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# MISSILE AERODYNAMICS

This article describes the role of the aerodynamicist as a member of a missile development team, the preliminary design tools available to him, the potential problem areas in designing aerodynamically efficient configurations, and the types and sources of aerodynamic data needed during the engineering development and flight-testing process. The discussions deal primarily with tactical surface-to-air missiles, although the general development philosophy also holds for other types.

## SETTING DESIGN REQUIREMENTS

The goal of the development team is to develop a tactical missile system either to counter an expected threat to one's own defended area (a defensive system) or to destroy or do significant damage to the enemy's defended area (an offensive system). For the aerodynamicist, this means designing the external configuration of the airframe so as to provide sufficient capability (speed, range, and maneuverability) to accomplish the mission planned for the system.

The first task of the team is to ascertain the threat and, on the basis of feasible battle scenarios, develop a missile system concept to counter it. That concept will establish broad requirements in most technologies. The aerodynamicist must carry out his preliminary design study while recognizing the limitations on his options that are imposed by necessary choices in the other technologies or subsystems, as indicated in Fig. 1 and discussed in the next section. The mission analysis should lead to design goals for range, speed, and maneuverability of the missile, to fuzing and warhead needs, and to an overall guidance philosophy. At this stage, first-cut individual choices can be made by the several related technologies to achieve the mission. Modifications to those choices will be made as more-detailed interrelated studies of subsystem performance are made. Thus, a baseline configuration can be established from which further development can proceed.

## TECHNOLOGY INTERFACES WITH AERODYNAMICS

### Launching

Besides restricting the missile's weight, length, and span, the launching system may restrict its permissible motion early in flight. Also, such factors as the motion of the launcher and winds or extraneous flow fields about it will affect the missile's design. The external shape might also be affected by launching shoes or other devices that guide the missile out of the launcher. Such appendages add drag and weight and can affect the missile's stability or controllability. The span limitation for a given launching system may require lifting and control surfaces to be folded, which adds to missile weight and drag and introduces a potential dynamic disturbance during deployment. The aerodynamic design must be done with full knowledge of these considerations so that detrimental effects can be minimized.

### Propulsion

A missile's shape may depend strongly on its propulsion system. Designers of airbreathing systems

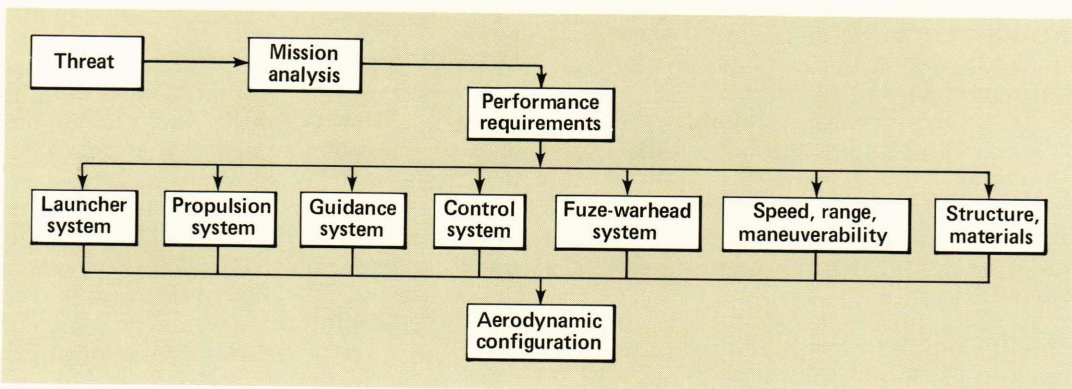


**Figure 1** — Factors and systems affecting the design of aerodynamic configurations.

prefer to locate the air inlets in areas free of degrading aerodynamic interference such as shock waves, vortices, or wakes. At the same time, the inlet itself may degrade the aerodynamic performance. Thus, a compromise must be made between propulsion performance and aerodynamic performance, or, if possible, a design should be sought that takes advantage of favorable interactions that improve thrust, lift, stability, and controllability or that reduces drag.

As fuel is consumed, the center of gravity may shift, thereby changing the controllability of the missile. In general, the center-of-gravity shift is more troublesome with solid-fueled propulsion systems than with liquid-fueled propulsion systems, which have more flexibility in the location of fuel tanks. Offsets of the thrust axis from the center of gravity may also occur for certain propulsion systems (e.g., strap-on booster systems) or may result from design tolerances or from center-of-gravity travel that moves the center of gravity off the thrust axis. Such offsets can result in overturning moments that require additional control capability from the airframe.

## Guidance

The choice of guidance system will affect the demands on missile maneuverability and response, which, in turn, may affect the choice of lifting and control surfaces. Furthermore, the design of domes to protect guidance sensors usually calls for compromises. For example, a hemispherical dome is usually considered the optimum choice for the sensors, but it has high drag. A dome with a high fineness ratio (i.e., length/diameter ratio) has low drag, as shown in Fig. 2, but tends to degrade the reception of signals by the seeker. A guidance system that uses interferometric homing with spike-like antennas at the nose of the missile (as the Talos missile did) can have significant effects on the stability and control as well as on the drag of the configuration. Air-data probes needed for setting autopilot gains (as in the Terrier I missile) or for regulating fuel flow may have similar effects, depending on their placement.

## Warhead and Fuze

The demands of the warhead and fuzing on the aerodynamic performance occur primarily during the brief interval prior to target engagement when the missile should be placed in a position and an attitude that will maximize the kill by the warhead. The other subsystems (guidance, control, propulsion) must work in concert with the airframe to provide this favorable condition.

The aerodynamic design is also influenced by the location of the warhead (usually a very dense package) because it affects the missile's center-of-gravity location and travel.

## Autopilot and Control

Three aerodynamic control systems use all-movable control surfaces: canard controls located

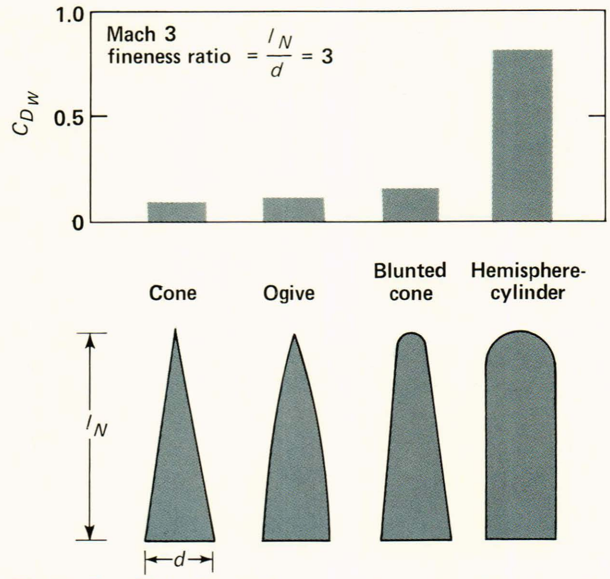


**Figure 2** — The effect of sensor dome bluntness on the wave drag coefficient, $C_{D_W}$.

well forward on the missile, tail controls located well aft, and wing controls located near the midbody. Although several early missiles used wing control (Talos, Terrier I,[1] and Sparrow), the missiles requiring high maneuverability generally resort to tail control. With canard control (Fig. 3a) or tail control (Fig. 3b), maneuverability is achieved by having the entire airframe at an angle of attack to the airstream and is controlled by forces from small surfaces at a large distance from the missile's center of gravity. A wing-controlled missile (Fig. 3c), on the other hand, operates at a much smaller angle of attack and derives a large portion of its lift from the deflected wings. Canard controls can be placed near their source of information – the guidance package (which is usually far forward) – but their effectiveness may be partially compromised by "interference" moments from surfaces situated downstream from them. In some cases the control moment from forward controls (canard or wing) may be greatly diminished or even reversed[2] through interference moments from the aft surfaces. An illustration of interference effects for the wing-controlled missile of Fig. 3c is shown in Fig. 4. The force normal to the missile centerline (proportional to the coefficient $C_N$) increases nearly linearly with wing incidence when the body is lined up with the flow ($\alpha = 0$), as shown in Fig. 4a. When the tails are not present, the force is given by the colored curve. The downwash on the tails from the deflected wings produces a downward force, causing the resultant force on the configuration to drop to the black line. This downward force results in a nose-up pitching moment (proportional to the coefficient $C_m$) that overpowers the nose-down pitching moment from the wings (colored line in Fig. 4b) to yield a resultant nose-up pitching moment for the full configuration (black line). The effect of downwash is the difference between the two curves in

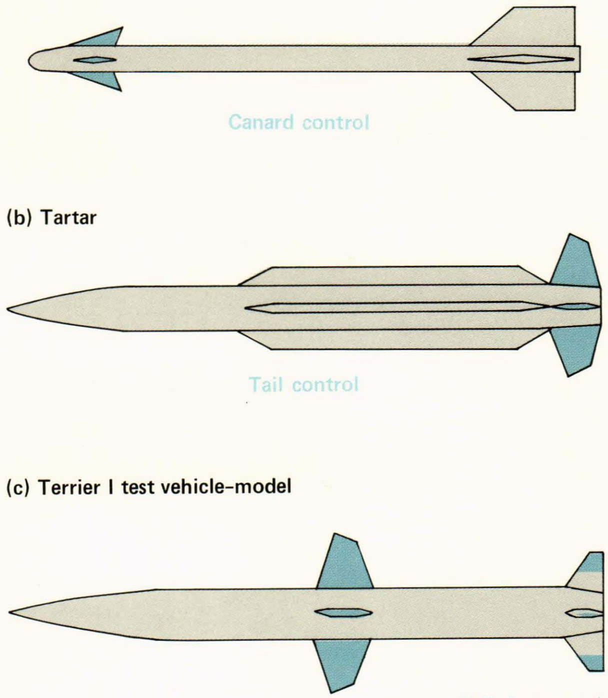


**Figure 3** — Types of aerodynamic control.

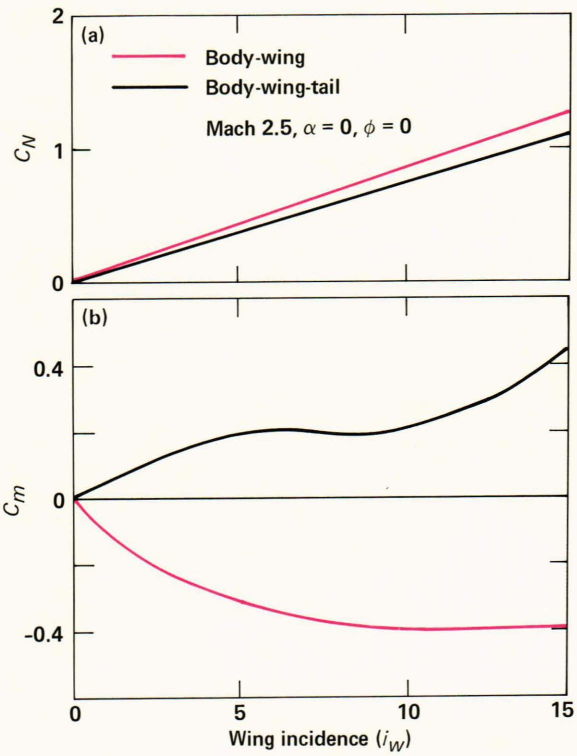


**Figure 4** — The effect of downwash from wing on tail as a function of wing incidence, $i_W$.

each case. Other types of aerodynamic controls are tip controls and trailing edge controls in which only a portion of an aerodynamic surface is rotated to produce control forces.

With thrust vector control, the flow leaving the exit nozzle is deflected to produce a pitching moment. Obviously this system is operable only when the engine is delivering thrust. Such systems are well suited to quick reaction when aerodynamic forces are low, such as for turning a missile shortly after it leaves its launcher or for a rocket missile at an extremely high altitude when aerodynamic forces are small. Control by means of side jets, augmented by natural aerodynamic interference, has been used on some short-range missiles but may not be adequate for high-performance, medium- to long-range tactical missiles.

Thus, the type of control system chosen will determine the locations of lifting and control or stabilizing surfaces and will have a major effect on the missile's stability and control characteristics.

The choice of autopilot to provide proper signals to actuate the controls that guide the missile to the target depends on the airframe and controls selected. For example, with a skid-to-turn autopilot, a missile achieves a maneuver in a given direction by pulling maneuvers in two component directions at right angles to each other. Such an autopilot is appropriate for a cruciform configuration, which has equal lifting capability in two mutually perpendicular directions. On the other hand, with a bank-to-turn autopilot, the missile achieves the desired maneuver by banking (or rolling) to the desired direction and pulling the maneuver in that direction. This is appropriate for a configuration with a preferred lift direction (e.g., a ramjet missile with an air inlet on one side or a missile with a single pair of wings). Some comparisons of homing performance have been made[3] for selected configurations using skid-to-turn or bank-to-turn steering policies.

In summary, the aerodynamic configuration depends strongly on the requirements of the other missile technologies; therefore, achievement of the design goal is usually attained by compromising among them all.

## PRELIMINARY AERODYNAMIC DESIGN TOOLS

In preliminary design, the aerodynamicist may use the following tools to develop a baseline configuration and to assess the effects of potential configuration changes:

1. Existing experimental data bases;
2. Theoretical methods;
3. Handbooks of theoretical, semi-empirical, and empirical design charts;
4. Computer programs, including computerized handbooks, computerized theoretical methods, computerized data bases, and computational aerodynamics;
5. Exploratory wind tunnel tests.

## Existing Experimental Data Bases

Whenever practical, a designer will base the preliminary design of a missile on an existing data base for similar configurations and use interpolation or extrapolation as necessary. For example, in an evolving program such as Standard Missile, there is a wealth of data for the preliminary design of advanced versions. With such data, the designer can not only get the baseline design started but can also plan the necessary wind tunnel test program.

In general, it is possible to compile data (forces and moments) on the several components of a configuration (body, wings, tails, etc.) with reasonable confidence for moderate angles of attack and Mach numbers. More difficult is the assessment of aerodynamic interactions or interference among those components that add to the total aerodynamic behavior of the missile. Thus, a data base with full-configuration data, complemented with data on its components, is very important because the interference effects can be extracted.

The usual design approach consists of building up the aerodynamic characteristics of a full configuration from a knowledge of the characteristics of its component parts, augmented by estimates of the mutual interference of the parts. The acquisition of information on interference phenomena has usually lagged behind the development of methods for calculating the aerodynamic behavior of individual components. As Mach number and angle of attack increase, the interference effects become much more complex and more difficult to predict. A reliable set of test data on the full configuration is required for the detailed engineering design of the missile. If the design requirements point to a configuration considerably different from those contained in the existing data bases, one may turn to other methods discussed in the following subsections.

## Theoretical Methods – Inviscid Flow

*Bodies.* Most early developments in supersonic missile aerodynamics started with the assumption of inviscid flow that was given a small perturbation by the movement of the missile. If the body were sufficiently long and thin, the "slender body" theory could be used to describe the perturbed flow. A linearized partial differential equation, the potential equation, described the flow field. That simple solution yields estimates of dimensionless coefficients of lift ($C_L$) and drag due to lift ($C_{D_L}$) that are independent of Mach number and body shape (within the slenderness restrictions of the theory) and of the static pitching moment ($C_m$) that depends on missile volume:

$$C_L = 2\alpha, \tag{1}$$

$$C_{D_L} = C_L \, \alpha/2 = \alpha^2, \tag{2}$$

$$C_m = -2\alpha\left(1 - \frac{volume}{l\, S_{\text{base}}}\right), \tag{3}$$

where $\alpha$ is the angle of attack in radians, $l$ is the body length (reference length), $S_{\text{base}}$ is the base area (reference area), and the reference center for $C_m$ is the vertex of the nose. The wave or pressure drag, on the other hand, requires integrations involving second derivatives of the axial distribution of the cross-sectional area.[4]

Eliminating the slenderness restriction but still having the restriction of a small perturbation, the first-order (or linear) theory was applied, which led to theories for axial flow (giving the drag[5]) and inclined flow (giving the lift and the pitching moment at small angles of attack[6]). The equations had to be solved numerically. Similar solutions for ducted bodies of revolution were also obtained, including the effect of the deflected air entering the duct.[7,8] Further improvements, using an iteration process, led to the second-order theory by Van Dyke,[9] which also required a numerical integration. Since the second-order theory could handle axial flow but not cross flow, a hybrid theory combining second-order theory for axial flow and first-order theory for cross flow was adopted. Even with pretabulated functions, the second-order axial calculations were tedious.[10] With modern computers the solutions became more feasible and were included in the original Naval Surface Weapons Center (Dahlgren) computer code.[11] A more exact method for axial flow is the method of characteristics (e.g., Ref. 12), also too tedious for preliminary design calculations. Several of these methods provide pressure distributions in addition to forces and moments.

The foregoing perturbation methods are satisfactory for the lower supersonic regime. Other methods were developed for higher speeds. The most frequently used are the generalized shock-expansion method[13] and an improvement on it, the second-order shock-expansion theory,[14] both of which are based essentially on the fact that at high speed, with a high body fineness ratio, the flow can be considered to be locally two-dimensional, so that basic shock-wave and expansion-wave theories are applicable. For even higher speed, the noses of the bodies are usually blunted to alleviate a local thermal condition; to account for blunt noses, the calculation procedure has been modified to allow the use of the Newtonian impact theory over the forward portion of the body and an appropriate matching at some location where the shock-expansion theory can proceed.[15,16] For very high Mach numbers, the Newtonian impact theory is appropriate.[17]

Although much effort has been expended on the theoretical analysis of base flow (with and without the effects of propulsive jets[18]), one generally has recourse to empirically derived design charts for estimating base drag because the theoretical flow models are quite complex.

For the transonic flow problem, great effort has been expended in analyzing the flow fields for a variety of conditions (e.g., Ref. 19), but the calculations are very tedious because the perturbation equations are nonlinear and require numerical integration. Subsonic flow has been handled by the slender body theory and linear theories (as was supersonic flow). The solution in the slender body theory, $C_{L_\alpha} = 2$, assumes potential flow. The linear theory solutions[20] are satisfactory for incompressible flow (Mach = 0) but generally require a compressibility adjustment at higher subsonic Mach numbers. In the design of high-speed, high-performance missiles, the greatest needs are at high angles of attack, and they cannot be handled by the aforementioned perturbation methods.

*Thin Lifting Surfaces.* Most early theoretical approaches to the problem of inviscid flow about wings resulted in solutions of the linearized potential flow equation for thin wings at small angles of attack.[21,22] Although the solutions for zero-lift wave drag and slopes of lift and pitching moment coefficients have been published for a variety of wing planforms, their applicability to higher angles of attack is somewhat limited. Higher-order approximations are best obtained by turning to two-dimensional wing theory, which is the basis for the so-called shock expansion theory mentioned for bodies. Using two-dimensional theory along streamwise strips does not account for the tip losses inside the Mach cone associated with the disturbances from the outermost point of the leading edge. However, as the Mach number increases and the Mach cone angle decreases, the affected region becomes smaller, so that the approximation may be satisfactory.

*Interference Effects.* When a lifting surface is attached to a body, the aerodynamic forces on the combination generally exceed the sum of the forces on the isolated elements because the two flow fields interact.

A research program on supersonic wing-body interaction was conducted in the Bumblebee program at Cornell Aeronautical Laboratory in 1947-1951.[23,24] It provided theoretical methods for calculating the velocity potentials corresponding to the flow perturbation of the body on the wing and the wing on the body. The methods were validated by detailed pressure measurements. Although the results have provided a better understanding of the flow phenomena, the designer can obtain satisfactory engineering approximations with less effort using the method of Morikawa.[25] The solutions are meant to be restricted to small angles of attack and moderate supersonic Mach numbers for wing-body configurations with no afterbody. Nevertheless, the so-called Morikawa factors have been used successfully over a wider range of parameters. An illustration of the several components contributing to the total lift resulting from wing-body interference is given in Fig. 5 for a delta wing mounted on a cylindrical body.

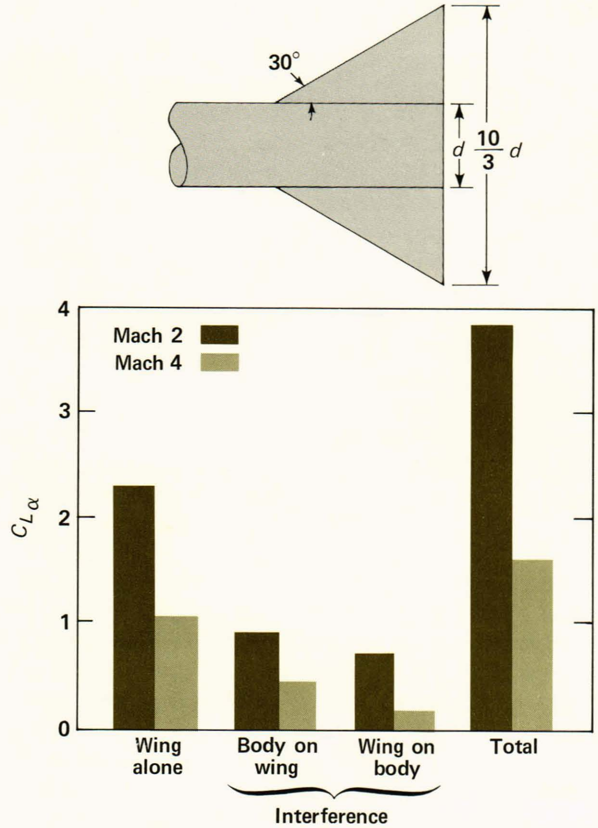


**Figure 5 —** Wing-body interference – linear theory.

On the other hand, when lifting surfaces are in tandem (such as a canard followed by a wing or a wing followed by a tail), the flow past the forward surface is deflected (downwash) and also loses energy so that less lift is produced on the aft surface. These effects determine the so-called efficiency of the aft surface. Although there are many techniques for calculating the downwash, such calculations[26] may not be warranted if one needs only a rough estimate of tail lifting efficiency for preliminary design.

*Combined Angles of Attack and Sideslip.* Most theoretical approaches have been developed for cases in which the missile or one of its components is at an angle of attack to the flow with no sideslip. One can also obtain effects of sideslip with zero angle of attack. But the problem of combined angles of attack and sideslip, a truly three-dimensional problem, is not easily handled by these theoretical methods. Some of the most recent attacks on the problem have been made by Nielsen *et al.*[27]

*Full Configurations.* The characteristics of a full configuration are calculated theoretically by combining the characteristics of the component parts and their mutual interferences. The results are limited by whatever restrictions are inherent in the theories for the components and their interferences. Consequently, nonsymmetrical configurations are usually very difficult to deal with theoretically.

### Theoretical Methods – Viscous Effects

The two most important viscous effects are those in the flow direction that produce skin friction drag and those normal to that direction (cross flow) that produce additional lift and pitching moment at higher angles of attack. To calculate skin friction drag during preliminary design, the aerodynamicist generally treats the missile configuration as a set of simple geometric elements (flat plates, cylinders, etc.) on which the turbulent skin friction drag can be calculated by a method such as that of Ref. 28. This skin friction drag is combined with wave and base drags to give total missile drag. The additional lift and pitching moment resulting from viscous cross flow are calculated by a method such as that given in Ref. 29. They are combined with the inviscid lift and pitching moment to give the totals for the missile.

### Handbooks

Many of the foregoing theoretical methods and some of the wind tunnel and flight data have been assembled into handbook form as curves and tables so that preliminary design can proceed by a build-up process without individual calculations having to be made. The most well known of these handbooks are:

1. *Handbook of Supersonic Aerodynamics,* NAVORD Report 1488 (published between 1950 and 1966),
2. Royal Aeronautical Society, *Engineering Sciences Data Units* (*Aeronautical Series, Aerodynamics Sub-Series*) (published between 1943 and the present),
3. *U.S. Air Force Stability and Control DATCOM* (initially issued in 1956 and updated periodically).

The *DATCOM* has been computerized so that much of the data extraction from families of curves has been speeded up, but preparation of the input to the program is time consuming. Consideration is being given[30] to the development of a handbook (based on *DATCOM*) aimed specifically at missile design (rather than at general aircraft design as was the original *DATCOM*).

### Computer Programs

The following four programs now being used are representative of those that exist:

*Approximate Aeroprediction Code – NSWC/DL.*[31,32] Available analytical and empirical procedures are used to calculate static and dynamic coefficents for configurations with axially symmetric bodies and streamwise wing and tail tips. The reported region of validity is $0 < M < 8$, $0 < \alpha < 180°$, although this region does not hold for all components. It is useful for early design studies when drag, normal force, and longitudinal static stability are the primary concerns.

*PANAIR – NASA (by Boeing Military Airplane Co.).*[33,34] In this program, "panel methods" are used, i.e., a set of linear partial differential equations of potential flow is solved numerically by using "singularity strengths" on the set of panels to describe the configuration geometrically. The configurations can be arbitrary in shape.

*Mark IV Supersonic-Hypersonic Arbitrary Body Program – AFFDL (by McDonnell Douglas).*[35,36] As an engineering approach to preliminary design, methods are used that can handle configurations not suited to linear theory without going to the method of characteristics or to finite-difference techniques. Many analytical techniques are programmed; the user makes the choice of what is best for his problem. The configuration is represented geometrically by sets of quadrilaterals (panels) on which the forces are calculated. The code is applicable from Mach 2 up to very high Mach numbers. Entering the geometry of the configuration is a tedious task.

*Numerical Aeroprediction Code – NSWC/WO.*[37,38] The inviscid supersonic flow field about finned configurations is calculated by finite difference techniques using mesh spacing that is adjusted to improve accuracy in regions of expected large flow gradients. It is best suited for selected check calculations because it requires much more computer time than, for example, the Approximate Aeroprediction Code. Also, it provides much more detailed information at each condition. Before using any such code, the user should see how well the calculations have agreed with test data on configurations similar to those being considered for the design.

### Exploratory Wind Tunnel Tests

It is always desirable to carry out exploratory wind tunnel tests, guided by the calculations discussed in previous sections. Such tests should be aimed at determining the variations from a basic design by making configurational changes in the components, by spanning the expected Mach number and angle-of-attack ranges, and by validating the calculations made for the baseline configuration. In addition, measurements at nonsymmetric conditions (such as a cruciform configuration maneuvering out of its planes of symmetry) are needed to assess yaw and roll stability not easily calculable by standard methods. Measurements of hinge moments of control surfaces are needed for sizing control servos. It must be remembered, however, that these moments may be changed considerably in the design process by configuration modifications upstream of the surface. The selection of a final hinge line must take into account such modifications.

## PROBLEM AREAS IN CONFIGURATION DESIGN

### Geometric Limitations

Geometric limitations usually result from the compatibility requirements of the launching and handling systems. Restrictions on length place a limit on available body lift (or normal force). The slope of the normal force coefficient curve, $C_{N_\alpha}$, generally tends to increase with body fineness ratio (Fig. 6) although this behavior also depends on the Mach number and fineness ratio of the nose section. Since normal force resulting from viscosity is a function of cross-flow drag, the normal force coefficient, $C_N$, also increases with body fineness ratio because there is an increase of body planform area on which the cross flow can act. The variation of $C_N$ with fineness ratio and angle of attack is shown in Fig. 7 for bodies at Mach 7.69. A further observation is that the Newtonian theory agrees quite well with experimental data at that Mach number except at low angles of attack.

Restrictions on the span of stabilizing and control surfaces result in surfaces of lower aspect ratio, *AR*, that generally produce a smaller slope of the normal force curve than those of higher aspect ratio having the same planform area, as is shown in Fig. 8 (curve *W*). Because the viscous normal force at angle of attack depends primarily on the planform area, the total normal force (potential plus viscous) does not show as great a variation with aspect ratio as does the slope of the normal force curve. The carryover normal force from the body to the wing and from the wing to the body also tends to lessen the difference attributed to the difference in aspect ratio. An illustration of the total potential normal force from linear theory is presented in Fig. 8 (curve $W + W_B + B_W$). The contribution from the wing alone (curve *W*) decreases with the reciprocal of the aspect ratio, whereas the total $C_{N_\alpha}$, including interference effects, peaks near $AR = 0.5$ for those rectangular wings evaluated at Mach 2.24.

Another limitation is the space available for control servos of tail-controlled configurations. The servos are usually housed in the annular volume around the throat of the propulsion nozzle. Optimum design requires careful attention to the selection of an appropriate hinge line for control surfaces in order to minimize torque requirements over the missile's full operating range. This spatial limitation is generally more severe for a ramjet missile than for a rocket missile because the former requires a larger nozzle throat area to accommodate the greater mass flow from the combustion chamber.

## Center-of-Gravity Travel

The static stability of a missile is a measure of its tendency to return to its equilibrium attitude after being disturbed. It depends on the relative location of the center of gravity (the point at which the resultant of the inertial forces acts) and the center of pressure (the point at which the resultant of the aerodyamic

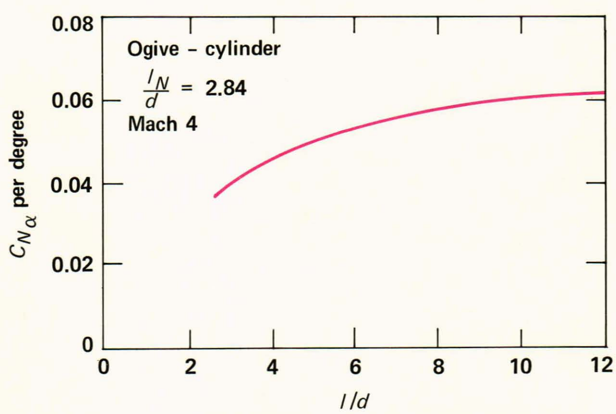


**Figure 6** — The effect of fineness ratio on the body normal force coefficient.

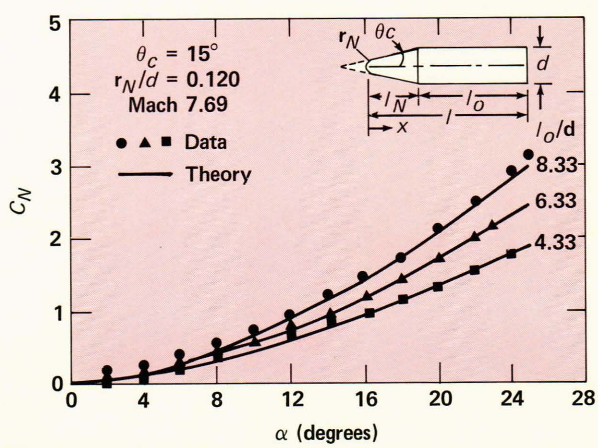


**Figure 7** — The effect of aft body length on the normal force coefficient.

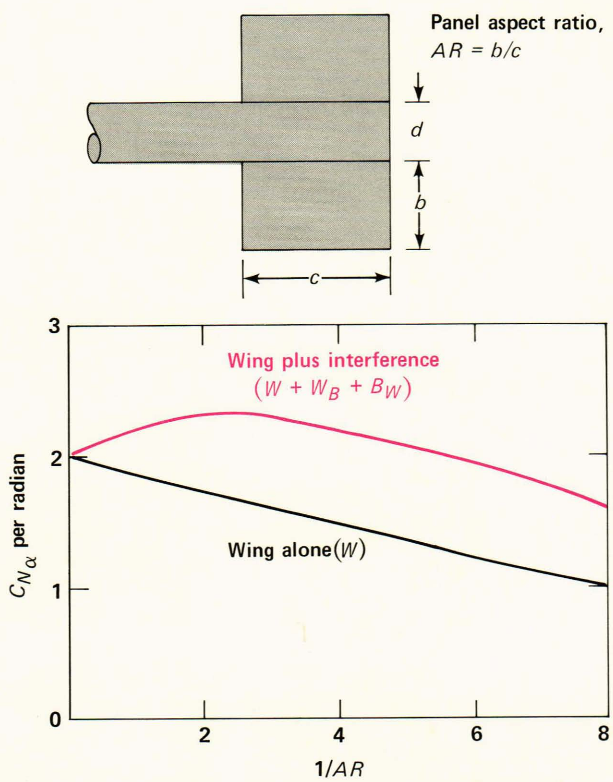


**Figure 8** — The effect of wing-body interference on the slope of the normal force coefficient at Mach 2.24.

forces acts). A very stable missile has its center of pressure well aft of its center of gravity and requires a large control authority to maneuver it to another position. For a highly maneuverable missile, it is desirable to minimize the margin of stability.

In the case of missiles propelled by solid rockets, the change in the center of gravity from ignition of the rocket to burnout may be large, so the spread in static stability for a given Mach number may also be large. In order for the missile to accomplish its mission (near or after burnout), it must be maneuverable near the target, at which time the center of gravity is usually in a very forward position. The forward position favors stability and thus requires a large control authority. If the missile is designed for very low stability at that condition, it may result in unacceptable instability early in flight when the center of gravity is in an aftward position. Since the center of pressure of a configuration varies with Mach number, it is clear that the designer should consider simultaneously the time histories of center-of-gravity travel and Mach number in establishing margins of stability.

## Spread in Mach Number and Altitude

The center of pressure of a configuration varies with Mach number. Each component contributes to this variation. As Mach number increases, $C_N$ for the body varies only slightly, and the center of pressure (with a few exceptions) moves aft slightly (Fig. 9). $C_N$ for the tails decreases (nearly inversely with Mach number), and the center of pressure varies only slightly. As a result, the center of pressure of such a body-tail configuration moves forward with increasing Mach number because of the lowered tail force coefficient. If intercept occurs at high Mach number, this center of pressure movement with Mach number, which favors instability, is desirable because the demand on control moment is lessened.

Consideration must be given early in the design process to the maneuverability requirements at the highest altitude because maneuverability depends on controllable lift. The latter depends on the configuration lift coefficient attainable with the available control authority and the dynamic pressure, $q$, at which the missile will operate:

$$\text{Maneuverability (in } g) = \frac{lift\ (lb)}{weight\ (lb)} = C_L q \frac{S}{W}\text{, and}$$

$$q = \frac{\gamma}{2} p M^2 ,$$

where $C_L$ is the lift coefficient, $S$ is the reference area upon which $C_L$ is based, $W$ is the missile weight, $p$ is the static pressure at the flight altitude, and $\gamma$ is the ratio of the specific heats of air.

For example, at the same speed and for the same maneuver, the missile needs a lift coefficient at 80,000 ft altitude that is more than 40 times the sea-level value. Dynamic pressure is also an important parameter in designing the autopilot and in selecting its gain program.

## High Angle-of-Attack Phenomena

High angle-of-attack ($\alpha$) phenomena arise at both ends of the Mach number regime. During launch, un-

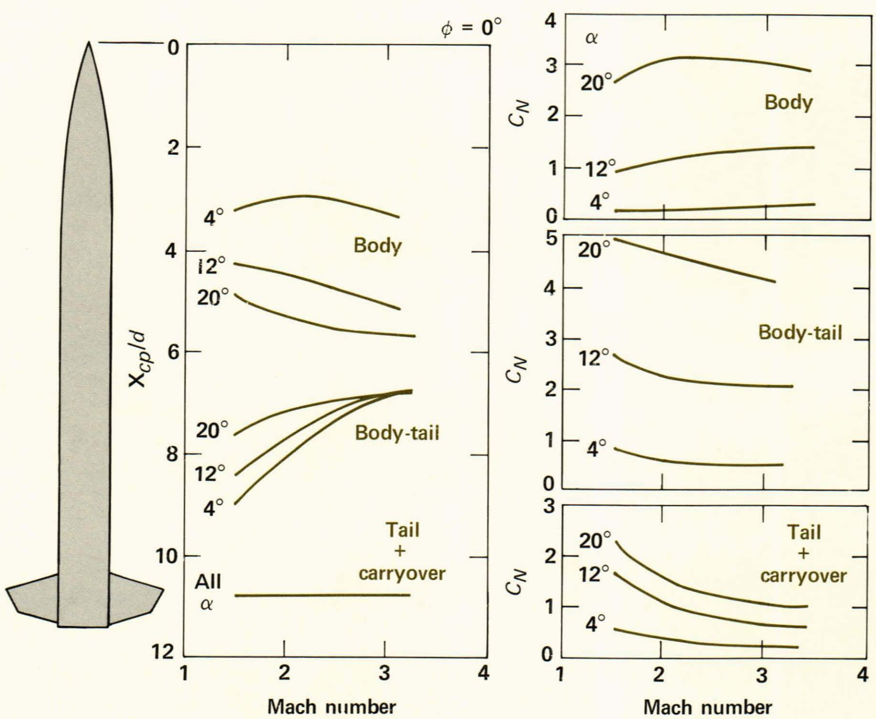


**Figure 9** — The normal force coefficient and center of pressure – body, body-tail, tail plus carryover.

der conditions of launcher motion and high winds, the low subsonic motion of the missile may occur with high angle of attack where the stability characteristics are very nonlinear and the control effectiveness is limited because of low dynamic pressure on the surfaces. The dynamic motion required to achieve the proper attitude may dictate a need for a supplementary launch-phase control system or may impose additional requirements on an aerodynamic control system intended for the entire flight phase. During the high subsonic and transonic phases, if the missile is required to operate at high angle of attack in order to maintain its position in a desired trajectory, it may experience a shedding of unsymmetrical vortices from its lee side, resulting in side forces and moments on a symmetrical airframe in a symmetrical attitude.[39] This phenomenon may present another control problem.

Another high angle of attack phenomenon is that of coupling between the yaw and roll modes of motion (pitch-yaw-roll coupling).[40] Coupling occurs when the missile attempts to maneuver in the yaw direction while pulling a large maneuver in the pitch direction. Increased loading on the windward surfaces (behind the strong body shock waves) and decreased loading on the lee side (in vortex flows) combine to produce instabilities in roll and yaw and induced moments resulting from the roll and yaw control deflections that are required to counter those instabilities. The phenomenon is highly dependent on the configuration's shape and attitude in roll. A proper design study of this phenomenon requires a coordinated effort between the autopilot designer and the aerodynamicist in order to achieve maximum controllable maneuverability. The data necessary for such an investigation should be obtained from detailed wind tunnel tests that provide a three-dimensional description of the aerodynamic forces and moments.

### Launching Environment

The housing of a folding mechanism may require additional thickness of the inboard cross section, thereby adding to drag. Furthermore, one should investigate the dynamic behavior of the missile during deployment of the surfaces, which usually occurs while the missile is under the influence of somewhat random flow fields near the launcher.

The environment of shipboard launchers includes the ship's angular motions, relative winds, disturbed flow fields about the superstructure, and enveloping gases from the missile's own rocket, each of which taxes the missile's controllability. In the case of launching from aircraft, the aerodynamic interference between the flow fields of the aircraft and those of the missile is a major factor to be considered and has been investigated extensively in recent years.[41]

### Staging

For a multistage missile, one must be concerned with the aerodynamic design of the full configuration during each stage, taking into account the Mach number and altitude regimes covered by it. A key problem to be attacked early in the preliminary design is the separation of the stages so as to avoid any possible recontact if the relative drag and thrust forces are not sufficient to ensure clean separation. In addition, the presence of the separating stage (the booster) from the continuing stage (the missile) may result in an interference that adversely affects the missile's stability. It is important that the control system be designed to cope with this change in stability and that it be activated without excessive delay.

## DATA NEEDED FOR DETAILED DESIGN, FLIGHT TESTING, TROUBLE SHOOTING

Various methods to provide aerodynamic data for preliminary design were described earlier. Many of the problems discussed in the previous section cannot be addressed using the type of data provided by those methods. Thus, early planning should be made for detailed wind tunnel testing to provide the data needed for such critical analyses.

### Three-Dimensional Data for Six-Degree-of-Freedom Simulation

A six-degree-of-freedom simulation should be able to describe the missile motion in three translational and three rotational modes. The appropriate aerodynamic forces (axial, normal, lateral) and moments (pitching, yawing, rolling) must be provided as functions of Mach number, altitude, angle of attack, angle of sideslip, and control deflections in pitch, yaw, and roll. A well planned wind tunnel testing program must be conducted to acquire these data efficiently and economically. First, one must decide how the data will be used and what format might be best for the simulation. Those factors will have significant influence on the test plan. Wherever possible, advantage should be taken of known symmetries or known regions of small variations in the expected data in order to reduce the required testing.

The aerodynamic data will be needed in the engineering design phase in order to design the autopilot and to check it out over a wide range of potential maneuvers. The aerodynamicist should assist in planning the flight tests and in analyzing the flight data to validate the aerodynamic description of the configuration. He also should assist in troubleshooting when flight anomalies appear. The money spent in providing a proper three-dimensional representation of the aerodynamic characteristics is well spent if it makes possible a more productive and less costly flight test program.

### Pressure Distributions, Panel Loads, and Moments

Pressure distributions may be needed for structural design and for thermal analysis. In some cases, they may be obtained with sufficient accuracy for preliminary design from theoretical calculations or from computer codes using finite difference methods to calculate the flow fields. For critical conditions that may involve complex flow fields and shock waves interacting with each other or with the boundary layer, or impinging on surfaces, it is usually necessary to include some wind tunnel tests with a pressure model and with flow visualization techniques to be able to identify critical areas of high temperature or pressure. Because the volume inside the model is limited, the number of points at which pressure may be measured is also limited. Thus, it is important to confine measurements to areas of expected high pressure gradients and to limit them in areas of low pressure gradients. When panel flutter may be a design problem, pressure distributions are needed for the aeroelastic studies.

Accurate measurements of control surface hinge moments are required for sizing the control servos. The design goal is to choose a hinge line that minimizes the hinge moments over the entire flight regime. A surface planform and cross section is desired with minimum center-of-pressure travel over the full range of Mach number, angle of attack, and angle of incidence for the various roll orientations. An important caution is that any changes in the geometry of the surface or of the missile ahead of the surface are likely to affect the hinge moments. For that reason, detailed hinge moment measurements are usually postponed until the preliminary design has reached the point where only minor modifications are expected. Theoretical estimates of hinge moments are rather tedious to make and are not very reliable because the center of pressure of the control forces cannot be calculated with the needed accuracy as a result of the complex flow conditions associated with angle of attack, roll angle, and control deflections, and of the many interferences from the body, the forward surfaces, or protuberances. It is customary to measure panel normal loads, hinge moments, and spanwise bending moments simultaneously. If the model size permits, the measurements are obtained at the same time that the six components of force and moment are measured on the full configuration.

A considerable effort was expended in arriving at a wing planform for the Talos wing-controlled missile in order to minimize the wing hinge moments.[42] That planform proved to have the desired limited center-of-pressure travel and has been used for the control surfaces of Terrier, Tartar, and the Standard Missile family. The hinge line location (in percent of root chord) has been adjusted according to the Mach number regime to keep the center-of-pressure travel to a minimum and thus to minimize the design hinge moment.

## Effects of Elasticity on Aerodynamics

Under sufficient loading, a missile may change its shape and thereby cause changes in its aerodynamic characteristics.[42] The body may bend as a freely supported beam, the surfaces may "wind-up" about the hinge line, and the shaft itself may twist. These elastic effects are usually accounted for by making a "quasi-static" correction. A structural analysis, which depends on a sufficiently accurate distribution of air loads and inertial loads, must provide the description of the distorted shape. The distorted shape essentially describes the changes in angle of attack or incidence of the various elements of the configuration. Forces and moments resulting from the changes are added to those of the rigid body to give the quasi-static aerodynamics of the configuration. The process is iterative but converges rapidly for a properly designed airframe. Figure 10 illustrates the effect of elasticity in the Talos missile.

## Dynamics of Separation

At separation of the missile from the booster in a two-stage vehicle, at least two goals are sought. The first is a clean, quick separation. That condition can be ensured if the axial forces on the booster greatly exceed the axial forces on the missile at the instant of separation. If the booster cross section is sufficiently larger than that of the missile and if the booster thrust tail-off is steep, a clean, quick separation should be expected since such a relationship between axial forces should exist. One factor that might oppose a clean separation is the existence of an angle of attack on the missile-booster configuration at separation; that factor could result in individual dynamic motion of the missile and the booster where each could be affected by the other. The angle of attack may result from the use of guidance during the boost-phase of flight or, for an unguided boost phase, from manufacturing misalignments (particularly in the booster fins and rocket nozzle) that could cause a stable configuration to seek an equilibrium angle of attack to balance the resultant pitching moments.

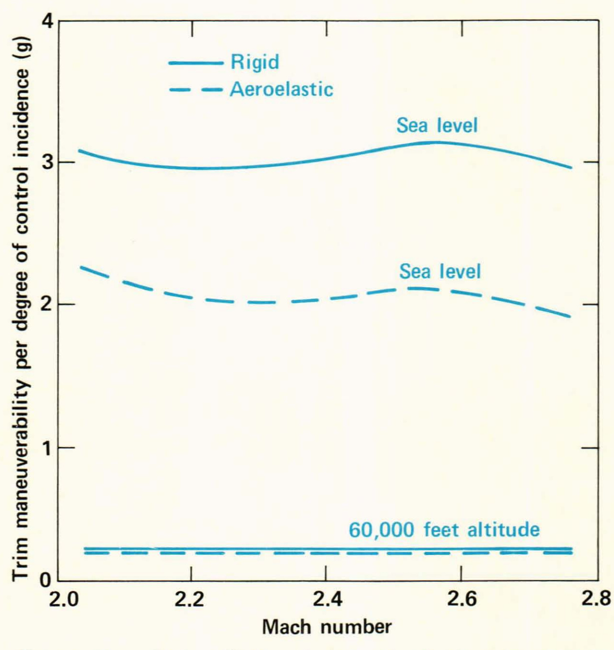


**Figure 10** — The effect of aeroelasticity on maneuverability.

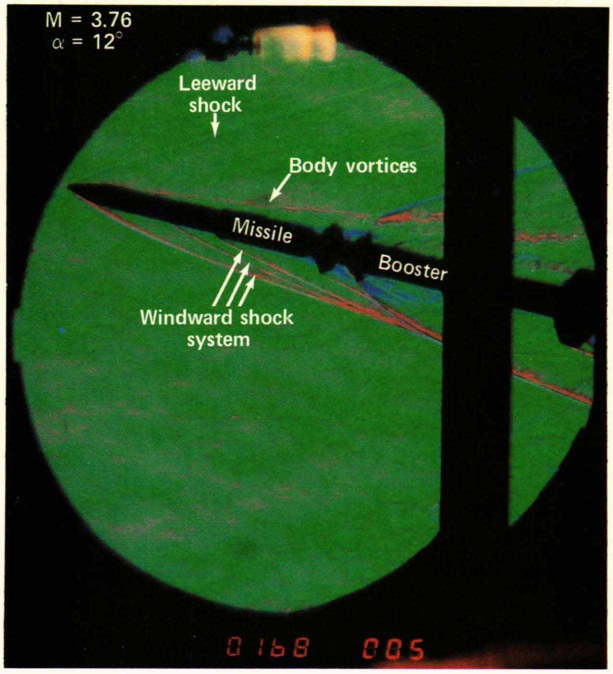


**Figure 11** — Missile booster, first stage.

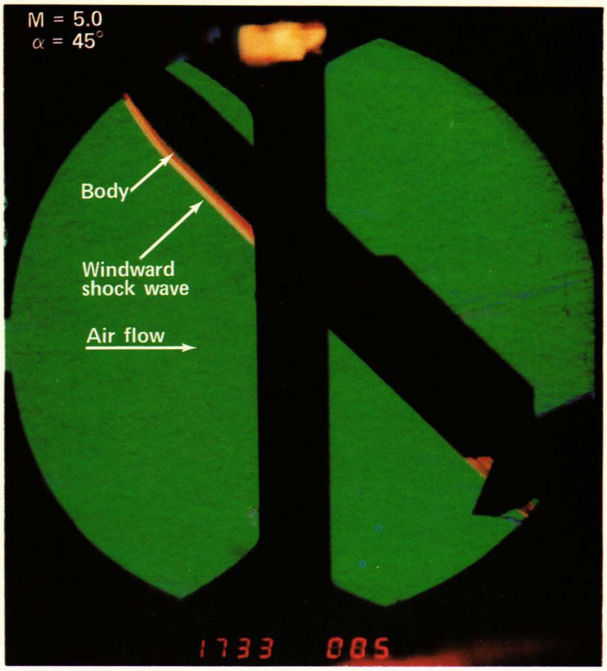


**Figure 12** — Missile, second stage.

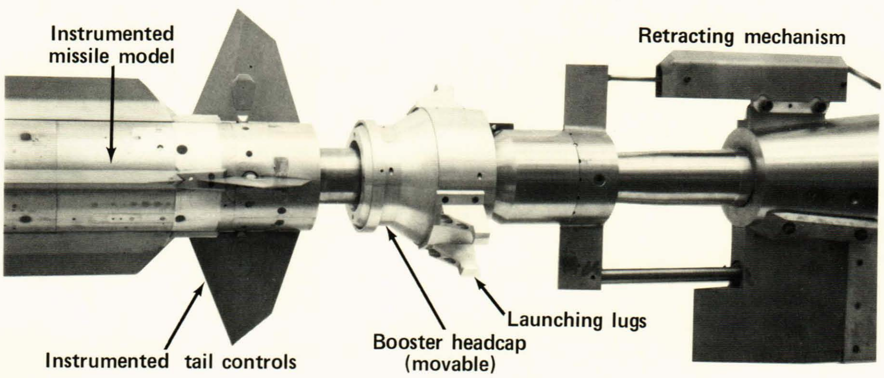


**Figure 13** — Missile booster, separation test model.

The second goal is to activate the missile control system as soon as possible after separation. Then, if the missile is unstable in the presence of the separating booster, the transient angle of attack can be minimized, thereby decreasing missile drag and increasing the chance for a clean separation. Since tail stabilization and control may be adversely affected by the flow disturbances caused by the booster head cap, it is desirable to obtain wind tunnel test data simulating missile-booster separation conditions for both the missile alone and the separated booster.

## CONCLUDING REMARKS

Missile design involves many interacting technologies, most of which have significant input to the choice of an aerodynamic configuration. The process should lead to a compromise solution that seeks an optimum missile system for the mission. The solution, however, is likely to be less than optimum for each of the technologies contributing to the system.

The many interactions among technologies seeking solutions for the proposed system have a profound effect on the philosophy of the wind tunnel testing needed to arrive at the eventual configuration and to provide an accurate definition of its aerodynamic characteristics for detailed engineering design and flight testing. Preliminary testing over a broad range of parameters should include the so-called "build-up" data, which isolate the contributions of the several configurational elements (body, wings, tails, launcher shoes, etc.) to the overall forces and moments measured on the full missile configuration. As changes are necessitated by findings during the preliminary design process, the aerodynamicist can evaluate quantitatively the effects that will result from those changes, using the body of acquired parametric data. When design has progressed to the point where only minor external changes are expected, extensive testing can proceed for a three-dimensional description of the aerodynamics of each configurational phase of the weapon (first stage (Fig. 11), second stage (Fig. 12), and separation phase (Fig. 13) ).

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