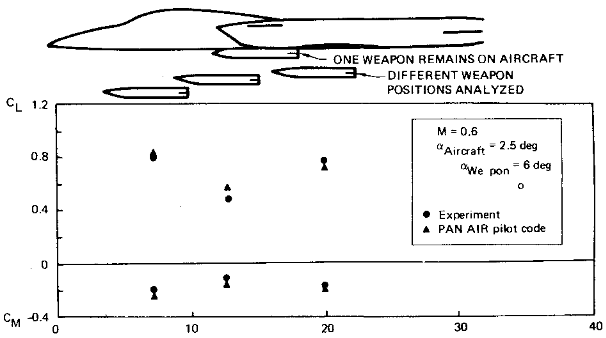

Fig. 16 Generic store separated from aircraft, $M = 0.6$.

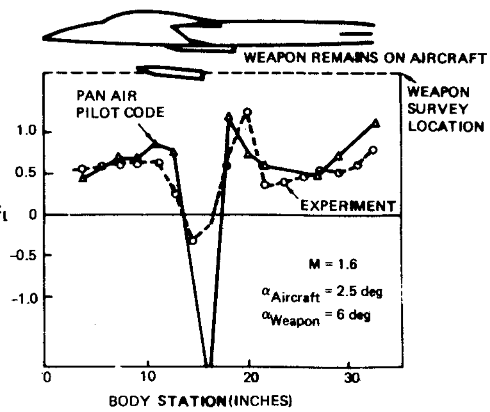

Fig. 17 Lift on separated store, $M = 1.6$.

In the PAN AIR pilot code, for each store position analyzed, influence coefficients for the complete aircraft store combination had to be recalculated. In the PAN AIR production code only those coefficients which change will have to be recalculated each time the store position is changed. This will result in a large savings of computer resources when analyzing a series of positions. Using the summer 1979 version of the pilot code, the CPU time for a single analysis at one Mach number was approximately 700 s on a CDC CYBER 175 computer.

Separated store and moment comparisons for three centerline locations are presented in Fig. 16. The computed results and experimental test data are for 0.60 Mach number with the store at 6 deg angle of attack and the aircraft at 2.5 deg angle of attack. The store locations are illustrated in the figure. Excellent correlation is seen between the computed results and the test data.

The supersonic case, $M = 1.6$, proved to be much more difficult than the subsonic case. The computed and experimental off-body flowfield pressures had indicated the presence of a large compression emanating from the region of the inlet. Figure 17 shows the experimental store lift coefficient variation as a function of axial position at a fixed height below the aircraft. Also presented are calculated results. The weapon pitching moment which affect the pitch motion of the store as it separates from the aircraft are shown

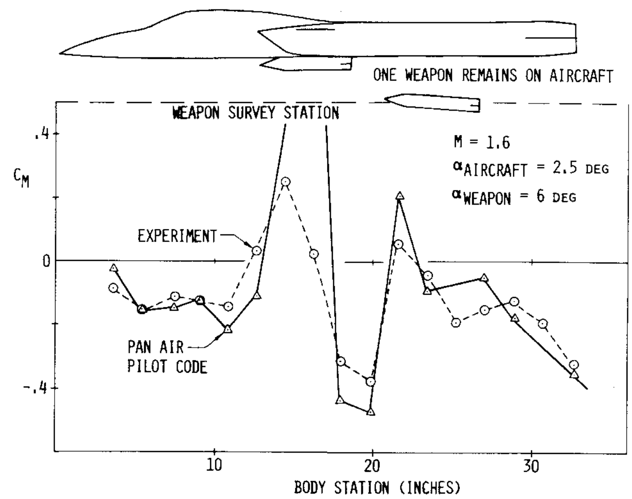

Fig. 18 Pitching moment on separated store, $M = 1.6$.

in Fig. 18. It is quite evident from these comparisons that, while the computed results do not match the measured data in the highly nonlinear region, the theoretical results do reflect the proper characteristics. The real flowfield in this region must be very complex with strong disturbances which are not very amenable to linear theory analysis. Built-in program diagnostics indicated the computed results not to be reliable in this region.

V. Conclusions

The application of the PAN AIR pilot code to the analysis of weapons, carriage, and mutual interference effects during separation has demonstrated some of the capabilities of this method. In this type of analysis, the capability of simulating detailed and complete geometric shapes was an absolute requirement. The individual aircraft and weapon configurations were generally complex and nonslender in shape. The study involved making comparisons with experimental force and moment data on the carriage aircraft, a generic store configuration, and the weapon in the presence of the aircraft at various positions. Also, comparisons were made with experimental flowfield data at various locations beneath the aircraft. Both subsonic and supersonic cases were considered.

The PAN AIR pilot code demonstrated unique capability and versatility in analyzing the complex vehicle/weapon combinations. The capability and versatility of the method to model the complex geometries involved is well illustrated by the fidelity with which the panelings used in the analysis represented the actual configurations (compare Fig. 4 with Fig. 1). No equivalent body or other extreme geometric simplifications were required. However, simplifications such as the "thin wing" approximation were used when deemed reasonable and cost effective.

The PAN AIR pilot code was able to correctly predict forces and moments on the carriage vehicle with and without externally mounted stores as illustrated in Figs. 6 and 13. Forces and moments on the generic store were equally well predicted. Flowfield characteristics, including regions of large gradients associated with strong disturbances, were successfully predicted. For subsonic and low supersonic Mach numbers, where nonlinear effects were small, the pilot code gave excellent correlation with experimental data. At the higher supersonic Mach numbers, results indicated that some correction was necessary to account for curved Mach line and local Mach number propagation effects. A successful but simple correction for these effects was illustrated in Fig. 8.

The PAN AIR technology was also successful in predicting forces and moments on separated weapons in the presence of the carriage aircraft. For the subsonic Mach number, correlation with experimental data was excellent. At the supersonic Mach number analyzed, the correlation with experimental data was good, considering the highly nonlinear response of the store to axial position beneath the aircraft. In a trajectory analysis, where a large matrix of points has to be considered, local discrepancies in C_L and C_M would be expected to have only marginal impact on the final results.

The results of this and other studies[5,6] have shown the PAN AIR technology as demonstrated by the PAN AIR pilot code to be a powerful analysis method. This method has capabilities, unmatched by other methods, for analysis at both supersonic and subsonic speeds of complex weapons, carriage, and separation cases as well as other general aircraft cases.

Acknowledgments

This paper is based upon work conducted under U.S. Air Force Contract F33615-79-C-3016 and also upon work conducted for the Boeing Independent Research and Development Program.

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