

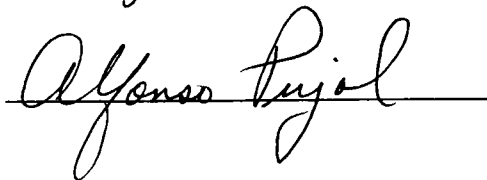
To the Graduate Council:

I am submitting herewith a Thesis written by William Anthony Oefelein entitled "Ordnance Separation Flight Test Matrix Reduction." I have examined the final copy of this Thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.



William Lewis, Major Professor

We have read this thesis and
recommend its acceptance:



Accepted for the Council:



Associate Vice Chancellor and
Dean of The Graduate School

ORDNANCE SEPARATION FLIGHT TEST MATRIX REDUCTION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

William A. Oefelein
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ABSTRACT

This study deals with the methods a program manager may use to reduce the size of an Ordnance Separation Flight Test Matrix. A program manager involved in military flight test and evaluation of ordnance separation projects has various concerns which must be contended with throughout the life-cycle of the program. One of these is minimizing the size of the flight test matrix. This can be done in various programmatic and technical ways. One programmatic solution is the formulation of an integrated test team which uses an integrated approach to the flight test. Another programmatic solution is properly applied risk management, including configuration control and store release restrictions. Accurately modeling the performance of the system is a technical solution to minimizing the size of the flight test matrix, particularly in the EMD phase. By using current flight test performance predictors such as wind tunnel analysis and demonstrations based on analogy, the program manager has shown that one can avoid unnecessary incremental build-up. Computer-based simulations are increasing test team confidence so that critical areas can be identified and appropriate testing can be accomplished. CFD such as SPLITFLOW and using unstructured grids are the most accurate modeling techniques currently available for the ordnance separation modeling problem. Future applications such as virtual prototyping and virtual piloting are giving the program manager new methodologies in his desire to keep cost and schedule demands low. When applied in an integrated manner, they give the program manager a way to safely minimize his flight test matrix, avoiding unnecessary incremental build-up and keeping the overall costs of his program down.

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DISCLAIMER

Any analysis and conclusions drawn from this data are those solely of the author. They do not represent those of the Naval Air Warfare Center-Aircraft Division, the Patuxent River Naval Air Station, or the U.S. Government.

Chapter 1

Introduction

General Background

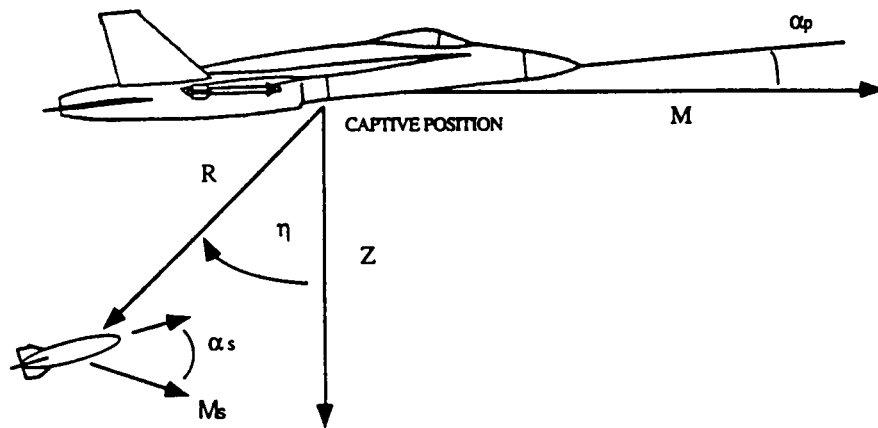
A problem facing all program managers is how to minimize the size of their program while meeting various timelines and performance criteria. In military flight test and evaluation (T&E), the problem is often compounded due to the new technologies being implemented and the safety concerns associated with piloting air vehicles. Further issues must be addressed in Ordnance Separation Flight Test where the test matrices are often long and arduous, utilizing “incremental build-up” and inaccurate models as performance forecasters. The program manager, in this case, is forced to follow a long and costly road to complete the project.

This thesis will cover methods available to the ordnance separation project manager during the attempt to minimize the size of the test matrix in an effort to reduce program cost and schedule demands. Prior to obtaining an understanding of the research objectives, it is necessary to expand on the problem.

Ordnance Separation Flight Test

The separation of an external store (ordnance) from an aircraft is a complex event requiring a detailed knowledge of the influence of the aircraft’s flow field upon the store, the store’s physical and aerodynamic characteristics, the release device used, and the

installation of the store on the aircraft. Several factors must be taken into account when analyzing ordnance separation. Store density, center of gravity, location, and moments of inertia in pitch, roll, and yaw are factors affecting the separation characteristics. Further factors of interest are flight parameters such as airspeed, normal acceleration (g), dynamic pressure, sideslip angle, and angle of attack, as well as aircraft design parameters such as wing/ fuselage geometry, chordwise and spanwise flow, the location of the store, means of store stabilization, and ejector rack design. Figure 1 depicts the aerodynamic forces and moments involved in a generic ordnance separation from a host aircraft.



where α_p = angle of attack of the parent aircraft
 α_s = angle of attack of the store
 M = Mach number of the aircraft
 M_s = Mach number of the store
 R = radial distance from the store to the captive position
 Z = normal forces
 η = grid traverse angle from the vertical

Figure 1

Aerodynamic Forces and Moments on a Store

The process of certifying a store to be safe for release from an air vehicle is difficult, both from an engineering standpoint and a programmatic standpoint. The flight testing associated with ordnance separation must be very detailed to observe the complex aerodynamics and ensure the safety of the test aircrew and of the air vehicle itself. In today's testing world where a program cannot risk the loss of a single test asset, a cautious approach must be made. Particularly hazardous flight test areas must be identified and then approached with caution to ensure the requisite data is collected without harm to the test article or test aircrew. Should any other approach be used which would result in the loss of a test asset or test aircrew, the program would almost certainly face termination. Gone are the days of going straight to the edge of the envelope.

Incremental Build-up

The approach utilized in ordnance separation to cautiously proceed through a flight test program is known as incremental build-up. This approach provides a safe method to develop and proceed through a flight test matrix enroute to some desired endpoint.

As an example, consider a generic weapon to be mounted on an aircraft. It is desired that this weapon have the capability to be released in dive angles up to 60 degrees, load factors up to 6g's, and airspeeds up to 1.2 indicated Mach number (IMN) and 600 knots Calibrated airspeed (KCAS). One cannot simply proceed to these endpoints and perform the test. To do so would be too risky in today's military T&E world. The program manager needs to possess the confidence that the test can be safely conducted. Thus, a cautious approach is employed, starting at some lower airspeed, dive

angle and g level; such as 300 KCAS, 1g, straight and level. After a safe display of release characteristics at this flight condition, one proceeds to another flight test point by adjusting one parameter at a time while holding the others constant to see what effect, if any, this change has on the release. These adjustments would come in predetermined increments such that the test can be carefully observed as singular parameters are altered by a small degree. In this way, one may incrementally build up the safe release envelope to that which is desired. The assembly of these incremental build-up points would then constitute the matrix to be executed in the flight test. As additional external store loading configurations are examined, the matrix must be re-executed to varying degrees for each configuration. Moving a test weapon from one weapon release station to another on the aircraft requires additional testing as well as testing a weapon next to various other existing stores. Each additional store next to which the test article will be employed must be analyzed to some degree. Thus, the Ordnance Separation Flight Test Matrix can rapidly become very large, requiring significant investments in time and money.

Research Objective

The research objective is to investigate alternatives available to the ordnance separation project manager to reduce the size of the test matrix. The study will begin with an overview of ordnance separation flight testing and life cycle analysis (Chapter 2) in order to provide a basic understanding as to the programmatic and technical issues involved with this type of flight test. The reduction of an Ordnance Separation Flight Test Matrix will then be addressed from two standpoints: programmatic solutions and technical solutions.

Two programmatic solutions to ordnance separation flight test matrix reduction will be offered: proper integration of test team members and appropriate risk analysis. These solutions are implemented early in the program and exercised throughout the test life-cycle. It is very important that the program manger, early in the ordnance separation project, understand the necessity to take an “integrated approach” to the test. To this end, the importance of assembling appropriate test team members and conducting the evaluation in an integrated manner will be discussed (Chapter 3). This is followed by ordnance separation flight test risk reduction methods and their applicability to the minimization of cost and schedule requirements (Chapter 4).

The study will then shift focus to that of providing the program manager with solutions to the technical problem of accurately modeling separation characteristics in an attempt to minimize the ordnance separation flight test matrix (Chapter 5). The need for accurate models will be defined and solutions to accurate prediction of separation characteristics in the Engineering, Manufacturing, and Development (EMD) phase of the flight test will be offered. After this, new modeling and flight test research will be discussed for its future applicability to ordnance separation flight test (Chapter 6).

The programmatic and technical solutions will be summarized (Chapter 7) and specific recommendations will be offered (Chapter 8) to the Ordnance Separation program manager so that one may effectively reduce the size of the flight test matrix.

Specific examples of “real world” ordnance separation test programs will be cited as evidence that the ideas presented are valid and that flight test matrix reduction possibilities exist in ordnance separation flight test. Two projects that the author has

managed and executed during his experience as a Naval Test Pilot will be extensively cited. Both of these test projects involve air vehicle/store compatibility during ordnance separation envelope expansion flight test. This is to say these projects examined how a store that was carried, jettisoned, fired, or otherwise released from an existing production air vehicle (an F/A-18 Hornet in this instance) interacted with the aerodynamic flow field of the aircraft at flight conditions never before achieved. These projects are chosen because they illustrate various ideas and considerations when assembling flight test matrices and point to ways to minimize them. The AMRAAM project will be analyzed because it details how one may proceed to envelope endpoints in a test program given an existing production aircraft (the F/A-18 C/D) and an upgraded weapon. The JDAM project will illustrate how even with extensive test planning, performance predictions and an existing aircraft (again the F/A-18C/D), one may still be compelled to exercise incremental build-up to ensure safety when dealing with a new weapon. An overview of these projects follows.

Overview of the Projects

The AMRAAM Project

The AMRAAM project (reference 1) was an upgrade to the existing model of an AMRAAM. This missile upgrade necessitated re-evaluation of the safe separation of the weapon from the F/A-18 C/D aircraft. A test strategy was devised that would minimize the required amount of flight test. This strategy was to forgo classical ordnance build-up, as discussed in the following chapters, and opt for testing at several endpoints within the existing envelope for the older AMRAAM models. This was possible due to the

existence of high-confidence analogous flight test data. An unclassified table of separation test points appears in table 1.

Table 1
AMRAAM Separation Test Points

Flight	Station	Altitude (ft)	Airspeed (KCAS)	Accel (g)	Dive (deg)	IMN ¹	q (lbs/ft ²)	Remarks
1	4	29,000	as req'd	2.5	< 60	0.6	140	Low speed
2	4	24,000	665	1.0	<60	1.55	1200	Super-sonic
3	4	25,000	as req'd	4.0	0	0.55	520	High Angle of Attack
4	4	10,000	500	5.0	0	0.9	780	High g

¹Indicated Mach Number

The separation test points were chosen as worst case and/or envelope outer limits. Once the points were identified by the test team, work was conducted with McDonnell-Douglas (now Boeing) to generate a separation prediction using wing tunnel analysis. After the test flights, post flight analysis was conducted using photogrammetrics and six degree of freedom (6-DOF) data obtained from the actual separation to analyze the separation test and to assess the accuracy of the wind tunnel predictions. The results of these comparisons of flight test data to the modeling data as well as flight test matrix reduction realized will be discussed in Chapter 5.

The JDAM Project

The JDAM project (reference 2) evolved from the desire to field a Global Positioning System (GPS) guided "smart weapon" that would enable precise targeting of

multiple targets by a single aircraft on a single ordnance delivery pass. The JDAM was a GPS-guided free fall weapon which fulfilled this desire. This 2000 lb. weapon was very similar to the MK-84 general purpose bomb. A major difference was that the MK-84 was unguided where the JDAM had the ability to direct itself to a specific target. This required the addition of flight control surfaces which gave the JDAM aerodynamic properties which needed to be evaluated in flight. The JDAM remained very similar to the MK-84 in appearance, so much of the safe separation program was modeled after the MK-84, using incremental build-up as seen in the test matrix presented in figure A-1.

From this matrix, much costly flight test would be required to provide the fleet operator with an employment envelope similar to what was being used for the MK-84. Like the AMRAAM, preflight wind tunnel analysis was accomplished, followed by post flight photogrammetrics and 6-DOF analysis. The results of these comparisons of flight test data to the modeling data as well as the flight test matrix reduction realized will be discussed in Chapter 5.

Limitations to the Scope of the Research

Although several applications of flight test matrix reduction ideas are presented, the study will focus primarily on air vehicle/store compatibility, or store separation flight testing, of new or upgraded weapons from aircraft currently in production. Programmatic solutions will be limited to integrated test team approaches and program risk reduction. Technical solutions will be addressed as related to testing new stores on existing aircraft in the Engineering, Manufacturing, and Development (EMD) phase of product life-cycle. The author will primarily address wind tunnel analysis, some mathematical and

experimental techniques, and performance demonstration based on analogy as performance predictors. The study will be limited to the unclassified details and non-proprietary aspects of the projects discussed.

Chapter 2

Ordnance Separation Testing and Life Cycle Phases

Ordnance Separation Flight Testing

Programmatic Overview

In the normal cost, schedule and performance considerations that face a program manager, there exist several areas of concern when developing a flight test matrix. The design complexity, new or existing technology applied in the system, safety of the pilot and test article, the hazards associated with the test, and the support assets required are a few in a long list of interests. When conducting ordnance separation flight testing, there are several processes which the program manager must follow in order to address areas of concern and proceed with the test. Listed in table 2 are some of the governing processes.

Table 2

Governing Primary Processes for Separation Testing

Plan Test Operations	Schedule Test Operations
Define Test Data Requirements	Resolve Range Scheduling Conflicts
Perform Risk Assessment	Perform Flight Scheduling
Manage Range Safety	Direct Test Operations
Obtain Environmental Approval	Operate Range Equipment
Prepare Range Equipment and Facilities	Perform Range Communication
Obtain Flight Clearance	Conduct Test Operations
Coordinate Instrumentation/Modifications	Acquire and Present Test Data
Execute Instrumentation/Modifications	Perform Data Analysis
Perform Radio Frequency Management	Report Test Results

(Source: Naval Air Warfare Center-Aircraft Division)

In addition to table 2, figure A-2 depicts a typical scenario for testing of a generic air-to-ground weapon with representative costs beginning from the customer's request to the close out of the test. Many processes are required when conducting this type of flight testing. Assuming all other aspects of the test are absorbed into the overall project, figure A-2 shows that the execution of a single test point costs well over \$27,000. With large separation programs involving incremental build-up, it is not uncommon for these test programs to run into the millions of dollars. The program manager has to be keenly aware of any means to cut cost and keep the schedule on its timeline. The ability to remove one test point will result in substantial savings.

In addition, the program manager must use some means to evaluate the process in an attempt to refine it and avoid unnecessary costs and delays. Table 3 depicts some of the metrics used to assess the processes listed above.

Table 3
Governing Process Metrics

Response Time upon Request (Cycle Time)	Planned vs. Actual Test Schedule
Customer Satisfaction	Planned vs. Actual Test Costs
Estimated Cost vs. Actual Cost	Test Crew Satisfaction
Benchmark Cost of Nominal Products	Number of Test Plan Amendments
Test Plan Cycle Time	Quality of Product

(Source: Naval Air Warfare Center-Aircraft Division)

Two solutions to these programmatic concerns will be delineated Chapter 3 and Chapter 4. Chapter 3 will specify the need for the program manager to take an "integrated" approach to the testing. Chapter 4 will detail the risk reduction considerations that must take place when planning for ordnance separation flight test.

Prior to proceeding with these programmatic solutions, it is necessary to summarize the technical problems associated with ordnance safe separation flight test.

Technical Overview

Several technical issues must be addressed by the program manager when conducting ordnance separation flight test. One of the foremost issues is that of accurately predicting the separation characteristics of the test store. The most critical features that determine a store's separation characteristics during an isolated release (singular release of one store) are the carriage moments (reference 4). These moments are principally caused by the aircraft flowfield and vary considerably throughout the flight envelope, particularly the transonic region. Therefore, the first step in an analytic store separation analysis is to estimate the region of the flight test envelope that might have the worst carriage moments by deriving an estimate of the aircraft flowfield (reference 8). These estimates are then used to simulate the store's trajectory. The simulated trajectories are used to help design appropriate wind tunnel tests to ensure the critical regions of the envelope are tested. After completion of wind tunnel tests, data are compared to analytical solutions to search for discrepancies. Sensitivity studies provide regions of the flight envelope where store release problems may be encountered (reference 8). At this point, flight testing may commence.

The amount of flight testing required will be directly dependent on how well these models can predict separation characteristics and how much confidence the test team has in these models. In order to fully realize the benefits of ordnance separation flight test

matrix reduction and where these benefits may be applied, it is necessary to define the life-cycles where the solutions may be implemented.

Life-Cycle Phases of Ordnance Separation Flight Testing

Life-cycle phases of a flight test program may be broken into the four following categories: Concept Exploration (CE), Demonstration and Validation (DEMVAL), Engineering, Manufacturing and Development (EMD), and Production (reference 1). These life cycle phases are well defined when applied to new aircraft designs. However, ordnance separation flight testing life-cycle phases are very dependent on the type of aircraft and type of store to be tested. For this reason, it is necessary to define these phases. This will be done assuming the testing to be accomplished is for new or upgraded stores to be released from existing production aircraft.

Concept Exploration Phase

Given a production aircraft upon which a new store would be tested, the CE phase becomes a paper study of the aircraft/store compatibility. New stores in today's T&E world are designed to meet user (warfighter) operational requirements for a variety of production aircraft. Thus, the store is designed to fit on and be employed from several different aircraft. Common suspension equipment and similar load bearing characteristics among various aircraft usually result in well-defined physical characteristics of new stores. Hence, the CE life-cycle phase is not generally a major concern for the ordnance separation program manager and will not be discussed further.

Demonstration and Validation (DEMVAL)

In the DEMVAL stage, the ordnance separation program manager must demonstrate the fact that a new or significantly upgraded store can be safely carried and released from the host aircraft. This is generally done in response to a contractual agreement to illustrate satisfactory release characteristics prior to proceeding with any envelope expansion flight test. It is accomplished at one or two very benign release points with these test points chosen to avoid areas where adverse store separation characteristics may most-likely occur.

DEMVALs are usually conducted only on those store separation programs that have test stores which are significantly different from existing stores (such as the JDAM). Minor changes to existing weapons typically do not require DEMVAL testing (like the AMRAAM). Thus, stores that require DEMVALs do not have much existing data on separation characteristics. Although data for the aircraft's flowfield exists, it is difficult to accurately model separation characteristics due to the lack of store carriage load data and store/aircraft interference data. Thus, during this life-cycle stage, the program manager is faced with the technical challenge of developing models using computer-based simulations and any other existing data (such as wind tunnel analysis) to assess separation characteristics. As separation data becomes available from DEMVAL releases, the models are further developed and validated, increasing test team confidence in the model. These models are then carried over to the next phase where envelope expansion occurs.

Engineering, Manufacturing and Development (EMD)

EMD is that life-cycle phase where most ordnance safe separation flight testing is accomplished. For this reason, it is the phase that is of the most concern to the program manager. The purpose of this phase is to conduct envelope expansion of new or upgraded weapons with the ultimate goal of arriving at the largest possible flight envelope to release the weapon. The amount of flight testing required depends on several factors including the weapon characteristics, the release envelope desired, and the predicted separation characteristics. If the test store is analogous to other existing stores (only minor changes have been made), then the problem is not very difficult to understand and the test team can proceed with the testing with a high degree of confidence, conducting most of this EMD testing on the basis of analogy. However, if the store is significantly different from any existing store, a condition where test team confidence is low, then a cautious approach utilizing incremental build-up is necessary. The program manager may reduce this incremental build-up to some degree by developing and validating a reliable model of the system.

When using production aircraft, much data is available with regard to the host aircraft flowfield. In addition, the DEMVAL phase may have provided some initial models for store carriage loads and flowfield interaction with a resultant increase in test team confidence based on the data. These models are used in the EMD phase to identify areas of concern for subsequent releases. These areas include such things as investigation of transonic release characteristics and testing next to various other stores. As EMD progresses, the models are refined in an attempt to provide high fidelity store separation

predictions. If high fidelity exists, the program manager may eliminate some of the incremental build-up required in EMD. The problem that is faced is that of obtaining the required modeling performance to allow one to safely do this. To this end, several technical solutions to the ordnance separation EMD modeling problem are discussed in Chapter 5.

Production

Production store separation flight test is any flight test which occurs after store safe separation envelopes have been established. This includes operational evaluation of the store. In the production phase, a large data base has been established with respect to store separation characteristics and accurate models are available which detail store separation. Test team confidence in these models is high. Any flight testing conducted in this phase is a result of minor changes to existing stores and is conducted within the safe separation envelope established in EMD. Therefore, the ordnance separation flight test approach in this phase is typically one based on analogy, as discussed in Chapter 5.

With this basic understanding of ordnance separation flight test and associated life-cycles, it is now possible to expand upon the programmatic and technical solutions to the problem of ordnance separation flight test matrix reduction. The first programmatic solution to be offered is that of the organization of the test team.

Chapter 3

Ordnance Separation Flight Test Team Formation

Introduction

There exist several programmatic approaches that the manager can employ when faced with an ordnance separation flight test. The problem must be approached in a manner that allows safe minimization of flight testing in an effort to save time and money. A “good business practice” that is becoming standard in all flight testing is that of approaching the problem with an integrated test team. Particularly with respect to the period of time in the project life-cycle inclusive of DEMVAL and EMD testing, a properly organized test team will allow concurrent testing and engineering and avoid duplication of test points. Prior to the expansion of this idea, two general structures of test teams will be defined: the “classical” test team and the integrated test team.

Classical Test Team

The classical test team draws its talent from a relatively small pool of available personnel and conducts very specialized testing such as flutter, loads testing, captive carriage, separation, etc. It is typically thought of as a team composed of contractor personnel only or government personnel only with a program manager for each of these discrete phases. The contractors will conduct proof of concept testing and developmental test (DEMVAL) while the government will conduct further developmental test, check for

specification compliance, conduct EMD testing, and then perform operational assessments. This is a very serial process in that one test phase must be completed prior to the completion of the next test phase. Historically, most test teams followed this classical approach.

Integrated Test Team

The integrated test team utilizes a larger pool of talent, drawing personnel from government and industry to work cooperatively. They work closely together under one program manager in order to facilitate communication and resolve problems quickly. The contractor is able to utilize government talent for specialized testing such as carrier suitability, store separation and Operational Assessment, providing the capability to conduct these test early on in the program where design changes are cheaper and easier to implement. The need for specification compliance testing is reduced by incorporating DEMVAL and EMD into a single integrated test matrix, alleviating duplicated test points. The process allows for parallel completion of tests so that concurrent engineering can occur. This type of test team composition and general approach to flight testing is being successfully implemented in many of today's military programs as seen in the F/A-18E/F and F-22.

The F/A-18 and F-22 Integrated Test Teams

The use of an Integrated Test Team (ITT) by the F/A-18E/F program is one way a program manager may model the test team. By concurrent testing, this ITT is rapidly proceeding through its test matrices. For example, the ITT clears a specific area of a flight envelope through flutter analysis. They then proceed with loads testing and safe

separation testing within this envelope while the flutter team starts concurrently clearing another portion of the envelope. Initial operational assessments are made early in the program as well. By forming this team composed of industry and government and applying a concurrent approach, the F/A-18E/F program manager has been able to avoid duplication of test efforts and is rapidly proceeding through the integrated test matrix. These benefits of the ITT have lead to less duplication of flight tests between the Navy and McDonnell-Douglas. Previous to the ITT, several test points were duplicated as the contractor performed a test point and the military (Strike Aircraft Test Squadron for NAWC-AD as an example) tested the same point for Specification Compliance. This resulted in a larger overall test matrix that would have to be completed when taking a test article from DEMVAL to production. By integrating the contractor and government and integrating the test matrix as well, the F/A-18E/F program manager is avoiding this duplication with the end result being a smaller test matrix.

The F-22 is also using an integrated approach to its store separation testing (reference 5). A team composed of Lockheed and the Air Force engineers at Wright-Patterson and Arnold Air Force Base is working to solve the problems associated with releasing stores from the weapon bays. Most store separation tests utilize a captive trajectory system (CTS) where data is obtained using a wind tunnel model by simulating the trajectory of the released store (reference 6). However, these tests are limited to very static release conditions. A rolling pull-up maneuver model was desired which could not be accurately assessed using the CTS approach. The test team took an integrated

engineering approach to introduce new computer models to perform free-drop testing, leading to accurate computer models for the store separation in this dynamic situation.

This integrated approach and subsequent ordnance separation flight test matrix minimization was made possible by the proper assembly of the integrated test team. This "good business practice" is an approach all program managers should utilize when faced with an ordnance separation program.

Chapter 4

Ordnance Separation Flight Test Risk Reduction

Introduction

The second programmatic solution to ordnance separation flight test matrix reduction lies in the application of proper risk reduction. Similar to the integrated test team approach discussed in Chapter 3, risk management must be used throughout all life-cycle phases of the program. By alleviating or avoiding unacceptable risks in a program, the manager is better able to keep the program on cost and on schedule. However, the risks must be identified prior to alleviating them. This is accomplished using a technique referred to as Operational Risk Management. Once unacceptable risks are identified, two specific programmatic methods are used in ordnance separation flight test to reduce or eliminate them: configuration control and release envelope limitations. With both of these methods, time and cost benefits are realized when unnecessary incremental build-up is alleviated or particularly adverse separation configurations or flight regimes are avoided. Alleviating even one test point saves not only the time required to conduct that test point and reduce the data obtained, but also the test day costs associated with executing the flight test. Similarly, avoiding areas of known high-risk flight test will aid in alleviating unnecessary delays or costly program set-backs. Risk reduction solutions will begin with an examination of Operational Risk Management.

Operational Risk Management

Envelope expansion flights can be very challenging and sometimes dangerous. A method has been developed which gives the program manager a quantifiable means to classify this type of testing. The Naval Air Warfare Center - Aircraft Division conducts a hazard analysis to classify the level of risk a series of flight tests may have according to a residual risk matrix in an attempt to increase the safety of the test program. A sample hazard analysis and a copy of the residual risk matrix appear in tables B-1 and B-2 respectively. When conducting the hazard analysis, the test team identifies potential hazards associated with the flight test. They identify the causes of the hazards and suggest ways to eliminate these causes. By analyzing the possibility of occurrence and the severity of the consequences should this hazard occur, a risk assessment can be made. This risk assessment results in a classification of the test from A to D, with D posing the most severe potential risks or the largest amount of intangible factors. When conducting envelope expansion testing in an ordnance safe separation test program, an operational risk assessment will result in a classification of category C flight test. Because of this classification, a cautious approach must be utilized by the test team. Incremental build-up is the standard approach to the development of the flight test matrix. However, there are programmatic and technical methods to reduce the amount of incremental build-up required in a test program. Prior to discussions of two of these programmatic risk reduction solutions later in this chapter and the technical solutions presented in Chapter 5, it is prudent to further define incremental build-up.

Incremental Build-up

MIL-STD-1763A (reference 7), MIL-HDBK-244A (reference 3) and local NAWC-AD and test wing standard operating procedures give standards for incremental expansions in airspeed and dive angle from point to point within a given flight test matrix. The general strategy is to build up in dynamic pressure and mach number and build down in release interval (as applicable) and normal acceleration (dive angle). This, in some cases, may unnecessarily limit the program manager to costly flight test or cause one to consume valuable time obtaining waivers. Table 4 delineates the typical incremental build-up mandated by the directives under which NAWC-AD conducts its stores separation testing of new (untested) stores.

Table 4

Mandated Incremental Build-Up

Dive Angle	IMN	IMN	IMN	IMN	IMN	IMN
0	0.8	0.9	0.95			
30			0.95			
45			0.95			
60			0.95	0.97	1.1	1.3

In the example outlined in table 4, it is desired to reach a final release condition of 1.3IMN and up to a 60 degree dive angle. The first test point for the flight test is recommended to be a single store, level delivery from parent racks at airspeeds which provide for an examination of the basic weapon dynamic behavior during separation. These characteristics are most easily observed during releases with low local flow angularity and low dynamic pressures (reference 8). Thus, the flight tests begin at 0.8

1MN and straight and level flight (0 degree dive angle). The test team would then build up airspeed in a straight and level condition until the transonic area is reached (0.951MN in this example). Once in the highly non-linear transonic regime where separation characteristics are hard to predict, the team will hold release Mach constant and adjust dive angles incrementally up to the maximum of 60 degrees. As dive angle increases, aerodynamic forces and store dynamics have a greater influence on separation characteristics due to a reduction of the gravity force normal to the aircraft's Armament Datum Line (ADL), necessitating caution in the test process. If satisfactory release conditions are still apparent, the team will then continue building up the release Mach to the final value of 1.31MN at a constant 60 degree dive angle. This one release condition would then have taken 9 test flights and nearly two months to accomplish. Similar tests would then have to be completed for each desired configuration or release interval.

In addition to the incremental build-up, calibrated airspeed is associated with the release Mach number in order to attain desired dynamic pressures at release. Also, target normal acceleration values (g-levels) are associated the dive angles. These parameters are critical for each release condition with the following tolerances allowed at each point tested:

Airspeed ± 10 KCAS

Mach Number ± 0.01

Load Factor ± 0.1 g

If these tolerances were not met, the test point would be considered invalid and would have to be re-flown. Typically 1 in 10 ordnance separation test flights at NAWC-AD are

repeated due to the tolerances being exceeded at release. Thus, the program manager has to allow for these additional costs and schedule delays to complete the matrix. While incremental build-up is recognized as a safe approach to ordnance separation flight testing, attempting to implement risk management in this rigid form can lead a program to unnecessary test points, program delays and high flight test costs. Thus, two programmatic risk reduction methods are used to minimize the amount of incremental build-up required and avoid potential repeated test points: configuration control and release envelope restrictions.

Configuration Control

Configuration control is one method the ordnance separation program manager can reduce risks associated with flight test and avoid increased incremental build-up (reference 2). Configuration control refers to the practice of restricting the allowable external loading of the aircraft. This is done by permitting the test article to only be placed on certain release stations or next to particular adjacent stores. In doing this, the program manager avoids configurations which exhibit particularly poor separation characteristics or other adverse flight characteristics. One not only avoids the potential set-backs that may be encountered should something go wrong at these more hazardous test conditions, but avoids the incremental build-up required to get to that endpoint. The end result is a smaller flight test matrix requiring less time and money to execute. A good example of this idea is the F/A-18 C/D Departure Demonstration program.

F/A-18C/D Departure Demonstration Program

The F/A-18 C/D Departure Demonstration program was developed as a tool to train Naval Aviators in the recognition of and recovery from out-of-control flight. Since several normally prohibited maneuvers were to be performed in this flight profile, a flight test program had to be developed to examine these maneuvers and assess their applicability in the planned departure demonstration flight. Further, the program was considered "very delicate" in that any loss of an aircraft due to out-of-control flight would result in immediate program termination.

Once the desired departure demonstration maneuvers were identified, a thorough hazard analysis was made. One result of this hazard analysis was that the aircraft's external configuration had to be closely controlled. If several configurations were to be utilized in the departure demonstration program, then a rather large demonstration flight development test matrix had to be completed in order to adequately explore all potential risks associated with each configuration. In the interest of reducing program and cost risks, it was decided to conduct the departure demonstration flights in only one specific configuration with the thought that the training provided by the program could still be accomplished adequately. The end result was a smaller flight test matrix.

Applicability to Ordnance Separation Flight Test

Many ordnance separation programs follow this same thought process. By limiting the allowable configurations, the program manager is required to only test to these configurations of interest and thereby keep within the budgetary constraints. An important point, however, is that one must ensure that the configurations one tests give

the operator the most mission essential loading. As seen in figure A-1, the JDAM program conducted testing in only three particular configurations. This worked well in this instance as these allowable JDAM configurations were sufficient to effectively employ this weapon. However, a tightly controlled configuration may lead to a very restrictive weapon employment capability. This situation must be avoided.

Release Envelope Limitations

Similar to configuration control, release envelope limitations are another programmatic tool used to control schedule and budgetary risks (reference 2). Release envelope limitations are those which restrict the flight parameters from which the store may be released. These could be dive angle restrictions, airspeed restrictions, normal load factor restrictions, or a combination of these. Referring to figure A-1 as an example, the release limits for the JDAM were 1.3 IMN maximum and 0.5g minimum. It was decided that these release limits would be sufficient for effective operational use of the weapon. Again, the program manager must exercise caution that any release restrictions imposed are not too limiting to the operator.

This risk reduction technique is of particular use when faced with near-term schedule deadlines. In these cases, the program manager limits the separation testing to a particular set of release conditions so that the store is sent on to production testing (operational evaluation) as soon as possible. This allows the completion of EMD separation testing on schedule and will not preclude return to EMD for further envelope expansion testing at a later time. For instance, the JDAM could have only been cleared to subsonic releases (a consideration that was being made) so that this weapon could

complete EMD testing as soon as possible and enter operational evaluation. The thought was that the supersonic portion of the release envelope could be cleared at a later time if needed. This option was not ultimately exercised, however it illustrates the potential for this application.

Summary of Risk Reduction

In all phases of ordnance separation flight testing, proper application of Operational Risk Management will ensure test hazards are identified and if not eliminated, then approached with caution. Configuration control and envelope restrictions are two methods the ordnance separation program manager can use to reduce time and budget risks associated with the program. However, if the program manager is faced with a project which is bounded by a given configuration and release criteria, one cannot utilize these risk reduction techniques and must find alternative ways to minimize the flight test matrix to keep the program on cost and on schedule. Technical solutions to minimizing the size of the ordnance separation flight test matrix and realizing time and money savings are the subject of the next chapter.

Chapter 5

Ordnance Separation Flight Test Modeling in EMD

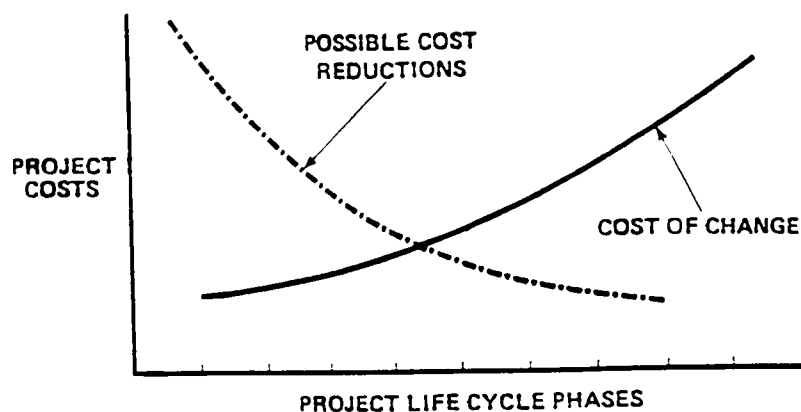
Introduction

The remainder of this paper will focus on solutions to the technical problem of obtaining accurate performance predictors to increase test team confidence in existing models. With this confidence, the team may alleviate unnecessary test points and incremental build-up in the EMD phase of ordnance separation flight test. The end result will be minimization of the flight test matrix and subsequent cost and schedule savings.

Need for Accurate Performance Models

There are several reasons for seeking accurate means to predict the performance of a test article. Using accurate models early on in the EMD phase leads to less costly changes should problem areas arise. As seen in figure 2, any change to the system design will be more costly as the product matures. If accurate models are available, the initial design in the early stages of EMD can be made with great confidence, reducing the likelihood of costly changes later in the development process.

An additional benefit of using accurate models early in the test matrix development process is the possible identification of problem areas (poor transonic store separation characteristics, for example). With these areas defined, one may want to concentrate testing in these specific areas to accurately assess system performance.



(Source: Kerzner)

Figure 2

Cost vs. Timing of Change Implementation

Another need for accurate performance models is that of avoiding costly incremental build-up. As shown previously, incremental build-up can lead to a very large flight test matrix, especially when applied to store separation testing using a wide range of possible configurations. This is compounded by the fact that to date, there is no satisfactory analytical method to accurately estimate the flow pattern effects on adjacent stores. This will necessitate the need to proceed cautiously through any store separation testing next to adjacent stores. If the test team has a high degree of confidence in the models, they can make informed decisions whether the incremental build-up is unnecessary and may be safely bypassed.

With the need for accurate modeling in the EMD phase defined, it is now possible to explore the performance predictors one may use as tools to reduce the size of the flight test matrix.

Current Flight Test Performance Predictors

General

The methods which are used as performance predictors in ordnance separation flight test can be categorized into three broad groups: theoretical, empirical, and analogous. The theoretical method is a purely analytical approach which utilizes the solution of the fluid equations to solve the equations of motion. The empirical method is an observational approach utilizing a specified survey of points throughout a flowfield which offers aerodynamic information about the store's movement. The analogy method relies on comparisons between similarly shaped stores in order to draw conclusions about store movement.

Currently two of these methods are being used in EMD flight test matrix development in nearly all ordnance separation test programs at NAWC-AD. The empirical method of wind tunnel analysis is used extensively as are demonstrations based on analogy. The third method, that of analytical modeling, is emerging as a cost effective way to reduce the size of a flight test matrix. Exactly which method the program manager will use in EMD performance modeling depends on several factors, including the type of store and aircraft to be used. Proper application of the appropriate technique requires one to have a thorough understanding of the modeling methods. For this reason, these methods will be discussed in detail in the following sections. Prior to examining analytical methods, analogous methods and wind tunnel methods will be discussed.

Demonstration by Analogy

Test point demonstration by analogy is an excellent means to keep flight test matrices to manageable levels. Many ordnance systems under test lend themselves to analysis by similarity to existing systems. By demonstrating endpoints based on analogy, much costly flight test is avoided. There are two factors that must exist prior to endpoint demonstration: analogous test data and the flight test engineering experience to determine whether or not the systems are indeed analogous (reference 10).

Analogous test data is data obtained from similar systems under similar conditions. How analogous a system is depends on many things (reference 8). The analogy is established based on similarities between the physical properties. The location of a store's lifting surfaces has to be accounted for, as well as similarities between the store's suspension systems.

As an example of successful flight testing and flight test matrix reduction on the basis of analogy, the AMRAAM missile upgrade will be examined. The AMRAAM missile upgrade consisted of, among other things, a redesigned wing and control laws. The main body of the missile remained unchanged. A comparison between the current AMRAAM wing and the redesigned wing is seen in figure 3. The changes in physical appearance are apparent. However, the wing areas differed by only 2 in² between the B and C models. In addition, the location of the wings on each model of missile were the same. Further studies were conducted to outline the similarities in mass properties.

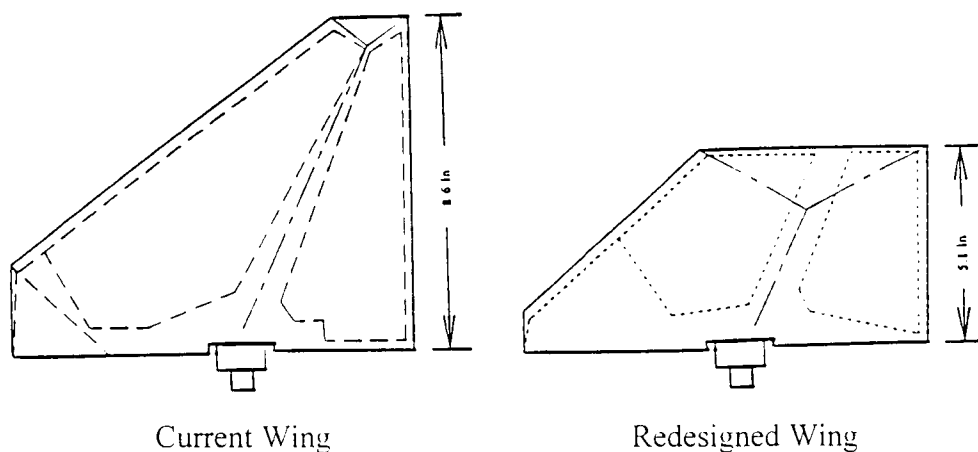


Figure 3

Current AMRAAM Wing vs. Redesigned AMRAAM Wing

This was accomplished by an analysis of moments of inertia, total physical measurements, and CG. The results of this study appear in table 5.

Table 5

AMRAAM Model Physical Comparisons

Properties	AIM-120B with Telemetry Package	AIM-120C with Telemetry Package	Changes from B
Mass (lbs.)	329.62	329.31	0%
Length (in.)	144	144	0 in.
Pitch Moment of Inertia (slug-ft ²)	95.08	95.33	0.2%
Yaw Moment of Inertia (slug-ft ²)	95.08	95.33	0.2%
Roll Moment of Inertia (slug-ft ²)	0.57	0.54	5.3%
CG (in.) ¹	80.82	80.24	0.58 in.
Diameter (in.)	7.0	7.0	0 in.
Wing Area (in ²)	42	40	-2 in ²
Fin Area (in ²)	74	70	-4 in ²

¹Missile station zero is 3.2 inches aft of radome tip

Table 5 points to very similar mass properties between the AIM-120 B and C. Since the C model AMRAAM was to use the same suspension equipment on the F/A-18 as the B model AMRAAM, it was determined by the test team that the two articles were close enough in physical characteristics that endpoint demonstrations could be made in developing the flight test matrix, thereby avoiding incremental build-up to these points. In fact, the entire DEMVAL phase was avoided and the program began flight testing in EMD since the separation was to be conducted from a production aircraft and a large database existed. The endpoints included high g, high and low airspeed, and high angle of attack, as seen in table 1. However, rather than incrementally build-up to these envelope endpoints as in previous flight test, the team proceeded directly to the endpoints and then, based upon similarities in flight test data between the B and C models, cleared the remainder of the separation envelope by analogy. This required, in addition to the physical property analysis, the availability of historical data for the B model separation from the F/A-18. This historical separation data was sought to identify worst case separation characteristics and provide analogous data for the C model separation envelope. Similarities between B model and C model separation characteristics were examined. The similarities looked for in the data would typically be those of magnitude of the air vehicle/store separation (defined for the CGs of the store and aircraft as "R" in figure 1) and trend of this separation ("R" should never decrease. It should always increase.). MIL-HDBK-244A and other local directives gave guidance on trends and separation distances. In summary, they stated that no part of the store can close within 2 inches of any part of the aircraft following release and that the store's center of gravity

(CG) must exhibit a continuous trend away from the aircraft. Thus, rather than trying to match traces between B model and C model identically, the team compared the trends. The envelope for the new store could be cleared if trends and separation distances were sufficiently matched to historical data for similar weapons. A sample comparison showing good flight test agreement between the B model and C model AMRAAM appears in figure A-3.

The usability of analogous data and subsequent decisions to bypass incremental build-up rests, in large part, with the experience of the test team and the confidence they have in the analogy. There are no directives which give the exact magnitude of physical similarities or matching of predicted data. This experience and confidence has a direct impact to the ultimate size of a proposed flight test matrix. For instance, when proposing flight test data points for the JDAM safe separation project, several analogies were made to MK-84 type gravity bombs. Figure 4 shows the physical similarities.

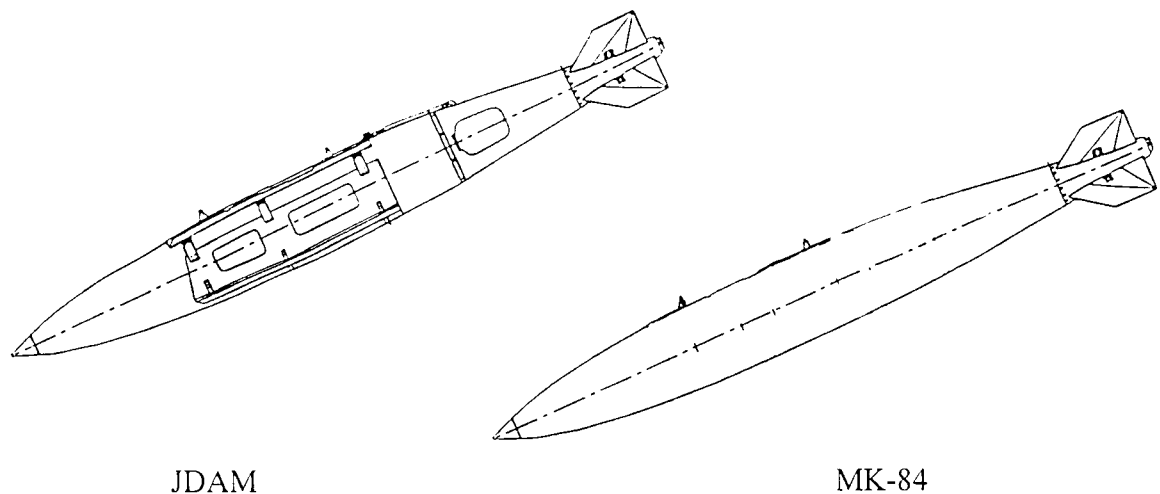


Figure 4

JDAM and MK-84 Body Shape Comparison

Although there were additional airfoils on the JDAM that were not on the MK-84, several engineers with MK-84 safe separation experience were able draw conclusions based upon their experience which led the test team to a higher initial Mach number from which to start the test points (the test matrix was started from 0.91MN rather than 0.81MN as shown in figure A-4). While this resulted in the alleviation of test points, the test team was not able to avoid incremental build-up altogether. The JDAM will be discussed further at a later point in the paper.

Program Manager Applications for Endpoint Demonstrations Based on Analogy

Endpoint demonstration by analogy is best suited for testing of minor changes for previously cleared stores throughout the test envelope on production aircraft. Test team confidence in the analogies must be high. The AMRAAM upgrade is an excellent example of this type of testing where an upgraded store (the AIM-120C) was designed to be mated to an existing aircraft. The program avoided flight test demonstrations (DEMVAL) and proceeded directly to envelope expansion (EMD) testing.

Other programs safely demonstrated that by using this methodology, the ordnance separation program manager minimizes the size of the flight test matrix. The Swiss AIM-9 separation program (reference 11) conducted at NAWC-AD also verified endpoints based on analogy. However, this program differed from the AMRAAM in that changes to the missile were not the reason separation tests needed to be accomplished. It was the suspension equipment (the wing pylon and rack) that was different. Another program that successfully conducted endpoint demonstrations based on analogy was the B-1B Weapon Conventionalization project (reference 10). Sufficient data existed on non-

conventional stores separation that gave the B-1B test team a high degree of confidence to safely conduct endpoint demonstrations based on analogy.

Demonstrations based on analogies must be approached with caution. One application that must be avoided is the development of analogies based on other analogies. That is to say, if the test team is attempting to avoid incremental build-up based on analogy, the comparison data must not be based on analogy as well. Rather, one must go back to review the original data. Nearly 1/3 of the current F/A-18 weapons configurations are based on analogies. However, it is becoming apparent that not all of these weapon configurations may allow for safe store separation, a problem that has only recently surfaced with the F/A-18 program.

Wind Tunnel Analysis

Wind tunnel analysis is another tool the program manager uses in the development and subsequent minimization of the EMD ordnance separation flight test matrix. Wind tunnels have been used since the 1960s for store separation analysis with four methods typically used: the Captive Trajectory System (CTS), the Grid, Flow Angularity, and the Freedrop. These methods provide precise, repeatable control of the operating environment and allow the program manager to obtain predictions in the particularly challenging regions of transonic store separation and testing next to adjacent stores. However, they are not without their problems. Altitude effects, Reynolds number, aerodynamic interference, and others combine to limit the usefulness of wind tunnel predictions. The Captive Trajectory System (reference 12) is used extensively at NAWC-AD. This method offers the ordnance separation program manager the ability to

measure actual forces and moments acting on the store during the separation trajectory. CTS can simulate varying aircraft load factors and maneuvers, varying ejection force parameters and varying store thrust that other methods, such as freedrop, cannot. It provides the most accurate experimentally determined data for store position in its separation trajectory, but it has its limitations. It does not adequately provide the user with a useful data base with which one may perform sensitivity studies of separation characteristics to such things as aircraft Mach number, angle of attack, dive angle and store mass and inertia property changes. This is needed since flight test often results in store development and improvements which may alter the mass and inertial properties. This exact problem occurred during the JDAM separation testing.

The JDAM was, very simply, a MK-84 gravity drop bomb that was made steerable through the addition of stationary forebody strakes and movable tail fins. Guidance was provided via a Global Positioning System (GPS). The store exhibited many physical and inertial similarities to the MK-84 which allowed the test team to make some analogous comparisons leading to an initial DEMVAL release at an airspeed of Mach 0.9. From this point, incremental build-up was exercised (as previously outlined) to develop a flight test matrix designed to reach three endpoints: (1) release of a single JDAM from an inboard F/A-18 weapon station (station 3) at speeds up to 635 KCAS / 1.3 IMN and dive angles up to 45 degrees, (2) release of a single JDAM from an outboard F/A-18 weapon station (station 2) next to an external fuel tank on the inboard weapon station (station 3) at speeds up to 635 KCAS / 1.3 IMN and dive angles up to 45 degrees, and (3) release of a single JDAM from an inboard F/A-18 weapon station next to a High

Speed Anti-Radiation Missile (HARM) on the outboard weapon station at speeds up to 635 KCAS / 1.3 IMN and dive angles up to 45 degrees. To reach the desired final release condition at these three configurations of interest, the test team had to derive a flight test matrix to incrementally build-up to the desired airspeed/configuration combination. The initial separation flight test matrix contained 50 test points, all subject to the standard ordnance test point validity tolerances previously listed. Thus, the program manager had to plan on at least 55 necessary test points based upon repeated test point statistics. Successful wind tunnel simulation resulted in separation predictions which allowed the test team to concentrate the testing to those points which had the worst separation characteristics. This led to the ultimate tailoring of the initial flight test matrix of 50 points to the one in figure A-1 which contains 22 test points. This matrix was divided into three areas to cover the three configurations listed above: Inboard Ejection, Outboard Ejection, and Adjacent Stores Ejection matrices. Incremental build-up was exercised extensively in the transonic region and during configuration changes.

During JDAM separation test planning, the test team received several traces showing separation predictions based upon wind tunnel data. Based upon these data, it was predicted that the JDAM would exhibit adverse separation trends in the transonic region. (It would not exhibit a continuous motion away from the aircraft and clearance would fall inside the minimum 2 inches.) Figures A-4 and A-5 delineate wind tunnel predictions for subsonic and transonic freestream release airspeeds of Mach 0.90 and 0.94 respectively for one particular configuration (single JDAM mounted on the F/A-18C inboard weapon station). Wind tunnel predictions of JDAM fin and F/A-18C pylon miss

distance as a function of time following release are shown in the figures as lines connecting squares with the solid line showing predicted miss distance between the nearest portion of any part of the JDAM to the pylon (see legend in the figures). Figures A-6 and A-7 delineate the associated pictorial views obtained through six degree of freedom analysis.

Scrutiny of these and similar traces led the test team to two conclusions: the adverse transonic separation effects appear as freestream Mach number increases above Mach 0.92 and becomes more favorable as freestream Mach number goes supersonic. By identifying these areas of concern, incremental build-up could be applied during the test execution around this critical area to accurately document safe separation. It was very important that after the team flew one of these transonic test points where the wind tunnel models predicted minimal clearance, the results were compared to predicted values prior to flying the next point so the model could be refined and updated. This would help validate the model, increase test team confidence in the model, and allow those points with small predicted miss distances to be closely monitored. However, even in doing this, the test encountered an unexpected and unpredicted problem.

Problems arose during this transonic portion of the testing in the actual modeling of the separation. Again, referring to figure A-5, it can be seen that the predicted miss distance for the JDAM shows an adverse trend on nearing the pylon approximately 0.08 seconds after release. This meant the JDAM fins were coming dangerously close to the F/A-18 pylon. However, the test team felt that based upon flight test results up to this point that indicated greater than predicted miss distances, that the wind tunnel predictions

were not accurately taking into account all the dynamics of the release. Indeed, one of the limiting factors of CTS was that it was not accurately modeling the reaction of the aircraft following store separation. As the test weapon was released from the aircraft, the aircraft was exhibiting a pronounced roll away from the store. Figure 5 depicts this phenomenon.

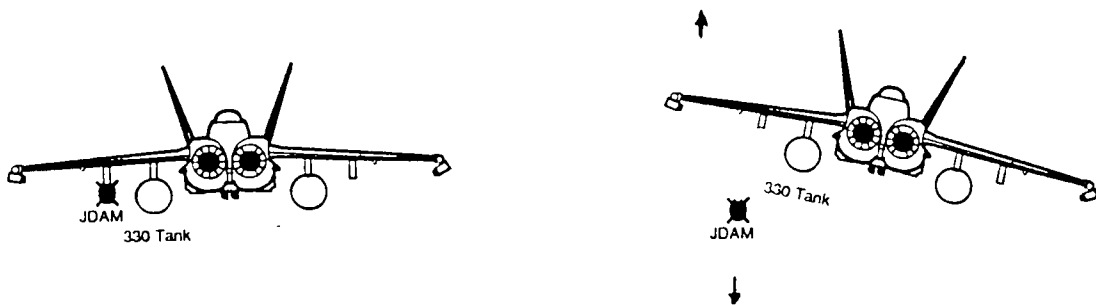


Figure 5

F/A-18 Post Separation Roll Motion

As seen in figure 5, as the store left the aircraft, the wing rolled away due to the sudden loss of the store weight and the existing aileron trim away from the store. This was actually having the effect of increasing miss distance, as seen in figure A-8. This inaccurate modeling resulted in delay of two months while awaiting new wind tunnel research and performing programmatic risk assessments prior to proceeding with the flight test.

Program Manager Applications for Wind Tunnel Analysis

Wind tunnel analysis affords the ordnance separation program manager with a very useful means of determining EMD separation performance, particularly in the transonic region and when conducting adjacent store testing. Test team confidence is

increased through flight test validation. As shown in the JDAM program example, this leads to methods of tailoring a flight test matrix to those areas that necessitate incremental build-up, while avoiding excessive matrix in areas that do not require such an approach.

However, wind tunnel applications have their limitations. The methods are not very conducive to timely analysis of changes to the test article or release conditions. Dynamic aircraft responses are difficult to model, even when using a production aircraft. Scaling effects result in inaccuracies manifested by disparities between flight test data and wind tunnel predictions. The models must be validated with flight test data and this has a large impact on the accuracy and subsequent test team confidence in the application of these models. These disparities are evident as shown in figure A-4, where aircraft telemetry data shows JDAM-pylon impact at 0.12 seconds after release, a condition that was not predicted by the wind tunnel analysis. For this reason, wind tunnel testing must be approached with caution in all phases of ordnance separation testing.

There are methods becoming more predominant in the ordnance separation performance prediction regime that offer promise to the program manager faced with these problems. Several of these emerging flight test performance predictors will be analyzed next.

Emerging Flight Test Performance Predictors

Emerging flight test performance predictors can substantially reduce the amount of incremental build-up necessary in category C testing. Further, they can be of great assistance in two particularly challenging areas of flight test in stores separation testing:

testing at transonic speeds and testing next to adjacent stores. The modeling technique that will be explored to this end is computer-based theoretical predictions.

Computer-Based Theoretical Predictions

PAN AIR

The purely analytical method of computer-based solutions to solving equations of motion and obtaining store separation predictions is becoming more useful with the advent of better programs and faster computers. One such application is known as paneling aerodynamics (PAN AIR) (reference 13). As applied to store separation, this method (in the most rudimentary sense) is a solution to the linear Prandtl-Glauert equation for the configuration of interest. This equation, derived from Prandtl's Lifting Line Theory, is shown in figure 6.

$$Cd_i = \frac{Cl^2}{\pi eAR}$$

Figure 6

Prandtl-Glauert Linearized Equation

Although it appears to be a simple calculation, solving for this in a stores separation application is quite an involved process necessitating significant computer support. Paneling methods (setting up vortex lattices in a coordinate system depicting flowfields) are used to solve the Prandtl equation. A three dimensional boundary value equation is then solved which will govern the subsonic and supersonic flow regimes.

The first step in the theoretical analysis of a new store is understanding the store's freestream aerodynamics which leads to a determination of the carriage moments. A

detailed computer analysis is performed to collect this data and preliminary trajectories are computed to determine what kind of flight testing may be warranted. PAN AIR is the primary analytical tool used at NAWC-AD for this purpose (reference 4). This technique had been validated for most Navy aircraft, including the F/A-18. Changes to aircraft configuration shape such as fuel tanks, pylons and other stores can be easily modified. The problem with this particular technique is that it uses linearized models for a highly non-linear regime. The "real world" shapes and aerodynamics are very complex. One particular area that this technique had problems with predictions was determining yaw associated with JDAM separations in the transonic region.

As the JDAM program proceeded through its flight test matrix, a phenomenon was observed as the store separation tests entered the transonic regime. As the JDAM separated from the aircraft, a significant nose-in yawing action was observed. Comparing the pictorial of the sub-Mach 0.9 test point of figure A-6 to the transonic test point of Mach 0.94 as depicted in figure A-7, this yawing motion can be seen. This yaw action continued as the store left the aircraft's flowfield, with the tail following the helical trajectory depicted in figure 7.

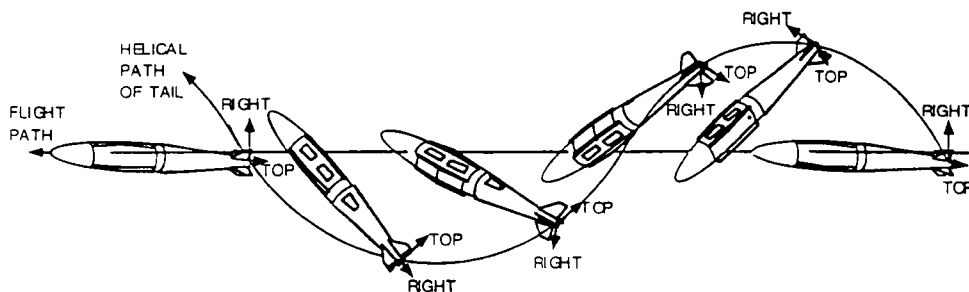


Figure 7

JDAM Tail Helical Trajectory in the Transonic Release Regime

The end result was that the store was falling well short of the intended point of impact and concern was raised as to the ability of the store, as designed, to actually impact the target. PAN AIR computations had been made but did not reveal any yawing moments during store carriage (where analysis of separation characteristics begins). Further analysis of the flight test data revealed something surprising. As depicted in figure 8, a significant yawing (C_n) and pitching (C_m) moment did in fact exist prior to release in the transonic regime.

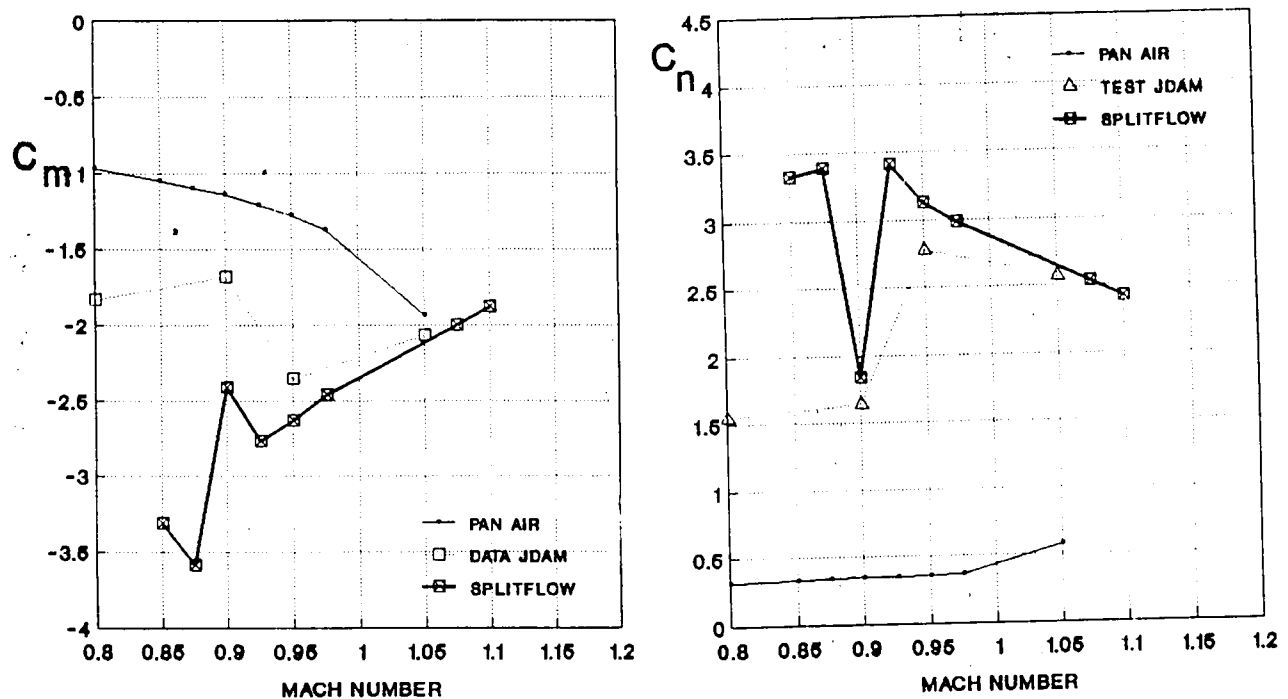


Figure 8

Mach Effect on JDAM Yawing and Pitching Moment

This proved to be a "show stopper" with the program. As it turned out, the tail fins did not possess the control power to arrest the helical instability. This is currently necessitating a complete re-design of the tail fins and subsequent re-fly of several EMD

separation test points, negatively impacting the size of a flight test matrix. Inaccurate analysis will lead to inappropriate testing. Thus, PAN AIR applications should be limited to first order trajectory studies only when dealing with store separation analysis.

Higher Order CFD

Other theoretical approaches are also evolving which may aid in the analytical approach of using computer-aided methods to predicting system performance. Advanced Computational Fluid Dynamics (CFD) is the preferred method and is rapidly becoming a much used way to predict performance of test systems, particularly the transonic store separation problem (reference 14). This technique uses an Euler or Navier-Stokes algorithm that is numerically and iteratively solved using a contour-conformal grid scheme (flowfield mapping along the shape). The latest advances applicable to store separation testing lie in the area of grid usage (reference 15). Structured grids were typically used in ordnance separation analysis. This led to a large number of approximately factored, time-integration grids used to map the field. Aerodynamisists at NAWC-AD are now utilizing unstructured grids as seen in figure A-9 which depicts the flowfield interaction occurring on an F/A-18C carrying a JDAM on the right outboard weapon station and an external fuel tank on the right inboard weapon station. These grids use an explicit Runge-Kutta method such that they are close approximations away from the area of interest (away from the store) and more precise (triangular in shape) near the area of interest. This allows for a more exact mapping of the flow field than structured grids, particularly in stagnation regions created by shock waves associated with transonic

flow. Figure 9 shows the beginning of a stagnation point for the figure A-9 configuration at the inboard side of the JDAM as predicted by an unstructured grid CFD analysis.

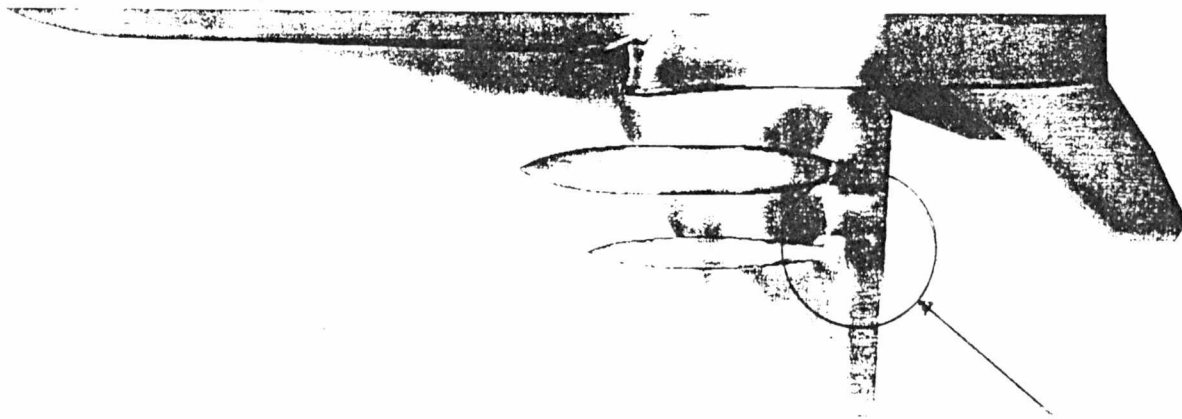


Figure 9

Formation of a Stagnation Point on Outboard JDAM

Advantages to this technique include the flexibility to concentrate the grid in particular areas of interest and its applicability to any air vehicle/store configuration. It is easily adaptable to allow for a sensitivity analysis to changing release conditions. After determining the aircraft flowfield, an Influence Function Method (IFM) (reference 16) is used to determine the effect of the flowfield on the store's moments. This leads to the determination of carriage coefficients that ultimately lead to the determination of store

separation characteristics. The accuracy of this method is promising and will lead to a high degree of confidence in the models. Again, referring to figure 8, the CFD technique known as SPLITFLOW (reference 17) shows that this method did in fact predict the yawing and pitching moments observed during the JDAM transonic testing.

The big disadvantage to CFD in ordnance separation analysis now is that it requires significant computing power and time to model the system. A large database must exist for the production aircraft. Complex CFD calculations can take weeks to complete. This equates to a significant time and financial investment. However, as computers continue to evolve and the method matures, this technique is becoming more useful and may find its way to becoming a primary technique to predict system performance in transonic and adjacent stores testing.

Program Manager Applications for Computer-Based Analytical Techniques

Computer-based theoretical predictions are becoming a viable means to predict system performance, especially in today's military flight test where aircraft and weapons shapes are becoming more complex. Effective early diagnosis of aircraft flowfields increases test team confidence and is vital to successful store separation testing and flight test matrix reduction in the EMD phase. Advanced CFD are building on the existing experimental database to provide timely solutions to separation problems. Similar to wind tunnel testing, their accuracy is very much dependent on validation through flight test. Therefore, continual refinement of the models is necessary as the program progresses through EMD to ensure an accurate modeling, test team confidence, and subsequent safe reduction of incremental build-up.

Integrated Approach to Performance Modeling in the EMD Phase

One must continually refine the model to be used in an attempt to accurately predict the performance of a system. The most accurate model will be realized if an integrated approach is made to the performance modeling of ordnance separation systems in the EMD phase. In this approach, several modeling techniques are used on any given program (references 4, 18). The method most commonly used now is the integration of wind tunnel data, analogous flight test data, and advanced CFD. When using this method, wind tunnel data and any existing analogous test data is fed into the CFD model to derive an accurate analytical performance forecast tool. Using this tool, complete sensitivity studies can be accomplished. The test team realizes a high degree of confidence in the model such that appropriate decisions can be made regarding areas that may not require traditional incremental build-up. Flight test can then begin in areas of particular interest to the test team with incremental build-up being substantially reduced or eliminated. This flight test data is then used to further refine the existing CFD model. In this iterative process, the program manager will realize a high fidelity CFD model of the test system. Subsequent flight tests can be tailored to the areas of concern (typically transonic or adjacent store testing) or endpoint demonstration. Continual refinement of the model should occur throughout the EMD phase resulting in a mature, reliable model that can be used should any further testing be required as the test program leaves the EMD phase and enters the production phase. Only by using this integrated approach to ordnance separation flight testing will the program manager best realize accurate

performance modeling, high confidence, and subsequent flight test matrix reduction throughout the EMD phase and life of the test program.

These solutions are providing the program manager with a timely means to conduct separation analysis at a wide range of flight conditions and configurations. This is leading to the early identification of non-solutions (bad configurations or release conditions) to weapon separation and better identification of problem areas (such as transonic releases). Such a trend will continue to make ordnance separation testing less dependent on DEMVALs and will continue to lessen the testing required during EMD. The next chapter highlights some potential future solutions to the ordnance separation flight test matrix reduction problem as an effort to continue this trend.

Chapter 6

Future Applications

Introduction

The ordnance separation performance modeling problem is one that will be a constant technical challenge to the program manager. There are new processes being developed which may have future applications to solving the ordnance separation flight test matrix minimization problem. The processes that will be explored are virtual prototyping, stereolithography, and virtual piloting.

Virtual Prototyping

Virtual prototyping is the next apparent step in computer-based performance modeling techniques. Virtual prototyping is defined by the Department of Defense as "...a computer based simulation of a prototype system or subsystem with a degree of functional realism that is comparable to that of a physical prototype" (reference 19). Virtual prototyping is the use of a computer-based model with such high fidelity that static and dynamic responses may be accurately modeled and easily analyzed. It is the next step to computer aided design, making use of the higher order CFD (Euler and Navier-Stokes based analysis using compressible and incompressible fluid models) to model components of a system in flowfields. The various modules of a test system are formed and assembled together in the computer to analyze the interactions between the

systems. From these analysis, sensitivity studies may be made and design changes may be implemented on the prototype in this virtual environment before physical products are constructed. Thus, virtual prototyping is viewed as the process of using a virtual prototype, in place of a physical prototype, for simulation and assessment of specific characteristics (such as performance or usability) of a candidate design. It can be used to omit physical prototype test articles allowing a test team to proceed directly from a digital model to the production floor, or in the case of ordnance separation test, bypass DEMVAL at benign test points and proceed directly to transonic or adjacent store testing in EMD. Several examples of this applied technology exist in the T&E world.

Autonomous Scout Rotorcraft Testbed

The U.S. Army sponsored a technology demonstration of the Autonomous Scout Rotorcraft Testbed (ASRT), reference 20. The ASRT is depicted in figure 10.

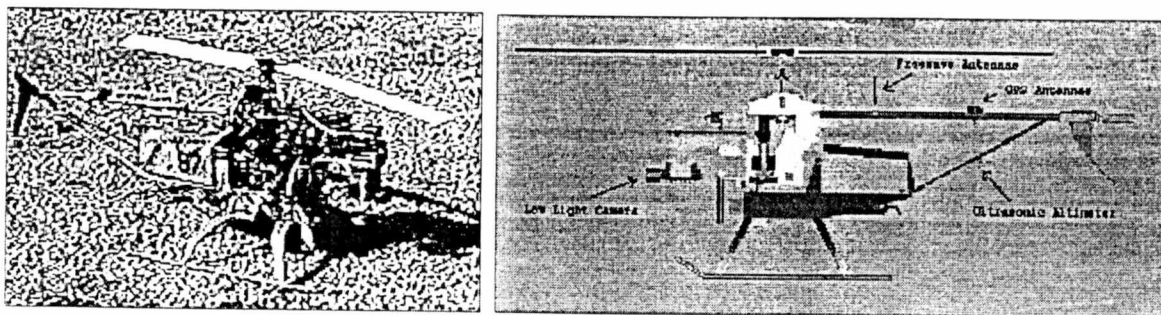


Figure 10

Autonomous Scout Rotorcraft Testbed

Other members of this demonstration team included Sikorsky Aircraft and the Georgia Institute of Technology. This project was to demonstrate automation technologies for vertical takeoff and landing Unmanned Air Vehicles (UAVs) and demonstrate an Integrated Product and Process Development Approach for technology programs. Specific tasks for this UAV included a vertical takeoff, low altitude (50 foot) flight to a surveillance area, selection and stable surveillance (track) of a man sized object, and return and vertically land at a prescribed location. An interesting aspect of this effort was that virtual prototyping served as the study tool for the aircraft design effort. The process was very straight forward. High fidelity computer models of the aircraft components were consolidated together into a composite model of the entire aircraft. The composite model was used to study the overall layout of the aircraft. Material properties were assigned to the modeled parts to assure proper weight and balance of the aircraft. Testing was done on the virtual prototype to obtain estimates of inertial properties and analyze stability and aerodynamics associated with the vehicle. Required design changes were directly determined and performed in the virtual prototype model allowing great flexibility when conducting sensitivity studies.

Integration of payload elements was also studied with the virtual prototype. A model of the payload of interest was added to the virtual prototype allowing an analysis of the weight and balance and interference effects to be conducted for various mission payloads. This had the immediate benefit of allowing a great deal of flexibility with configuration early in the design process and points to a potential applicability to stores separation testing.

Boeing Aircraft Applications

Boeing is making extensive use of virtual prototyping in its newest aerospace test programs. This has led directly to reductions in the amount of flight testing required on new designs, saving time and money, with the end result being decreased time from concept exploration to production. Successful virtual prototyping was used in the development of the Boeing 777 commercial aircraft (reference 21). Eliminating the need for a physical prototype allowed Boeing to bring this advanced aircraft to the market in less than half the time it previously would have required. The Commanche program (reference 21) is yet another way virtual prototyping is being used to reduce flight testing. The Commanche team made extensive use of its virtual prototype and won the Army's largest aviation program. They did this by "flying" the virtual prototype during the Concept Exploration phase of the program, gaining insights to the advantages and problems of their design.

Applications to Store Separation Testing

Very little non-proprietary information exists on virtual prototyping in relation to ordnance separation which makes it difficult to accurately assess its applicability to this type of flight testing. However, based upon the ability to model discrete modules and assemble them in a test system as shown in the ARST example, store separation testing should lend itself well to this modeling philosophy. Using an existing database, a valid model of the host aircraft and carriage equipment could be developed in the DEMVAL phase with such high fidelity that the test team could decide to bypass traditional DEMVAL testing with a high degree of confidence. Instead, one could model new stores

and analyze separation characteristics in the same means as being demonstrated in the ASRT and Commanche programs in this phase. Then throughout the remainder of the product lifecycle, the model is refined to provide accurate system characteristics such that any testing required in the later stage of production is largely conducted in this virtual test arena.

NAWC-AD currently does not utilize virtual prototyping as a design method in store separation analysis. However, the U.S. Navy has conducted studies regarding this design process and NAWC-AD is well aware of the cost and time savings that could be realized by proper application of this technique on the design process. A Naval Air Systems Command study (reference 19) states that virtual prototyping "has the potential to allow technically superior systems to be developed while reducing the time to first article and reducing present day costs by 20 to 25%" and "that this technology has the potential to revolutionize the Department of the Navy's acquisition process". However, further studies are required to accurately assess how virtual prototyping may be properly implemented in store separation programs.

Stereolithography

Another area in store separation where virtual prototyping has provided an applicable spin-off technology is stereolithography. In stereolithography, a digital model is created by computer-aided design and then this is used to rapidly produce a plastic prototype. These rapid prototypes support concurrent engineering by allowing engineers to better assess and modify their designs. Stereolithographic-produced parts also enhance assessment of proper fit and interference for new stores. With high fidelity models, this

will have the immediate effect of all but eliminating the need for DEMVALs of most ordnance separation programs.

Other Research in the Virtual World

Much research is currently being conducted in the aeronautical and aerospace fields with respect to flight test modeling in the virtual world, from virtual prototyping of UAVs to engineering analysis of entire programs (references 18,22). The U.S. Navy and numerous aerospace companies are involved. Further, many non-aerospace companies are contributing to virtual prototyping for applications to their specific fields of interest. One area particularly interesting is that of the virtual pilot.

An area where the virtual world is being exploited in flight test is X-36 remotely piloted vehicle (reference 23). In this program, a human "pilot" interfaces with an advanced remotely piloted vehicle (RPV), testing a tail-less, highly maneuverable aircraft. The pilot sits in the telemetry room at a station configured with flight controls. Video and audio are provided from the aircraft via telemetry allowing one to have a cockpit view from the aircraft. This project is providing a low cost, safe way to test a radical new design in aviation. It does have its drawbacks however. On one particular flight, the pilot's video telemetry was lost resulting in the inability to manually control the aircraft. Fortunately, the aircraft was programmed to enter a holding pattern at a select waypoint should this problem occur. Telemetry was restored after several minutes and the flight was safely terminated. Should this simulation technique fully mature, new, high risk, proof of concept aircraft and systems can be tested at a substantial cost reduction over full scale developmental programs. As applied to ordnance separation

testing, this method could provide safe category D testing of new stores on new non-production aircraft, typically a combination of air vehicle and store considered too risky to test in most ordnance separation programs.

Future Applications in Product Life-Cycle Development

To fully benefit from these future applications, one must become aware of the appropriate life-cycle phase in which to implement them. As stated in Chapter 5, most ordnance separation flight test matrix reduction is realized through proper application of various modeling techniques in the EMD phase. A study prepared for the North American Technology and Industrial Base Organization (reference 26) suggests ways these future applications can be applied to the entire life-cycle of the test product. Using this study as a guide, one can visualize and integrate virtual prototyping into the entire life-cycle of the ordnance separation program.

First, if one is going to use virtual prototyping, one must start doing so early. For the ordnance separation program, this would involve the development of the virtual prototype in the DEMVAL stage. This development could be accomplished using experimental and analytical databases derived from the applicable techniques discussed in Chapter 5, such as wind tunnel analysis and computer-based simulations. With the existence of a virtual prototype model in which the test team has strong confidence, DEMVAL ordnance separation flight testing could be avoided and the program could proceed directly to EMD, similar to the Boeing 777 program.

In the EMD phase where most ordnance separation flight testing occurs, actual flight testing can begin at those areas identified by the virtual model as potential areas of

concern. Using data obtained from flight test, the computer-based theoretical models are refined and the virtual prototype model is updated as necessary. This process is continued in an iterative manner with the end result being the existence of a virtual prototype model which approximates actual store separation characteristics with very high resolution.

As the envelope expansion flight test ends and the EMD phase is completed, a virtual prototype model exists with such high fidelity that any subsequent testing required in the production phase is largely reduced to that which may be accomplished using computer simulations alone. If flight testing is required in this phase, it would then typically be conducted as endpoint demonstrations based on analogy. An ordnance separation program using this approach in the entire life-cycle would be able to safely avoid, to the maximum extent possible, any non-essential incremental build-up. The end result is the realization of the program manager's desires: successful ordnance separation flight test matrix reduction and subsequent program cost and schedule savings.

Chapter 7

Conclusions

General

The ability to reduce the flight test matrix is hinged to the degree of confidence the airworthiness authority has that the program is low risk. The tools available to the program manager must convince the authority that the risk is being adequately managed. In order for the program manager to safely avoid unnecessary incremental build-up and subsequently reduce the ordnance separation flight test matrix to the largest extent possible, an integrated testing approach is utilized with risk minimization as a continual focus. The exact approach taken varies according to the life-cycle phase and the characteristics of the store. Several programmatic solutions are employed throughout the entire life-cycle of the store to reduce matrix and minimize risks. Technical solutions are utilized to accurately predict store separation characteristics and increase test team confidence in the model to assess critical areas where incremental build-up may be safely avoided.

Programmatic Solutions Summary

Integrated Test Team Approach

An integrated test team approach is an effective means to reduce the size of an integrated flight test matrix. By co-locating the test team members under one program

manager, avoiding duplication of flight test efforts and utilizing a concurrent engineering approach, the program manager realizes significant reductions in the size of his flight test matrix throughout all phases of the program life-cycle, particularly the DEMVAL and EMD phases.

Risk Reduction

Risk identification, analysis, and reduction (or avoidance) are utilized to safely reduce the size of a flight test matrix. By identifying hazards and their causes, the test team avoids particularly hazardous areas of test and proceeds cautiously where warranted. Operational risk management, configuration control, and store release restrictions are utilized in all phases of the program life-cycle.

Technical Solutions Summary

Modeling

Identifying potential changes, discovering problem areas, and increasing test team confidence to bypass unnecessary incremental build-up are reasons to accurately predict performance when developing an EMD ordnance separation flight test matrix.

Current Flight Test Performance Predictors

Wind tunnel analysis and endpoint demonstration by analogy are methods used to minimize or avoid costly incremental build-up in the EMD phase and, in some cases, proceed directly the edge of the test envelope. The amount of matrix reduction that occurs is a result of the accuracy of the performance predictors and test team confidence in the models. Limitations to current flight test performance predictors include limited wind tunnel predictions with respect to flight conditions and limited usefulness of

endpoint demonstration by analogy due to the requirement to have analogous flight test data.

Emerging Flight Test Performance Predictors

Computer-based simulations are becoming extensively utilized in the EMD phase of ordnance separation flight testing. Ones such as PAN-AIR have limitations which confine their usefulness in complex ordnance separation study. New CFD techniques, such as SPLITFLOW, are being applied to the EMD phase of stores separation flight test programs and lead to more accurate modeling of adjacent store releases and transonic releases with a resultant increased test team confidence in the prediction model. With test team confidence and proper application and refinement of the models, unnecessary incremental build-up is avoided and time and cost savings are realized.

Future Applications

Much research is being conducted on modeling techniques and methods in the virtual world, with virtual prototyping lending itself to inclusion in store separation analysis. These new methods will allow accurate modeling of a system, increasing test team confidence and enabling the program manager to identify better designs earlier in the life-cycle process, locate potential areas of concern, and avoid unnecessary incremental build-up. They can be applied throughout the life-cycle of the ordnance separation flight test program such that flight test matrix reduction benefits may be realized in all phases of the product life-cycle.

Benefits

It has been shown that by reducing incremental build-up, the flight test matrix can be minimized and time and money savings can be realized. Using the scenario shown in figure A-2, removing just one test point anywhere in the test program life-cycle will result in a savings of over \$27,000. Additionally, due to the tight tolerances necessitated in ordnance separation flight test points, additional costs may be avoided by reducing the number of repeated data points. Existing NAWC-AD statistics indicate that a reduction in the size of the test matrix should result in a reduction in the amount of repeated test flights. Alleviating flights (reducing the size of the test matrix) reduces this potential and will save time and money.

Summary

There are many concerns which must be contended with when conducting ordnance separation flight testing. This includes completing projects safely, on time, and within budget. One is concerned with keeping the size of the flight test matrix as small as possible. There are several tools with which one may do this. The integrated approach of the test team using risk reduction techniques and operational risk management play a large part, as well as accurately modeling the predicted performance of the system. This has been proven using several examples of actual ordnance separation programs conducted at NAWC-AD and elsewhere. When properly applied, these tools give the program manager a way to safely minimize the flight test matrix, avoiding unnecessary incremental build-up and keeping the overall costs of the program down.

Chapter 8

Recommendations

General

An integrated T&E approach must be made to store separation testing to minimize the size of the flight test matrix. The modeling facets of the test program should be managed by one person, who is not necessarily an expert in CFD methods or wind tunnel testing, but understands the code, applications, and limitations. The program manager should have the authority and responsibility for ensuring the flight test program is conducted safely and cost-effectively. An integrated test team should be assembled as a conglomerate of talent that is physically co-located to facilitate open communication, rapid problem solving, and concurrent engineering. In all phases of the ordnance separation flight test life cycles, operational risk management should be implemented to avoid areas of unacceptable risk. In other words, the appropriate approach to ordnance flight test matrix reduction must come from a programmatic application of proper test team composition and operational risk management throughout all life-cycle phases of the test program. This must be coupled with a balanced, integrated technical application of the appropriate modeling techniques throughout the EMD phase.

Specific Recommendations

The exact modeling approach to be employed depends largely on the type of store to be tested. If the store is analogous to existing stores and a large data base exists, demonstrations based on analogies are the best way to minimize the flight test matrix. If large data bases do not exist, wind tunnel tests should be performed as an effort to gather data to identify critical areas. This data should be used in advanced CFD, such as SPLITFLOW with unstructured grids, to model the system such that sensitivity studies can be readily made.

If the store is not analogous to existing stores, wind tunnel data need to be obtained and a computer-based model needs to be derived, validated and verified. An iterative process for accomplishing this must be employed using flight test data as it becomes available. This improves the fidelity of the model and increases test team confidence when deciding which incremental build-up points, if any, can be avoided. If maneuvering flight separation characteristics are desired, then wind tunnel analysis can provide the initial database from which a computer-based model may be derived. However, sensitivity studies to these dynamic flight regimes should be made in the computer model.

Life-Cycle Phase Considerations

Further considerations depend on the life-cycle phase. Testing in the DEMVAL stage may be avoided with test team confidence in an existing model. If this is not the case, as with an entirely new store, or an existing model and/or test team confidence does not exist, then one or two test points must be flown.

Testing in the production phase should be largely reduced to endpoint demonstrations based on analogy or studies completed using CFD models, perhaps high fidelity virtual prototypes. This, again, depends on the confidence of the test team with these models.

In the EMD phase, the appropriate approach for modeling and subsequent matrix reduction of ordnance separation flight test is one which utilizes a combination of computational aerodynamics, wind tunnel testing, and flight testing to ensure safe store separation in a timely and cost effective manner. The program manager should not rely on any one technique (whether analytical or computational) to predict the store separation characteristics. Rather, the techniques should be combined, exploiting the benefits of one to aid in the other. This means using wind tunnel and analogous test data to aid in the development of proper CFD models so that complete sensitivity studies may be accomplished. These models are then refined using flight test results such that the test team can obtain a high degree of confidence in the model and very accurate predictions can be made.

Recommendations Summary

New methods of ordnance separation analysis are surfacing that will allow accurate methods to model a system, enabling the program manager to identify better designs earlier in the EMD phase, locate potential areas of concern, and avoid unnecessary incremental build-up. When integrated with current modeling methods, these give the program manager a powerful tool in the effort to accurately predict the separation characteristics of the test article. These performance forecast techniques, when

applied in an integrated approach which identifies and reduces risks throughout the product life-cycle, will give the ordnance separation program manager a viable way to avoid unnecessary incremental build-up and minimize the flight test matrix. By accomplishing this, significant cost and schedule savings will be realized while safely and successfully testing the weapon the warfighter requires in today's military environment.

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Appendices

Appendix A

Figures

TEST POINT	AIRCRAFT STATION									RELEASE CONDITIONS								REMARKS:
	1	2	3	4	5	6	7	8	9	ALT (ft MSL)	ALT. LOSS (ft)	BOTTOM ALT. (ft)	AIRSP (KIAS)	MACH (M/N)	ACCEL (g)	DIVE (deg)	DELIVERY MODE	
001										5000	N/A	N/A	550	0.90	1.0	0	QTY=1 MULT=1	= MK 81 Conical store code = 16
002										5000	N/A	N/A	575	0.95	1.0	0	QTY=1 MULT=1	= JDAM-84 store code = 14
003										5000	N/A	N/A	575	0.95	1.0	0	QTY=1 MULT=1	= JDAM-109 store code = 14
004										7000	4000	3000	575	0.97	0.7	45	QTY=1 MULT=1	= CATM-7 store code = N/A
005										12000	4200	7800	600	1.10	0.7	45	QTY=1 MULT=1	= empty 330 gal fuel tank store code = 01
006										20000	4700	15300	635	1.30	0.7	45	QTY=1 MULT=1	= empty 330 gal fuel tank optional store code = 01
007										20000	4700	15300	635	1.30	0.7	45	QTY=1 MULT=1	= Optional wing tip cameras store code = 7
008										20000	4700	15300	635	1.30	0.7	45	QTY=1 MULT=1	= Optional fuelage cameras store code = N/A
009										20000	4700	15300	635	1.30	0.7	45	QTY=1 MULT=1	

Figure A-1

JDAM Test Matrix

Inboard Ejection Test Matrix

TEST POINT	AIRCRAFT STATION									RELEASE CONDITIONS								REMARKS:
	1	2	3	4	5	6	7	8	9	ALT (ft MSL)	ALT. LOSS (ft)	BOTTOM ALT. (ft)	AIRSP (KIAS)	MACH (MIN)	ACCEL (g)	DIVE (deg)	DELIVERY MODE	
O10										5000	N/A	N/A	500	0.82	1.0	0	QTY=1 MULT=1	= MK 83 Conical store code = 16 = JDAM 84 store code = 14
O11										5000	N/A	N/A	550	0.90	1.0	0	QTY=1 MULT=1	= JDAM-109 store code = 14
O12										5000	N/A	N/A	575	0.95	1.0	0	QTY=1 MULT=1	= CATM-7 store code = N/A
O13										7000	4000	3000	575	0.97	0.7	45	QTY=1 MULT=1	= empty 130 gal fuel tank store code = 01
O14										12000	4200	7800	600	1.10	0.7	45	QTY=1 MULT=1	= Optional wing up cameras store code = 7 = Optional fuselage cameras store code = N/A
O15										20000	4700	15300	635	1.30	0.7	45	QTY=1 MULT=1	
O16										20000	4700	15300	635	1.30	0.7	45	QTY=1 MULT=1	

Figure A-1 continued

JDAM Test Matrix

Outboard Ejection Test Matrix

TEST POINT	AIRCRAFT STATION									RELEASE CONDITIONS								REMARKS:
	1	2	3	4	5	6	7	8	9	ALT ft HSL)	ALT. LOSS (ft)	BOTTOM ALT. (ft)	AIRSP (KTAS)	MACH (M/N)	ACCEL (g)	DIVE (deg)	DELIVERY MODE	
O17										5000	N/A	N/A	575	0.95	1.0	0	QTY=1 MULT=1	= MK 83 Conical store code = 16 = MK 84 General Purpose store code = 14 = JDAM-84 store code = 14 = JDAM-109 store code = 14
O18										7000	4000	3000	575	0.97	0.7	45	QTY=1 MULT=1	= CAPTIVE JDAM-84 store code = 13
O19										7000	4000	3000	575	0.97	0.7	45	QTY=1 MULT=1	= CATM-88 store code = 64 = CATM-7 store code = N/A
O20										5000	N/A	N/A	575	0.95	1.0	0	QTY=1 MULT=1	= empty 330 gal fuel tank store code = 01 = Optional wing tip cameras
O21										7000	4000	3000	575	0.97	0.7	45	QTY=1 MULT=1	= Optional fuselage cameras store code = 7 = Optional fuselage cameras store code = N/A
O22										7000	4000	3000	575	0.97	0.7	45	QTY=1 MULT=1	

Figure A-1 continued

JDAM Test Matrix

Adjacent Stores Ejection Test Matrix

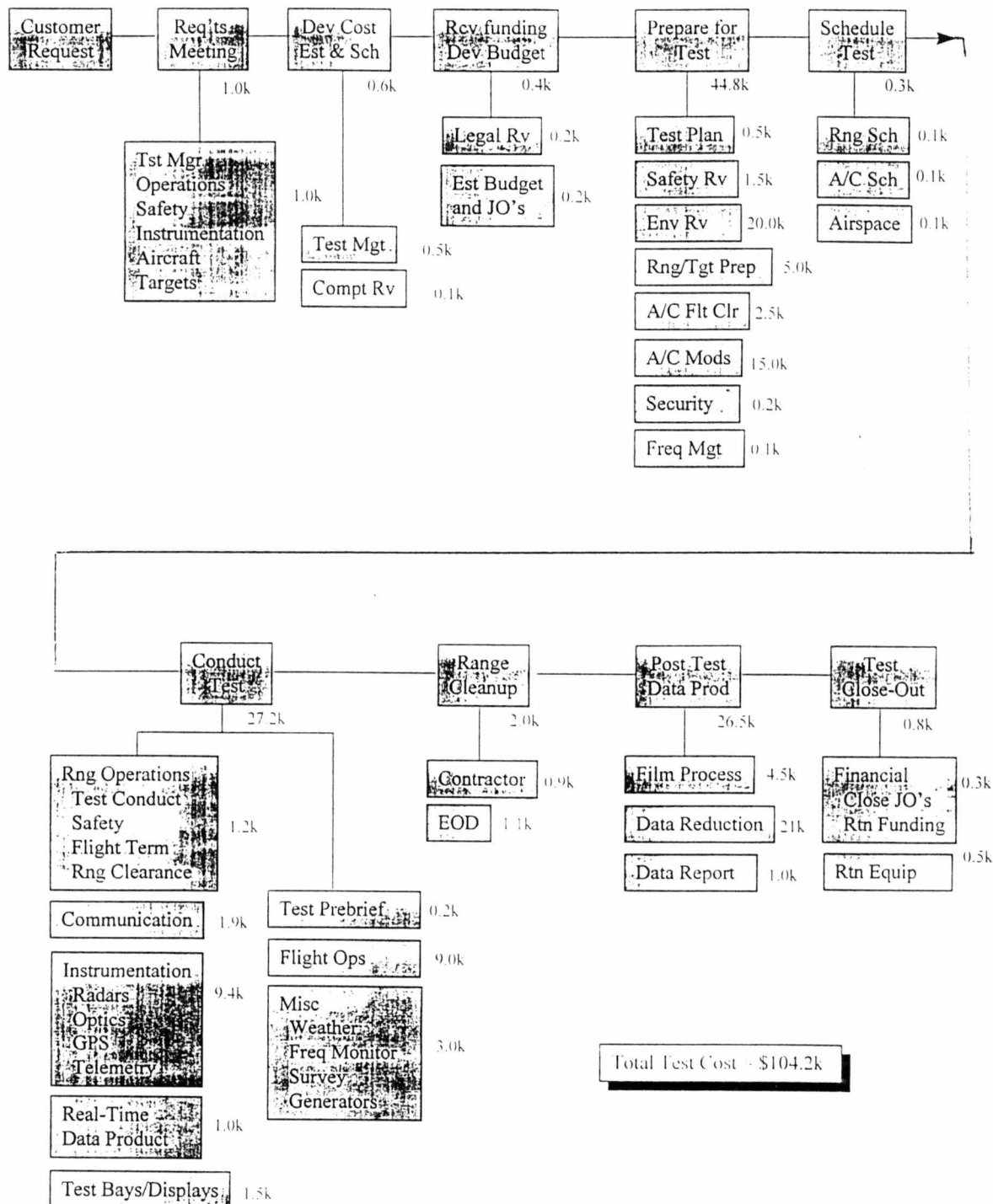


Figure A-2

Typical Test Scenario of an Air-to-Ground Weapon

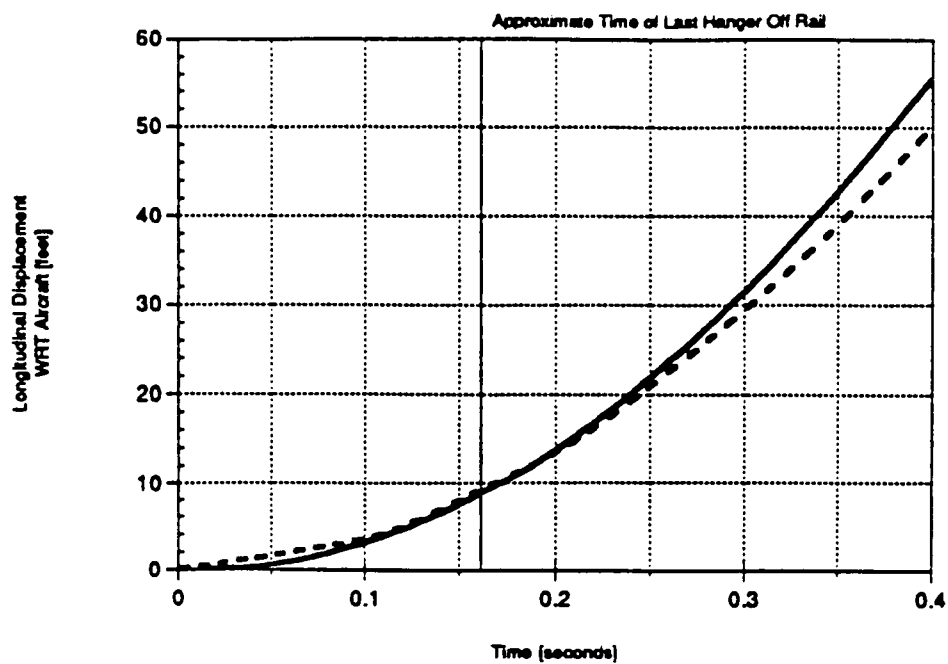
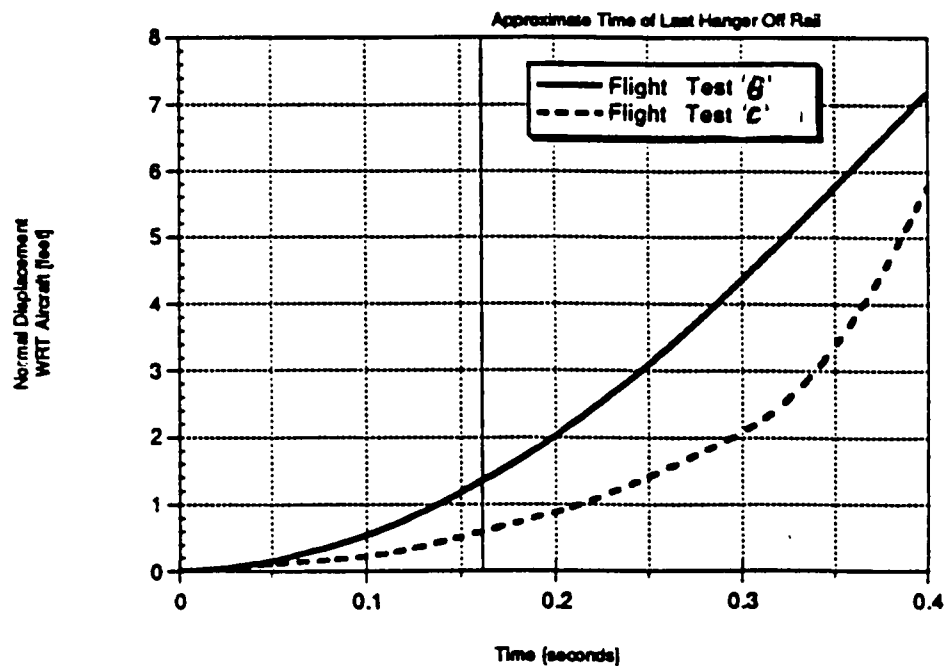
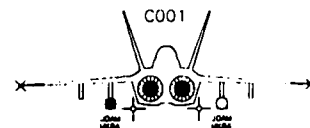


Figure A-3

AIM-120B Flight Test Data vs. AIM-120C Flight Test Data

JDAM/MK-84 / F/A-18 C/D FLIGHT TEST COMPARISON - FLIGHT 847
 JDAM FROM STA 3, AIM-7 ON STA 4
 0 896M/4624 FT/1 02G/0 DEG DIVE



SYM SOURCE
 □ 0.2 MODULAR SDF RESULTS
 ○ 5.0 PHOTOGRAMMETRY DATA
 ▲ 10.0 INTEGRATED WEAPON TELEMETRY DATA

— ABOVE
 - - - INBOARD
 - - - OUTBOARD

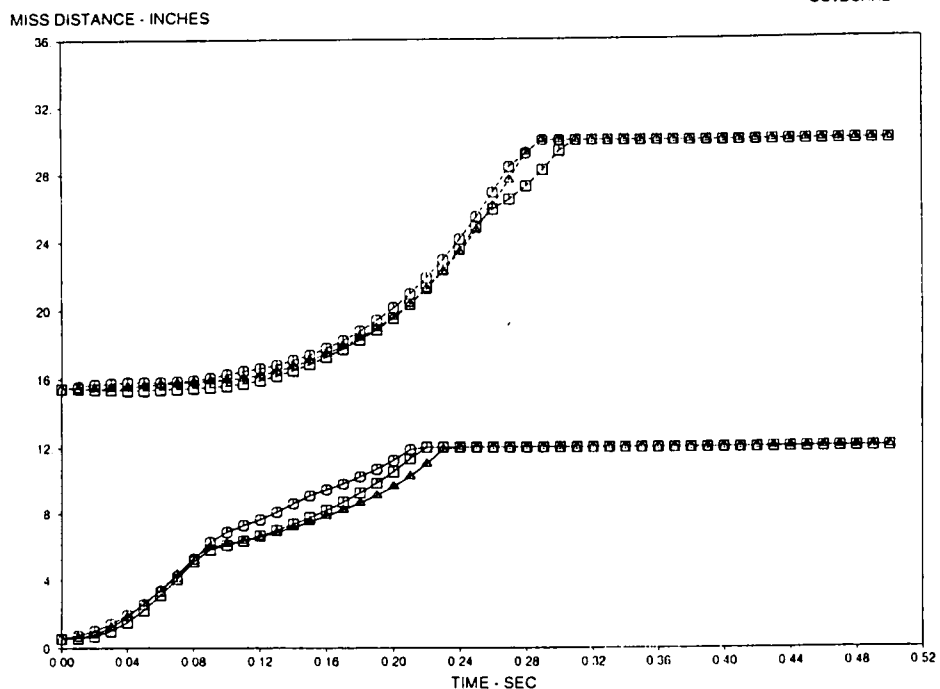
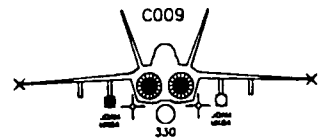


Figure A-4

JDAM Separation Predictions and Flight Test Data

0.9 IMN

JDAM/MK-84 / F/A-18 C/D FLIGHT TEST COMPARISON - FLIGHT 853
 JOAM FROM STA 3, AIM-7 ON STA 4, 330 GAL TANK ON CENTERLINE
 0.943M/4315 FT/0.82G/0 DEG DIVE



SYM SOURCE
 □ 02 MODULAR SDF RESULTS
 ○ 50 PHOTOGRAMMETRY DATA
 ▲ 100 INTEGRATED WEAPON TELEMETRY DATA

— ABOVE
 - - - INBOARD
 - - - OUTBOARD

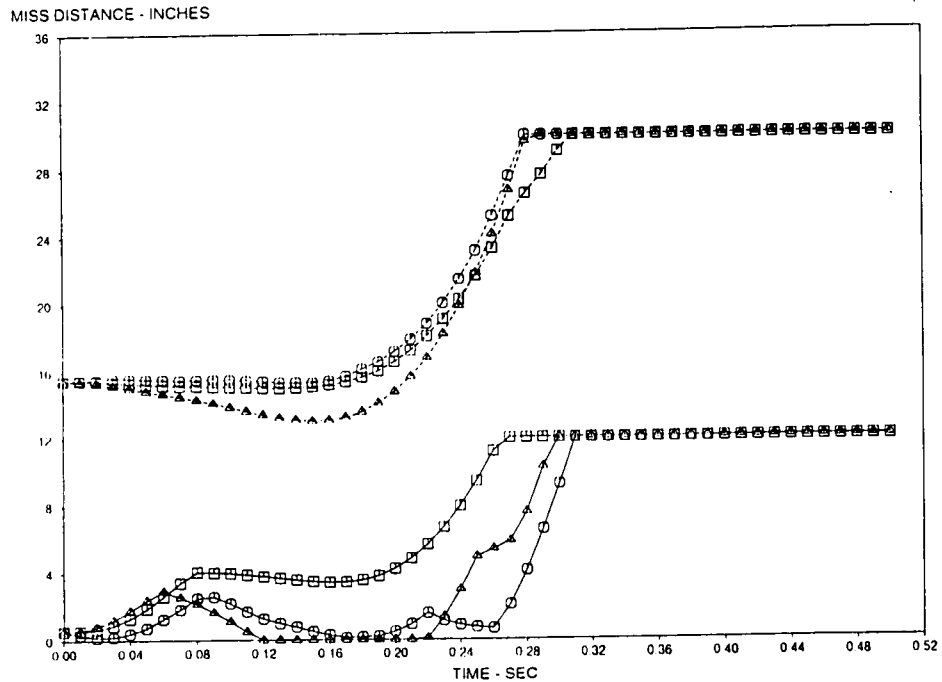


Figure A-5

JDAM Separation Predictions and Flight Test Data

0.94 IMN

F/A-18 C/D STORE SEPARATION
MDA JDAM/MK-84 FROM STATION 3 INBOARD PYLON
AIM-7 ON FUSELAGE

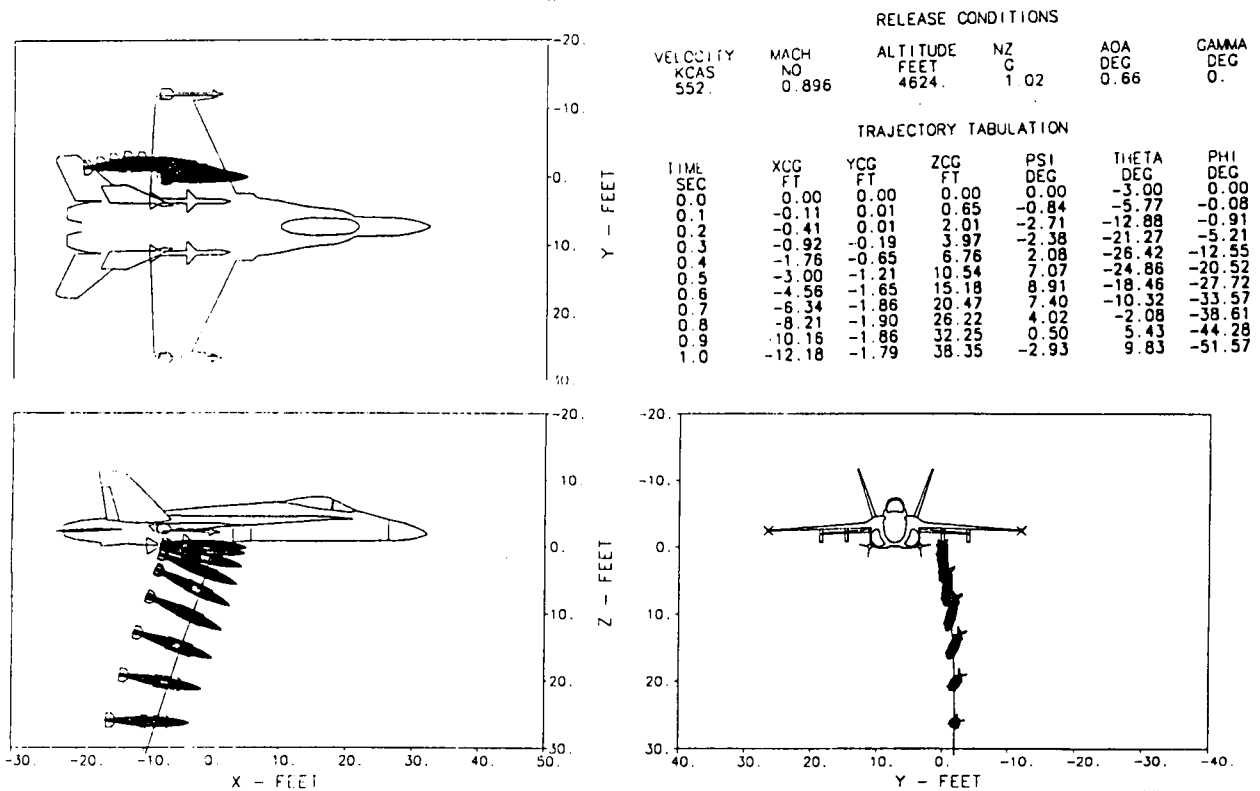


Figure A-6

JDAM Separation Pictorial

0.9 IMN

I/A 18 C/D STORE SEPARATION
MDA JDAM/MK-84 FROM STATION 3 INBOARD PYLON
AIM-7 ON FUSELAGE, 330 GALLON TANK ON CENTERLINE

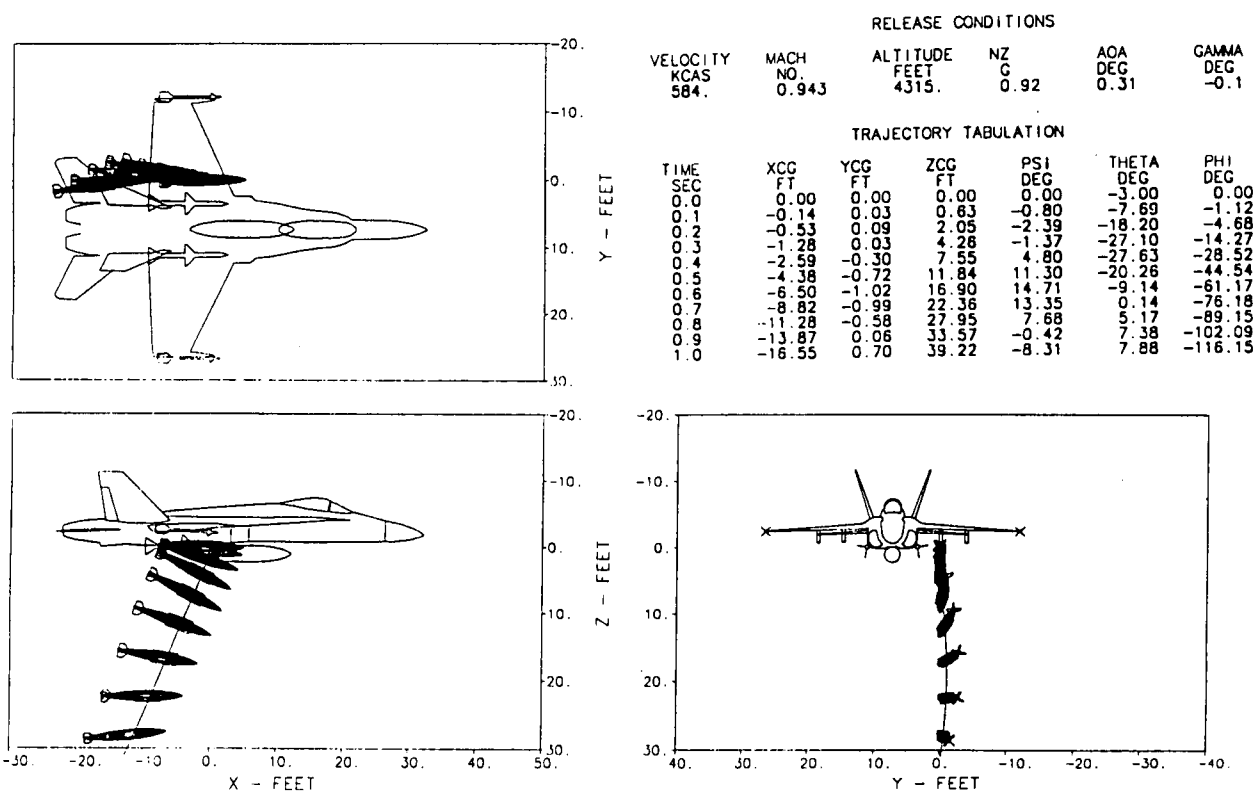


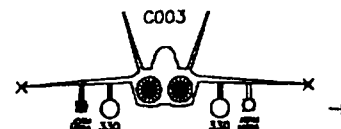
Figure A-7

JDAM Separation Pictorial

0.94 IMN

F/A-18 C/D / JDAM/MK-84 FLIGHT TEST PREDICTION - A/C ROLL EFFECT
 JDAM FROM STA 2, 330 GALLON TANK ON STA 3
 TEST POINT 15, 835 KCAS / 20,000 FT / .71 G / 46 DEG DIVE

NOTE: ONLY THE ABOVE CASE IS SHOWN
 (DISTANCE BETWEEN PYLON AND STORE FIN)



— ABOVE
 - - - INBOARD
 - - - OUTBOARD

MISS DISTANCE - INCHES

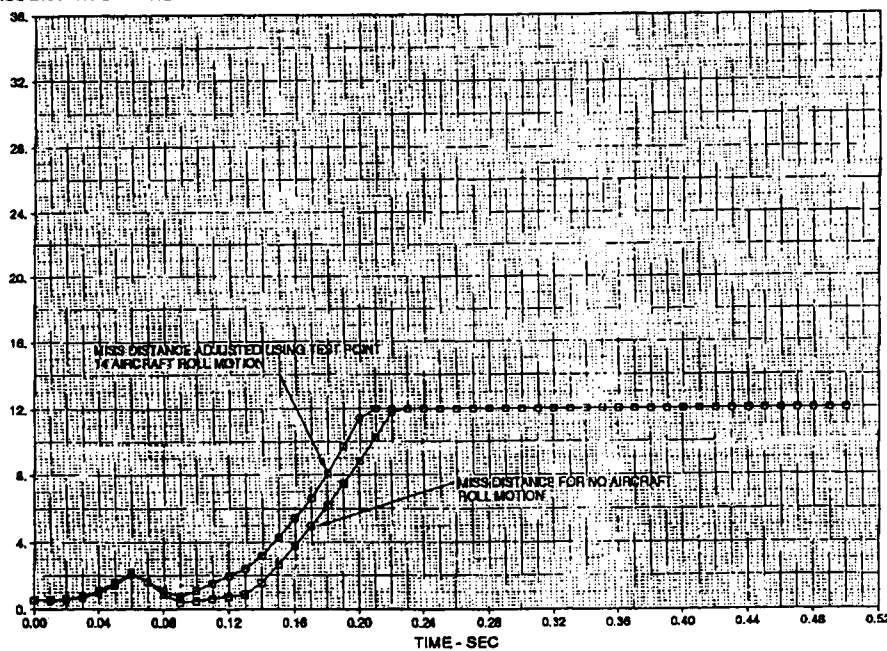


Figure A-8

JDAM Increased Miss Distance

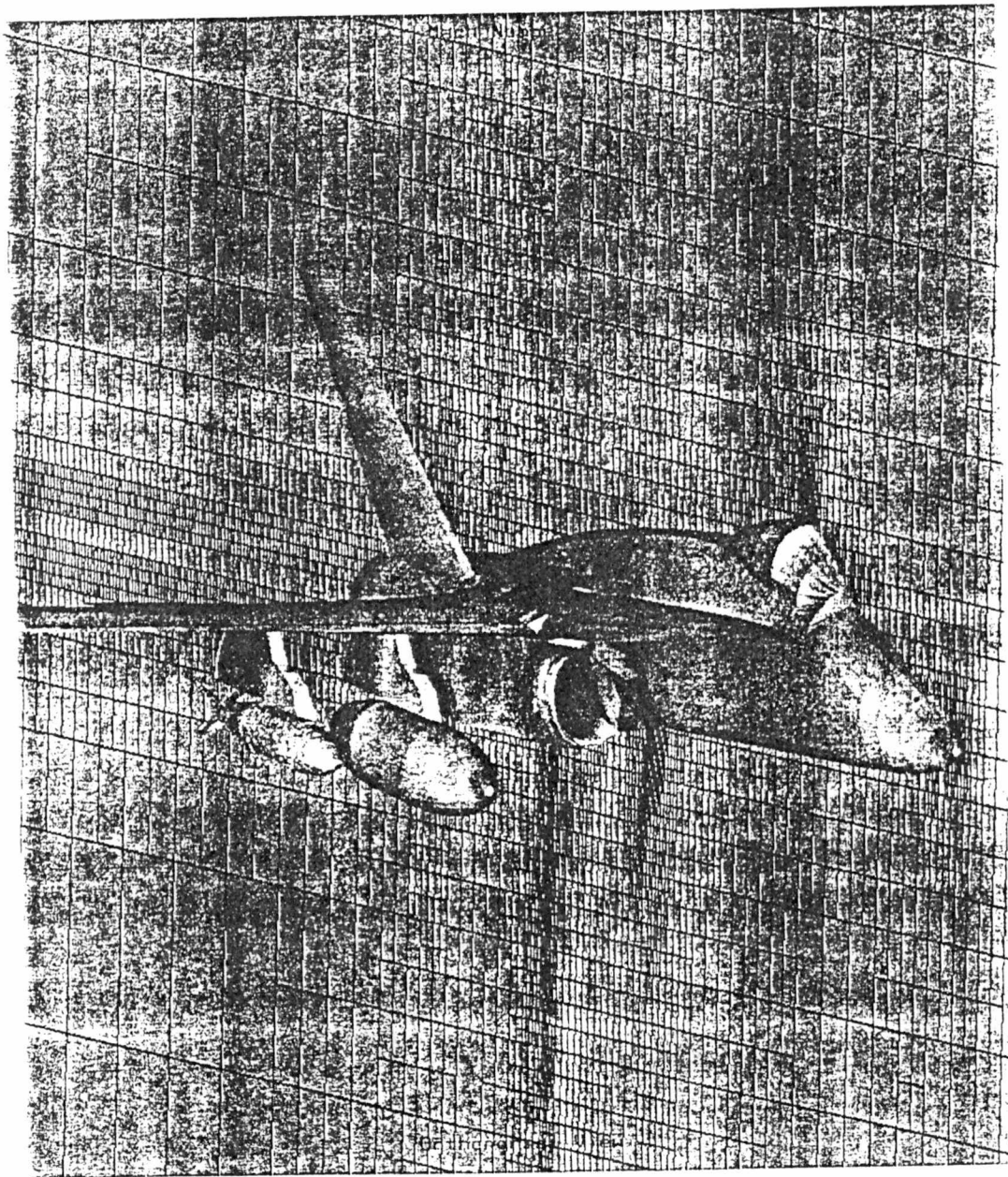


Figure A-9

JDAM Higher Order CFD Predictions Using Unstructured Grid

Appendix B

Tables

Table B-1

Sample Test Hazard Analysis

Hazard Condition	Cause	Effect (Severity)	Precautionary Measures	Corrective Actions	Risk Assessment	Hazard Level
Midair Collision	- Non adherence to altitude assignments - Lost sight of participating aircraft during maneuvers - Non participating aircraft (interloper) enters engagement - Excessive closure rates.	Loss of aircrew or aircraft	- Brief Knock-it-off criteria, remain in VMC and use good lookout doctrine. - Respond to traffic advisory calls promptly. - Notify participating aircraft of any interlopers. - Strict adherence to USNTPS Training Rules and pre-briefed altitude and operational maneuvering assignments	- Call "knock-it-off" - Establish safe separation between aircraft and conduct controllability checks at a safe altitude. - Terminate flight and proceed to nearest suitable airfield.	B	D-I
G-induced loss of consciousness (G-LOC)	Rapid onset of load factor (g)	Loss of aircrew or aircraft	- Perform g-awareness maneuvers prior to high-g (> 4g) maneuvers - Practice good aircrew coordination. - Review aircrew physiological stressors prior to flight (rest, nutrition, etc.)	- Cease aircraft maneuvering and call "Knock-it-off". - Non G-LOC aircrew will take control of aircraft and establish level 1g flight. - Terminate flight and proceed to nearest suitable airfield. - Inform Safety Officer after landing.	B	D-I
Aircraft departure from controlled flight	- High AOA. - High Yaw rate - Aft center-of-gravity. - Lateral asymmetry. - Misapplied control inputs.	Loss of aircrew or aircraft	- No high AOA (> 35 alpha) maneuvers are planned. - Brief Out-of-Control characteristics and recovery procedures. - Strict adherence to NATOPS flight limitations and procedures will be followed.	Perform NATOPS recovery procedures for Out-of-Control flight.	B	D-I

Table B-2
Residual Risk Matrix

Mishap Probability	Hazard Severity			
	I Catastrophic	II Critical	III Marginal	IV Negligible
A - Frequent	UA	UA	Risk Category C	Risk Category B
B - Probable	UA	Risk Category C	Risk Category C	Risk Category A
C - Occasional	(Note 1)	Risk Category C	Risk Category B	Risk Category A
D - Remote	(Note 2)	(Note 2)	Risk Category A	Risk Category A

Notes:

(1) The determination of a test project whose residual risk assessment falls under I/C will require up front discussions with TCT prior to proceeding with the test program development.

(2) Assignment of Risk Category where residual risk falls under I/D or II/D will require up front discussions with the TCT to determine whether Risk Category A or B is applicable.

(3) UA - Unacceptable risk, project residual risk too high to proceed.

(4) Risk Category C - Test or activities which present a significant risk to personnel, equipment or property, even after all precautionary/corrective actions are taken.

(5) Risk Category B - Test or activities which present a greater risk to personnel, equipment or property than normal operations.

(6) Risk Category A - Test or activities which present no greater risk than normal operations.

Appendix C
List of Acronyms and Definitions

List of Acronyms

ADL-	Armament Datum Line
AIM-	Air Intercept Missile
AMRAAM-	Advanced Medium Range Air-to-Air Missile
AR-	Aspect Ratio
ASRT-	Autonomous Scout Rotorcraft Testbed
C_{di} -	Coefficient of Induced Drag
CE-	Concept Exploration
CFD-	Computational Fluid Dynamics
CG-	Center of Gravity
Cl-	Coefficient of Lift
Cm-	Coefficient of Pitching Moment
Cn-	Coefficient of Yawing Moment
CTS-	Captive Trajectory System
DEMVAL-	Demonstration and Validation
DOF-	Degree of Freedom
e-	Efficiency Factor
EMD-	Engineering, Manufacturing and Development
F-	Fighter
F/A-	Fighter/Attack
g-	Normal Load Factor
GPS-	Global Positioning System

HARM-	High Speed Anti-Radiation Missile
IFM-	Influence Function Method
IMN-	Indicated Mach Number
ITT-	Integrated Test Team
JDAM-	Joint Direct Attack Munition
KCAS-	Knots Calibrated Airspeed
M-	Mach number of the aircraft
M_s -	Mach number of the store
MK-	Mark
MIL-HDBK-	Military Handbook
MIL-STD-	Military Standard
NAWC-AD-	Naval Air Warfare Center-Aircraft Division
ORM-	Operational Risk Management
PAN AIR-	Paneling Aerodynamics
R-	Radial distance from the store to the captive position
RPV-	Remotely Piloted Vehicle
T&E-	Test and Evaluation
UAV-	Unmanned Air Vehicle
Z-	Normal forces
α_p -	Angle of attack of the parent aircraft
α_s -	Angle of attack of the store
η -	Grid traverse angle from the vertical

Definitions

In an effort to standardize the terms used in the paper, the following are offered as generic definitions of many of the topics discussed. Where appropriate, the definitions refer to ordnance separation testing applications.

Air Vehicle - any device designed to be operated and controlled in the air. These can be manned or unmanned (remotely piloted or autonomous) and includes fixed wing airplanes and helicopters, but excludes air-launched missiles and flying bombs. This paper will use this term synonymously with aircraft.

Air Vehicle/Stores Compatibility - the ability of an aircraft, stores, stores management system, and related suspension equipment to coexist without unacceptable effect of one on the aerodynamic, structural, or functional characteristics of the others under all flight and ground conditions expected to be experienced by the aircraft/store combination (reference 3).

Flight Test - performing specific maneuvers with an airborne air vehicle such that specific observations can be made and data collected on parameters of interest (such as performance, flying qualities, etc.).

Flight Test Matrix - a table of the specific maneuvers to be performed by the airborne air vehicle. In ordnance separation testing, the aircraft's external loading configuration, aircraft Mach number and calibrated airspeed at release, normal acceleration at release, and release pitch angle are typically delineated in the matrix.

Modeling - a representation of anticipated flight test conditions for the purpose of forecasting system performance. Models may be computer simulations, scaled replicas

subjected to wind tunnels, analogous systems, or the like. In this paper, modeling will be used synonymously with performance predictions.

Photogrammetrics - an analysis technique used in ordnance separation testing where the test aircraft is outfitted with externally mounted cameras to simultaneously track specific points on a store and aircraft, as marked by highly visible "targets", to determine the spatial orientation of the store as it is released from the aircraft and exits the aircraft's flow field.

Simulation - an imitative representation of the functioning of a system. This paper will be concerned with theoretical simulations, such as computer-based simulations, as well as empirical simulations, such as wind tunnel studies.

Six Degree of Freedom Analysis - a simulation derived by the sum of flow field interference and store aerodynamic data that, when combined with appropriate initial conditions, provides rapid predictions of separation characteristics. Six parameters are generally used: X, Y, and Z position of the store in a three dimensional grid, and pitch, roll, and yaw.

Stores - any non-permanent device design to be carried by an air vehicle. This includes, but is not limited to, ordnance and jettisonable and non-jettisonable tanks, pods, and expendable.

Vita

Vita

William Oefelein was born in Ft. Belvoir, Virginia on March 29, 1965. He attended various public elementary and junior high schools while often relocating with his family due to military moves. He graduated from West Anchorage High School in Alaska in 1983. At this point, he enrolled the University of Alaska-Anchorage in 1983, transferred to the University of Alaska-Fairbanks in 1984, and transferred again in 1985 to Oregon State University where he received a Bachelor of Science degree in Electrical Engineering with a control systems concentration in May 1988. He entered the Naval service as a student Naval Aviator in August 1988 was designated a Naval Aviator in September 1990. He completed operational deployments in the F/A-18 Hornet and was selected to attend the United States Naval Test Pilot School in January 1995. Following successful training in December 1995, he began work as a developmental test pilot at the Naval Air Station, Patuxent River, Maryland. During this period, he entered the University of Tennessee's Master of Science program, receiving his degree in December, 1997.

He is presently an instructor at the United States Naval Test Pilot School, awaiting orders back to an operational F/A-18 Hornet squadron.