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Store Separation: State-of-the-Art

Summary Report

by

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ABSTRACT

Fields of past and present activity related to the development of operationally safe release envelopes for stores separating from aircraft in flight are surveyed. Various available theoretical methods for determining the complex interfering flow fields around aircraft-store combinations are examined, and some show promise sufficient to warrant further development on a priority basis. For this reason, the state-of-the-art of theoretical methods is emphasized in this report.

Available wind tunnel scale testing techniques are described. A degree of uncertainty remains as to the accuracy with which wind tunnel data can be employed to represent full-scale flight conditions. It is probable that much of the existing correlation data between full-scale experience and wind tunnel testing is invalid or inconclusive. Extensive flight testing, cumbersome and expensive, must still be employed at the present time for complete and final certification of store separation envelopes. There is a great need for a general mathematical model and computational capability that can describe the separation motion of stores from aircraft readily and accurately.

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FOREWORD

This report is part of a broad investigation of the separation of stores from aircraft under the Store Separation Program sponsored by William Volz, Aerodynamics Technology Administrator (AIR-320C) of the Naval Air Systems Command. It covers the past 2 years of effort under the program except for the analytical portion, which describes work accomplished, for the most part, in FY 1971 and FY 1972.

The task of assembling the information contained in this summary was performed during FY 1972 and FY 1973 under AirTasks A320320C/216B/2F00323201 dated 21 October 1971 and A3200000/008B/3F32320000 dated 7 September 1972.

This report is released at the working level for informational purposes only.

Under authority of
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19 June 1973

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INTRODUCTION

In July 1971, the Naval Weapons Center (NWC), China Lake, received an AirTask titled "Store Separation Program," the purpose of which is "to develop a coordinated technology to make a comprehensive evaluation of store separation in general and such integrated systems as conformal carriage; in particular, the analytical and simulation techniques and full-scale testing will be integrated into a program which utilizes to the maximum extent the advantages of each." One requirement of the AirTask is an annual state-of-the-art review of the work accomplished during the past year and the relationship of this work to work undertaken by Air Force, Army, and contractor facilities. This report is intended to satisfy that requirement, but covers the past 2 years of effort in the field.

The subject to be covered is, specifically, store separation, i.e., having to do with the motion of the store while in close proximity to the launch aircraft. However, where appropriate, comments regarding the larger field of aircraft/store compatibility are set forth. Since this is the first report, some space is devoted to reviewing past history to provide background for the last 2 years' work.

BACKGROUND

External weapons carriage on aircraft dates back to the early days of World War I and no doubt immediately resulted in store separation problems. The rapidly expanding technologies associated with aircraft design and the great increases in usable aircraft performance have (1) resulted in similar changing and increasingly severe problems in obtaining uniformly satisfactory separation of weapons from aircraft, and (2) strained the capacity of our military managements for farsighted planning and coordination necessary for solving these problems. Several milestones along the way are worth noting. The rapid development of the jet engine and its application to fighter and attack aircraft in the 1950-1960 time period provided the capability for ever-increasing airspeeds and increased load-carrying capability. The U. S. political and military strategy of nuclear deterrent up until the early 1960s led to the development of the A-4 aircraft, a lightweight, compact, relatively simple aircraft intended to carry one or two large, heavy weapons over short distances to strategic and large tactical targets, a mode for which the aircraft was never used.

Upon the entry of the United States into the Southeast Asia (SEA) conflict, strategies were shifted rapidly to those applicable to limited conventional warfare, marked entirely by the need for tactical rather than strategic air support. Although the Navy had maintained its fleet of A-1 (formerly AD) propellor-driven aircraft until the early stages of the SEA conflict, this aircraft--ideally suited for carrying large numbers of conventional munitions in the close-air-support (CAS) role--was rapidly phased out in favor of jet attack aircraft and had little direct U. S. use. The need was for aircraft to carry large numbers of conventional munitions, both those in stockpile (many of which were leftover from World War II) and a large number of new developments. This need sparked the rather hurried development of the means to allow the then current aircraft with few store-carrying stations to carry as nearly as possibile the numbers of weapons that represented their weight-limited capacity. Thus, the multiple bomb rack (MBR), which adapted up to six bombs to a single aircraft store station, was rushed into operation. Since this was a nonejection (gravity-drop) rack, a number of problems immediately arose due to collision of weapons with each other near the carrier aircraft, with the aircraft, or with weapons still on the aircraft--a very hazardous situation. The MBR was quickly replaced by the multiple ejector rack (MER) which also carried six weapons, and the triple ejector rack (TER) which carried three weapons. The MER and TER remain today the racks primarily used for adapting large numbers of munitions to a variety of attack and fighter aircraft. Since these racks had forced ejection, many of the problems with the MBR were relieved, but most were simply moved out to higher airspeeds and dive angles. Problems still existed, including weapon-aircraft collisions and large dispersions due to release perturbations. The practical result of these problems was to restrict--on an individual basis as problems arose--the numbers, positions, and mixtures of weapons carried, as well as the release speeds and dive angles for particular weapons-aircraft rack combinations.

While the Fleet operational personnel were encountering problems, the technologists also were having difficulty. The motion of a separating store depends on the forces and moments it experiences as it departs the aircraft. The forces and moments are determined by the initial release conditions (speed, altitude, dive angle, aircraft angle of attack, etc.), the net action of an ejector (where used), and the aeroballistic characteristics of the store, which include its mass and radii of gyration. The aerodynamic forces (and moments) can be conveniently split into the forces that would be acting if the aircraft were not present and the forces due to the nonuniform airflow about the aircraft, usually referred to as "interference" forces and moments. This last effect causes difficulty in predicting by theoretical, experimental, or empirical means, although the exact force-time history produced by an ejector in flight also remains a mystery. In the mid-1950s, methods of computing the flow about the aircraft based on linear aerodynamic theory were developed, and reasonably good correlations with experimental results were demonstrated for the relatively low-speed, simple single-store carriage systems then in use. However, the advent of aircraft capable of speeds beyond the critical speed--causing local supersonic flow and shock waves--and the introduction of the multiple carriage system so complicated the problems of computing the flow fields and forces induced on stores in these flow fields that only recently has the capability of high-speed computing machines raised hopes of developing reasonably valid, generally applicable theoretical methods.

The use of wind tunnels to test scale models of stores during separation from scale-model aircraft progressed reasonably well. By the mid-1960s, two general techniques had been developed which are now called dynamic-scaled free-drop and captive trajectory support (CTS) systems.

The dropping of dynamically scaled model stores from scale models of aircraft in wind tunnels was one of the earliest tunnel techniques used to study store separation problems. The dynamic scaling laws were well-known and by the mid-1960s the impossibility of exact scaling due to the intractability of gravity also was well-known. Heavy and light scaling techniques were improved to approach proper scaling from both sides. Although other problems exist, this technique remains a valuable tool capable of contributing to solutions of problems in store separation when properly used.

The CTS system is a much more complicated and sophisticated system. Development of useful systems centered on engineering development of support systems and linkages to provide large angular and position variations of the model store, of high-speed servodrive and controls, of on-line linkage to high-speed analog (in some cases digital) computers, and of software to rapidly and accurately perform the computations and control commands to the model support servodrive system. Again by the mid-1960s, a number of good systems were in operation in various industrial and government-operated wind tunnels. The captive trajectory support system can be used in two modes of operation: (1) to trace out a simulated trajectory under the influence of the measured and computed forces, or (2) to place the store model in a grid of positions relative to the aircraft model and measure and record the forces acting on the model at the grid points. This grid of space-dependent forces can then be used in a computer program to compute actual trajectories. A third technique, certainly not new, is greatly facilitated by use of the CTS system. This is to measure the flow field about the aircraft in terms of flow speeds and direction. To calculate store separation trajectories, it is necessary to be able to calculate the aerodynamic forces on the store in this nonuniform flow field. None of these wind tunnel techniques have turned out to be the ideal way to solve store separation problems.

Full-scale flight testing has long been employed as the final answer, which--almost by definition--it is. A major problem, however, has been the difficulty of accurately measuring all the variables of interest in the separation phenomena so an accurate data base is available for comparison with predictions and validation of prediction techniques. A number of techniques have been proposed; the combination of airborne and ground metric photography still seems to be the best way to determine the motions of the store and aircraft and their relative motions. Measurements of other variables, such as ejector force, aircraft angle of attack, etc., each present certain problems. None of the problems present serious technological difficulties except that, so far, the cost for obtaining the data is enormous. Thus, a large amount of drop testing has been and is being performed without obtaining useful data for store separation correlations.

While the technologist has been struggling to develop techniques and equipment to study and predict store separation phenomena, development groups and organizations also have been trying to solve "the store separation problem." New rack and ejector concepts have been proposed and in some cases carried into engineering development. Modular weapons concepts married to tangential or conformal carriage concepts have been proposed, and one (conformal carriage) is currently undergoing a full-scale flight evaluation. However, none of the proposed systems have, to date, demonstrated a feasible across-the-board solution to all the problems involved in the store separation process, and some have even introduced new problems of their own.

As mentioned earlier, in the past there have been a number of efforts to solve the store separation problem. A difficulty here has been that there are many problems associated with the store separation phenomenon and a solution to only one of these might not help the overall situation a great deal--indeed, might even make it worse. For example, being able to predict store separation motions accurately does not automatically insure improvements to unsatisfactory separations, and making separations "safer" could lead to increased dispersion, etc.

In the following sections of this report, each of the areas discussed previously will be reconsidered in more detail, particularly in the light of recent developments.

THEORETICAL METHODS

GENERAL COMMENTS

The most widely used methods of obtaining aircraft-store combination flow-field characteristics have been experimental. These wind tunnel and flight test techniques, which are discussed later, are time-consuming and expensive, and often leave many questions unanswered. Thus, it was decided to investigate present analytical methods that possibly could be used, perhaps with moderate development, to guide and supplement these experimental techniques. This section reviews currently available analytical techniques that have been or could be applied to store separation calculations. The material contained herein has received limited distribution via Ref. 218.

In this fast-moving field, any survey of the literature would be out of date almost immediately upon publication. Much progress has been made in the 2 years between the major work of this survey and publication, but this summary at least should give the newcomer to the field an idea of the techniques available and where to go for further information. The reader is urged to consult the original references for complete and accurate details. It should also be emphasized that this paper, of necessity, is not an evaluation of the work that has been done.

The user of analytical techniques is cautioned to employ them within their applicable bounds. For example, many techniques mentioned here are based on potential flow; often they are restricted to linear solutions to what, in reality, may be nonlinear problems. The assumptions for each method should be thoroughly examined for applicability to the particular problem; but, with judicious use, these techniques can serve as a guide to experiment and can indicate when one should expect a problem that needs further experimental investigation.

The work of Hess (Ref. 104-112) on wing-body interference flow fields is used here by Ryan (and in Ref. 214) to give a fundamental understanding of the basic concepts of finite elements involved in most of the techniques applied to store separation. The theory Hess employs for thickness effects serves as a useful background to other currently existing flow-field determination techniques. The description given here is necessarily brief, so the reader is referred to these references for details.

Hess' recent work on lifting effects brings his efforts to the stage where direct application to store separation problems is possible and highly desirable. An extension of his three-dimensional case with lift could be made for store separation problems. A known aircraft flow field, obtained either empirically or analytically, may be used in the program to save computing time; then the aircraft effect on the store would be known. The effect of the store on the aircraft flow field would not be known, but the effect would be small for a nonlifting store. It could be important for a lifting store. Such a program could be used as a subroutine for a trajectory program, but would take about a year to prepare.

Another investigator, Carmichael (Ref. 45-48), has used different types of singularities in an attempt to better represent a practical configuration with less computer time. Labrujere, et al (Ref. 145) have also worked on a wing-body interference problem in a somewhat similar manner.

Lockheed, in an unpublished work, has proposed attacking the problem using an integral technique involving an unsteady finite difference scheme valid throughout the subsonic, transonic, and supersonic flow regimes. This method satisfies the conservation equations throughout the flow field with the surfaces of the configuration as the flow boundary. The technique involves unsteady methods so the problem relaxes to the correct solution. As the complexity of the configuration increases, computer time also increases rapidly for this type of solution. The time involved for real cases might be excessive. But the computer time can be reduced substantially by making a good guess for the initial flow conditions. Recent advances in these time-dependent techniques indicate considerable saving in computer time may be possible It would be of interest to see further effort directed toward this type of solution. While there might be many difficulties in implementation, the possible results would be worth the effort.

Other workers, Fernandes (Ref. 71-76) and Nielsen (Ref. 190-191), have applied their efforts more directly to the store separation problem than to the more general wing-body interference flow problem. Their efforts, of course, would have more interest for the worker in the field than for the more general, but nonapplied, interference studies. Nielsen and Goodwin (Ref. 95-96) have, perhaps, the most comprehensive subsonic engineering approach available at this writing. They have had the advantage of experimental data (Ref. 209, 210, and 248) designed specifically to check their theory. Thus, they are in a position to determine the simplest analytical techniques required to obtain acceptably accurate results for the particular problem with minimum computer time. This effort has been linked with a trajectory program to present the results in a form needed by operational engineers.

Fernandes' encouraging results were obtained by employing linear theory, without two-dimensional or slender-body assumptions, to predict the loading on pylon-mounted stores in both subsonic compressible flow and supersonic flow. The flow field produced by the aircraft wing, nose, inlet, and pylons is predicted by the method, as are the locations of aircraft shock waves in supersonic flow. Their effect on the flow field is included through a transformation of the aircraft geometry. The interference loading is integrated over the store length by considering the local crossflow, its axial and radial derivatives, and buoyancy.

Many workers have directed their efforts toward predicting the trajectory after having assumed, or otherwise obtained, a flow field. Two of these efforts are an experimental-statistical approach by Sekellick (Ref. 229-231) and an analytical safe-separation criteria based on geometry, force, and mass inputs by Covert (Ref. 52-54). Other programs designed to predict captive flight loads are those of Grose (Ref. 98, 99), Thomas (Ref. 257-259), and Serbin (Ref. 232). Finally, the works of Rubbert at Boeing[1] (Ref. 215-217), Martin at Auburn (Ref. 180, 181), and Chadwick at Dahlgren (Ref. 49) should be cited.

To summarize, in using analytical techniques, the investigator should keep in mind at least two main ideas: (1) the approximations must be consistent with the realities of the configuration being studied and (2) the results should be used first as a guide to testing and to cut down the amount of test time required. Computer time may be expensive, but it is much less so than wind tunnel or flight test time. In using analytical techniques, it is possible to determine when an extreme situation will occur, but the behavior under these circumstances cannot be well-calculated at this time, nor can very complex configurations.

There continues to exist, then, a great need for a general mathematical model and analytical capability, perhaps complemented with limited tunnel data, which will describe readily and accurately the separation motion of arbitrary stores from arbitrary aircraft, to the end that safe and functionally acceptable flight separation envelopes can be developed and maximized on the computer. It is asserted by authorities Nielsen and Fernandes that the present state-of-the-art could, in all probability, be extended to adequate general usefulness by a concentrated, integrated effort. It is the opinion of the authors that a planned, priority program that sponsors the best talent in the country in a major effort to advance this capability is clearly in order.

In the following pages, various of these theoretical methods are discussed in more detail.

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[1] Rubbert, P.E. "Feasibility Study Concerning the Computation of Sideslip Effects Utilizing Current Numerical Methods." (Unpublished Boeing Report, performed under contract NAS 2-5006.)

INTERFERENCE FLOW FIELDS

Hess (Ref. 104-112)

For over 13 years, John L. Hess and A.M.O. Smith of McDonnell-Douglas, Long Beach, have been developing a general method for calculating the incompressible potential flow about arbitrary shapes. With the recent introduction of lift effects, the technique is at the stage of development where it could be useful for flow field calculations in connection with store separation problems. The theory employed for thickness effects serves as a useful background to the other currently existing flow field determination techniques. The description given here is necessarily brief; therefore, the reader is directed to the references for details and is warned of the dangers of too concise a presentation.

The Navier-Stokes equations are the basis of any aerodynamic program of this type. The assumption of potential flow (no viscosity, $\eta = 0$) and incompressible flow (density constant, ρ = constant) yield the Eulerian equation of motion

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \text{grad})\, \vec{V} = - \frac{1}{\rho}\, \text{grad } P$$

and the continuity equation

$$\text{div } \vec{V} = 0$$

where

V = velocity
P = pressure
t = time
ρ = density

Whenever assumptions are made, the question must be asked, "When do the solutions resemble real flow?" Since viscosity is assumed zero, the technique is not accurate near catastrophic separation such as wakes. The assumption of incompressible flow restricts the Mach number to ≤ 0.5, although under some circumstances solutions are acceptable to Mach 1 when there are no local supersonic regions.

The flow is split into two velocity fields

$$\vec{V} = \vec{V}_\infty + \vec{v}$$

where $\vec{V}_\infty$ is the onset flow and has no boundaries. It is not necessarily irrotational. $\vec{v}$ is the disturbance velocity due to boundaries. The disturbances are not necessarily small, but the flow is irrotational.

The resulting equation is Laplace's

$$\nabla^2\phi = 0, \quad \phi = \text{velocity potential}$$

with boundary conditions

$$\text{grad}|\phi \cdot \vec{n}|_S = \frac{\partial\phi}{\partial\eta}\Big|_S = \vec{V}_\infty \cdot \vec{n}|_S - F$$

where

n = normal to the surface S
η = dummy variable
F = force

and regularity condition

$$|\nabla\phi| \to 0 \text{ at } \infty$$

A small number of analytical solutions of this equation are available and they are obtained by the separation of variables technique. The primary value of these solutions is in the evaluation of approximate solutions or exact numerical methods.

Exact numerical methods may be defined as exact analytical formulations solved by approximate numerical methods such as rounding off of decimals and integral solution by quadrature. The errors may be made small by refinement of the numerical calculations. Approximate solutions introduce analytical approximations into the formulation of the problem. Thus, there is a limit on the accuracy of the solution, regardless of how the numerical procedures are refined. Examples of such approximations are the assumptions of slender body, thin wings (interior singularities), and small perturbations. Before the general availability of high-speed electronic computers, the approximate techniques were the most widely used.

With the advent of large digital computers, numerical techniques have become a very powerful tool. Some numerical techniques available are the finite difference approximation of the Laplacian operator or a form of Green's function. Of the several methods, the most efficient appears to be one that forms an integral equation over the boundary surface. A brief, cursory outline of this method will be presented next.

Consider the potential, ϕ, at point P with coordinates (x,y,z) due to a point source located at point p_1 which has coordinates (x_1, y_1, z_1),

$$\phi = \frac{1}{d(P,p_1)}$$

where d is the distance between P and p_1.

$$d(P,p_1) = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2}$$

The potential ϕ satisfied the Laplace equation at all points except p_1, and the solution to the problem is made of a distribution of elementary potentials of this form.

Now consider p_1 a general point of the flow with $\sigma(p_1)$ the source strength at that point. The potential measured over the surface is then

$$\phi = \iint_S \frac{\sigma(p_1)}{d(P,p_1)}\, dS$$

A Dirac delta function is used for the representation at the point p_1 on the surface.

Differentiating this potential and allowing P to go to p and satisfying the boundary conditions, yields

$$2\pi\sigma(p) - \oiint_S \frac{\partial}{\partial n}\left(\frac{1}{d(p,p_1)}\right)\sigma(p_1)\, dS = -\vec{n}(p) \cdot \vec{V}_\infty + F$$

This expression is a Fredholm equation of the second kind over the surface S. The first term comes from the Dirac delta function. The kernal in the second term, $\frac{\partial}{\partial n}\left(\frac{1}{d(p,p_1)}\right)$, is the outward normal velocity at point p due to a unit point source at point p_1. This factor depends only on the geometry of the surface S. The boundary conditions enter only on the right-hand side of the equation.

The surface can be any arbitrary body and need not be limited to slender or analytic. But the prescribed boundary value must be a continuous function of position on the surface. Thus, the method is not suitable for problems having unknown boundaries, such as might be encountered in a design study.

Two methods of solution suggest themselves for this type of problem. One is a direct solution of the integral equation using an iterative procedure appropriate for the Fredholm integral equation. The other, the one used by Hess and Smith, is to approximate the integral equation by a set of linear algebraic equations and solve the set by the usual techniques.

The boundary or body surface is approximated by a large number of surface elements, the characteristic dimensions of which are small compared to those of the body. The value of the surface source density is constant for each element. Thus, there is one constant σ for each element and, therefore, the unknown σ can be taken out of the integral. Then the integral is a function of known geometrical quantities only.

A control point is selected on each element where the equation holds and the normal velocity takes on its prescribed value. Thus are obtained the same number of algebraic equations as unknown σ's. When these equations are solved, the velocities and pressures at the control points may be calculated.

The input to the computer consists of the body surface about which the flow is computed. This input usually consists of the coordinates of points distributed over the surface. If the onset flow is not a uniform stream, it must be input. Unless the prescribed normal velocity is the usual value of zero, it also must be input.

The accuracy of the calculation depends on the number and distribution of surface elements. A very simple shape can usually be approximated by less than 200 elements. A fairly complex shape including multiple bodies requires 500 to 1,000 elements to be properly represented. Elements should be concentrated where the body geometry or the flow properties are changing rapidly but the size of neighboring elements must not be too dissimilar.

Computing time is hard to estimate because it depends so much on the machine used. However, a general idea of the order of magnitude can be obtained from the Douglas experience with the IBM 7094. For the axisymmetric and two-dimensional problems, time is approximately proportional to the cube of the number of elements. For 100 elements, about 0.6 minute is required for the computation of the linear algebraic equations. The rest of the problem takes about 1 minute for the two-dimensional case and 2 minutes for the axisymmetric part. A three-dimensional body with 650 elements and one symmetry plane takes about 1 1/2 hours. If the case is unfavorable, it could take 3 hours. The time is approximately proportional to the number of elements squared.

For most store separation problems, lift is quite important, but the inclusion of lift is a difficult problem that has been solved only recently. For three-dimensional configurations, there are fundamental questions concerning the nature of lift. For example, what are the tip problems, what is a trailing edge, where and how must the Kutta condition be satisfied, how does one take care of the vortex sheet for deflected flaps? For two-dimensional problems, Hess handles the lift routinely, including the unsteady shed vortex wake. Three-dimensional problems can be handled with his most recent work, which has answered some of the above questions.

The computing times involved for most practical store separation problems are excessively long. Also, with a limitation of 1,000 panels for the three-dimensional case, simulation of real configurations may not yield the accuracy desired. For these reasons, among others, superposition techniques are being developed. Using these techniques, it is also possible to calculate three-dimensional lifting flows by superposing lifting two-dimensional solutions and various nonlifting solutions. In some cases, computing time may be avoided entirely by superposing previously calculated results.

Consider the case of body A in the presence of another body B when it is desired to compute the flow field around body B. The "exact" solution simultaneously satifies all flow conditions and boundary conditions (call it $\vec{V}_T$ - exact). The most approximate solution can be obtained when conditions are satisfied for body B alone ($\vec{V}_T$ - isolated). The interference may be expressed as $\vec{V}_T$ - exact minus $\vec{V}_T$ - isolated. Note these velocities ($\vec{V}_T$ - exact and $\vec{V}_T$ - isolated) are tangent to the particular bodies since the boundary condition of no flow through the surface is satisfied.

The flow field due to body A may be calculated at the location where body B would be, but not satisfying the boundary conditions for body B. This velocity may be called $\vec{V}_S$. The velocity at some average point of where body B would be (e.g., the centroid) may be labelled $\vec{V}_O$. Of course, these velocities are not tangent to body B, since no attempt was made to satisfy the boundary conditions for body B. Our purpose now will be to calculate the flow field at body B using superposition techniques.

The first and usually most accurate form of superposition is to consider flow $\vec{V}_S$ (obtained as described above) as the onset flow. That is, substitute $\vec{V}_S$ for $\vec{V}_\infty$ in the equation

$$2\pi\sigma(p) - \iint_S \frac{\partial}{\partial n} \frac{1}{d(p,p_1)} \sigma(p_1) dS = -\vec{n}(p) \quad \vec{V}_\infty(p) + F$$

For this type of superposition, the effect of body B on body A which, in turn, can change the flow field in the region of body B, is neglected; but this effect is usually small.

The second and usually next most accurate form of superposition employs $\vec{V}_O$, the velocity at the centroid, as the onset flow to body B. In this case, in addition to the assumption above, the variation of the onset flow over the body is neglected.

Another superposition technique is to vectorially add the entire velocity due to the isolated body B ($\vec{V}_T$ - isolated) plus the perturbation velocity due to body A ($\vec{V}_S - \vec{V}_\infty$) at the location of body B. This vector sum is not tangent to body B. In the usual case, the third most accurate type of superposition is to consider the tangential component in this vectorially summed velocity.

The accuracy indications given above were obtained from computer experiments using cylinders as the bodies. For a particular class of configurations, the range of validity may be obtained by comparing the "exact" solutions with the superposed solutions. These superposition techniques must be used with care.

A possible extension of the three-dimensional case with lift could be made for store separation problems. A known aircraft flow field, obtained either empirically or analytically, may be used in the program to save computing time. Then the aircraft effect on the store would be known. The effect of the store on the aircraft flow field would not be known, but the effect would be small for a nonlifting store. It could be important for a lifting store. Such a program could be used as a subroutine for a trajectory program, but would take about a year to prepare.

The existing potential flow program has been widely distributed; 62 companies had the program in 1964. The most used program is the axisymmetric which is about two boxes of cards long. Representative computing time on an IBM 360-65 is approximately 1 hour for one case, of which, about one-half is CPU time. The present three-dimensional program, consisting of about two full boxes of cards, is essentially unsolved, since it does not contain lift. The addition of lift will probably mean the addition of another box of cards.

Carmichael (Ref. 45-48)

With the advent of high-speed computing machines, the finite element method became practical. The technique is not merely an extension of methods used before the widespread availability of computers, but is a combination of analytical and numerical methods having application to complex configurations limited only by the computing time and capability available.

As described previously, the method consists of solving the linear partial differential equation by the superposition of large numbers of elementary solutions with approximate satisfying of the boundary conditions. Carmichael's approach is to employ several different types of finite element components used to their best advantage.

Each of these finite element components is an exact solution to the linearized partial differential equation and thus the superposition is also an exact solution. The approximation comes into the choice of number and location of control points for satisfying the boundary conditions.

There are three types of elementary solutions. One type is the point elements, which are sources (and sinks) or doublets. The line elements are sources, doublets, and vortices. The line sources can be conveniently used to describe a body of revolution with zero angle of attack. The addition of line doublets will simulate angle of attack.

Surface elements (thickness and lifting) can be used to describe wings. Wedges with swept leading and trailing edges are used for thickness. For the lifting effect, thin surfaces are used which will support a constant pressure differential across the surface.

Carmichael chooses line elements to describe the isolated body and surface elements for the isolated wing. These elements in close proximity will violate the boundary conditions of no flow through the surface. Therefore, in the presence of interfering flow fields, additional elements are needed to satisfy the boundary conditions. He does this by locating surface elements on the body and adjusting the pressures simultaneously on the wing and body. Since this technique provides mutual interference, no iteration is required.

The wing-body-tail program can handle 100 surface panels on the wings and 100 surface panels on the body. This program has been widely distributed and is in use by many investigators, mostly for configuration analyses. The original program is limited to smooth bodies of circular cross section, reasonably thin wings, and a constant diameter body in the region of interference. This program is based on work by Woodward and Boeing, both under contract and in-house.

An extension to the program allows 10 bodies (256 body surface panels) and 20 wing segments (256 wing surface panels), but requires a large computing machine. Typical run times on an IBM 360/67 duplex system are 10 to 12 minutes. The assumptions in the program include linearity, boundary conditions are satisfied at a finite number of points, pylons are treated like wings, characteristic lines are linear, and trailing vorticity is assumed to go straight back.

The primary input data is the geometry of the system. There are three types of possible solutions:

1. Given loading, compute shape.
2. Given shape, compute loading.
3. Given total lift, obtain the surface for minimum drag (supersonic flow).

Comparisons with linear theory and slender-body theory are very good thus far. There are problems with high wing sweep (75 deg) as C_L (lift curve slope) is over-predicted. Another unresolved problem is the inclusion of $\dot{\alpha}$ (change of angle of attack with time). Perhaps the major difficulty concerns the directional problem and, as yet, no satisfactory solution has been found.

Labrujere, Loeve, Slooff (Ref. 145)

In previous work the authors presented two-dimensional flow solutions with and without lift, and the nonlifting three-dimensional case. The paper described here (AGARD 1970 No. 11) is an attempt to include lift in the three-dimensional case for a wing-body configuration.

The equation for potential flow assuming small perturbations and incompressible flow is Laplace's

$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0$$

where the boundary conditions are

$$\phi = 0 \text{ at } \infty \text{ upstream}$$

$$\frac{\partial\phi}{\partial n} = -\vec{n}\vec{U}_\infty \text{ at the body surface}$$

where

ϕ = velocity potential
x,y,z = coordinate
n = normal
U_∞ = free-stream velocity

The inclusion of lift (circulation) requires representing the wake as a vortex sheet. The assumption is made that the vortex sheet behind the body is a continuous extension of the sheet behind the wing. The shape of this sheet is unknown, yielding a nonlinear problem. It may be linearized by requiring the sheet to be rigid with a prescribed direction at the trailing edge (here velocity is taken tangent to the sheet at the trailing edge).

The resulting problem can be solved in a manner similar to that used by Hess-Smith. The configuration surface is divided into many quadrilateral panels each containing a source singularity. The division is such that the source distribution is of constant strength. In addition there must be a series of horseshoe vortices located along the surface of discontinuity behind the wing and body and along the camber surface of the wing with extension inside the body.

Each panel has a source located at its centroid. Additional control points are also chosen for each panel that contains a vortex sheet. The choice of these latter control points is not an easy matter.

The resulting system of equations may be expressed in matrix form.

$$[M] \cdot \vec{m} = \vec{R}$$

where $\vec{R}$ is the vector of boundary values, $\vec{m}$ is the vector of unknown singularities, and [M] is the matrix of influence coefficients and is dependent on geometry.

The authors present this equation in expanded form in order to look at the physical meaning:

$$\left[\begin{array}{c|c} S_b & V_b \\ \hline S_v & V_v \end{array}\right] \cdot \left|\begin{array}{c} \sigma \\ \hline \Gamma \end{array}\right| = \left|\begin{array}{c} R_b \\ \hline R_v \end{array}\right|$$

where

S_b represents the influence of the sources on the surface control points

S_v represents the influence of the sources on the vortex sheet control points

V_b represents the influence of the vortices on the surface control points

V_v represents the influence of the vortices on the vortex sheet control points

σ is the source strength

Γ is the vortex strength

R_b is the source boundary condition

R_v is the vortex boundary condition.

Thus the matrix form can be broken up as follows:

$$S_b\sigma + V_b\Gamma = R_b$$

$$S_v\sigma + V_v\Gamma = T_v$$

or

$$\Gamma = (R_v - S_v S_b^{-1} R_b)/(V_v - S_v S_b^{-1} V_b)$$

S_b can be approximated by

$$A = \begin{vmatrix} A_1 & 0 & \cdots & 0 \\ 0 & AL & & \vdots \\ \vdots & & \ddots & \\ 0 & \cdots & & Am \end{vmatrix}$$

Thus

$$\Gamma = (R_v - S_v S_b^{-1} R_b) B^{-1}$$

where

$$B = V_v - S_v S_b^{-1} V_b$$

and

$$\sigma = A^{-1}(R_b - V_b \Gamma)$$

Let $A^* = S_b - A$, the error in the approximation. Then an iterative procedure may be followed by replacing R_b by $R_b^{(1)} = -A^*$ (the residue solution) and R_v by $R_v^{(1)} = 0$. Then

$$\Delta\Gamma = B^{-1}\left(R_v^{(1)} - S_v A^{-1} R_b^{(1)}\right)$$

$$\Delta\sigma = A^{-1}\left(R_b^{(1)} - V_b \Delta\Gamma\right)$$

For the cases considered thus far, convergence has been obtained in 10 to 15 iterations; but the convergence rate depends on the complexity of the configuration and could be excessive for store separation problems. However, the iterative solution gives a very considerable saving in computer time over the direct method.

Corrections for compressibility (below the critical Mach number) may be obtained by the usual transformation

$$x_a = x, \quad y_a = \beta y, \quad z_a = \beta z \quad \text{where } \beta = \sqrt{1 - M_a^2}$$

The authors have extended this transformation empirically to more accurate representations for several types of wings and bodies:

Two-dimensional airfoil
Infinite sheared wing
Center section of infinite swept wing
Finite wing
Bodies.

Calculations of pressure coefficient on simple straight wing-body combinations compare well with experiment. Calculations of pressure coefficient for other configurations compare reasonably well for the data that are available, although the maximum disagreement is as much as 20% in some regions. The theory always overestimates the lift due to the effect of viscosity in the real flows.

Lockheed

Lockheed-Sunnyvale has developed an approach to flow field determination very different from the finite element technique in use by most other analytical investigators. The finite element methods using various elemental singularities distributed over surface quadrilaterals or along internal lines of symmetry are limited, because they are based on potential flow and sometimes linear theory. The inclusion of mixed flow problems is not as yet possible.

Most practical problems involve mixed flow, that is, some transonic flow including shocks. Potential theory cannot handle this problem. The Lockheed approach involves an integral technique using an unsteady finite difference scheme which is valid throughout the subsonic, transonic, and supersonic flow regimes.

Much of the original work on unsteady flow regime differences was done in Russia by Godunov. He determines the steady-state distribution of pressure, density, and velocity as a result of the "settling down of the flow." The fundamental relations used in this iterative scheme are the Eulerian conservation laws for mass, momentum, and energy in integral form. The fluid is divided into layers or cells at the initial time and, for each cell, values are assumed for the flow field quantities. The boundaries of the problem are the surfaces of the configuration for which the flow is being determined.

Perhaps the biggest advantage of this technique is that transonic flow (as well as subsonic and supersonic) and shock waves can be handled. Since geometry is described point by point as a boundary, complex configurations can be analyzed. The boundaries need not be steady during the calculation (e.g., a jet). The complete inviscid flow equations are solved, thereby accounting for all interference effects, shock waves, shock reflections, and shock interactions. Limitations to the technique include long computing times and the exclusion of viscous effects. When viscous terms dominate or when separation occurs, this technique is not valid.

The input to the program is mainly geometry. The boundaries must be described as well as the cell system. These quadrilaterial cells need not be square nor even the same size, since the size and shape are more the function of the flow field complexity. The starting conditions are input and can even be free-stream or uniform-flow conditions. The number of iterations can be reduced by inputting an initial flow field as close as possible to the final flow field. The output is the flow field at a cell (or point) that yields the density and velocity-components from which the moments, total pressure, and pressure coefficient are obtained. Then those can be integrated to obtain the aerodynamic forces and moments.

Lockheed has used this technique to calculate the flow field on a flat plate at angle of attack, subsonic and supersonic flow around a wing, and other two-dimensional problems. The two-dimensional program is used whenever possible, because most three-dimensional problems can be simulated in two dimensions, resulting in a saving in computer time and input data. The three-dimensional program has been applied to subsonic flow around mountains. Where experimental data has been available (flat plate to α = 6 deg, blunt body to α = 45 deg), there has been good agreement.

The Lockheed people feel an extension of this method to store separation problems is not only feasible, but also promising. A three-dimensional unsteady finite difference technique applied to the external stores problem could be used to calculate forces and moments on the aircraft and store, and could account for all mutual interference effects, multiple stores on multiple pylons, stores on fuselage, mixed flows (subsonic, transonic, and supersonic) including shock wave effects, and any shape store. In combination with a trajectory program, the full dynamics of store separation can be predicted. However, the more complex the configuration, the more computing time is required.

An important consideration in this calculation technique is the computer time involved. A two-dimensional flow calculation around an airfoil requires approximately 12 minutes on a UNIVAC 1108 computer. Additional iterations were run for 23 and 40 minutes, but the results showed no significant changes. More cells are needed for more complex shapes and thus more computing time. If the real flow field can be approximated, the number of iterations required and the computing time can be reduced.

The unsteady finite difference technique and the potential flow "exact" methods both require excessive computing time. But the potential capability of the unsteady finite difference technique would seem to far exceed that of the potential flow method, although the application of unsteady finite difference techniques to the store separation problem is not as advanced as the potential flow method. Worthwhile efforts could be directed toward reducing the computing time required for the unsteady finite difference method.

DIRECT APPLICATION TO STORE SEPARATION

Fernandes (Ref. 71–76)

The methods described in the previous section have been general aerodynamic interference techniques. They are applicable to store separation problems, but have not been specifically applied. They share the problems of large computer storage usage and long computing times.

If an engineering technique is applied to a specific store separation problem, it may be possible to make approximations and thus obtain practical solutions to problems. Fernandes of General Dynamics, Pomona, started such an application in 1967. In 1968, he extended his method to supersonic flow. Since that time his efforts have been devoted to improving the approximations employed.

All of his work depends on the now demonstrated basis that the store angle of attack has a negligible effect on interference. Thus, the local store loading per unit length and per unit angle of attack due to the interference flow field is the same as in uniform flow. The disturbance flow field is predicted using linear theory of the superposition of elementary solutions to the potential equation. The strengths of these elementary solutions are computed and the boundary conditions matched by a computer program. No slender-body assumptions are used in any of the calculations, for the subsonic compressible case simulates the wing camber, twist, thickness, and angle of attack; the jet inlet ramp size, ramp slope, and lip interference; and the pylon thickness effects. Compressible effects are included by applying the Prandtl-Glauert rule.

To obtain the lifting effect of the aircraft, the wing is divided into panels with a bound vortex at the quarter-chord and a control point at the three-quarter-chord of each panel. The panel size is chosen so that the vortex strengths are approximately the same. Using the Biot-Savart law to relate the velocity to the vortex circulation and matching the downwash boundary conditions at the control point, the singularity strength may be determined by solving the following matrix equation

$$[H] \left[\frac{\Gamma}{4\pi V_o}\right] = \left[\frac{w}{V_o}\right]$$

where [H] describes the geometry, $[\Gamma/4\pi V_o]$ represents the singularity strength, and $[w/V_o]$ is the downwash boundary condition. Three sets of boundary conditions are used to satisfy the camber, twist, and angle of attack effects, and the resulting three sets of vortex circulations are added linearly to give the total singularity strength for a particular angle of attack.

Thickness effects (wing, jet inlet, pylon) are obtained by representing the configuration as stripes of constant slope (θ) resulting in a source distribution. The source is a solution to the incompressible potential equation

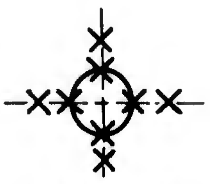
$$\frac{\phi}{V_o} = \frac{-1}{2\pi} \iint \frac{\theta \, dy, \, dx_1}{\sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2}}$$

where x_1, y_1, z_1 are specific points on the surface and x,y,z are any points on the surface. This expression can be integrated analytically spanwise and numerically streamwise to yield the potential from which the flow velocities can be obtained. The wing is assumed to be a planar (or thin) wing.

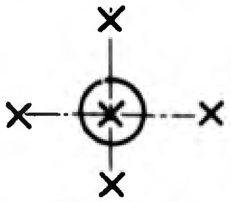
The procedure for supersonic flow is similar. The wing, pylon, and jet inlet are represented by linear source distributions. The nose of the aircraft fuselage is simulated by a source distribution on the axis of symmetry. The source strength for wing lift is determined by the "Mach Box" numerical procedure by Zartarian. For this technique the wing is divided into "boxes" whose diagonals are parallel to the Mach lines.

Mutual interference between aircraft components is not included. The cross flow effect is determined by multiplying the store load per unit length and angle of attack by the local interference angle of attack. The bouyancy effect is obtained by integrating the interference static pressure.

The flow field velocities at 12 axial locations are calculated at eight points in the mate (captive) position and five points away from the mate position as shown in the sketch (by x marks):



NEAR MATE



AWAY MATE

The aerodynamic coefficients of the store (C_N, C_m, C_Y, C_n, C_ℓ) may be obtained from this flow field information (C_N is normal force coefficient, C_m is pitching moment coefficient, C_Y is side force coefficient, C_n is yawing moment coefficient, and C_ℓ is rolling moment coefficient). Mach number and angle of attack are also obtained, but as yet, not sideslip. At the present time, calculation can be applied to external compressible ramps, some inlet geometry, almost any wing position, any nose, one store of any kind (fins, canards, any density), subsonic and compressible (less than the critical Mach number), and supersonic above Mach 1.2. Good results are not possible, as yet, with body-mounted stores. Stores can be mounted as far outboard as desired, but for a high wing with inboard stores mounted close to the body, results may be of doubtful accuracy.

Program inputs are aircraft and some missile geometry and store normal force data. The problem solution computation time for a typical problem of wing-pylon-store from the geometry to a numerical value is 2 to 4 weeks.

A typical singularity representation for the F-4 is as follows: 14 Mach boxes per semispan for the wing or, for subsonic flow, vortices are located at 6 to 10 spanwise and 4 chordwise locations, 2 thickness surfaces for the inlet ramps, 4 thickness surfaces for the inboard pylon, 2 thickness surfaces for the outboard pylon (for subsonic flow 2 or 3 vortices per pylon), and 12 line sources along the nose axis. Sources require relatively shorter computing time than vortices.

Agreement with data has been reasonably good, although there is an insufficiency of data and what does exist may have inherent position errors. Yaw and side force present a problem in calculation and, especially near the body, improvement is needed. Another major problem, which perhaps is responsible for the shift in peaks of the pitching moment in the supersonic calculation, is the neglect of shock curvature.

Future effort is planned to include improvement in yaw angle prediction, additional stores, more inlet geometry, and still later, wing body interference. These problems are being attacked in order of their priority as funding allows. Current work is concerned with correcting the flow field for the variation of the shock locations from the Mach line location. Reprogramming has been necessary to stay within computing machine capacity as program capabilities are expanded.

Nielsen, et al (Ref. 95, 96. 190, 191)

Dr. J. N. Nielsen, F. K. Goodwin, and others at Nielsen Engineering and Research, Inc., have looked at the entire analytical problem of store separation from a practical engineering viewpoint, using the simplest possible computation technique consistent with accuracy requirements. They consider the threefold problem of determining the nonuniform flow field in the vicinity of the store, calculating the consequent forces and moments of the store and then determining the resulting separation trajectory. Their entire analysis has been supported by extensive wind tunnel programs enabling them to make rational decisions as to how complex a computational technique is required. These experiments were specifically designed to provide data for a critical check of the theory.

Their initial results have been for the three-degree-of-freedom (pitch plane) case only and for subsonic flow up to the critical Mach number. Current work has extended the solution to the full six degrees of freedom. In addition, noncircular fuselages are being considered (a canopy on a circular body, cambering of the nose of the body, change in cross-sectional shape of the body, and the addition of inlets).

The result of the investigation is a computer program that will predict the trajectory of external stores dropped from under either the wing or the fuselage. The stores may be arranged singly on pylons or may be groups of stores on racks. The problem of determining the flow field and then the forces and moments is a difficult one due to the complex interference effects. The final part of the problem, integrating the equations of motion to determine the trajectory, is reasonably straightforward.

A brief description of the three-degree-of-freedom, subsonic program is included here. In order to determine the trajectory of the store at separation from the carrying aircraft, the forces and moments acting on that store must be known. These forces and moments may be determined from the velocity field in the vicinity of the store, due not only to the aircraft and store components, but also to their mutual interferences, and from the characteristics of the ejector motion.

Nielsen's method develops models simulating the fuselage volume and angle of attack; the wing thickness, angle of attack, camber and twist; the store volume; and the interferences due to wing-fuselage and wing-store. Pylon and rack effects have been included in a later program. Point sources are used to represent the fuselage and store volumes, and two-dimensional sources are used to represent the wing thickness in the vicinity of the store. Wing sweep and taper are included by simple sweep theory. The wing lift is simulated by a vortex lattice and the interferences are included as an induced wing camber. In the initial program, this first wing model is not modified as the store is ejected because the effect of the store on the wing flow field is considered a second-order effect, the inclusion of which would not warrant the extra computation time required. In considering safe separation trajectories, the initial motion of the store is of primary importance.

The velocity field over the entire length of the store is calculated for each point in the trajectory. The axial distribution of forces and moments due to buoyancy, potential flow, and viscous crossflow are then computed and integrated over the store length to obtain normal force and pitching moment. (Later programs extend the results to other degrees of freedom.)

Compressibility corrections are determined by considering the usual correction factor

$$\beta \doteq \sqrt{1 - M_\infty^2}$$

where

M_∞ = free stream Mach number.

Thus, a transformation is made to the equivalent incompressible coordinate system. Further calculations are then performed on the "equivalent" body and then transformed back to the original coordinate system.

As an example of the calculations for an asymmetric body at zero angle of attack, the fundamental equation for the stream function in terms of sources is obtained, and then nondimensionalized using the body length and the free stream velocity. The pertinent velocities are obtained by differentiating this expression appropriately. Three conditions are then used to determine the source strength:

1. Specification of the flow direction in terms of these velocities.

2. The sum of the source strengths must be zero (to obtain a closed surface).

3. There is a stagnation point (zero velocity) at the nose of the body.

Similar calculations are carried out for other components.

Lifting surface theory is employed for the angle-of-attack calculations. Two superimposed horseshoe vortices represent the basic and additional lift distributions. These vortices are placed in a lattice composed of area elements. The boundary condition of no flow through the wing is applied at specified control points in each element. A series of calculations help determine the size of lattice needed to minimize cyclic variations of the solution.

The interference potential under the wing for the wing-fuselage is obtained by an iterative approach. In the region of the fuselage, the additional fuselage solution required to cancel the wing-induced normal velocities is determined. Further accuracy may be obtained through iterations. The investigators are able to determine the detail necessary for engineering accuracy by comparison with experiment.

Having obtained this nonuniform flow field, the next step is to obtain the force and moment of the store due to primary interference (effect of perturbation velocities due to the aircraft components). The angular velocities of the store are added to this calculated flow field. The assumption of slenderness is made (except for fins and blunt noses). Due to the inherent nature of slender-body theory at high angles of attack, the change in pitch angle can be overpredicted. For the case of a store with fins, this effect is not significant because the fin effect is dominant.

Using the slender-body assumption and apparent-mass techniques, the normal and side force distributions on the store and the resulting moments may be calculated. Since slender-body theory is not applicable in a separated region, simple viscous crossflow theory is applied downstream of separation. Of course, even the determination of the location of separation is not a simple problem. The forces and moments can then be determined by integration over the store length.

The additional interference loading due to the pylon and the effect of the store on the wing is determined by a numerical technique including conformal mapping and numerical vortex methods. The reader is referred to Nielsen's report and references for a description of these methods.

The authors have made comparison of their analyses with experiment for the case of a single store under the wing of a wing-fuselage combination; for a single store under the pylon of a wing-fuselage-pylon combination; and for a triple ejector rack (TER) grouping under the wing of a wing-fuselage-pylon-rack combination. Both the experiments and analyses were run with components as well as complete configurations so that a build-up of effects could be understood. The accuracy of determination of the stream angle in these wind tunnel tests was very important for accurate comparisons. Appropriate modifications were made to the theory when the need was indicated by these comparisons.

Using these tools, the derivation of which is described briefly above, a computer program was written which integrates the equations of motion of the store to determine the time history of its location and orientation. Standard numerical integration techniques are used. The carrying aircraft may be in straight uniform flight, climbing, or diving.

The contents of the computer program may be summarized as follows: an axisymmetric and two-dimensional source distribution program, a vortex-lattice program, and a trajectory program. The first two portions need only be run once for a given aircraft-store combination and Mach number. The source distribution program is independent of angle of attack. The part of the vortex-lattice program that depends on angle of attack does so in a linear manner. The third portion may be run for various angles of attack, altitudes, and store initial dynamical conditions without rerunning the first two portions.

Future plans call for extending the method to steady maneuvering aircraft. Considerably more effort would be involved to include non-steady maneuvers. There is no clear-cut way to extend the program to the transonic regime, although it may be possible to obtain solutions near Mach 1. It should be possible to include the effects of launcher flexibility.

The basic material is available in the program to use for drag estimates. The problem is a linearized one now, i.e., the program is valid only for sufficiently small angles of attack that the aerodynamics are linear. It is desirable to extend the analysis to high angle of attack and this may be possible based on work now under way. This technique would have to include the effect of the symmetrical vortices shed from the nose of the body.

For some cases, the accuracies required may demand the use of an iterative technique. In other words, it may be necessary to determine the constantly changing effect of the separating store on the aircraft flow field. Then the aircraft flow field would have to be recomputed.

When analytical predictions are desired or when general operating envelopes are required, this set of programs is recommended. They serve as a compilation in one place of all the tools necessary to obtain an approximate engineering solution to the problem. As with all problems of this type, care must be taken to apply the portions of the program with judgment as to the accuracy requirements and to refrain from stretching the theory beyond its known limitations.

SAFE SEPARATION DETERMINATION

Covert (Ref. 52)

The author has developed a safe separation criterion based on the relative velocity of the store with respect to the carrying aircraft and the acceleration acting on the store at release. Diagrams are presented as velocity versus acceleration with "time-distance" limits imposed as boundaries.

The technique required the computation of the relative velocity of a point on the store with respect to the rack and the relative acceleration of the same point with respect to the rack. This calculation is done in rack coordinates at the instant of release. Assumptions involved in the vertical motion are that the aircraft motion is steady, the store is rigidly attached to the airframe, and the airframe is rigid.

Input to the calculation consists of geometry, force, and mass properties:

1. The radius distribution (including fins), the length, and center of mass of the store

2. The foot position of the rack in relation to the center of mass of the store and the location of each strike point

3. The Euler angles of the store and rack at launch

4. The store weight and moments of inertia about each axis of the store

5. Force versus distance or time for the rack ejector

6. The aircraft flight speed and dynamic pressure.

The free-stream aerodynamic conditions and the interference aerodynamics must be known.

The primary assumption of the criterion is that the near-field interference is of primary importance. That is, the trajectory near the aircraft is governed by the forces and moments acting on the store at the instant of launch and, further, they continue to act at the same magnitude. Slender-body theory is used for the far-field nonuniform flow field. The data needed for this criterion are the same as required to obtain airloads and stresses.

Thus, if the aerodynamic data are known or can be predicted experimentally, the safe launches can clearly be delineated from the unsafe launches.

Sekellick (Ref. 229–231)

This author has made an attempt to predict store separation behavior by statistical analyses. It is very difficult at present to define adequately the complex interference flow field around an aircraft-store combination. Thus, the approach was taken of analyzing a large number of launch events, classifying them as satisfactory or unsatisfactory, and defining a relationship between the configuration parameters, the launch conditions, and the resulting trajectory.

Unsatisfactory launches were defined as those with an initial maximum pitch angle greater than 15 degrees, erratic vertical motions (as a function of time) or pitch motion (as a function of vertical distance), or physical contact with the aircraft and/or other stores. The important physical and geometric features of the aircraft-store combination were identified. These parameters include the store center of gravity location with respect to the wing and the wing chord, thickness, and sweep angle.

The launch events and resulting separation trajectories were catalogued in terms of these various parameters and two statistical techniques were applied. The results were computer programs that would predict the nature of the separation and the degree of hazard for the particular conditions.

One statistical technique employed was a Regression Analysis based either on the initial store pitch maximum or the time integral of the store nose distance from the launch position. The other technique was a Discriminant Function Analysis which would find a function that would discriminate against satisfactory and unsatisfactory launches. Thus, the nature of the separation was determined, and an index found for the degree of hazard. In comparison with reality, the first regression method had about 23% error, the second about 18%. An apparently poor choice of independent variables resulted in unsatisfactory results for the discriminant technique. It is believed that, with further work, successful relationships could be obtained to predict hazardous store separations.

LOADS

Grose (Ref. 98, 99)

Grose, et al, have applied the method of Woodward (Ref. 268-270) to obtain interference loading for both subsonic and supersonic speeds. The application has been made for a store in the presence of a wing-body combination. Favorable comparisons with test data indicate the method is promising for the prediction of store interference effects based on the aircraft geometry.

The work of Woodward has been the basis of many analytical developments. The fundamental theory he employs is similar to that used by Hess except Woodward uses supersonic singularities as well as the usual subsonic and thus is able to extend his method to supersonic flow.

For this compressible derivation, the potential function for each singularity must satisfy the Prandtl-Glauert equation:

$$(1 - M^2)\ \phi_{xx} + \phi_{yy} + \phi_{zz} = 0$$

where

M = Mach number
ϕ = velocity potential
x,y,z = coordinates

Solutions to this equation may be written in integral form. For example, for line sources

$$\phi = \int \frac{-\xi d\xi}{[(x - \xi)^2 + (1 - M^2)\ r^2]^{1/2}}$$

where

$r^2 = y^2 + z^2$
ξ = dummy variable

Solutions for other types of singularities are similar and may be found in detail in Woodward's paper (Ref. 268).

Line sources and doublets are distributed along the body axis to simulate body volume, incidence, and camber; planar sources represent wing thickness; and planar vortex distributions represent the camber, twist, and incidence of the wing. The interference of the wing on the body is simulated by vortex distributions on the body surface. The singularity strengths are determined by the configuration geometry. The perturbation velocity components for the wing-body flow field may then be determined using

$$u = \frac{\partial\phi}{\partial x}\ ,\quad v = \frac{\partial\phi}{\partial y}\ ,\quad w = \frac{\partial\phi}{\partial z}$$

where

u,v,w = perturbation velocity components

These perturbation velocity components are assumed to vary linearily with aircraft angle of attack and thus only two points need be computed. The flow field components may be obtained either along the store axis or as a three-dimensional grid.

The aircraft flow field is calculated separately. The aircraft is assumed to have no yaw. The aircraft perturbation velocities are then transformed to the store axis system. The store may have both angle of attack and yaw with reference to the aircraft. Next, the potential flow solution is obtained for a cambered body of revolution at incidence and yaw (the store) immersed in the nonuniform flow field. The axial, vertical, and transverse components of velocity at a point are obtained by adding these two flow fields (aircraft and store). The pressure coefficient is then obtained. The force and moment coefficients are calculated by integrating the pressure coefficients over the surface of the body.

Comparisons of the analytical method with test data have been accomplished for a subsonic case (SUU-16A gun pod mounted on an outboard wing pylon of an F-4) and a supersonic case (a large sting-supported store at a number of locations below the wing of a fighter-bomber model at M = 1.61). Agreement was good, but several areas were exposed where corrections could be made to improve the agreement or where the theory is basically lacking due to its linear character.

Certain changes could be made to the program to improve the results. The bouyancy normal force due to transverse pressure gradients could be included by calculating these gradients at points on the store axis using the gradients of the flow field perturbation velocities. The effect of the store location on the aircraft flow field should be included when the store is in close proximity to the aircraft and may be accomplished by building up a table of flow field data as a function of store location. To calculate the loads on pylons and fins, the program should be extended to include lifting surfaces with arbitrary dihedral and flow field perturbation velocities on the surfaces. An empirical correction for nonlinear lift due to viscous cross-flow could be added using a cross-flow drag coefficient and cross-flow velocities. Improvement in the supersonic flow regime could be achieved by shifting conditions from the Mach lines to the corresponding characteristic lines.

The method outlined here has the advantage of including both lift and thickness effects in the same calculation. Because of the separate calculation of aircraft and store flow fields, it may be permissible for some configurations to calculate the flow field of the carrying aircraft only one time while doing computations for several stores and store locations. Thus, considerable computer time would be saved. It is understood that Grose now may be applying the Hess lifting program to the problem also.

Thomas (Ref. 257–259)

Thomas at NWC has adapted the methods of Borland, Schindel, and Chamberlain at MIT (Ref. 31, 223-225) to find the loads on a store in captive flight. The object of the program is to use modern analysis techniques along with modern digital computer capability.

Several theories are combined for use as building blocks in the more complex problem of captive flight. Weissenger's theory is used to determine the spanwise loads on fins and the vortex distribution due to fins. The Lawrence slender-wing theory computes the chordwise load distributions on fins and accounts for the interference effect of the wing on the body. Gray and Schenk give the effect of the body on the wing. Slender-body theory and the technique of conformal transformation are used to carry over the lift on the body aft of the fin due to the fin's vortex wake.

The solutions to the linearized equation for the perturbation velocity potential are derived and superimposed on the free stream flow, a doublet at the origin to simulate a cylinder, two vortices in the wake, and the "reflection" of the two vortices in the cylinder. Much time is consumed with the difficult problem of these two main vortices. Conformal transformation techniques are used and the problem is examined for turbulent flow using some empirical relationships.

The wing-body portion of the program is operational. This program calculates the loads and the vortex distribution for the wing-body combination. These components may be used as "building blocks" for calculation of the loads on the next wing-body combination downstream. The problem of determining the growing vortices being shed from the bodies is the last element required to make the entire program operational. Work has been discontinued on this project.

Serbin (Ref. 232)

Serbin, an independent consultant, pursues the problem of calculating the forces on a store within an aircraft flow field from a purely slender-body viewpoint. First he calculates the flow field around the aircraft, using a conformal transformation technique and assuming slender-body theory. That is, the flow at each cross section of the body is treated independently. Three component velocities result in the transformed plane and these flow fields are then superposed. The store is assumed to have negligible effect on the aircraft flow field. The forces on the store are calculated by applying slender-body theory to the store in the curved stream.

This technique has been programmed with input of aircraft and store geometry, aircraft flight conditions, and the geometrical relationship between the aircraft and store. The output is in terms of aerodynamic coefficients for side and normal force and pitching and yawing moment, and also pressure distributions, if desired. The investigator claims substantial qualitative agreement with theory, but his evidence of such is rather meager.

SUMMARY

Many of the currently available analytical techniques for predicting the interference flow field around aircraft-store combinations have been discussed. Most of the methods are based on the use of fundamental singularity distributions (surface and/or internal). Several somewhat fundamental type programs have been presented to illustrate this technique. One other method, referred to as a time-dependent technique, has been discussed even though no direct application of this method has been made to store separation. The recent progress of the development of these time-dependent techniques, as well as their potential wide applicability suggests that further consideration should be given to their application to store separation problems.

Two engineering methods (Nielsen and Fernandes) have been applied somewhat successfully to the real store separation problem. One of these methods (Nielsen) is backed up by considerable wind tunnel experimentation and contains the three essential parts to a definition of the complete problem: flow field calculation, aerodynamic coefficient calculation, and separation trajectory calculation. The other method (Fernandes) has also been experimentally verified to some extent and, in addition, has been successfully extended to supersonic speeds.

Also discussed briefly are some available techniques for predicting safe or unsafe store separation and captive flight store loads.

SCALE TEST TECHNIQUES

GENERAL COMMENTS

Scale model testing for store separation phenomena is, for all practical purposes, done entirely in wind tunnels. It is assumed that the reader has a general acquaintance with the various techniques now available, i.e., dynamic scale drop tests, the captive trajectory system and its derivatives, grid testing, trajectory tracing, and flow field mapping. If not, the bibliography (p. 44) lists many references containing information on these techniques and results obtained by them.

The major part of this section will deal primarily with problems or difficulties associated with each of these techniques, and with recent efforts within the Navy and other laboratories to overcome these problems, but, first, some general comments are made.

Facilities exist within the Navy, Air Force, National Aeronautics and Space Administration (NASA), educational institutions, and industry for conducting store separation tests using each or all of the techniques. The practical problems of scaling, model design and fabrication, test operation, data acquisition, data processing, and analyses have been solved to a great extent. In other words, a variety of types of testing can be done in wind tunnels to aid in predicting store separation motions and resolving problems. Considerable correlation of test results with full-scale experience has been accomplished and reported. In many cases, however, the correlations, while seeming good, are either invalid or inconclusive due to incomplete full-scale data or comparisons of results of tests of systems that are very insensitive to ejector and flow field interference forces and moments. Thus, only a limited amount of completely valid correlations exists, and cases of poor correlation of wind tunnel test results with full-scale test results are reported. For store separation testing where problems can be resolved within a short time, the cost of testing and analyses can be quite reasonable.

GENERAL PROBLEM AREAS

The large number of possible store, rack, and aircraft combinations now existing makes complete testing, whatever the method, entirely infeasible from the standpoint of the time involved and, of course, costs would be prohibitive. Thus, there is valid justification for development of theoretical and/or empirical techniques to bridge the gaps between the relatively few test data points it is feasible to obtain.

Since, for store separation tests, an airplane model must be put in the wind tunnel, in all but the very largest tunnels large-scale reductions are necessary (5 to 10%) and thus the store models are quite small. This has posed serious questions as to viscous effects both in the sense of the Reynolds number and in the proper amount of detail to be simulated, such as vents, wheel well doors, and other surface imperfections and protuberances on the aircraft model and on the store model. In addition, in many wind tunnels, the test section turbulence levels are not known, but even where known, the extrapolation of test data to turbulence-free conditions is at best only approximated by the concept of equivalent Reynolds numbers.

As previously mentioned, dynamic scale drop testing is hampered by the inability to scale gravity as required for complete dynamic similitude. Although electromagnetic fields can be used in conjunction with magnetic materials in the store model to induce a "field force" to modify the effects of gravity, there are no practical working systems at present. Scaling of ejector effects is also haphazard, since what is to be scaled is generally not known, structural flexibilities are not scaled, and it is difficult to reproduce force-time histories.

The CTS suffers from two primary faults. First, since the store model is suspended from a mechanical support system capable of up to six-degree-of-freedom motions, there is necessarily a large amount of impedimenta in the test section. Also, the store and aircraft models usually are sting-mounted. The interferences due to these mounting and drive mechanisms in the flow field have received very little attention and represent one of the major unknowns in interpreting test data. Also, the motions of the store model are generally quite slow compared to the dynamically scaled time. Thus, for trajectory tracing, the aerodynamic rate derivative coefficients must be input to the computer program which controls the support drive system. Also, at a given position in the trajectory, the local angle of attack of the store is not the same as for the full-scale situation, since the model does not have the correct velocity components corresponding to full-scale. It is possible to alter the geometric angle of the model so as to be at the correct angle of attack, but this causes the relative angle between the store and aircraft models to be incorrect, thus causing the flow field interference to be improperly measured. This effect has received recent attention by Nielsen, but no conclusive resolution has been obtained.

The lack of measured dynamic aerodynamic coefficients is a fault of grid testing also, although at least the static forces are correctly measured. The effect of nonuniform flow fields on the dynamic aerodynamic forces acting on stores is not known. In many cases, however, the effect is known to be small and can properly be neglected, but unfortunately at present we can *know* this only *after* the tests have been run and the results compared with full-scale data.

Measuring the flow field pressures and velocities around the isolated aircraft model, in addition to being time-consuming, also presumes that the presence of a store in the flow field does not change the flow field and that the forces on the store can be computed in nonuniform flows.

Each of the test techniques available has certain problems or drawbacks at the present time, which precludes considering any one of them the best way to study store separation. For any particular kind of store separation problem, there is an optimum combination that is most cost-effective, but there is no general way at present to determine this combination. The amount and kind of experience previously gained by the person(s) designing or performing the test and analyses most often determines success or failure. The best combination of talents probably now exists at the various aircraft manufacturers, where past experience has been documented and where people with long and varied experience are available. It is highly desirable, however, that some form of standard or specification be developed, backed by the necessary research, to define at least a satisfactory approach, so that store separation predictions can be made with sufficient confidence that program managers will feel justified in expending the time and money resources to do the necessary testing. This is particularly needed where a new weapon is in development for use on existing aircraft.

RECENT DEVELOPMENTS

Navy

The only Navy laboratory tasked specifically with the capability of performing wind tunnel store separation testing is the Naval Ship Research and Development Center (NSRDC). All of the types of testing can be accomplished at that facility in the 7- x 10-ft transonic wind tunnel. In particular, a new CTS system has been installed and checked out for operation. The system has been used in separation tests for Harpoon. All of the problems outlined earlier exist for this (and all other) facilities. The laboratory is planning and expecting funding for research to determine support interference effects applicable to the CTS system as well as other techniques. The need for this is urgent; however, the magnitude of testing required will be in part determined by a similar program in the Air Force also to measure support interference (discussed later). The possibility of mutually beneficial and supporting efforts is strong and must be encouraged.

The Naval Ordnance Laboratory (NOL), White Oak, has performed a limited amount of dynamic scale free-drop testing at supersonic speeds. While results are useful for the research involved, the small tunnel size precludes depending very much on this facility for normal weapon/aircraft development separation testing.

To the authors' knowledge, there are no other Naval wind tunnel facilities engaged in store separation testing.

Other Government Facilities

By far the most active group has been at the Arnold Engineering Development Center (AEDC), Tullahoma, Tenn., where Tunnel 4-T was constructed and operated for Eglin Air Force Base. This tunnel has the capability of all types of testing and has been used extensively by the Air Force for developmental testing. Both Eglin and AEDC are engaged in cooperatively defining a research program to determine and resolve "CTS problems." At the present time, a definite test plan is being pursued in several phases. NWC has been invited to provide inputs to this program, and a maximum effort is being made to coordinate AWDC/NSRDC/NWC results to avoid unnecessary duplication of effort on similar objectives.

At AEDC, the VKF tunnels A, B, and C have capability for free-drop testing and limited CTS capability with a three-degree-of-freedom (Aerospace Plane Support System) and a four-degree-of-freedom (Crew Escape Capsule Separation System) system. These systems have been used most recently for both B-1 bomber separation testing and NASA Space Shuttle orbital vehicle separation from the booster. VKF also has a six-degree-of-freedom CTS system to extend full CTS capability with the supersonic and hypersonic speed regimes in support of B-1 and Space Shuttle work. It is interesting that the Space Shuttle represents a store separation where, depending on one's viewpoint, the "store" is larger than the "carrier"!

In the past, NASA (and earlier the National Advisory Committee for Aeronautics (NACA)) performed a number of research studies relating to store loads and store separation. The bibliography lists the most recent reports on the subject. Although NASA has espressed interest in doing more store separation testing, none has been done, to the authors' knowledge. Testing can be done using the dynamic-scaled free-drop, grid, and flow field measurement techniques. CTS testing cannot readily be done due to NASA's lack of CTS systems.

Industry

Industry-owned facilities include Cornell Aeronautical Laboratories, Ling-Temco-Vought, and Convair-San Diego. These facilities have CTS installations and can perform all types of separation tests at subsonic through supersonic speeds.

FULL-SCALE TEST TECHNIQUES

At the present time, extensive flight test programs are still required to certify the safe and functionally acceptable separation of stores, in various loading combinations and permutations over stated operational flight envelopes, for each new and sufficiently changed model of carrier aircraft. Moreover, each new store must similarly be certified on each operational aircraft model with which it is to be employed. This extremely costly and time-consuming situation is due to two basic factors: (1) the incomplete development at the present time of an adequate general theoretical or theoretical/semi-empirical mathematical model that can describe the mutually interacting flow fields surrounding airframe, pylon, rack, and stores, and in particular their integrated effect on the stores in terms of interference forces and moments; and (2) the continuing uncertainty as to the degree of accuracy with which wind tunnel model force, moment, and trajectory data can be scaled to represent full-scale flight conditions. This wind tunnel data uncertainty stems from the basic tunnel and instrumentation effects and model scaling problems discussed previously.

The Navy's present requirement for the demonstration by aircraft contractors of safe and acceptable store separation in flight stems from Military Specification MIL-D-8708, *Demonstration Requirements for Airplanes*. Addenda to this specification are prepared by the contractors which set forth (1) the planned store separation flight program (including recommended release conditions and schedules), and (2) the required onboard and supporting instrumentation. These addenda are reviewed and approved jointly by the Naval Air Test Center (NATC), Patuxent River, Md., and the Naval Air Systems Command, Washington, D.C., and become binding contractual documents. Depending upon the type of weapon system or store to be demonstrated (guided missile, free-fall stores, or special weapons), the flight programs take place at NATC, the Naval Missile Center (NMC), Pt. Mugu, or the Naval Weapons Evaluation Facility (NWEF), Albuquerque. Some tests of weapon system accuracy, influenced by store separation perturbations, are also made at NWC.

The most sophisticated present approaches to the task of demonstrating safe and acceptable store separation involve the extensive prior calculation (by computers) of many six-degree-of-freedom separation trajectories for each store over its required release flight envelope. In these calculations, the sensitivities of the separation trajectories are examined for changes in such parameters as Mach number, altitude, g's, store station, wing sweep, adjacent stores, angle of attack, aircraft attitude, and ejector performance. In this way, critical release conditions can be identified and avoided or approached cautiously in the actual flight program.

The value of these analyses, however, is critically dependent on the validity of the wind tunnel data employed in defining the full-scale flow field forces and moments on the store, and the uncertainty surrounding these data has been discussed previously. Moreover, the required extent of the analysis requires a massive quantity of data, and wind tunnel data cost can approach the actual store separation flight test costs.

Nevertheless, this is the art state that prevails at the present time. Initial store releases are now made at flight conditions proven by prior analyses not to be critical, and the resulting six-degree-of-freedom separation trajectory observed is compared with the predicted trajectory. If acceptable agreement is obtained, then more critical test conditions are selected for the next release. The process is continued until safe and acceptable separation characteristics have been demonstrated at all critical points within the release envelope.

However, if correlation between actual and predicted trajectories is not achieved, a comprehensive reexamination of the trajectory prediction methodology and basic data is made to pinpoint the contributing cause of the discrepancy. If ejector or launcher performance is determined to have been normal, the carriage loads and near- and far-field interference cooefficients are adjusted until the observed full-scale trajectory is matched. Sometimes the store aerodynamic coefficients are reestimated, the original estimate having been made because of the nonavailability of such aerodynamic data for the store. Upon obtaining store motion and trajectory correlation, the balance of the scheduled releases are then repredicted.

With regard to the unavailability of store aeroballistic data, it would seem that simple propriety requires that each configuration be adequately measured by the development agency and the results properly documented, but this appears to be far from the case. Notwithstanding the fact that the static and dynamic stability of the store rank high in importance in separation considerations, the necessary aeroballistic data for these determinations are often extremely difficult to acquire even if they exist (often they do not), and the individual forecasting the chances of safe separation for such a store is forced to estimate their characteristics. Major guided missile developments (e.g., Phoenix, Sparrow) are usually well investigated and documented in this regard, but many free-fall stores (most unstable ones) are sadly lacking in available aeroballistic data. A priority requirement is clearly indicated for adequate geometric, inertial, and aerodynamic data, published in a standard format for reference by those engaged not only in separation studies, but also in fire control ballistic investigations.

As a store separates, its actual motion and orientation with respect to the aircraft are universally determined from film records carried on the aircraft. Various photogrammetric techniques are employed, ranging from the utilization of but one camera (Ref. 32, 50, and 66) to the utilization of one or more arrays of two or more cameras used in conventional triangulation solutions. The latter techniques have become highly computerized in the reduction of the camera data, employing six-degree-of-freedom trajectory programs which utilize lens calibration and camera deflection subroutines to correct for the effects of individual lens distortion and fuselage and wing flexure (Ref. 100). However, at the present time these camera techniques still require manual reading (or manipulation of image positioners) for each film frame of interest.

To circumvent this time-consuming and costly process, various optical scanning schemes are being considered (but are not known to be operational) to digitize and process raw camera data automatically. One example is the Television Data Acquisition (TELEDAQ) system (Ref. 38). Here, two 2-color cameras with automatic tracking capability track color spots on the store. The digital coordinates of the spots are transferred to a digital tape recorder for computer triangulation of store position and computation of attitude.

Major onboard installations of recording and telemetry instrumentation are employed in current contractor demonstrations of store separation. These are for the purpose of recording and monitoring parameters that can be categorized as (1) flight conditions at the time of release, (2) timing, (3) engine performance during missile and rocket firings, and (4) the state of aircraft internal systems--for example, wing and control surface positions. Pulse code modulation telemetry systems are in being which provide a capability of recording on the order of 600 measurements, with a signal capability air-to-ground of some 300 measurements. These data signals are computer-processed at ground stations and select, reduced data are displayed in real time.

Only a part of this large data-taking capability is required in store separation tests. The flight conditions of interest at release will usually include:

Aircraft CG 3-component accelerations
Mach number
Angle of attack
Outside air temperature
Airspeed
Altitude
Aircraft 3-axis angular rates
Aircraft 3-axis attitudes.

In the case of guided missile firings, the following missile parameters are telemetered separately during a launch:

Missile 3-axis angular rates
Control surface positions
Longitudinal accelerations
Pitch and roll attitudes
Pitch and yaw accelerations.

This is done not only to monitor missile behavior as a functional entity, but also to avoid confusion between missile malfunction and basic separation problems.

Data handling and reporting problems in a full-fledged store separation demonstration program rapidly become unwieldy and contribute a substantial part to the overall program cost. The state-of-the-art at the present time, then, is that--through a prodigious amount of wind tunnel testing, preliminary analysis, flight testing, and data reduction--a finite release envelope can be demonstrated for a given model of aircraft and a designated store. Various stores (and various store positions) may have (will probably have) various release envelopes. Also, these boundaries will demark a flight envelope less than that attainable by the loaded aircraft, so that in combat operation the aircraft will be limited in attacks to that flight envelope set by store separation.

Moreover, the separation envelopes discussed above are not general; they apply only to the aircraft and store involved and, as has been said, are obtained only after the expenditure of large amounts of time and money. The development of release envelopes for other aircraft would require the expenditure of similar amounts of investigative effort. It is reiterated that there continues to exist a great need for a general mathematical model and analytical capability that will describe the separation motion of arbitrary stores from arbitrary aircraft readily and accurately, to the end that safe and functionally acceptable flight separation envelopes can be developed and maximized on the computer.

ORGANIZATIONS AND RELATED PROBLEMS

As pointed out in the introduction, many problem areas and deficiencies have been studied by special study groups. These studies have defined problems; but, with regard to separation problems, no solutions have been found. Within the NASC exist organizational elements responsible for aircraft, for suspension and release equipment, and for weapons. There is no specific organization responsible for interfacing these elements. Reliance has been placed upon mutual cooperation between the existing organizations. The results have been highly unsatisfactory. Problems have been addressed on the basis of very restrictive single technology areas. The group responsible for suspension and release have attempted to solve the store separation problem through new rack concepts. Other narrow programs include the Grid Data Bank of NSRDC and the Airborne Balance work at NWC. Such narrowly defined programs were doomed to failure from the start--the problem is truly of a systems nature, and it must be approached by considering the aircraft, rack, and weapons as a system.

It is not surprising, then, that a limited number of unofficial, but officially recognized, groups have been formed. Listed below are some official and unofficial groups that are active at present, along with a brief description of their current work.

NAVAL AEROBALLISTIC ADVISORY COMMITTEE (NAAC) PANEL ON SEPARATION OF STORES FROM AIRCRAFT

This panel was formed in 1969 and met for the first time that October. The panel report for the year included a fairly comprehensive review of store separation problems and work being done, and recommended several actions that would have been of considerable value to the Navy. Since the committee and the panels have no funds and no direct control over funds, the accomplishment of these recommended actions was never completely achieved. Meeting each year since 1969, the panel has served as an important means of communication between Navy laboratories and between Navy laboratories and industry.

JOINT TECHNICAL COORDINATING GROUP (AIR-LAUNCHED NONNUCLEAR ORDNANCE)

The Joint Technical Coordinating Group for Air-Launched Nonnuclear Ordnance (JTCG/ALNNO) was chartered in October 1964 by joint action of the Air Force Systems Command, Army Materiel Command, and the office of Navy Material. The charter was revised on 23 May 1967. Within the area of air-launched nonnuclear ordnance, the JTCG is charged with effecting detailed interservice RDT&E review and coordination at the technical working level. To effect this action, the group is organized into twelve working parties listed below. Working Party 12, in its general consideration of aircraft/store compatibility, has addressed the problem of store separation in its proposed handbook entitled *A Guide to Aircraft/Stores Compatibility*. This handbook has recently been published as a JTCG report (identified only by title) and has also been submitted through standardization channels to all services for coordination and eventual publication as a MIL-Handbook.

Working Party for Target Acquisition and Identification, WP-1
Working Party for Missiles and Rockets, WP-2
Working Party for Fire Control, WP-3
Working Party for Guns, WP-4
Working Party for Pyrotechnics, WP-5
Working Party for Shipping/Storage Containers for Air-Launched Weapons, WP-6
Working Party for Flame and Incendiary Devices, WP-7
Working Party for Warheads and Explosives, WP-8
Working Party for Fuzes, WP-9
Working Party for Bombs, Clusters, Dispensers, and Air-Delivered Land Mines, WP-10
Working Party for Racks, Ejection Cartridges and Munitions Handling Equipment, WP-11
Working Party for Aircraft/Store Compatibility, WP-12

ADVANCED AIRCRAFT SYSTEMS PROGRAM OFFICE (AASPO)

An AASPO has been established at NWC to implement the designation of NWC as the Leading Field Activity for Deputy Program Direction of both Attack and Anti-Air Aircraft Systems Exploratory and Advanced Development. The establishment of a single group authorized to formulate and develop both aircraft and weapons concepts and design criteria in a unified system, for the first time, founds a powerful potential for effectively addressing in an integrated way the many-faceted technical nature of the store separation problem.

AIRCRAFT ARMAMENT COORDINATION TASK (AACT)

Now included within the AASPO at NWC is the earlier organized effort known as the Aircraft Armament Coordination Task (Ref. 187). This effort proposes to continuously monitor the aircraft-armament interface, discovering and pinpointing problem areas, developing solutions to these specific problems, and monitoring the results of introducing these solutions. Its overall objective is to obtain a reasonable degree of control over the aircraft-armament interface. With respect to store separation, it is well-known that, in large measure, its problems have proliferated through lack of systems control of hardware at the aircraft/store interface.

GENERAL COMMENTS

Unofficial groups such as NAAC and JTCG suffer from two primary difficulties. They do not have funds to support work that needs to be done. After devising recommended work that represents a consensus of the group, it is generally still necessary for someone to propose to and convince a potential sponsor of the advisability of the actual work. Also, the sheer magnitude of the administrative job of coordinating essentially volunteer members causes considerable difficulty.

Official organizations such as AACT and AASPO at NWC are funded and, since members are generally paid salaries for their participation, administrative difficulties are minimized. However, the fact of their funded status has brought with it considerable pressure to invent solutions to current problems, which has tended to focus attention on application of current technology and ignore the needs for advancing technology before good solutions may be obtained.

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13. ABSTRACT

Fields of past and present activity related to the development of operationally safe release envelopes for stores separating from aircraft in flight are surveyed. Various available theoretical methods for determining the complex interfering flow fields around aircraft-store combinations are examined, and some show promise sufficient to warrant further development on a priority basis.

Available wind tunnel scale testing techniques are described. A degree of uncertainty remains as to the accuracy with which wind tunnel data can be employed to represent full-scale flight conditions. It is probable that much of the existing correlation data between full-scale experience and wind tunnel testing is invalid or inconclusive. Extensive flight testing, cumbersome and expensive, must still be employed at the present time for complete and final certification of store separation envelopes. There is a great need for a general mathematical model and computational capability that can describe the separation motion of stores from aircraft readily and accurately.

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