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Wind-Tunnel Test Techniques for Unmanned Aerial Vehicle Separation Investigations

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Wind-tunnel tests of an unmanned aerial vehicle (UAV) separating from two fighter aircraft have been conducted. UAVs present different concerns in separation testing than do conventional stores due to the presence of large lifting surfaces, physical size, and control surface effects. The planning and results of these recent investigations give several new results with respect to the separation testing of complex configurations. Separation trajectory simulations using experimental data have been used to demonstrate the unique requirements of UAV separation testing. The simulation demonstrates that simplifications in the aerodynamic grid proximity testing matrix can be made without sacrificing simulation accuracy. Results indicate that simplification in ejector modeling used with simple stores should not be applied to UAVs. The simulations also indicated that it is important to properly model the aircraft control surface effects on the UAV.

Nomenclature

M_∞ = freestream Mach number
X, Y, Z = store longitudinal, lateral, and vertical displacements in the aircraft axis system (aligned with the aircraft longitudinal axis, origin is at the store center of gravity); positive forward, right and down, ft
X_P, Y_P, Z_P = store longitudinal, lateral, and vertical displacements in the pylon axis system (aligned with the store longitudinal axis, origin is at the store center of gravity); positive forward, right and down, ft
α = aircraft angle of attack, deg
Θ = store pitch angle, positive nose up as seen by the pilot, deg
Φ = store roll angle, positive clockwise rotation looking upstream, deg
Ψ = store yaw angle, positive nose right as seen by the pilot, deg

Introduction

RECENT events have validated the need for an unmanned aerial vehicle (UAV) to fill the reconnaissance mission. The capability of this vehicle is greatly expanded by enabling air launch from a manned aircraft. This significantly increases the effective range of the UAV, while not subjecting the releasing aircraft to hostilities. However, for successful air launch certification, it is necessary to demonstrate that the UAV be able to separate safely from the carriage aircraft. This is complicated by the fact that, in general, UAVs have several inherent characteristics that make separation a larger concern than for other stores that are normally separated from aircraft (bombs, missiles, pods). Due to complex interaction between the aircraft and the UAV, an accurate assessment of the separation characteristics is essential.

To initiate this process, existing analytical techniques may be applied early in the flight certification process.[1] This will help diagnose major problems and allow for intelligent planning for subsequent ground testing. However, it is vital that comprehensive ground testing and analysis take place prior to the flight test. Lacking this, it has been demonstrated that unexpected results may occur during the flight test.[2] Ground test techniques that use wind tunnels to examine traditional store separation characteristics are well established and accepted. However, UAVs present possible complexities that should be addressed when developing a wind-tunnel test plan.

Recently, two wind-tunnel tests have been conducted on an unmanned air vehicle separating from two different fighter aircraft. Each test was run at a different test facility using slightly different approaches. It is the intent of this article to analyze the results of these tests and give insight into proper techniques for testing and subsequent analysis of UAV separation from aircraft.

Background

The UAV in this study is the BQM-145 medium range UAV. The BQM-145 is a jet powered UAV in the 2000-lb class, it is approximately 18 ft long, and has a 10.5-ft wingspan. Longitudinal control is accomplished by elevons on the horizontal tail. The BQM-145 will be both air and ground launched. Air launch is desired from both a carrier-based F/A-18 and a land-based F-16. Figures 1 and 2 show the carriage configuration of the BQM-145 on the F/A-18 and the F-16, respectively.

Two geometrically similar models of the BQM-145 were constructed to match the scale of the releasing aircraft. For the F/A-18 test the model was 6%, and for the F-16 test the model was 6.67%. For purposes of this article, the 6% test will be referred to as test A, and the 6.67% test will be referred

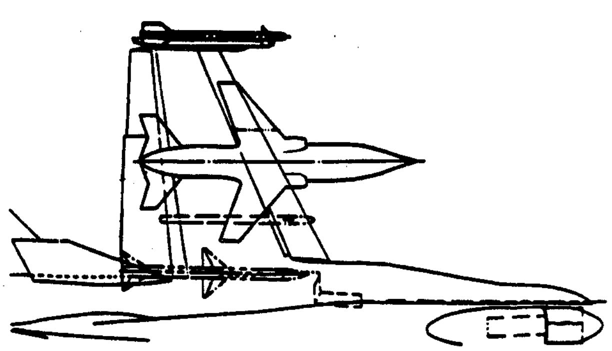

Fig. 1 Test A configuration.

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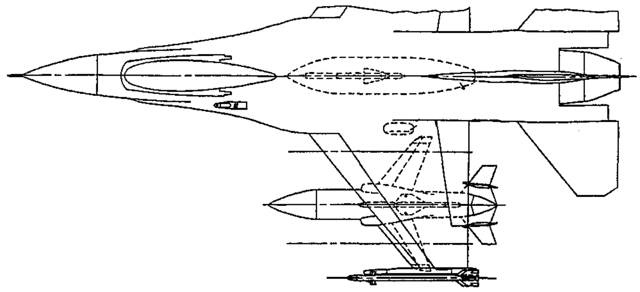

Fig. 2 Test B configuration.

to as test B. Test A was conducted in the Calspan Corporation 8 Foot Transonic Wind Tunnel, Buffalo, NY.[3] Test B was conducted in the Arnold Engineering Development Center (AEDC) 4 Foot Transonic Wind Tunnel (4T), Arnold AFB, TN.[4]

The objectives of these wind-tunnel tests were to obtain data necessary to make a preliminary assessment concerning the separation of the UAV from these aircraft. Both tests obtained UAV freestream aerodynamics for use as a baseline and to correct for scale effects. Each facility also has a dual sting capability, referred to as a captive trajectory system (CTS), that was used to obtain separation trajectory data online in the wind tunnel. Also, each test obtained aerodynamic grid data for the UAV in proximity to the aircraft for use in subsequent off-line trajectory analysis. Test A also obtained UAV loads at carriage via an instrumented pylon mounted store for use in off-line analysis.

Discussion

UAV separations present situations not necessarily encountered during traditional store separation analyses. In the cases analyzed here, the UAV wing, which is significant with respect to the aircraft wing, is in close proximity to the parent wing. Also, the UAV is situated with one wing forward of the parent wing leading edge, and one wing behind it. As such, it causes an asymmetrical lift distribution that is likely to induce a large roll response upon release. Additionally, the empennage of the UAV is situated such that a deflection of the parent wing trailing edge will change the loading on the UAV.

The situations listed above have given rise to some important observations concerning test techniques that should be applied to such an investigation. In particular, this study has addressed four areas of interest and their effect on UAV trajectories. The first is the manner in which an aerodynamic grid matrix is best structured. The second is the effect of store motion during the ejector stroke. The third is the effect of using pylon-mounted store loads on the trajectory. The last is the importance of matching the proper control surface deflection effect with the releasing aircraft angle of attack.

Grid Matrix Structure

Traditional store separation testing for simple stores generally involves the acquisition of aerodynamic grid data in proximity to the releasing aircraft. In order to accurately describe the aerodynamics of the store, data must be obtained covering the full range of store positions and attitudes. However, since these grid coefficients are a function of six independent variables, taking all possible combinations of the independent variables into account creates an extremely large test matrix.

For simple stores (i.e., gravity bombs and slender missiles), it is well accepted that simplifying assumptions can be made concerning the impact of the variation of one variable on another. In such cases, the effects of varying one variable are tested while holding the others at a constant, nominal value. These individual decoupled effects are then assumed to be linearly additive in order to fully describe the store aerodynamics at a particular position and orientation in the aircraft flowfield. Such an approach could reduce a matrix consisting of 5 values of yaw, pitch, and roll angles from 125 to 13 runs per traverse location.

When developing the test matrices for the UAV separation tests described above, it was not known if this decoupling technique would give accurate results for complex stores such as a UAV. Test A, due to the large number of configurations that had to be investigated, was conducted using a decoupled grid matrix. However, test B was conducted using a full grid matrix, which consisted of all possible combinations of three nominal values for the angular orientations (yaw, pitch, and roll), which results in 27 runs per traverse location. Therefore, a subset of the data obtained in test B is equivalent to a decoupled grid matrix. More specifically, this decoupled matrix consists of a grid traverse with all angles at the nominal zero position along with two traverses for each angular variable, where the angle is varied plus/minus about its zero point while holding the other two angles at zero. This gives 7 runs per traverse instead of the 27 runs needed for the full grid.

The full grid and the subset representing the decoupled grid were used individually as inputs to an aerodynamic grid-based six degree-of-freedom, off-line trajectory simulation code. This code uses the grid data in a delta coefficient sense to describe the flowfield effect on the store.[5] The delta coefficient represents the aircraft flowfield influence on an otherwise undisturbed store. The simulation combines the delta coefficient with the store freestream aerodynamics to fully describe the store loads. The intent was to determine if the decoupled grid provides an adequate representation of the flowfield when compared to the full grid.

First, the full grid results were compared to on-line trajectory data to validate the off-line trajectory code. Figure 3 indicates that the trajectory code accurately duplicated the on-line data when using the full grid database. The full vs decoupled grid comparisons were made for three different flight conditions representing different regions of the jettison envelope. Figures 4–6 indicate that the decoupled grid gives an adequate representation of the resulting trajectories. The slight discrepancy in roll is likely due to the roll angle response

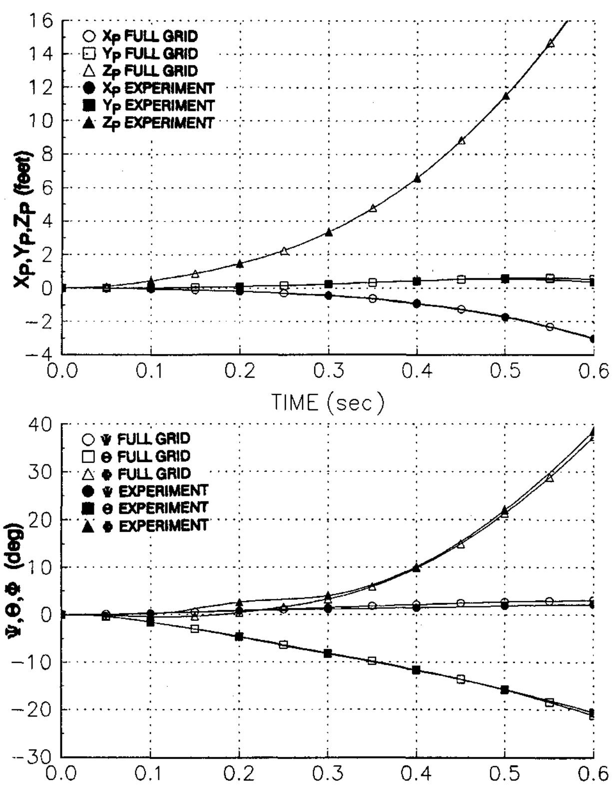

Fig. 3 Comparison to experimental data (M = 0.65, α = 2.3).

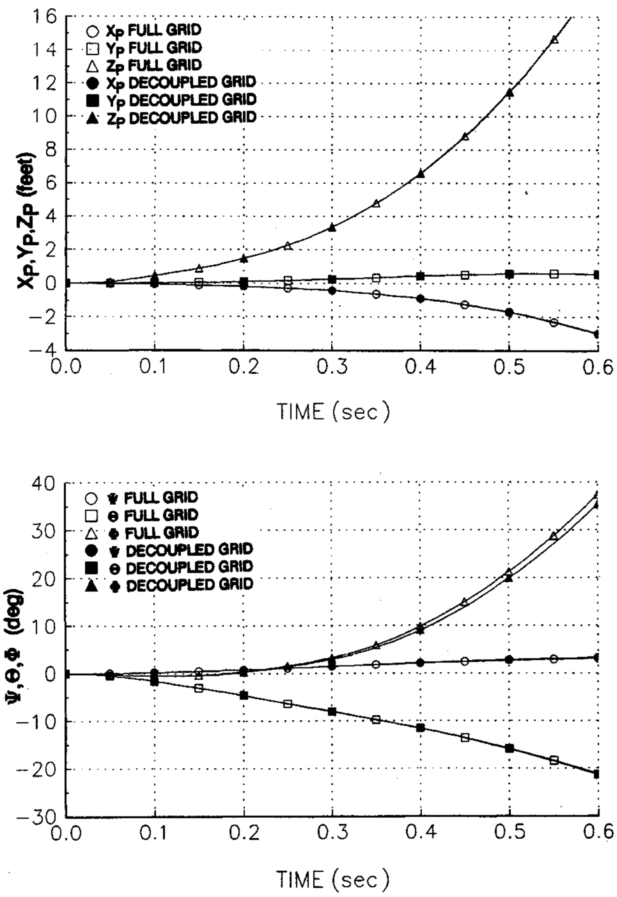

Fig. 4 Full/decoupled grid comparison (M = 0.65, α = 2.3).

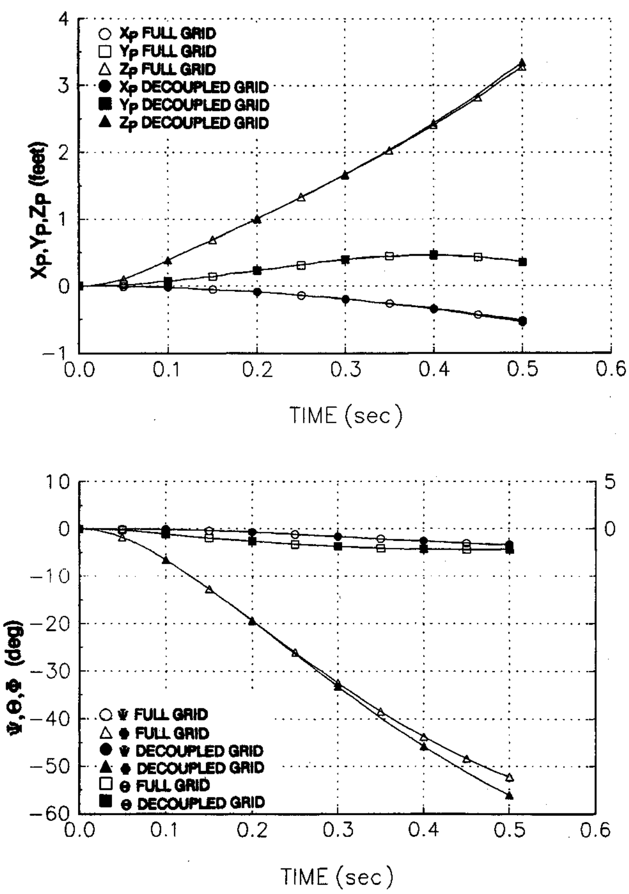

Fig. 5 Full/decoupled grid comparison (M = 0.53, α = 10.0).

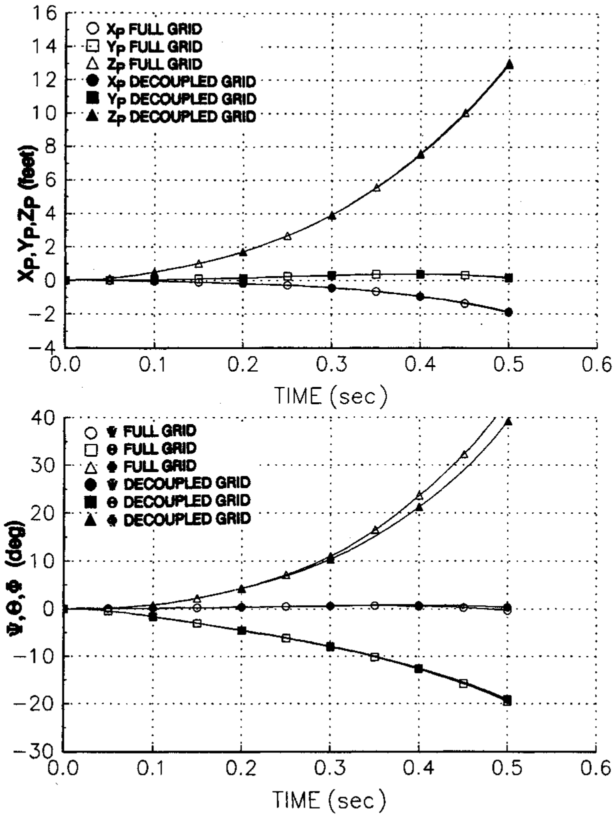

Fig. 6 Full/decoupled grid comparison (M = 0.80, α = 2.1).

exceeding the plus/minus bounds of the roll angle in the grid matrix. These results indicate that a decoupled grid is adequate when structuring an aerodynamic grid matrix for UAVs. Such an approach reduced the required grid data by 74%. This savings can then be used to test more configurations or increase the number of nominal values of each independent variable which would likely increase the accuracy of posttest simulations.

The simplifying assumption of using only a decoupled grid may be taken one step further. In this case, the matrix would consist of only pitch variations, holding yaw and roll angles at zero. As shown in Fig. 7, this also gives good correlation for some regions. However, the potential for errors using this technique are not consistent with the added savings in test time and is not recommended unless no other option for testing exists.

Store Motion During Ejector Stroke

There exist two primary ways of initiating a trajectory simulation on-line in the wind tunnel. The first is to initiate the trajectory as close to carriage as possible and mathematically model the ejector force history vs time or displacement, allowing full store motion during the ejector stroke. The second is to initiate the trajectory at the end of stroke, using predetermined store states (positions and rates) at this point as initial conditions for the on-line trajectory software. Often, when using the second approach, in order to simplify the determination of the store states, the store is translated vertically to the end of stroke location without regard for other store motion during the ejector stroke. The initial conditions may also be simplified by ignoring store rates other than vertical velocity.

While these simplifying assumptions may be valid for simple stores, it was not expected to hold for UAVs, where significant motion may occur while the ejector is acting on the store, after release from the carriage sway brackets. Test A used the end of stroke approach to initiate the on-line trajectories. However, in order to determine the store motion during the stroke, grid data obtained early in the test was

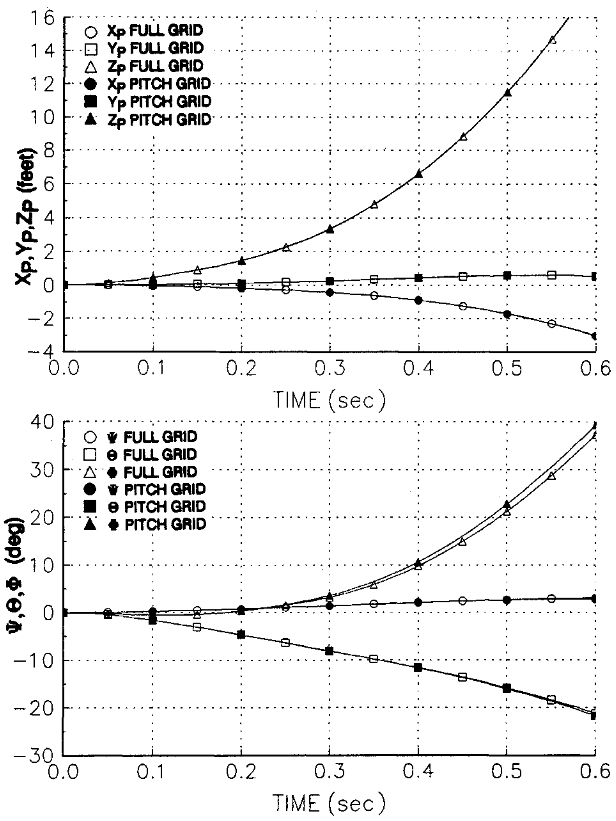

Fig. 7 Full/pitch grid comparison (M = 0.65, α = 2.3).

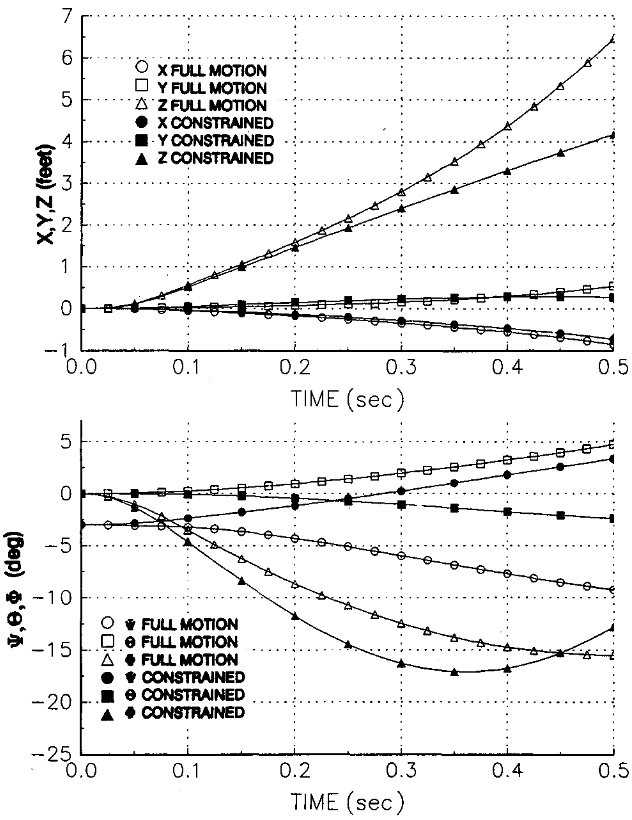

Fig. 8 Effect of ejection motion constraint (M = 0.6, α = 3.1).

used in a six degree-of-freedom simulation that included an ejector force history. The end of stroke positions, orientations, and rates, in all axes, were then used as inputs to the on-line trajectory software as initial conditions.

Using the grid data, a post-test simulation was conducted to determine the importance of this extra effort. A simulation was run in which full motion was allowed in all six DOF. This was compared to a simulation where the store motion was limited to motion in the vertical direction (holding the other five DOF fixed) during the ejector stroke with full motion thereafter. Figure 8 shows this comparison for M_∞ = 0.6, α = 3.1, and emphasizes the need to take store motion into account when using an end of stroke approach. In the restricted motion simulation, all actual store rates were used at the end of stroke. The comparison would have been further degraded if only the vertical velocity was used as is sometimes the case. Of course, modeling the ejector time history in the on-line trajectory software eliminates this problem, but this may introduce errors since the store cannot be positioned at the true carriage position by the dual sting hardware.

Pylon Mounted Loads

Traditionally, wind-tunnel trajectory simulations are initiated using the store loads at the closest location obtainable by the dual sting hardware as the initial loads rather than actual store carriage loads on the pylon. Recent testing has shown that there can be significant differences, up to a factor of three, between the loads at this closest position and the actual carriage loads.[6] These differences may be aft mounted sting effects or sudden jumps in mutual interference and may cause large changes in the resulting trajectory. The carriage load data from Test A showed an expected rise in loads between the closest position and carriage loads, with no "unusual" behavior that would indicate hardware interference.

Using the grid data from Test A, simulations were performed using the loads from the closest dual sting position and carriage loads obtained using a pylon balance, as initial conditions for the trajectories. Figure 9 is a schematic of the pylon balance installation. When using the carriage loads, the simulation linearly interpolates between the carriage loads and grid loads until the first grid point is reached. Figure 10 shows the resulting comparison between these two simulations. The comparison indicates some changes in the magnitude of the trajectory response, although the trends are accurately duplicated. The discrepancies are not as great as those seen in other studies where the carriage and grid loads differed to a larger degree. In general, the large discrepancies have been noted at transonic Mach numbers for stores that are small with respect to the sting. In contrast, the UAV is larger with respect to the sting and is separating at lower speeds, which may explain why large discrepancies in loads and vastly different trajectories are not seen.

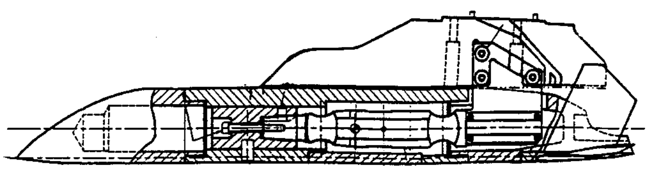

Fig. 9 Diagram of pylon mounted balance.

Flap Schedule Effects

The F/A-18 has a leading- and trailing-edge flap schedule that is dependent upon Mach number and angle of attack. By necessity, grid data acquisition is limited to predetermined angles of attack. In post-test simulation it is important to interpolate to the proper angle of attack being investigated, in order to model the proper flap setting. In the case of UAVs, separating from aircraft with angle of attack-dependent flap schedules, this becomes even more important due to the proximity of UAV empennage to the trailing-edge flap.

Figure 11 depicts the pitch and vertical displacement sensitivity to proper interpolation. The angle of attack of this simulation is 7 deg, however, grid data was taken at 6 deg

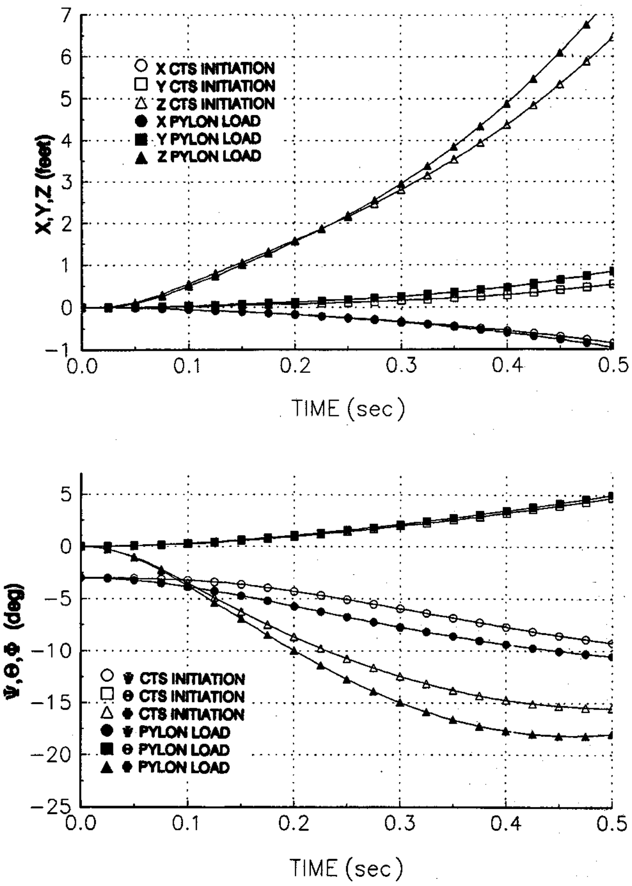

Fig. 10 Effect of pylon mounted carriage loads (M = 0.6, α = 3.1).

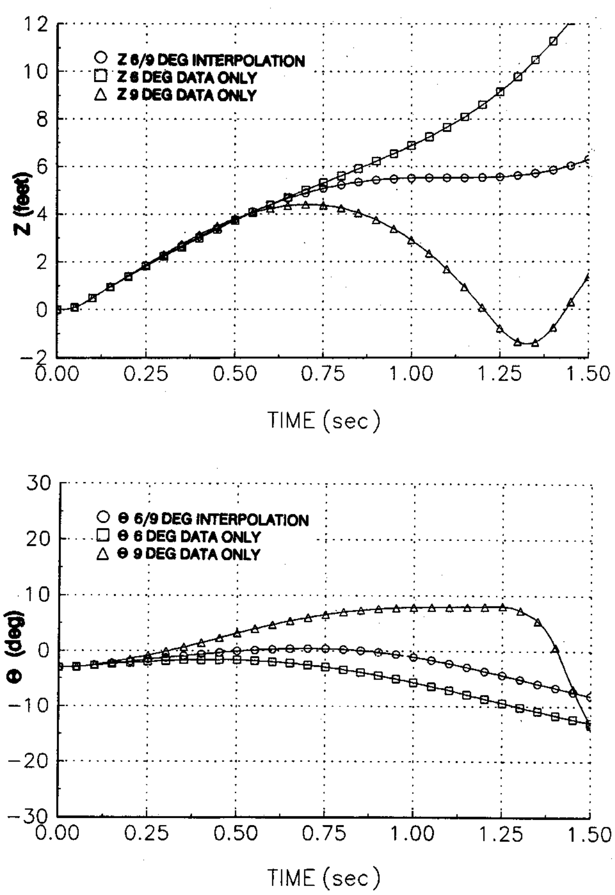

Fig. 11 Combined effect, angle of attack/flaps (M = 0.4, α = 7.0).

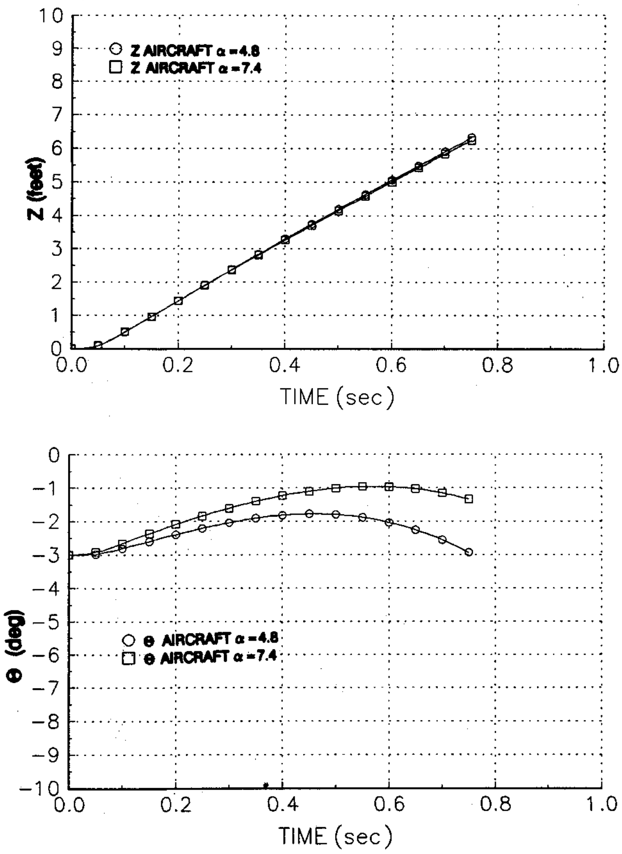

Fig. 12 Isolated effect of angle of attack (M = 0.4).

and 9 deg each, with its corresponding flap setting. If only the 6-deg grid data (with corresponding flap setting) is used the separation appears safe, and if only the 9-deg grid data (and flap setting) is used, the trajectory is certainly unsafe. However, interpolation between the 6- and 9-deg data yields a completely different trajectory, as shown in Fig. 11, which appears to be marginally safe.

This analysis indicates a strong dependence on the separation trajectory to flap setting. In fact, it is not the change in angle of attack that causes the large change shown in Fig. 11, but the accompanying change in flap setting. This is demonstrated by Fig. 12 which compares the pitch angles and vertical displacements of two on-line trajectories at different aircraft angles of attack (7.4 vs 4.8), where the aircraft model had a constant flap setting.[3] There is only a slight difference between these cases, which is not as severe as the difference when the true flap settings are included.

Conclusions

The separation of a UAV from the wing of an aircraft is a complex event that may not be properly modeled by test and analysis techniques used on simply shaped stores. Recently, wind-tunnel tests have been conducted on an unmanned aerial vehicle separating from two different aircraft. These tests have made possible several observations concerning proper test technique and analysis methods that will enhance the accuracy of such investigations.

First, it is not necessary to obtain a grid data base that contains all possible combinations of the nominal store orientations. A decoupled grid does not appear to sacrifice accuracy, but saves considerable test time allowing expanded test configurations or larger matrix boundaries.

Second, if it is necessary to use end of stroke conditions to initiate on-line trajectories, the motion of the store during the ejector stroke must be taken into account. This can be accomplished by using grid data obtained earlier in the test, if available. If this is not an option, a simple decay of carriage loads over the stroke length should give a good representation of store motion and rates. The store positions, orientations, and rates are then input as initial conditions to the on-line software.

Third, it was shown that the difference between UAV loads at the closest dual sting position and UAV pylon mounted loads caused some changes in the resulting trajectory. Although this difference was not as severe as seen in other store programs, carriage loads data should be measured during testing for maximum accuracy in post-test analysis.

Lastly, it was shown that when the releasing aircraft has an angle-of-attack dependent flap schedule, the actual flap setting for the angle of attack being investigated must be modeled. While it is not practical to obtain grid or tunnel trajectories for every possible flap position, it is possible for grid-based simulation codes to interpolate to the proper angle-of-attack/flap setting.

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