JOURNAL OF AIRCRAFT
Vol. 32, No. 6, November–December 1995

Computational Estimate of the Separation Effect

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The trajectory simulations, run by aircraft fire control computers, do not consider ejection forces and flowfield effects after the release of a store from an aircraft. The separation effect is an initial–conditions–perturbation vector used to compensate for these effects, by adding it to the initial conditions of three-degree-of-freedom stores trajectories, computed by the ballistics algorithm of the fire control computers. This article presents a method of separation effect computation that utilizes simulated six-degree-of-freedom trajectories instead of the conventional method that involves a large number of drop tests. The input to the simulations consists of aerodynamic data, based on wind-tunnel experiments and the ejection-forces time history. The ejection forces acting on the store are evaluated by a semiempirical method that takes into account, among others, the aircraft wing elasticity. The separation effect is evaluated by fitting emulated fire control computers trajectories to simulated six-degree-of-freedom trajectories. Comparison of separation effect calculated by the present method, to that based on drop tests, shows that the drop tests can be replaced by simulations. The analysis of the separation effect dependence on various parameters indicates that inclusion of the release altitude in the polynomial representation of the separation effect provides a significant improvement in the store delivery accuracy.

Nomenclature

F = ejection force, kg
H = altitude at release, m
M = Mach number at release
n = aircraft load factor at release, g
T = time after release initiation, s
V = velocity increment due to separation effect, m/s
Z = ejector piston movement, cm
γ = flight-path angle, deg

Subscripts
ej = ejector
exp = experimental
sx = in direction of aircraft velocity
sz = perpendicular to sx (downward)

Introduction

MODERN-AIRCRAFT fire control computers, when in the air-to-ground mode and before the store is released, perform predictions of both the aircraft trajectory and the three-degree-of-freedom ballistic-trajectory simulations of the store. During every computational cycle (0.02–0.25 s), the fire control computer runs such a simulation, and therefore, the simulation algorithm must be as simple as possible.

A store is represented in the air-to-ground module as a point-mass located at its c.g. The only forces acting on the store are the drag force (represented usually as a polynomial in Mach number) and gravity. The atmosphere model uses measured, in-flight data.

The actual dynamics of a store from the captive phase to the free-flight phase is much more complicated than that modeled in fire control computers, due to the fact that forces and moments act along all three axes of the store.[1] Among these forces and moments the most significant is the ejection force applied on the store during approximately the first 0.1 s of its trajectory, to ensure safe separation from the parent aircraft. Additionally, during the first stage of the store trajectory, forces and moments are generated on the store by the flowfield induced by the proximity of the aircraft. These forces are in addition to the aerodynamic forces acting on the store during the free-flight stage, and depend on the position and attitude of the store relative to the aircraft. Finally, during the free-flight stage, small, but not negligible angles of attack and sideslip angles are developed. These angles induce aerodynamic loads on the store, which alter its ballistic trajectory. To compensate for the effects of the previously mentioned phenomena, which are not simulated by the ballistic algorithm in the fire control computer, an increment to the store initial-condition vector is computed. In most airplanes it is implemented by the addition to the three-degree-of-freedom model of the delay time T_{ej} and normal ejection velocity V_{ej}. These two parameters depend only on the combination of aircraft, store, and ejection unit types. In modern airplanes such as the F-16, an additional velocity-vector increment is defined in the aircraft velocity axes. This vector is dependent also on the release conditions. It is usually represented as a polynomial in Mach number and normal acceleration and is called the separation effect polynomial.

As an illustration to the role the separation effect plays in matching three-degree-of-freedom trajectories to six-degree-

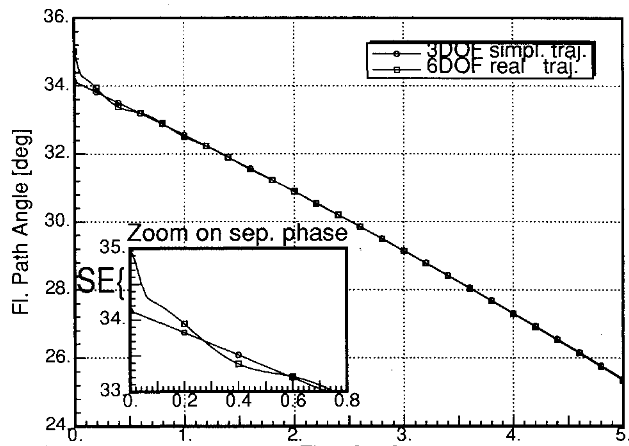

Fig. 1 Six-degree-of-freedom and simplified three-degree-of-freedom dynamics during the first 5 s after release.

Received Nov. 7, 1994; presented as Paper 95-0061 at the AIAA 33rd Aerospace Sciences Meeting, Reno, NV, Jan. 9–12, 1995; revision received May 24, 1995; accepted for publication May 24, 1995.

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of-freedom trajectories, a comparison of a simplified three-degree-of-freedom trajectory adjusted by the separation effect, and the true six-degree-of-freedom trajectory of a store, during the first 5 s after release is shown in Fig 1. As expected, the trajectories differ mainly immediately after release, where the real six-degree-of-freedom trajectory is strongly influenced by the proximity of the aircraft.

Separation Effect Evaluation Methods

The usual method for separation effect evaluation relies on a large number of drop tests.[2] The store flight trajectories are evaluated from the drop test results out of cine-theodolites and/or radar data. The separation effect components at specific points in the release envelope are evaluated by emulating the fire control computer store trajectories. In these emulations the miss distance from the target obtained in the drop tests is annulled by changing the store initial conditions. The initial velocity increment thus evaluated is a value of the separation effect at the tested point. After repeating this procedure in the whole release envelope, the previous separation effect values are used to evaluate the separation effect polynomial coefficients. This process is expensive and time consuming.

Goldberg et al.[3] present a method based on captive trajectory system (CTS) wind-tunnel tests (replacing drop tests) to compute the separation effect. For each point to be checked in the store release envelope, a CTS wind-tunnel test is conducted instead of a drop test, thus, reducing the overall cost. Massengill[4] presents a further cost reduction method in which six-degree-of-freedom simulations replace the drop tests. The input data to the simulations are based on just a few wind-tunnel tests.

This article presents an expansion of the previous method. This is achieved by incorporating a good evaluation of the ejection force impulse and a reliable evaluation of the aerodynamic loads in the vicinity of the parent aircraft, utilizing a series of wind-tunnel tests performed by various methods. A user-selected part of a six-degree-of-freedom trajectory is matched to the same part of the fire control computers emulated trajectory (including separation effect), thus taking into account both the range and altitude data.

Description of the Method

The present method is based on a limited number of wind-tunnel tests. Accurate measurement of aerodynamic loads induced on the store by the flowfield around the parent aircraft is essential to the method. The wind-tunnel tests cover all three phases of the store trajectory. The first phase is the captive one that is covered by captive model tests, providing very accurate captive aerodynamic loads on the store. Aerodynamic loads are measured on the store model at different Mach numbers and aircraft angles of attack. In this test method the strain-gauge balance is fixed to the aircraft model. The store model is mounted on the balance. The second phase, the near-aircraft phase, is covered by grid tests on the store model in the vicinity of the aircraft model. In this test method, the store, mounted on a sting-balance, scans the near-aircraft flowfield. These tests provide the dependence of the aerodynamic loads acting on the store, on its position, and orientation relative to the aircraft. The third is free-flight. Wind-tunnel tests are carried out on the isolated store model to obtain free-flight aerodynamic loads at different Mach numbers. In this test method, the store, mounted on a sting-balance, scans different angles of attack or Mach numbers. The second phase overlaps the first and third stages, so that cross-checking of the experimental results may be carried out. Results from the first two types of wind-tunnel tests are usually available from the aircraft store separation analysis, whereas the free-flight tests results are usually available from the store aerodynamics development phase.

The wind-tunnel results and other aerodynamic data computed with the aid of semiempirical or computational fluid dynamics methods, together with the aircraft and store inertial data, constitute the input to the six-degree-of-freedom simulation. In addition to this, the time history of the ejection force, acting on the store, is evaluated. Accurate estimation of the ejection forces and the total impulse acting on the store during the separation phase from the parent aircraft is essential in the separation effect evaluation. It is achieved by taking into account the aircraft wing elasticity and the aircraft load factor at release. Harmatz[5] presents a semiempirical method to model the time history of the ejection-force function. This method uses experimental ejection-force data from a very stiff foundation at load factor 1 g, which usually is supplied by the ejection unit manufacturer. The ejection unit semiempirical model, that evaluates a real ejection force curve and its impulse, uses the following expression:

$$F = F_{\text{exp}}(Z) + \left(\frac{\partial F}{\partial t}\right)_{\text{exp}}(Z) \times [t - t_{\text{exp}}(Z)]$$

The experimental data required include the following:

F_{exp} = experimental ejection force vs Z on the store from a stiff foundation
t_{exp} = inverse function of $Z(t_{\text{exp}})$ obtained from the same experiment
$(\partial F/\partial t)_{\text{exp}}$ = partial force derivative at fixed Z obtained from several experiments from a stiff foundation with different store masses

This model is incorporated in a three-degree-of-freedom simulation of aircraft and store dynamics that also includes a simplified representation of a real, elastic aircraft wing as a single mass on single tension/compression and torsion springs, connected to the aircraft body mass. The wing mass and elasticity parameters are computed from ground tests or using a finite element flutter-analysis model. In such a computation, an input force and moment step function are applied on the wing at the ejection unit position. The wing deflection at $t \to \infty$ obtained from this procedure is used to compute the elasticity parameters, whereas from the second deflection derivative at $t = 0$ the wing inertial parameters (mass and moment of inertia) are computed.

This method was applied to a MAU-12 ejection unit mounted on an F-16 wing at station 4. The results obtained lead to the conclusion that wing elasticity reduces the ejection force impulse by 10% compared with the stiff foundation case and a load factor of 4 g reduces the ejection force impulse by approximately 35% compared to the 1-g flexible case. The combination of the wing elasticity and release at a high load factor results in a 45% loss of ejection-force impulse compared to the 1-g load factor! These results are very significant for the separation effect evaluation method.

The six-degree-of-freedom simulation program Astos-6 computes the flight dynamics of a store released from the parent aircraft, taking into account a real ejection force, the store aerodynamic-model dependence on the relative store-aircraft position during the separation phase, and the free-flight aerodynamic model beyond the separation phase for the rest of the trajectory. These simulations constitute the database for the separation effect evaluation instead of the drop tests carried out in the conventional method.

The separation effect components are evaluated by matching a three-degree-of-freedom fire control computer emulated trajectory to a selected part of six-degree-of-freedom simulated trajectory. The matching is performed by optimization using the Newton–Raphson method with an exact computation of the sensitivity derivatives.[6] This procedure is done in the computer program Optvej. The optimal amount of change in the initial velocity vector is the separation effect at a single point in the release envelope. These separation effect data points are used to evaluate the separation effect polynomial coefficients, by means of a least-mean-square-fitting method.

Results

The separation effect computed by the presented method was compared to that derived from drop tests (the conventional method[2]) on a store released from an F-16 inboard wing station at three different release envelope points. The results are shown in Table 1. As can be seen in the table, there is a very good agreement between separation effect components derived from the two methods in the Z component. The problem in the comparison shown in Table 1 lies in the uncertainty of the wind regime in the field tests. Winds alter the store aerodynamic forces, and therefore, its trajectory. When the separation effect is derived from a drop test in which unknown strong winds act, there exists an inherent undesired wind contribution to the calculated separation effect in the wind direction (in the horizontal plane). The separation effect derived by the same method from a similar test, but with another unknown wind regime, will differ from the former separation effect. Therefore, an undesired contribution due to an uncertainty in wind measurement is included in the separation effect calculated by such a method, and its main influence is expected to appear in the X and Y components of the separation effect.

In the present technique this problem is bypassed. This is the reason for the larger differences between the two methods in the X component compared to the Z component of the separation effect as seen in Table 1. It should be stressed that the atmosphere algorithm in the fire control computer air-to-ground module takes into account the winds that are measured during the flight.

An important result of this study is the presence of a Y (lateral) component of the separation effect that is due to the aerodynamic side forces on the store in the vicinity of the aircraft, and which is not taken into account in the known separation effect expressions. This is why it is not shown in Table 1. The lateral separation effect component reaches values of the same order as X and Z components values, which are significant. Inclusion of a separation effect lateral component in fire control computer algorithms is not trivial, as it is wing dependent, i.e., the lateral separation effect component of a right-wing-mounted store will not have the same sign as that for a left-wing-mounted store.

Parametric Study

The dependence of the separation effect on the following parameters at release will be reviewed: flight-path angle, load factor, Mach number, and altitude. The flight-path angle was found to have a small influence on the separation effect. The dependence of the separation effect on the load factor is shown in Fig. 2. As the load factor increases, the absolute values of the separation effect components decrease, due to the decrease of the ejection force. Figure 3 presents the dependence of the separation effect on Mach number. The absolute values of the separation effect, as well as the separation effect rate of change, increase with Mach number. Figure 4 presents the separation effect dependence on the release altitude. The

Table 1 Comparison between separation effect derived from the conventional and the present method

Experiment	V_{sz},[a] m/s	V_{sz},[b] m/s	V_{sx},[a] m/s	V_{sx},[b] m/s
I	2.4	2.4	2.8	−0.9
II	2.6	1.9	0.1	−0.4
III	1.7	1.7	0.2	−1.0

[a]Experimental. [b]Calculated.

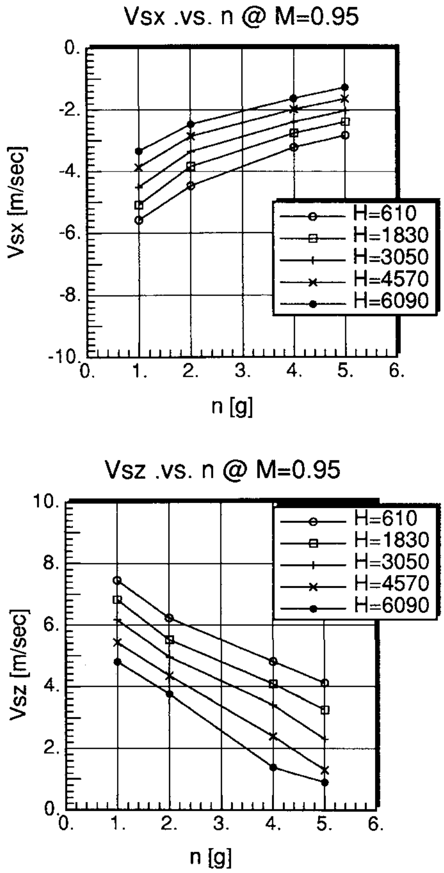

Fig. 2 Separation effect dependence on load factor at release.

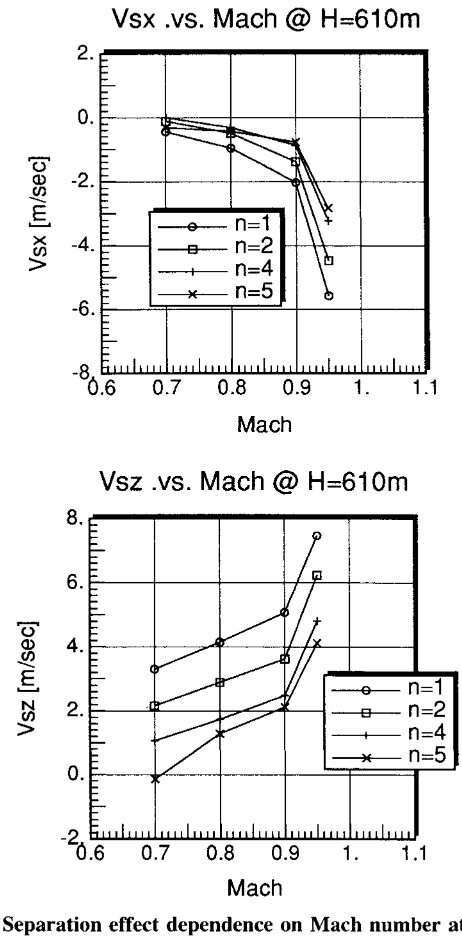

Fig. 3 Separation effect dependence on Mach number at release.

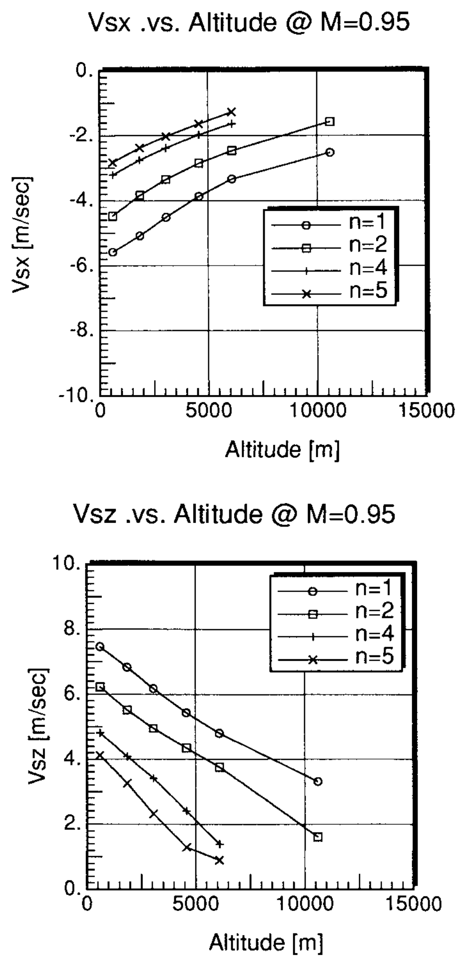

Fig. 4 Separation effect dependence on release altitude.

higher the release altitude, the lower the absolute values of separation effect components, due to the change in dynamic pressure and the consequent change in aerodynamic loads.

Based on the results of this study, the inclusion of the altitude as an additional parameter in the separation effect representation was tested. The test was carried out through simulated level releases in an altitude range of 2000–20,000 ft at $M = 0.95$. The inclusion of the altitude dependence in the separation effect representation decreased the miss distance from the target by up to 170 ft.

Recommendation for an Improved Separation Effect Representation

Trajectories computed with a separation effect polynomial implemented in the air-to-ground modules, show an increase in the accuracy of the trajectory relatively to the trajectories computed with a fixed ejection velocity.[2] The polynomial representing the separation effect in the air-to-ground module of the F-16 fire control computer depends only on Mach number and load factor. The parametric study presented in this article indicates a strong dependency of the separation effect also on the release altitude. The inclusion of the altitude as a parameter in the separation effect polynomial implemented in the air-to-ground module further improves the accuracy of the calculated three-degree-of-freedom trajectory of the fire control computers, as shown previously, and therefore, we recommend the inclusion of this parameter in the programming of the fire control computer.

Conclusions

A method to evaluate the separation effect and the ejection velocity by simulating released stores six-degree-of-freedom trajectories, was presented. The database to the six-degree-of-freedom trajectory simulation is based on wind-tunnel tests. The good agreement of the present results with those based on flight tests indicates that the flight tests can be replaced by simulations. Some of the method's advantages are as follows:

1) Each store usually has an aerodynamic database acquired by wind-tunnel tests. The low number of additional wind-tunnel tests needed to apply the presented method results in a very low-cost separation effect evaluation method.

2) The separation effect calculated by the present method does not contain undesired contributions due to uncertainties in measurement (e.g., wind, aircraft position, and orientation).

3) There is no limit to the number of release-envelope points that can be utilized, thus obtaining a better separation effect evaluation, a better parametric study, and a superior separation effect polynomial.

An important result of the parametric study of the store separation effect presented is the dependency of this effect on the release altitude, which is not taken into account in the current separation effect expressions. Another major outcome of this study is the presence of a Y component of the separation effect, due to the aerodynamic side forces on the store in the vicinity of the aircraft.

Based on the present work, it is recommended that the release altitude be included as a parameter in the polynomial representation of the separation effect and that the Y component of the separation effect be included in the air-to-ground module of the fire control computer.

Acknowledgments

The authors wish to thank A. Studnicki for his contributions to this work and H. Portnoy and E. Gersch for their helpful suggestions.

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