Influence Function Method Applications to Tow Target Trajectory Predictions

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Although tow targets have been flown for many years, until recently no method existed to predict analytically the target's trajectory separation characteristics. Conventional store separation techniques could not be applied because the cable tension force, which dominates the trajectory, was not accounted for. The influence function method (IFM), an innovative engineering approach for estimating store aerodynamic separation characteristics, has been adapted to the problem of towed targets by adding the effects of cable tension to the IFM determining forces and moments in calculating the target's trajectory.

Nomenclature

A_i = normal-force influence coefficient
B_i = pitching-moment influence coefficient
BL = aircraft Y coordinate, positive outboard, ft
C_n = yawing-moment coefficient
C_m = pitching-moment coefficient
C_N = normal-force coefficient
C_Y = side-force coefficient
WL = aircraft Z coordinate, positive down, ft
X,Z = Cartesian coordinates, positive forward and down, ft
α = angle of attack, deg
α_i = local angle of attack, deg
β = sideslip angle, deg
ϵ = downwash, deg
σ = sidewash, deg

Introduction

PREVIOUS methods for assessing the separation trajectory characteristics of stores from military aircraft were dependent on wind-tunnel simulations. These techniques required a large volume of test data to clear a store for safe separation throughout the entire release envelope. Clearly, considering the cost of wind-tunnel testing, computational techniques were desirable.

The influence function method (IFM) was based on the concept that the store's response to a nonuniform flowfield was determined by a set of "influence coefficients," which relate the store loads to the angle-of-attack distribution along the store. It differed from other flow-angularity techniques[1-3] by the development of a rational procedure to evaluate the influences of the various store segments on the total forces and moments. This process, known as store "calibration," requires that both total store forces and moments and the local angle-of-attack distribution be known for several axial store positions along a longitudinal traverse. Originally, this calibration was accomplished experimentally by traversing a store through a two-dimensional shock wave created by a wedge[4] or through the known flowfield created by an ogive-cylinder body.[5] It has since been shown that at subsonic and supersonic speeds these calibrations can be theoretically performed[6,7] and that calibrations are relatively independent of Mach number for low-aspect-ratio stores.[8] It has also been demonstrated that theoretical calibrations are practical at transonic speeds using a semiempirical calibration technique[9] to determine the influence coefficients, which is referred to as the (interference distributed loads) IDL/IFM code.

The IFM is used to predict store force and moment data at carriage and in a grid under an aircraft for which the flowfield is known or has been calculated. These forces and moments are then input into a six-degree-of-freedom trajectory program to predict the separation behavior of the store. In the case of towed targets, the trajectory program has been modified to account for the effects of tow cable tension on the subsequent target behavior.

This modified IFM technique has been applied to determine the launch trajectory of a towed target designated the TDU-34/A, used extensively in Navy aircraft training operations. Prior launch and retrieval operations from F-4 and A-6E aircraft were uneventful until a modification to the baseline target was added consisting of a 16-in. body extension and an increased internal systems weight. The modified target, designated TDU-34/A/A, hit the A-6E aircraft during its initial launch. Investigation of the trajectory characteristics of the modified target was thus the basis of the present work.

Technical Approach

Three calibration processes have been developed for the IFM. One was by traversing the store through the shock wave generated by a wedge (Fig. 1); the second was by traversing the store through the flowfield generated by a calibrator body (Fig. 2); and the third was by direct application of the IDL/IFM code. The first two calibrations could be done either theoretically or experimentally, whereas the last is theoretical. It has been shown that all three techniques give essentially the same store influence coefficients.[8,9]

None of the previously developed calibration techniques could be used for high-aspect-ratio nonaxisymmetric stores. Supersonic calibrations were used for low-aspect-ratio stores at subsonic Mach numbers by selecting the supersonic Mach number to match the subsonic lift curve slope. This is impractical for a high-aspect-ratio store. Although PAN AIR calibrations were successful for low-aspect-ratio nonaxisymmetric stores, the flowfield produced by the calibrator body would vary in the spanwise direction, whereas the IFM technique assumes that each store segment sees only one local angle.

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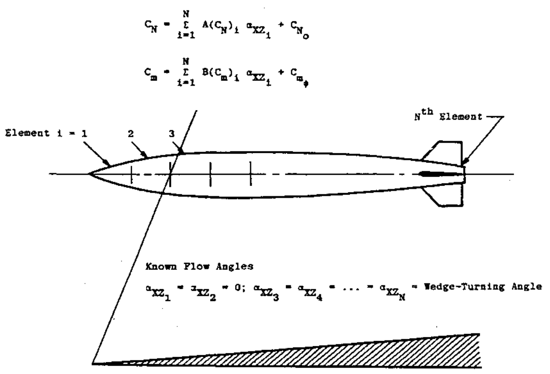

Fig. 1 Supersonic calibration.

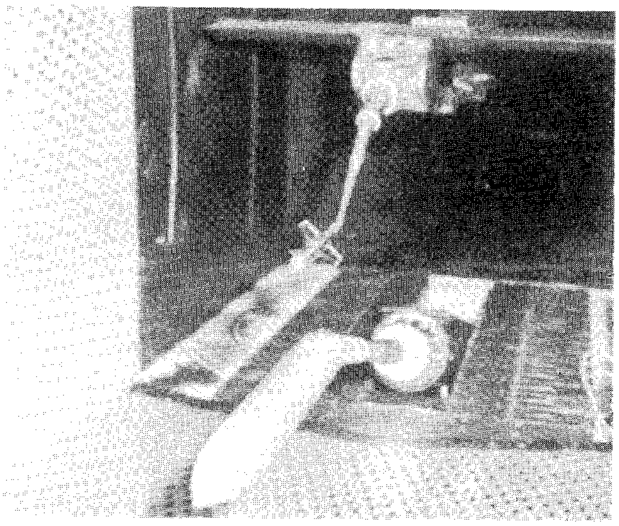

Fig. 2 Subsonic calibration.

For these reasons, a new approach, termed onset flow calibration, was developed.[10] This approach uses the concepts developed for the IDL/IFM code. An angularity discontinuity is developed by use of the onset flow capability of the PAN AIR program. The store is then passed through this discontinuity. This approach is analogous to supersonic calibrations at subsonic Mach numbers. The advantage of using the PAN AIR program is that stores of any geometry can be calibrated.

For this study, the onset flow calibration flowfield was generated by specifying sufficient mass flow, via defined boundary conditions applied on a planar plate, to provide a vertical angularity of 6–7 deg, which produced an angularity change of 5 deg at the target traverse location (Fig. 3). Although the angularity at the leading and trailing edges of the plate had a large change in strength, the flowfield at the store traverse location underwent a gradual change. Furthermore, the angularity change in the y direction was relatively minor, which meant that the flowfield was invariant in the spanwise direction for the TDU-34A traverse.

The TDU-34A tow target was also calibrated using the IDL/IFM code. Both the PAN AIR and IDL/IFM calibrations were used with measured A-6E flowfield data to predict loads on the TDU-34A. Since the influence coefficients generated by the two methods produced similar force and moment predictions for the nonuniform A-6E flowfield present at the TDU-34/A release position (Fig. 4), subsequent calibrations were generated by the IDL/IFM code, which is considerably easier to use and cheaper to run.

Flowfield Determination

The next step in the IFM process requires a determination of the aircraft flowfield at the store position. Since insufficient A-6E flight trajectory data needed for method validation were available, flight tests were carried out on the F-4 aircraft, which uses a centerline launch. Because test data for the F-4 aircraft flowfield at $M = 0.4$ were not available, the flowfield of the aircraft and reeling mechanism was estimated by the flowfield of the reeling mechanism and saddle (Fig. 5a). The reeling mechanism is attached to the aircraft pylon as shown in Fig. 5b. At target launch, the saddle travels approximately 2 ft down before target release. Since the target is launched from

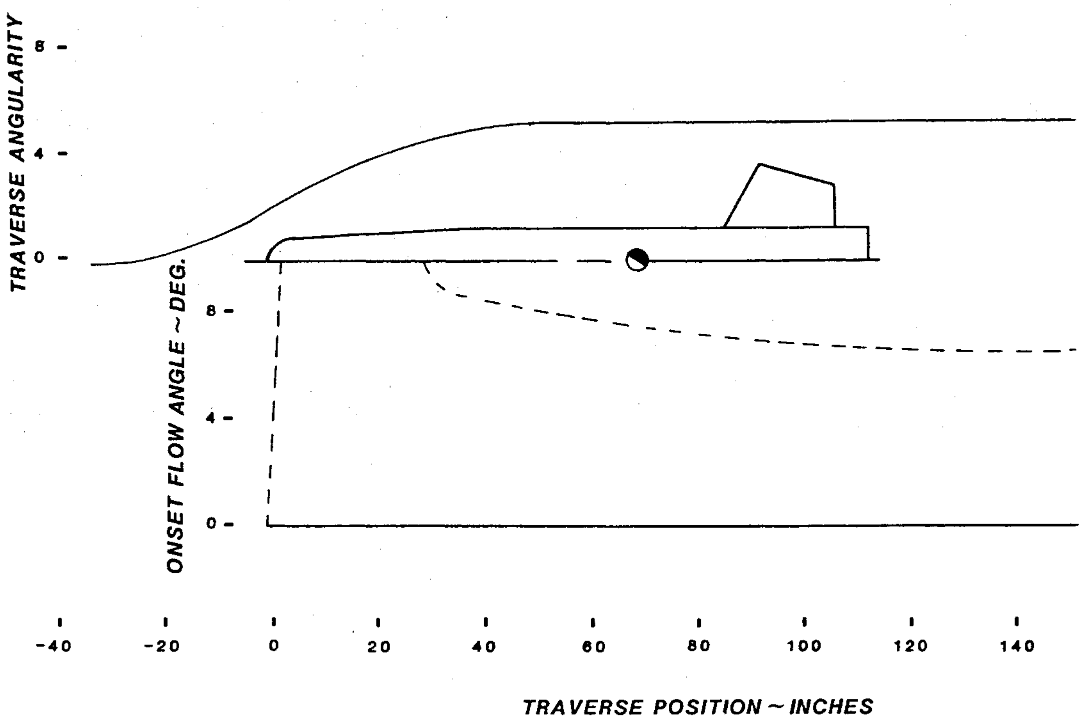

Fig. 3 Onset flow calibration.

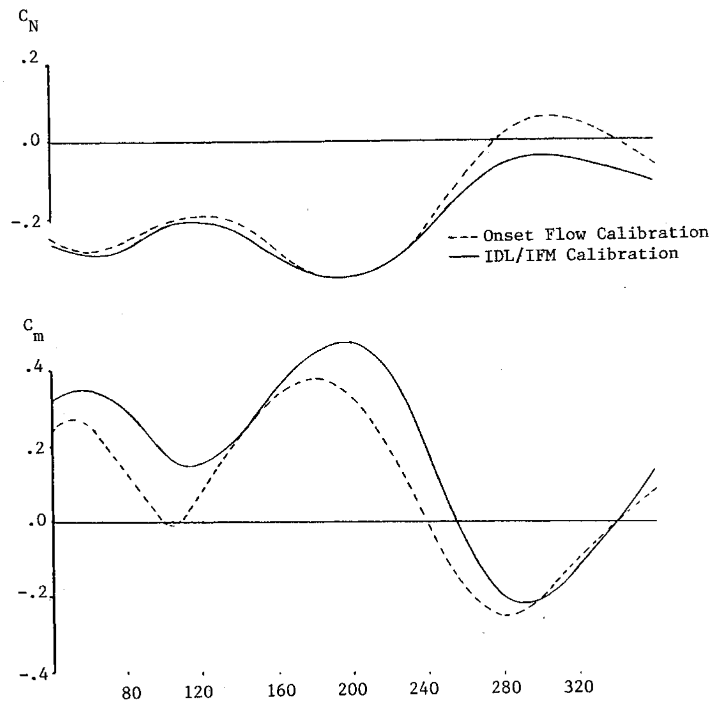

Fig. 4 TDU-34/A aerodynamic loads.

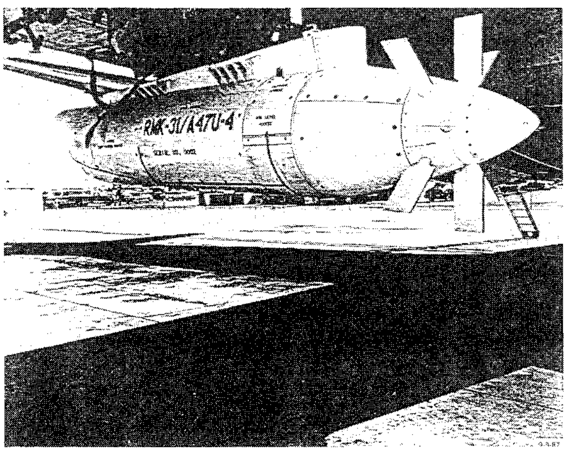

Fig. 5a Reeling mechanism and TDU-34/A with saddle.

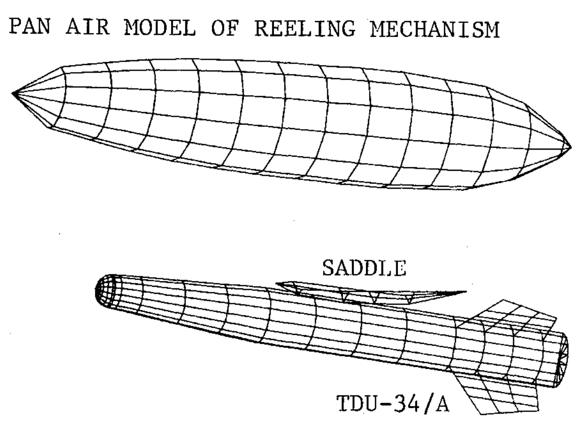

Fig. 5b Reeling mechanism attached to pylon.

the aircraft centerline, which is flat, and considering that the reeling mechanism and saddle produce a flowfield effect twice that due to the wing at the A-6E launch position, the effect of the F-4 flowfield on the target should be minimal.

The flowfield at the target launch position relative to the F-4 aircraft is shown in Fig. 6. The reeling mechanism starts at 190 in., and the saddle begins at 219 in. Note that the saddle mechanism dominates the flowfield and has to be accounted for in the force and moment calculations.

Trajectory Program

The six-degree-of-freedom trajectory program, which was incorporated into the IFM technology, enables theoretical analysis of the separation of externally carried stores from an in-flight aircraft. By applying the total six-degree-of-freedom equations, the store motion in the aircraft flowfield can be determined. The store trajectory must be calculated in an inertial reference system. Euler integration is used to update the store position as a function of time. The trajectory is referenced to the instantaneous aircraft axis system at a point in time at which the relative displacement of the store to the aircraft can be determined (usually carriage). Final results are presented as relative trajectories when referenced to the instantaneous aircraft axis system.

Five sets of data are required as inputs to the program. These are the aircraft initial conditions, store freestream aerodynamics, ejector time history, store carriage loads, and incremental store loads in a grid under the aircraft. The IFM technique was developed to provide the last two sets of data.

The six-degree-of-freedom program had to be modified to account for the effects of tow cable tension on the trajectory. The assumption made was that the tow cable effectively is a straight line connecting the target to the aircraft attachment point. This formulation was chosen because, for short cable lengths, this not only is a reasonable representation of the actual behavior of the system but also would lend itself to straightforward verification in a wind-tunnel test. It is anticipated that a wind-tunnel test could easily measure the effect of cable tension on the trajectory by modeling the cable tension as a force vector acting at an angle through the target center of gravity. The angle at which the cable force acts can be estimated by measuring the relative x, y, and z displacement of the target relative to the aircraft attachment point.

The six-degree-of-freedom program was modified by defining three new parameters XT and ZT, X and Z distance, in inches, from the target cable attachment point to the target c.g., positive forward and down, respectively, and TOW, the tow

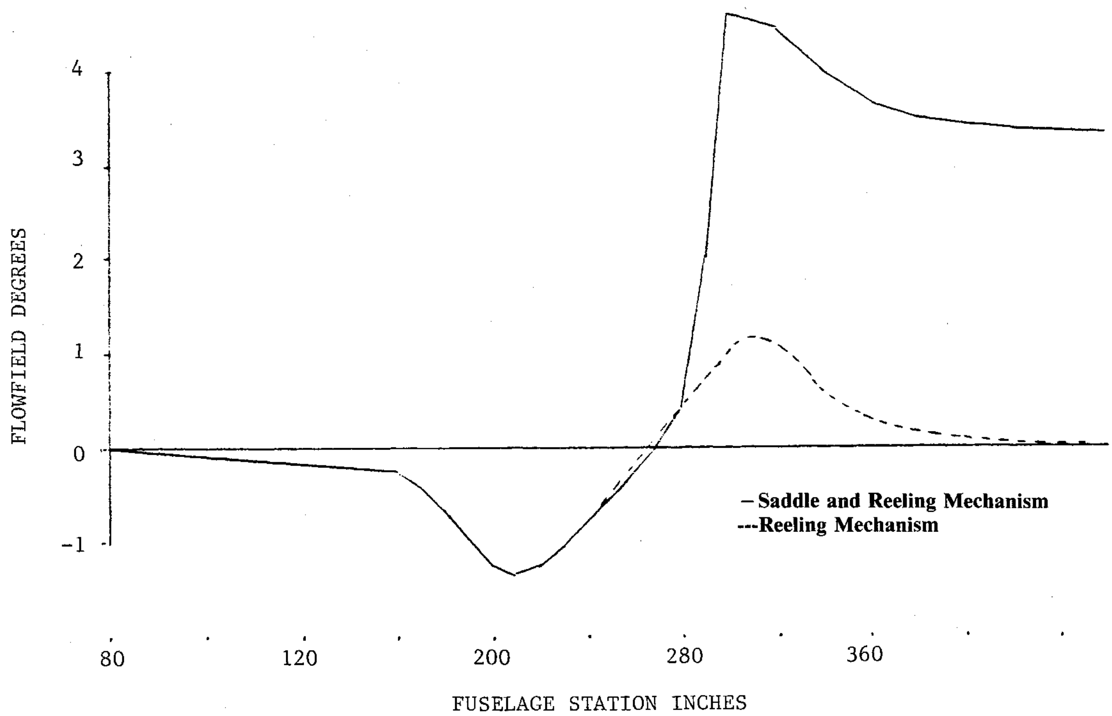

Fig. 6 Launcher flowfield.

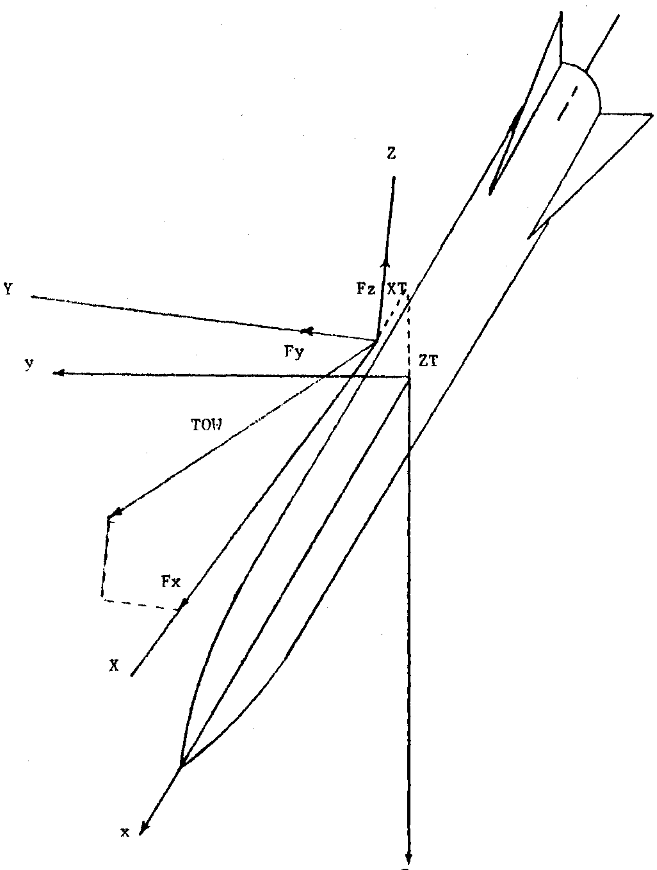

Fig. 7 Axes definition.

cable tension force in pounds. The tow cable tension force was the resolved into the aircraft axis system by use of the following relationships (Fig. 7):

$$Fx = -(X_{\rm rel})/l^*({\rm TOW})$$
$$Fy = -(Y_{\rm rel})/l^*({\rm TOW})$$
$$Fz = -(Z_{\rm rel})/l^*({\rm TOW})$$

where l is the cable length. These forces were then transferred into the store-body axis system using the Euler transformations.[8] The cable-induced moments were then calculated as

$$M = Fx'^*ZT - FZ'^*XT$$
$$N = Fy'^*XT$$
$$L = Fz'^*ZT$$

where Fx', Fy', and Fz' are the cable forces in the store-body axis system. For a more detailed description of the trajectory program, see Ref. 8.

The tension force due to the cable was compared to the aerodynamic forces and weight acting on the target. If the cable tension exceeds the vector sum of the other forces acting along the cable (i.e., tends to pull the target toward the aircraft), the resulting force in the cable direction is set to zero (indicating a slack cable). The target is not prevented from flying back toward the aircraft on its own accord.

Results

As previously mentioned, flight-test data, consisting of cable tension time histories and motion pictures of the corresponding trajectories, were obtained for the TDU-34/A/A tow target, which consists of the baseline TDU-34A configuration with a 16.6 -in. extension (Fig. 8), separating from the F-4 aircraft at $M = 0.42$, 0.45, and 0.48. The freestream aerodynamic characteristics for this extended body target were unchanged from the basic configuration (Fig. 9), but since it unexpectedly hit the A-6E aircraft during its first launch and because the $M = 0.42$ data for the F-4 exhibited the largest pitch variation, these were selected for further analysis.

Two separate launches were available at the same flight Mach number and initial conditions. The TDU-34/A/A aerodynamic forces at launch were predicted using the IDL code for the influence coefficients and the flowfield shown in Fig. 6. As can be seen in Fig. 10, the flowfield produces a large, nose-down pitching moment at the launch condition. Also shown in Fig. 10 are the PAN AIR predicted forces at launch. The trajectory was initiated about 0.3 s after the separation from the saddle, since that appeared, in the films, to be the time required for the cable attachment bolt to clear the saddle release mechanism. At that time the tow target was 4 deg nose-

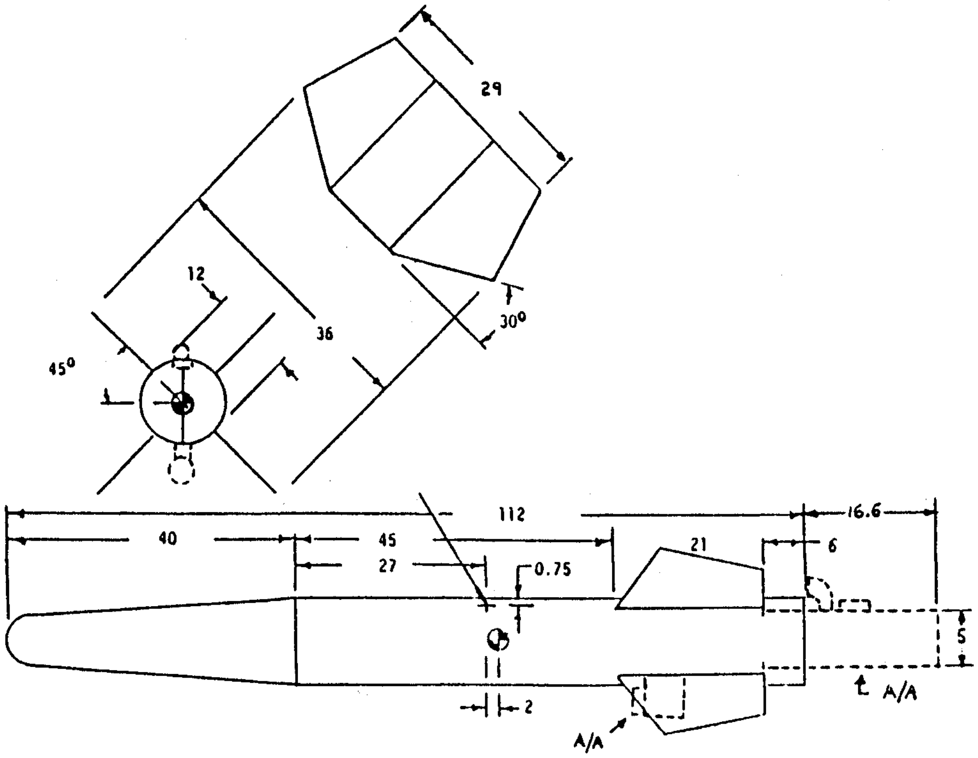

Fig. 8 TDU-34/A and TDU-34/A/A targets.

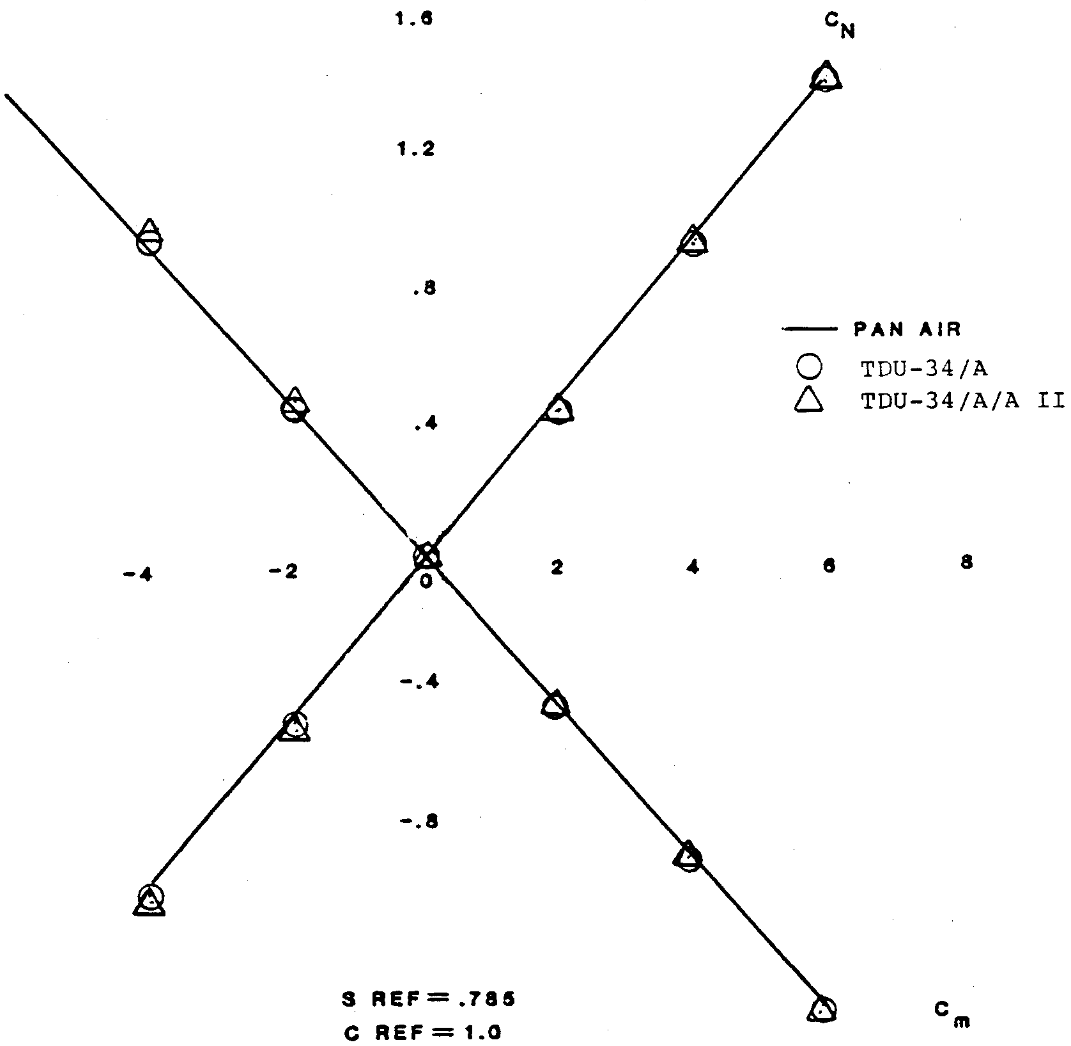

Fig. 9 TDU-34 freestream aerodynamics.

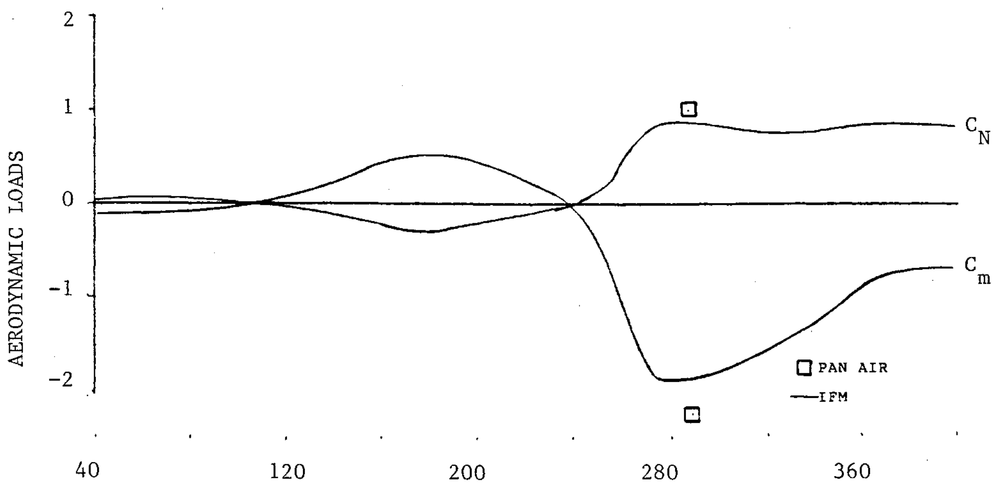

Fig. 10 TDU-34/A/A carriage loads.

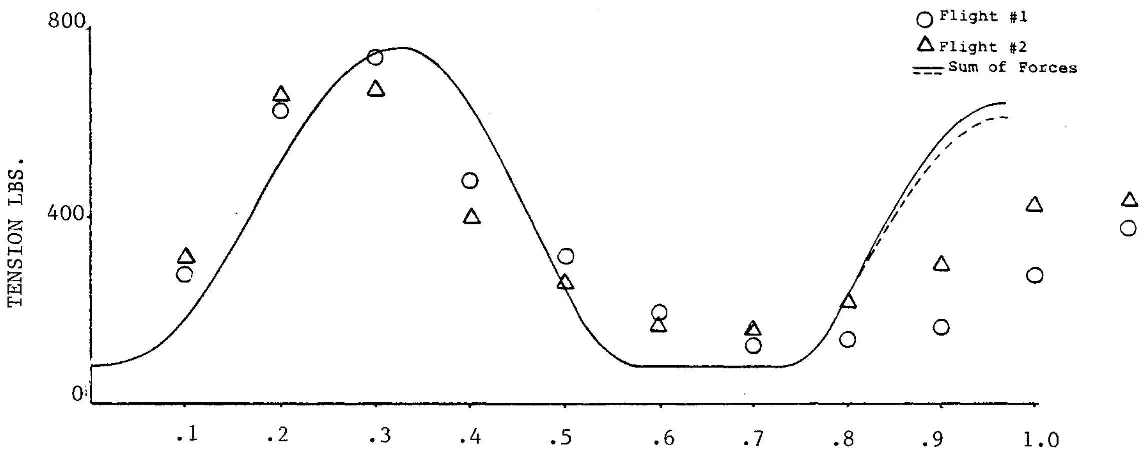

Fig. 11 Cable tension.

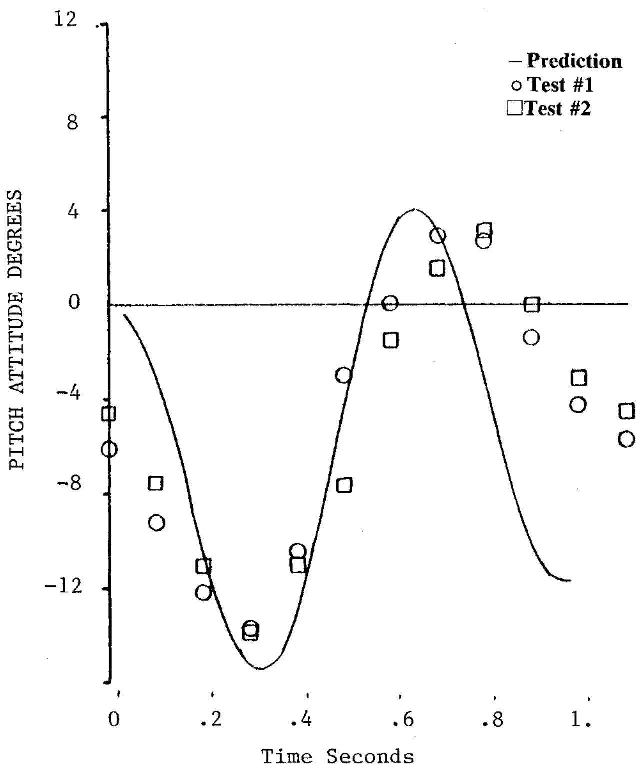

Fig. 12 Pitch attitude.

down relative to its initial condition or 6 deg nose-down relative to the aircraft fuselage reference line, with an ejection velocity of 3 ft/s downward.

The cable tension time history for these two launches is shown in Fig. 11. Also shown in Fig. 11 is a plot of the vector sum of the other forces that the six-degree-of-freedom program predicts act on the target. Since these forces are the cause of the tension in the cable, they should correspond to the actual cable tension. Although the magnitude of the forces is in reasonably good agreement with the flight-test data, the frequency of the predicted response appears to be about 0.2 s greater than that of the flight tests. A possible explanation of this discrepancy is that the target not only pitches about its tow point but also swings at the end of the cable. This would tend to lengthen the frequency of the target's response. Note that both the flight-test data and prediction indicate that the minimum tension occurs between 0.55 and 0.75 s. That means that the target tends to fly up toward the aircraft and represents the critical condition for this launch.

The pitch oscillations are shown in Fig. 12. Considering the uncertainty in the initial conditions and that the pitch angle could be estimated only to ± 2 deg from the movies, the predictions are in remarkably good agreement with the test data. As for the tension time history, the frequency of the oscillations is about 0.2 s faster that that indicated by the flight-test data. However, this makes the prediction more conservative, since the predicted maximum pitch angle occurs sooner (and therefore when the target is closer to the aircraft).

The vertical displacement of the target is shown in Fig. 13. The prediction was initiated with a vertical velocity of 2.5 ft/s

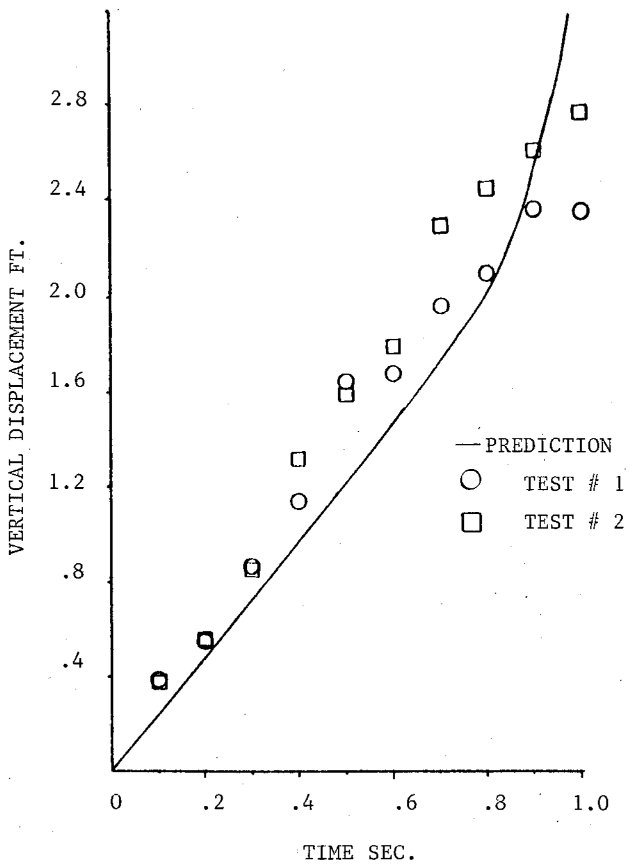

Fig. 13 Displacement.

to match the cable velocity at the release point. The prediction departs considerably from the test data after 1 s. The reason can be attributed to the fact that the target reeling mechanism restricts the maximum acceleration to 1.2 ft/s, which corresponds to about 6 lb in cable tension. Obviously, the only way to match the displacement would be to constrain the acceleration in the six-degree-of-freedom program and calculate the tension force required. This feature, as well as the ability to solve the rotational equations of motion at the cable attachment point, has been incorporated in a new[11] version of the program.

Although the tow target trajectory program shows promise, for proper validation a wind-tunnel test is required that will allow control of all of the factors affecting the trajectory. The test is planned for November 1988.

Conclusions

The IFM has previously demonstrated the ability to predict accurately store grid loads, store carriage loads, aircraft flowfields, and store trajectories at subsonic, transonic, and supersonic speeds. The method has now been shown to be applicable to towed targets.

The trajectory prediction program has been modified to account for the effects of tow cable tension. Comparisons with flight-test data indicate that the code can be a useful tool for evaluating target trajectories. Other comparisons, particularly with dedicated wind-tunnel test data, are needed for proper evaluation and demonstration.

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