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A REVIEW AND COMPARISON OF TACTICAL MISSILE CONTROL METHODS

by

R. H. NUNN

20 DECEMBER 1972

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ABSTRACT

Methods in use or proposed for the control of tactical missiles are identified, described, and compared. A brief and simplified discussion of missile response and flight dynamics is presented in order to illustrate the primary factors affecting control system performance. Aerodynamic (wing, tail, canard) controls are discussed as well as fluid interaction devices (thrust vector control, jet interaction, and others). Considering various performance factors, a rough comparison is made in an attempt to identify the most promising control methods for highly maneuverable missiles.

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I. INTRODUCTION

The variety of ways in which an object can be influenced in its flight through the atmosphere seems to be limited only by the imagination of aeronautical engineers. It is the purpose of this report to identify, describe, and compare the more common methods currently in use for the control of tactical guided missiles. The term "tactical" is used in this report to indicate those guided missiles for which maneuverability is a primary consideration. This class of missiles includes air-to-air missiles, surface-to-air missiles, and other missiles whose purpose is to intercept targets that are moving at high rates relative to the launch vehicle. The scope of this report has been

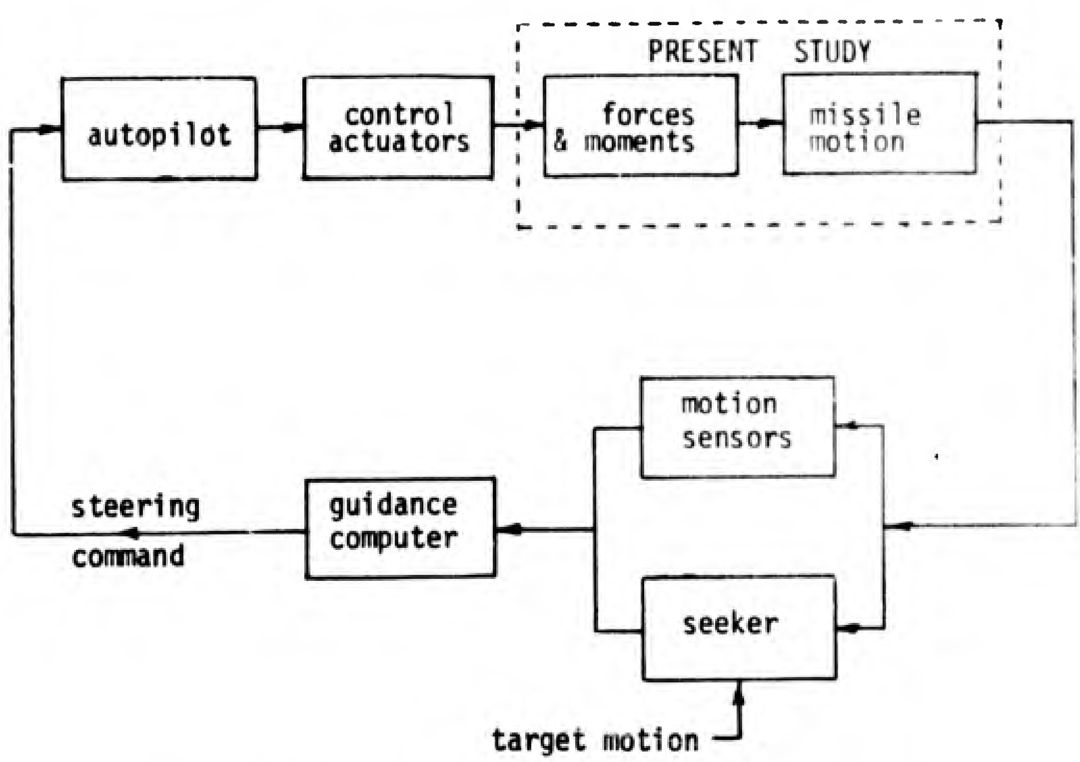


Figure 1. Guidance and control loop showing scope of present study.

limited to a consideration of only those devices that are used to generate forces and moments on the missile for maneuvering purposes. Thus, as shown in Fig. 1, a discussion of feedback elements, guidance laws, seeker characteristics, and autopilot, although of vital importance to the over-all guidance and control problem, is beyond the scope of the present study.

The basic function of any control method is to exert forces and moments upon a missile in order to rotate the missile and/or to move the center of gravity of the missile in a prescribed direction and at a prescribed rate. Perhaps the most crude division of methods for missile control can be accomplished by separating those methods that utilize aerodynamic surfaces from those whose effect upon the missile is largely due to fluid dynamic interactions. The former category utilizes aerodynamic surfaces in order to establish the desired pressure distributions upon the missile body as well as upon the surfaces themselves. Fluid interaction techniques include methods in which the main rocket thrustor is deflected (TVC), and in which external fluid jets alter body pressure distributions by means of fluid dynamic interactions with the external flow fields. As will be developed in later sections of this report, all systems have relative advantages and disadvantages, and very few systems can be eliminated from consideration because of a preponderance of disadvantages.

During the course of this study, a great variety of existing missile control systems were reviewed. These included missiles of the United States (SIDEWINDER, CHAPARRAL, BULLPUP, SPARROW, LANCE, SHILLELAGH, TARTAR, TERRIER, STANDARD, FALCON, HAWK, PHOENIX), the United Kingdom (SEA WOLF, SEA SLUG, and others), Italy (SEA KILLER, SEA INDIGO, and others), Norway

(PEQUIN) and Israel (GABRIEL). Of the missile systems mentioned above, the control method utilized ranged in popularity from tail control (40%) to TVC (10%), with wing control and canard control enjoying moderate popularity (30% and 20% respectively). Although these percentages convey no quantitative significance, preliminary studies did serve to indicate the wide variety of control methods presently in use throughout the world, and the necessity for a logical evaluation of the characteristics of the various methods.

In subsequent sections of this report an effort is made to present a logical progression of descriptive material leading to qualitative evaluation of variously commonly known control methods. The discussion is begun by presenting again the various mathematical expressions that describe the motion of a missile in space and the forces and moments affecting this motion. An effort is made to develop a simple analysis that illustrates the most important factors governing missile motion. Following the description of the governing relationships, several specific aerodynamic and fluid interaction control methods are described in sufficient depth to illustrate the features that characterize their performance. In the final section, the various control methods are grouped together in a comparative analysis designed to point out deficiencies and advantages. This comparison is necessarily qualitative, in the absence of specific mission requirements, but does serve to indicate those control methods that are especially promising for future generation highly maneuverable missiles.

It is hoped that the observations of this study will prove useful as building blocks to be utilized early in the selection of control methods for tactical missiles. There is no hope (or claim) for a completely comprehensive decision based upon these findings.

II. GOVERNING RELATIONSHIPS

The controls of an airframe have the ultimate function of providing the forces and moments necessary to maintain guidance error signals at acceptably low levels. This function is performed either directly by control forces and moments alone or indirectly by means of reorienting the airframe in such a way as to establish the necessary forces and moments. In most airframe control schemes both the control forces and moments and resulting airframe forces and moments give significant contributions to the ultimate vehicle motion.

The analysis of control performance [1-6] is typically separated into considerations of response (or maneuverability) and stability. Response considerations lead to measures that evaluate the rates of change of vehicle forces and moments with control input (surface deflection in the case of aerodynamic surface controls). The airframe motion resulting from control forces or other disturbing influences is generally referred to as flight dynamics and the extent to which the effect of these influences is felt and continues to be felt gives rise to considerations of stability.

As will be shown, control systems that are "good" from a stability point of view are almost never optimum from a maneuverability point of view. The finless ogive-cylinder is a near-optimum control design from the point of view of maneuverability since an extremely small control force will give large body rotations. This configuration is, however, unacceptable from a stability point of view since any disturbance will result in unbounded motion. Addition of stabilizing devices requires an inevitable loss in maneuverability. The angle that a body takes for a given sustained control force (due to wing deflection or change in thrust direction, say) depends upon the magnitude of the control force and its distance from the body center of gravity, relative to the restoring moment (static stability) produced by the body at angle of attack. For a given control force, a body with relatively high static stability will have a smaller angle of attack. Since normal force and therefore acceleration normal to the flight path is proportional to angle of attack, the more stable body will be less maneuverable than one whose response to control forces results in a high angle of attack.

The selection of an optimal control method is complicated by the large number of important factors to be considered. From an aerodynamic point-of-view alone the type of controls, their placement, and their shape and inertial characteristics are all vital factors influencing maneuverability and stability. In addition, the stability characteristics of a given body/control configuration will dictate the requirement for stabilizing devices and these in turn will inevitably affect the performance of the control system itself. The selection of a total configuration is thus iterative, involving many tradeoffs and nonlinearities.

In this section the equations of vehicle motion will be briefly exhibited and discussed in an effort to illustrate the complexity of the general problem. These equations can be written in a form that exhibits various <u>stability derivatives</u> and the more important of these will be emphasized to illustrate their effect upon missile control system performance. Some simplified cases will be treated in order to define and show the physical meaning of such terms as control effectiveness, load factor, and stability margin. No attempt will be made to describe the special characteristics of specific control devices, this being the main goal of the following section.

A. VEHICLE EQUATIONS OF MOTION

An unconstrained missile can travel and rotate in three-dimensional space so that the three translational and three rotational modes of motion lead to six degrees of freedom (see Fig. 2). For this discussion, all missile component masses are assumed to be fixed relative to the body center of gravity so that a six degree of freedom analysis is adequate. Application of Newton's second law gives:

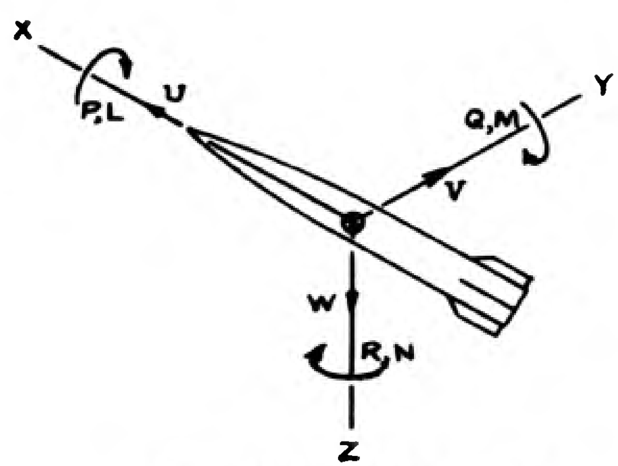
$$\sum F_i = \frac{d}{dt}(m V_i) \; , \; \sum M_i = \frac{dh_i}{dt} \tag{1a}$$

where $\sum F_i$ = summation of forces in the x, y, and z directions, respectively

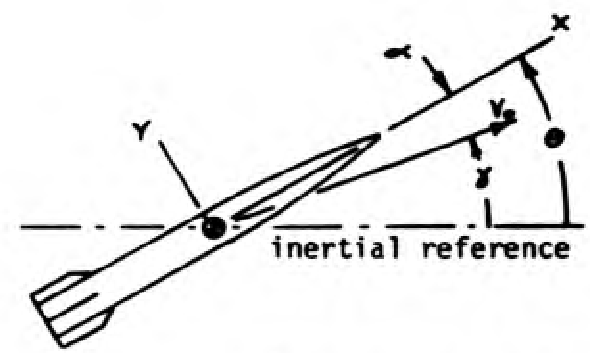
V_i = velocity components in the x, y, and z directions, respectively

$\sum M_i$ = summation of moments about the x, y, and z axes, respectively

h_i = moments of momentum about the x, y, and z axes, respectively



Coordinates and symbols



Angular coordinates

	Axis	Angular velocity	Moment
Roll	X	P	L
Pitch	Y	Q	M
Yaw	Z	R	N

Figure 2. Definitions.

Equations (1a) describe the motion of a particle (or center of gravity) in fixed space coordinates. In this mathematically simple form they are usually intractable because (a) the lefthand-side forces and moments are most often described in body-fixed coordinates (from wind-tunnel data, for instance) and (b) the inertia tensor is a complicated function of the space coordinates that changes with time due to motion of the vehicle. Conversion to a set of axes fixed with respect to the missile airframe yields, assuming constant mass, m:

$$X = \Sigma F_x = m(\dot{U} + WQ - VR)$$

$$Y = \Sigma F_y = m(\dot{V} + UR - WP)$$

$$Z = \Sigma F_z = m(\dot{W} + VP - UQ)$$

$$L = \Sigma M_x = \dot{P} I_x - (I_y - I_z) QR - I_{zx}(\dot{R} + PQ) \qquad (1b)$$
$$- I_{xy}(\dot{Q} - RP) - I_{yz}(Q^2 - R^2)$$

$$M = \Sigma M_y = \dot{Q} I_y - (I_z - I_x) RP - I_{zx}(R^2 - P^2)$$
$$- I_{xy}(\dot{P} + QR) - I_{yz}(\dot{R} - PQ)$$

$$N = \Sigma M_z = \dot{R} I_z - (I_x - I_y) PQ - I_{zx}(\dot{P} - QR)$$
$$- I_{xy}(P^2 - Q^2) - I_{yz}(\dot{Q} + RP)$$

The directional notations in these relationships refer to the axes fixed in the airframe as shown in Fig. 2 - the so-called Eulerian axes. These classical equations are derived in detail in several references [2-6]. In order to obtain the equations of motion in the form of Eqs. (1b) it is necessary to apply coordinate transformations relating the accelerations expressed in space coordinates to those relative to the Eulerian axes.

In theory, Eqs. (1b) permit the calculation of the time derivatives of U, V, W, P, Q and R at any instant of time provided that these velocities are known and the various forces and moments can be suitably expressed as functions thereof. The changes in these velocities can then be computed over a time interval sufficiently short so that $\dot{U}$, $\dot{V}$, $\dot{W}$, $\dot{P}$, $\dot{Q}$ and $\dot{R}$ can be assumed to be constant and, in this way, the trajectory of the missile can be computed over an indefinite period of time. Needless to say, the procedure is difficult, time consuming, and subject to considerable error. Jones [5] describes calculations in which several months were necessary to estimate (by hand) only a few trajectories.

In most cases, the forces and moments acting upon the vehicle are due to propulsion, gravity, and aerodynamic loads. These forces may be either "steady" or "unsteady". Unsteady aerodynamic forces result from vehicle accelerations (such as the "added mass" effect which is often negligible for vehicles in air) and from time dependent variations in the flow in the wake of the body. Steady aerodynamic forces are present whenever there is relative velocity between the vehicle and the surrounding atmosphere. For many practical cases unsteady effects are negligible. Notable exceptions include aeroelastic problems (in which high frequency structural vibrations occur), very highly accelerated flight, and flight at extreme angles of attack.

1. <u>Stability Derivatives</u>

A Taylor series expansion of the vehicle aerodynamic forces and moments expressed as functions of the instantaneous dynamical state (U, V, W, P, Q, R) leads to the definition of the stability derivatives. These quantities are useful in examining the dynamic stability of various missile configurations because they represent the nature of the missile response to small disturbances from dynamic equilibrium conditions. The more important of these derivatives are listed below in coefficient form:

C_{m_α} = static longitudinal stability

C_{n_β} = directional stability

C_{m_q}, $C_{m_{\dot\alpha}}$ = damping in pitch

C_{n_r}, $C_{n_{\dot\beta}}$ = damping in yaw

C_{ℓ_p} = damping in roll

The lowest subscript denotes, as is standard, differentiation with respect to that variable. Detailed derivations of these and other stability derivatives may be found, for instance, in Ref. 4. In order to illustrate the development of these quantities, consider the linear portion of the Taylor series expansion of the aerodynamic moment, M, about the y-axis:

$$M = M_o + \left(\frac{\partial M}{\partial U}\right)_o \delta U + \left(\frac{\partial M}{\partial V}\right)_o \delta V + \left(\frac{\partial M}{\partial W}\right)_o \delta W + \left(\frac{\partial M}{\partial P}\right)_o \delta P + \left(\frac{\partial M}{\partial Q}\right)_o \delta Q + \left(\frac{\partial M}{\partial R}\right)_o \delta R$$

A disturbance δW in the z-direction (for example) in the absence of all other disturbances, gives a change in M of

$$\delta M = M - M_o = \left(\frac{\partial M}{\partial W}\right)_o \delta W$$

For small angles between the missile axis and the velocity vector $\vec{V}_0$ the angle of attack, α , is given by $\alpha = w/v_0$. Thus

$$\frac{\delta M}{\delta \alpha} \approx \frac{\partial M}{\partial \alpha} = q_0 S_R \ell_R \left(\frac{\partial C_m}{\partial \alpha}\right) = q_0 S_R \ell_R C_{m_\alpha}$$

and C_{m_α} is a measure of the sensitivity of the pitching moment to a perturbation, $\delta\alpha$, in angle of attack. q_0 , ℓ_R and S_R are the freestream dynamic pressure, a reference length, and a reference area, respectively.

2. Control Effectiveness

In addition to questions of stability, the evaluation of a vehicle control system requires a measure of the extent to which aerodynamic forces and moments are stimulated by a control action. For a given control input, c (which may be due to a deflection of an aerodynamic surface or the actuation of other control devices), the following effectiveness derivatives are commonly defined:

$\frac{\partial C_m}{\partial c}$ = pitching effectiveness

$\frac{\partial C_\ell}{\partial c}$ = rolling effectiveness

$\frac{\partial C_n}{\partial c}$ = yawing effectiveness

Longitudinal Dynamics

An interesting case, for which solutions to Eqs. (1b) are easily obtained, is that in which a symmetrical missile initially in unaccelerated flight in the x-direction is subjected to a small angular disturbance velocity, q, about the y-axis. It is assumed that no motion occurs in other than the

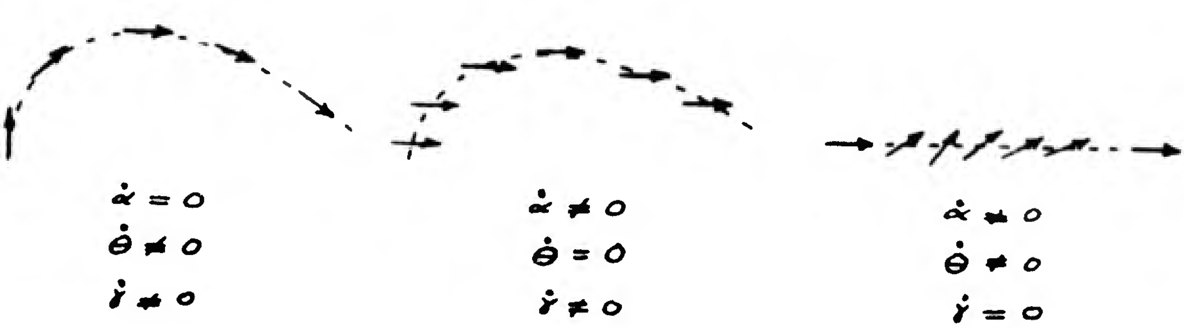
xz-plane and that the change in axial velocity is negligible in the first instance of disturbance. The resulting equations of motion are descriptive of what is called pure pitch control:

$$\Sigma f_z = m\,(\dot{w} - q\,U)$$
$$\Sigma m_y = \dot{q}\,I_y \tag{2}$$

Quantities in lower case refer to disturbances from the initial state. The missile angle of attack α, flight path angle γ, and orientation with respect to inertial space, θ, are related by $\alpha + \gamma = \theta$. In addition, $\dot{q} = \dot{\theta}$ and, for small angles, $\alpha = w/U$ so that $\dot{\alpha} = \dot{w}/U$. Using these relations, we have,

$$\Sigma f_z = m\,U(\dot{\alpha} - \dot{\theta})$$
$$\Sigma m_y = \ddot{\theta}\,I_y \tag{2a}$$

It is important to distinguish between the rate of change of angle of attack ($\dot{\alpha}$) and the rate of change of space orientation ($\dot{\theta}$). The sketch below illustrates three cases for which either $\dot{\alpha}$, $\dot{\theta}$, or $\dot{\gamma}$ is zero.



----- flight path
→ missile axis

In general, the forces and moments in Eqs. (2a) are functions of the angle of attack and the space orientation as well as any significant control system inputs. These functions may be formally written down if it is only assumed that the forces and moments depend upon the instantaneous values of the disturbance velocities, control inputs, and their derivatives, and that this dependency is expressable in Taylor series form. The restriction to consideration of instantaneous effect (neglecting, for instance, the past flight history) is widely accepted practice and seldom introduces unacceptable errors (see Ref. 1, Section 10.2). For the present problem we may write for the force Z, for instance,

$$Z = Z\,(U, V, W, \dot{V}, \dot{W}, P, Q, R, c, \dot{c})$$

where the variable c represents a control action. The restriction of the functional dependency upon only those variables listed is largely a matter of experience since there is no theoretical limit to the number of time derivatives that could be included in the list. Writing the appropriate Taylor series we have (recalling that for the case at hand we consider only changes in W, $\dot{W}$, Q, c, and $\dot{c}$)

$$\Sigma f_z = Z - Z_o = \frac{\partial Z}{\partial W} w + \frac{\partial Z}{\partial \dot{W}} \dot{w} + \frac{\partial Z}{\partial Q} q + \frac{\partial Z}{\partial c} c + \frac{\partial Z}{\partial \dot{c}} \dot{c} + \text{(higher order terms)}$$

with the relationships previously described $(q = \dot{\theta},\ w = \alpha U)$

$$\Sigma f = \frac{\partial Z}{\partial \alpha} \alpha + \frac{\partial Z}{\partial \dot{\alpha}} \dot{\alpha} + \frac{\partial Z}{\partial \dot{\theta}} \dot{\theta} + \frac{\partial Z}{\partial c} c + \frac{\partial Z}{\partial \dot{c}} \dot{c} \tag{3}$$

and, for the moments,

$$\Sigma m = \frac{\partial M}{\partial \alpha} \alpha + \frac{\partial M}{\partial \dot{\alpha}} \dot{\alpha} + \frac{\partial M}{\partial \dot{\theta}} \dot{\theta} + \frac{\partial M}{\partial c} c + \frac{\partial M}{\partial \dot{c}} \dot{c}$$

Here the directional subscripts have been dropped so that force increments (f) are in the z-direction and moment increments (m) are about the y-axis. Lower case variables are incremental (disturbance) quantities.

Equations (3) may be combined with Eqs. (2a) to eliminate the space orientation, θ, and its derivatives. In doing so we shall further simplify the notation by employing the convention $Z_\alpha = \partial Z/\partial\alpha$, etc. The result is:

$$A_1\ddot{\alpha} + A_2\dot{\alpha} + A_3\alpha = M(c) \qquad (4)$$

where

$$A_1 = I_y \frac{(mU - Z_{\dot{\alpha}})}{(mU + Z_{\dot{\theta}})} \approx I_y$$

$$A_2 = \frac{-Z_\alpha I_y - M_{\dot{\theta}}(mU - Z_{\dot{\alpha}})}{mU + Z_{\dot{\theta}}} - M_{\dot{\alpha}} \approx -\frac{Z_\alpha I_y}{mU} - M_{\dot{\theta}} - M_{\dot{\alpha}}$$

$$A_3 = \frac{M_{\dot{\theta}} Z_\alpha}{mU + Z_{\dot{\theta}}} - M_\alpha \approx -M_\alpha$$

$$M(c) = \frac{Z_{\dot{c}} I_y}{mU + Z_{\dot{\theta}}}\ddot{c} + \left(\frac{Z_c I_y}{mU + Z_{\dot{\theta}}} + M_{\dot{c}}\right)\dot{c} + M_c c \approx M_c c$$

Several of the terms in Eq. (4) can be neglected, with an acceptable effect upon the accuracy of the analysis, and these simplifications result in the approximations indicated above. For instance, $Z_{\dot{\theta}}$ is the change in pitch force due to a missile rotational velocity. Missile rotation results in an induced downwash on the body and lifting surfaces that gives rise to a net aerodynamic force that is usually negligible (although this conclusion will depend somewhat upon the configuration of the missile). Since the induced downwash forces may act with significant moment arm, the neglect of $Z_{\dot{\alpha}}$ does not justify the neglect of $M_{\dot{\theta}}$.

Eq. (4) may be recast in the familiar dynamical form

$$\ddot{\alpha} + 2\omega_n \zeta \dot{\alpha} + \omega_n^2 \alpha = \omega_n^2 (\alpha_f / c_f) c \tag{5}$$

with the following identities:

$$\omega_n^2 = A_3 / A_1$$

$$2\omega_n \zeta = A_2 / A_1$$

$$\alpha_f / c_f = M(c) / A_3 c$$

Using the approximations in Eq. (4), we have

$$\omega_n^2 = -M_\alpha / I_y$$

$$2\zeta = \frac{-\frac{Z_\alpha}{mU} - \frac{1}{I_y}(M_{\dot{\theta}} + M_{\dot{\alpha}})}{\omega_n}$$

$$\alpha_f = -\frac{M_c}{M_\alpha} c_f$$

and in coefficient form

$$\omega_n^2 = -C_{m_\alpha}\left(\frac{q_0 S_R \ell_R}{I_y}\right)$$

$$2\zeta = \frac{\left[C_{L_\alpha} - \frac{m \ell_R^2}{2 I_y}(C_{m_{\dot{\theta}}} + C_{m_{\dot{\alpha}}})\right] \frac{q_0 S_R}{mU}}{\omega_n}$$

$$\alpha_f = -\frac{C_{m_c}}{C_{m_\alpha}} c_f$$

The coefficients in the latter forms are defined in standard texts such as in Nielsen [1]. The subscript f refers to the final magnitude of the angle of attack (α_f) and the control input (c_f).

For several basic control inputs, solutions to Eq. (5) are well known. For instance, for a unit step change in the control variable, c, the solutions are of the form shown in Fig. 3.

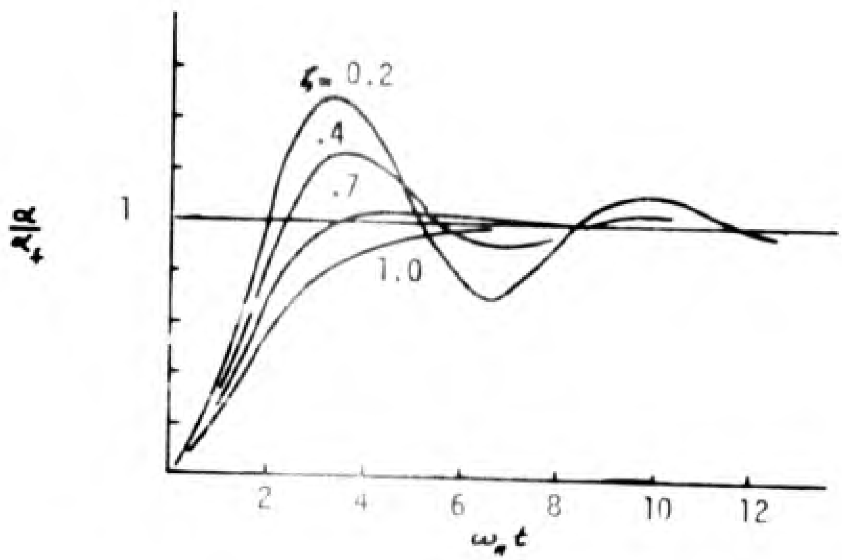


Figure 3. Response of second order system to a step input.

For a fixed value of ζ the time required to reach a given level of response is inversely proportional to ω_n. This can be written

$$t_r \propto \frac{1}{\omega_n} \propto (I_y/q_o)^{1/2}$$

and the response time is seen to increase with the moment of inertia and decrease with the freestream density and velocity. For less than critical damping ($0 < \zeta < 1$) the solution to Eq. (5) is

$$\frac{\alpha}{\alpha_f} = 1 - \frac{e^{-\zeta \omega_n t}}{(1-\zeta^2)^{1/2}} \cos\left[\omega_n (1-\zeta^2)^{1/2} t + \sin^{-1}\zeta\right]$$

To find the time t_f for the angle of attack to reach (and pass through) the trim value, setting $\alpha = \alpha_f$ gives

$$t_f = \frac{\pi/2 + \sin^{-1}\zeta}{\omega_n (1-\zeta^2)^{1/2}}$$

where successive values of $\sin^{-1}\zeta$ correspond to repeated crossings of $\alpha = \alpha_f$. For small values of ζ (ζ less than 0.1, say) $t_f \approx \pi/2\omega_n$. As the damping is increased, so also does t_f increase. Much additional comment on the solutions to Eq. (5) may be found in the literature on control theory.

The various stability derivatives affecting the response of the missile, for the case under consideration, are described briefly as follows:

a. Static longitudinal stability, C_{m_α}. This derivative describes the change in pitching moment due to changes in angle of attack. If Eq. (5) is rearranged in transfer function form, the aerodynamic static gain will be seen to be $\alpha_f/c_f = -(C_{m_c}/C_{m_\alpha})$ so that C_{m_α} exerts a direct influence upon the maneuverability of the missile. Large values (in the negative sense) of C_{m_α} lead to a "stiff" configuration and decrease the trim angle of attack.

b. Lift curve slope, C_{L_α}. This term, not strictly a stability derivative, is a measure of the extent to which the net lift force acts to inhibit a change in angle of attack. A negative C_{m_α}, required for stability, implies a net aerodynamic force acting aft of the c.g. and hence tending to resist the change in angle of attack. Large values of C_{L_α} lead to rapidly increasing restoring forces as α is increased and hence large values of ζ and sluggish response.

c. Damping in pitch, $C_{m_{\dot\theta}}$ and $C_{m_{\dot\alpha}}$. The rotation of the missile in pitch has the effect of increasing the effective angle of attack. That is, there is an induced angle of attack due to missile rotation that tends to restore the missile to its undisturbed state. Although the induced angle of attack is of a different sign for surfaces forward and aft of the c.g., the resulting moment is always negative for positive $\dot\theta$ and therefore $C_{m_{\dot\theta}}$ is negative and tends to damp (i.e. ζ is increased).

The coefficient $C_{m_{\dot\alpha}}$ is due to the time lags inherent between actions of forward located surfaces and their effects on aft located surfaces. Thus the change .n vorticity in the wake of a wing with wing angle of attack is felt as a change in downwash over a tail only after the vorticity is convected between wing and tail with the stream.

Expressions for $C_{m_{\dot\alpha}}$ involve the aft surface normal force derivatives, downwash angles, and the distances separating the interacting surfaces. The effect of wing downwash on a tail surface is to decrease its effective angle of attack and hence the restoring moment due to the tail. Due to the time lag involved, the destabilizing effect of downwash is delayed with the net result that $C_{m_{\dot\alpha}}$ is usually negative and hence serves to increase damping.

d. Pitching effectiveness, C_{m_c} . This term is a straightforward expression of the degree to which a given control input, c , results in a pitching action of the missile. It is a strong function of all aspects of the control system design and will be discussed in the following section in conjunction with specific control methods.

3. Maneuverability

The maneuverability is defined as the magnitude of load factor, n, that a missile develops in its trimmed or equilibrium condition. The load factor is defined as follows:

$$n = \frac{V_0 \dot{\gamma}}{g} \tag{6}$$

That is, the load factor is the acceleration of the missile normal to the flight path, relative to its weight, or the "g's" that the missile can "pull." From Eq. (2a) and Eq. (3) for trim conditions:

$$-mU\dot{\gamma} = Z_\alpha \alpha_t + Z_c c_t$$

but $U \approx V_0$ for small angles and $Z_\alpha = -N_\alpha$ and $Z_c = -N_c$ so that [1]

$$-mgn = Z_\alpha \alpha_t + Z_c c_t$$

As is shown in Eq. (5), $\alpha_t = -(C_{m_c}/C_{m_\alpha})c_t$ so that the load factor may be expressed in terms of the control deflection, c_t, as

$$n = \left[C_{N_c} - C_{N_\alpha}\left(\frac{C_{m_c}}{C_{m_\alpha}}\right)\right]\left(\frac{q_0 S_R}{mg}\right)c_t \tag{7}$$

But

$$\frac{C_{N_\alpha}}{C_{m_\alpha}} = \frac{\partial C_N}{\partial C_m} = \frac{l_R}{\bar{x}}$$

1. Here the symbol N represents a force in the negative z-direction (and not the moment about the z-axis).

where $\bar{x}$ is the normal force moment arm (negative aft of the c.g.) and is assumed to be constant with small changes in α (the neglect of this assumption can lead to serious miscalculation, however). Thus we have

$$\frac{n}{C_f} = \left(C_{N_c} + C_{m_c} \frac{l_R}{\bar{x}} \right) \left(\frac{q_o S_R}{mg} \right)$$

Since $\bar{x}$ is a measure of the static stability margin, it is again evident that stability increases are expensive in terms of maneuverability. The addition of damping terms to the preceding discussion, as might be expected, results in further reduction of the load factor per unit control deflection.

4. Other Complexities

In the example cited above several simplifications were introduced. If the missile axial acceleration had not been suppressed in the analysis, the third degree of freedom thereby introduced would have led to a quartic characteristic equation. The net qualitative result of this complication is the appearance of a slower (phugoid) mode of missile response (due to the affect of a slowly changing axial velocity) upon which is superimposed the higher frequency oscillation discussed above.

In spite of the gross simplifications leading to them, the previous conclusions remain qualitatively valid for more general motions. The terms neglected in arriving at the approximations of Eq. (4) can be carried along in the analysis but, in the final result, the missile response is dominated by those terms that were retained here.

Perhaps the single most drastic assumption in the foregoing discussion is the restriction to "pure" pitch. The resulting conservation of symmetry of motion is seldom obtained in actual flight where, in fact, all six degrees of freedom are active simultaneously. The "coupled" responses due to combined motions (in pitch and yaw, say) are significantly more complicated and often lead to the necessity of nonlinear analysis. These responses will be discussed, as is appropriate, when considering specific control configurations in the following section of the report. Throughout this section it has been the intent to illustrate, through highly simplified models, some of the basic terminology of missile control theory and the fundamental incompatibility between those design motives based upon rigid stability criteria and those in which high maneuverability is of prime importance. For detailed discussions of these and similar problems, the reader is invited to consult the references previously mentioned.

III. DISCUSSION OF VARIOUS CONTROL CONFIGURATIONS

In this section of the report various specific control configurations are described in detail with a view towards identifying those features that characterize each configuration. Following a discussion of some general problems inherent in the aerodynamics of slender bodies, the various control methods are arranged into categories for further discussion. In the "aerodynamic category" missile control by means of wing, tail, and canard devices is discussed. In addition to aerodynamic controls, some discussion is directed towards fluid interaction controls (external and internal). No attempt is made to describe the operation and performance of the wide variety of perturbations upon the methods discussed herein. These perturbations include various boundary layer control schemes, jet tabs, nose flaps, and body extensions and their overall effect upon missile flight can be estimated by comparison with the appropriate general categories included below. Although it is not the intention to discuss relative merits of various control systems in this section, some comparisons are necessary in order to illustrate the differences in flow characteristics of various control configurations. The control characteristics described in this section are pertinent to the general class of control method under discussion. There is no effort to collect and present the vast amount of aerodynamic data that is available, in some cases, for each control device.

A. GENERAL

In aerodynamic analysis it is common practice to construct the aerodynamic characteristics of a given missile configuration from the characteristics of individual components. Thus, the aerodynamic and stability coefficients, some of which were discussed in the previous section, are "built up" by considering the contributions of the body midsection, boat tail, base, and aerodynamic surfaces. In this process, it is necessary to take into account the influence of bodies in the neighborhood of the missile component under analysis. For instance, the total pitching stability (C_{m_α}) of a wing cylinder combination is made up of terms that describe the stability of the wing in the presence of the body and the modification to the stability of the body due to the presence of the wing. The sum of these factors, appropriately weighted, are then added to the aerodynamic stability of the body alone in order to obtain the overall stability of the combination under investigation. In general, the interference between various missile components can be categorized as either panel/body or panel/panel interference. As an example of the former category, the acceleration of air in passing over a cylinder at angle of attack will have the effect (referred to as "body upwash") of creating a locally high angle of attack near the roots of a horizontal wing attached to the cylinder. An important panel/panel interference mode is that which is often referred to as "reverse roll." If in a cruciform configuration roll control (counterclockwise as viewed from the rear of the missile) is applied by deflecting the horizontal panels, for instance, the righthand panel (viewed from the rear of the missile) will have a high pressure on its lower surface and a lower pressure on its upper surface. On the other hand, the lefthand panel will have high pressure on its upper surface and a low pressure on its lower surface. The upper vertical panel, therefore, is in a pressure field in which its righthand surface is under a relatively low pressure compared to its lefthand surface. The net effect then of the rotation of the horizontal surfaces to produce a counterclockwise roll, is to set up a pressure field about the vertical surfaces which will counteract the desired roll. That is, any roll maneuver is resisted by the induced pressure field acting upon alternate surfaces. This reverse roll phenomenon is unique to cruciform configurations since in monowing controls there is no surface interspaced between the roll control surfaces.

Another extremely important form of panel/body and panel/panel interference is that due to "downwash". In accordance with Newton's third law, a lifting body always extracts momentum from the surrounding flow in proportion to the lift produced. The flow leaving the trailing edge of a lifting surface is always at a reduced angle of attack relative to that of the approaching flow. This reduces the effective angle of attack of the stream striking downstream surfaces. The effect of downwash can in some cases be favorable as will be discussed in subsequent paragraphs.

The flow direction may be changed either by missile rotation with controls fixed, thereby effecting missile stability, or by deflection of surfaces for control purposes with the result that the change in flow conditions on aft surfaces will alter control effectiveness.

In addition to the interference factors discussed thus far, there are a wide variety of effects that are felt when control forces are applied at non-zero values of pitch or yaw. When pitch control is applied to a yawed missile, or when yaw control is applied to a pitched missile, the resulting unbalance of forces on a cruciform fin configuration gives rise to a negative (counterclockwise when viewed from the rear) rolling moment. When a missile at angle of attack or at angle of yaw is rolled in a positive direction the resulting pressure field on a cruciform fin configuration gives rise to fin forces that can have an important effect upon surface hinge moments even though no net missile force or moment occurs. When roll control is applied to a yawed body, a positive pitching force is established upon a cruciform fin configuration. When roll controls are applied to a body at angle of attack or when simultaneous pitch and roll control is applied, the result is a yaw force on the vertical panels of a cruciform configuration. In summary, the effect of these "roll coupling" interactions is to require pitch and yaw control whenever roll control is applied to a cruciform configuration. For more quantitative descriptions of these effects, the reader is referred to Nielsen [1].

A final class of interference problems is that which includes the mutual effects of bodies and panels upon each other when missile maneuvers are performed in both pitch and yaw simultaneously. All of these effects lead in one way or another to what is called "induced roll." Induced roll can occur (a) because of the blanketing of midwing surfaces by the body, (b) "tip effects" and "root effects" that are due to the change of regions of influence when bodies at supersonic speeds are yawed and pitched, and (c) the most important induced roll phenomenon which is due to the rotations of aft surfaces into and out of the downwash fields of forward surfaces.

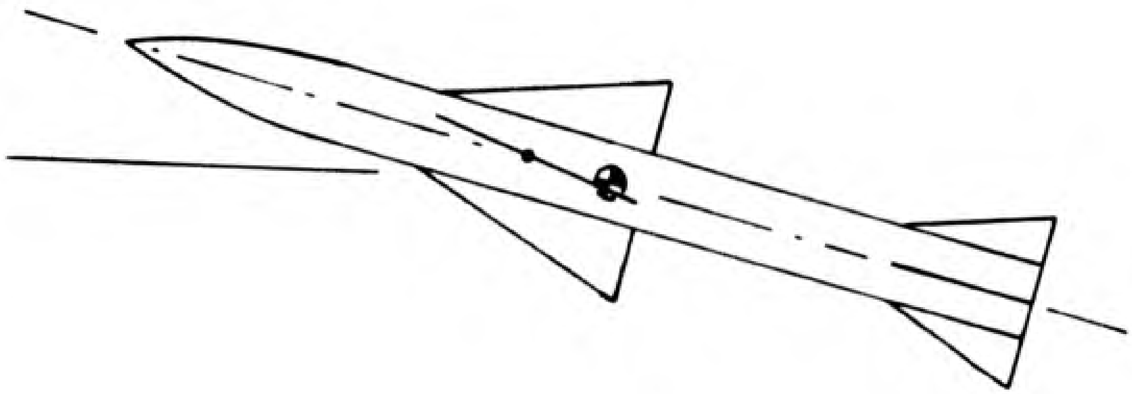
Although the analytical predictions of these various interference factors is possible for slender bodies at low angles, it is easy to see the extreme complexities involved with the accurate computation of all factors leading to a requirement for the control of missile roll. Roll control requirements are usually developed from wind tunnel tests in which the maximum value of incidence angle (in combined pitch and yaw) is determined for which roll control trim can be obtained with the available roll control system. If this maximum angle of incidence is less than that which is to be expected in the missile flight trajectory, then the roll control system is considered adequate.

B. AERODYNAMIC CONTROLS

Aerodynamic controls are defined here as those in which the angle of orientation of a missile is changed by means of the deflection of surfaces attached to the body and immersed in the relative wind. In the following discussion aerodynamic control by means of wings, tail, and canards are separately discussed. Before proceeding, however, it is important to note a few characteristics common to all aerodynamic control methods. Aerodynamic surfaces by their very nature are a disturbing influence upon the flow around a missile airframe. Every nonsymmetric protrusion from the missile body into the relative wind is affected by the missile body, and more importantly, has an effect on the body and all other surfaces that are in the wake of the protrusion. The brief discussion above indicates the variety of complications that can result from these asymmetric configurations and, it should be noted, no configuration is symmetric at all angles of attack, yaw, and roll. Moreover, aerodynamic surfaces possess linear aerodynamic properties only over a limited range of angles of incidence. As will be noted below some aerodynamic control methods are less sensitive to angle of attack problems than others, but all aerodynamic surfaces become ineffective and highly nonlinear at some limiting angle of incidence. The nonlinear behavior of aerodynamic surfaces at high angles of attack leads to in-flight anomalies that are theoretically unpredictable and can be operationally disastrous. Therefore, missiles utilizing aerodynamic controls (by far the majority of operational vehicles) are always limited to relatively low angles of attack with resulting limitations upon the envelope of tactical situations in which they can be launched. In addition, it is important to note here that aerodynamic surfaces are sensitive to changes in freestream dynamic pressure. For instance, the time, t_f, required to reach a final trim angle of attack for a given control deflection is inversely proportional to the configuration natural frequency (see discussion in Section II above). The natural frequency is in turn directly proportional to the freestream dynamic pressure, q_o , and, for a given vehicle velocity, decreases with density and hence altitude. Thus, as altitude is increased, freestream dynamic pressure and airframe natural frequency decrease, and the time to accomplish a given maneuver for a given control input increases. For example, for a missile with damping ratio of $\zeta = 0.1$ the value of t_f at 30,000 ft. is approximately double that at sea level. Altitude effects are, of course, also prevalent in reaction control systems but many of these systems can be designed so that this problem is minimized.

1. Wing Control

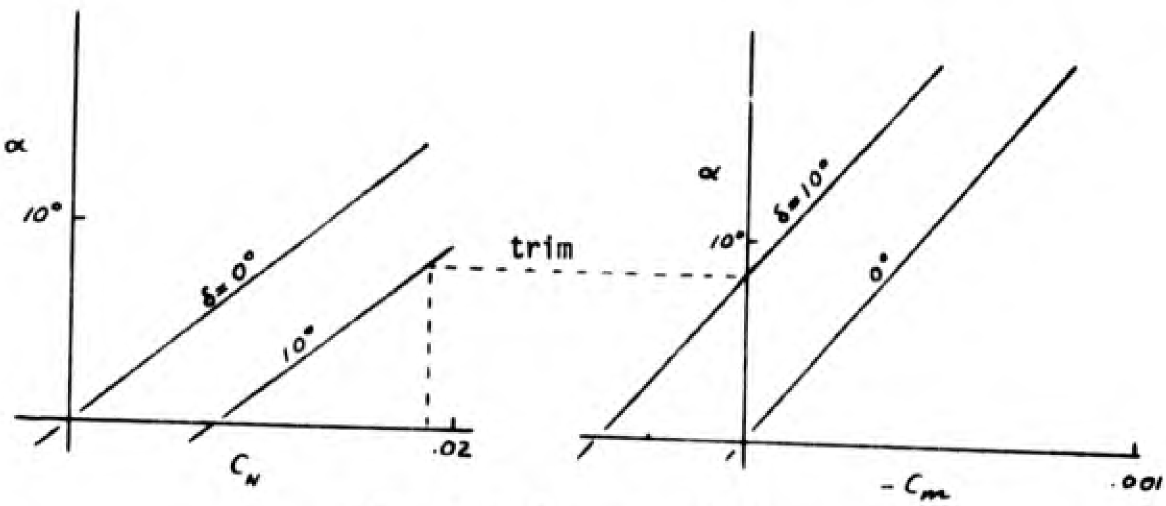
Wing control systems are those in which lifting surfaces are placed near the center of gravity of the missile body. (See sketch).



Missiles with wing controls are generally faster reacting than those with other aerodynamic controls because a force in the direction of desired missile motion is developed instantaneously upon deflection of the wing. Although additional lift is developed from the body in wing control systems, the major proportion of the maneuvering force is obtained from the wings themselves. Control effectiveness, C_{m_c}, for wing control systems is quite small due to the proximity of the wing force to the airframe center of gravity. The downwash effect upon stabilizing surfaces is generally favorable in wing control systems since a downward force is developed on aft surfaces thereby contributing to C_{m_c}. In fact, for most wing control systems the major contribution to C_{m_c} comes from downwash effect on aft surfaces. The center of gravity location is extremely critical in wing control systems. In the majority of rocket-propelled missiles a forward shift in the center of gravity is experienced as motor propellant is expended. This forward shift leads to decreases in control effectiveness and can, in fact, lead to control reversals if not carefully taken into consideration. As missile angle of attack is increased under wing control, the downwash effect on the tail surfaces is counteracted until stabilizing moments are developed by these aft surfaces. Thus, the aft surfaces while aiding in initial missile rotation ultimately develop a force that is opposite to the desired direction of missile motion. Therefore, at a trim condition, by far the largest part of the maneuvering force is due to the deflected wings. For this reason the wings of wing-controlled missiles are quite large, require large hinge moments, and can contribute heavily to the overall missile drag.

The downwash effects that are generally favorable for pitch and yaw maneuver, are counter productive when wings are used for roll control. When wings are deflected differentially for the purpose of roll control, the changes in downwash effect on the tail surfaces result in a rolling moment opposite to that desired. The opposing moments from the tail surfaces may in fact lead to roll reversal. In spite of the problems in utilizing wings for roll control, this method of roll control appears to be the most effective of the three types of aerodynamic controls considered here.

In the sketch below, typical (but idealized) pitching force and moment curves are shown for a wing control system. Fitts, et al [7] have compiled a large body of information with which to construct curves such as these for some forty-five various aerodynamic configurations.

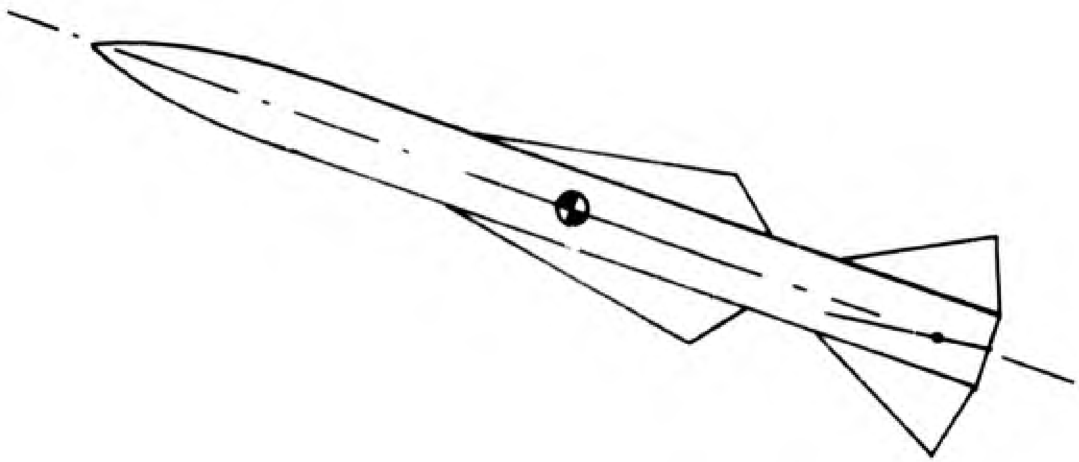


Wing Control Characteristics

Comparing the normal force and pitching moment characteristics of wing control systems with those of canards and tails (see below), it will be noted that the missile trim angle of attack is relatively small and yet large trim normal forces are developed since the angle of attack of the relatively large wing is determined by the sum of the wing deflection and the missile angle of attack. The missile load factor as given by Eq. (7) is relatively large since C_{m_c} is positive so that both terms add (C_{m_α} is negative) to give a large value. Sketches such as the one above can be used to visualize the effect of changing stability upon maneuverability. In the moment diagrams an increase in stability corresponds to a rotation clockwise of the lines in the sketch. This results in a decrease in trim angle of attack for a given control deflection and a resulting decrease in the trim normal force and hence maneuverability decreases.

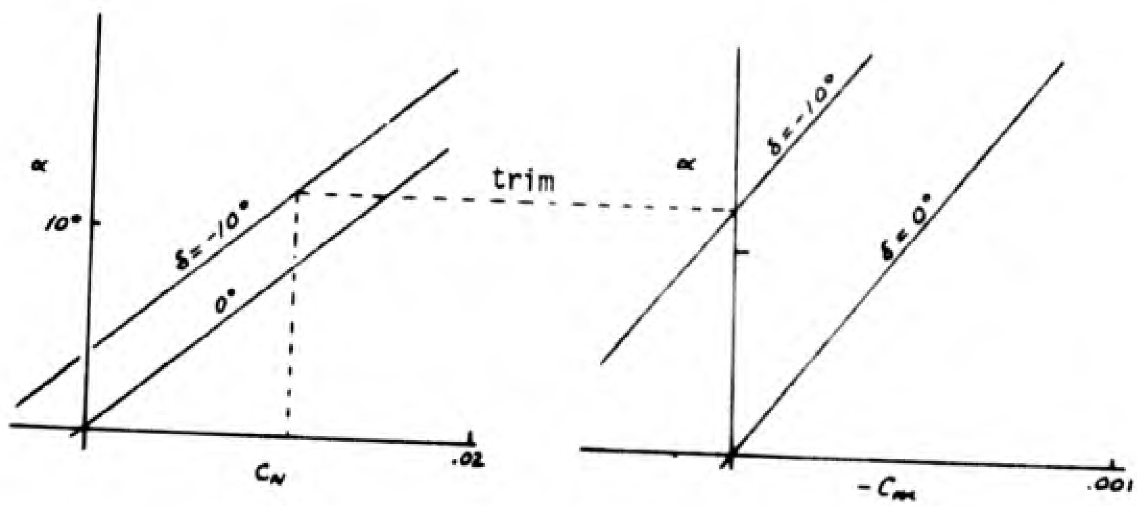
2. <u>Tail Control</u>

A typical tail control configuration is shown in the sketch below.



A distinguishing characteristic of tail control systems is that in order to rotate the missile to an angle of attack, control forces must be applied which are in a direction opposite to the desired direction of missile flight. The wings of a tail-controlled missile are for the purpose of increasing the normal force at angle of attack since the tail normal force is in opposition to missile travel.

In the trimmed condition the tail deflection is subtracted from the missile angle of attack to obtain the tail angle of attack, so that relatively small tail loads are required after the missile has been rotated and a turn has been established (as in the wing control system, once a turn has been established, the missile forces sustaining the turn are made up largely of wing and body contributions). An additional advantage to tail control surfaces is that downwash effects due to control surface deflections are not significant. In fact, the overall problem of panel/body and panel/panel interference is considerably simplified in tail control systems. For this reason, the aerodynamics of tail control configurations are more linear than other aerodynamic methods and are consequently more susceptible to accurate analytical prediction.



Tail Control Characteristics

Since C_{m_δ} is negative for tail control, load factors for a given deflection are reduced from those obtainable by forward control methods. Comparing the aerodynamic characteristics of wing and tail controls, it can be seen that in order for the two missiles described in the previous sketches to generate an equal normal force level, the tail control missile would have to rotate to an angle of attack of approximately 21° and this in turn would require a control deflection on the order of 18°. For both missiles to generate the same normal force

($C_N \approx 0.018$) the following approximate comparisons can be made (neglecting downwash):

	Wing Control	Tail Control
Missile angle of attack	8°	21°
Wing angle of attack	18°	21°
Tail angles of attack	8°	3°
Control deflection	10°	18°

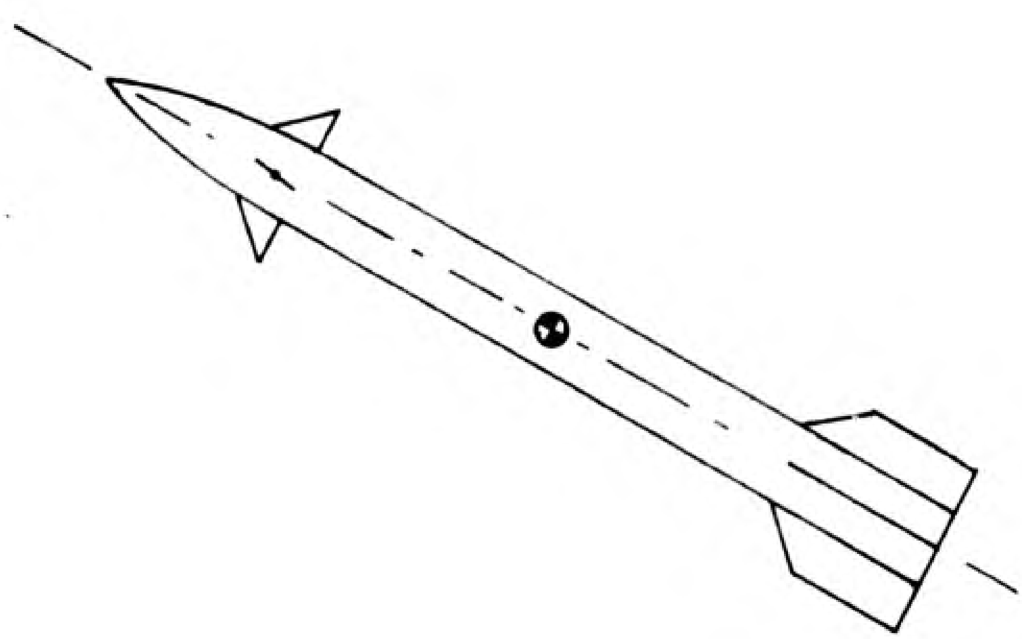
The wing and body of the tail-controlled missile are at relatively high angles. The wing of the wing-controlled missile is at a much higher angle than the tail of the tail-controlled missile. Although generalizations are difficult, it can be said that tail-controlled missiles maintain control effectiveness over a larger range of missile angles of attack, but that larger angles of attack are required for tail-controlled missiles to obtain the same maneuvering force.

Although downwash effects are somewhat more predictable for tail control missiles, this method is marginal for roll control because all interference effects, however predictable, are severely amplified due to the large moment arm associated with control forces at the tail. Although roll coupling forces are usually small in magnitude, their creation on tail surfaces can lead to large longitudinal moments.

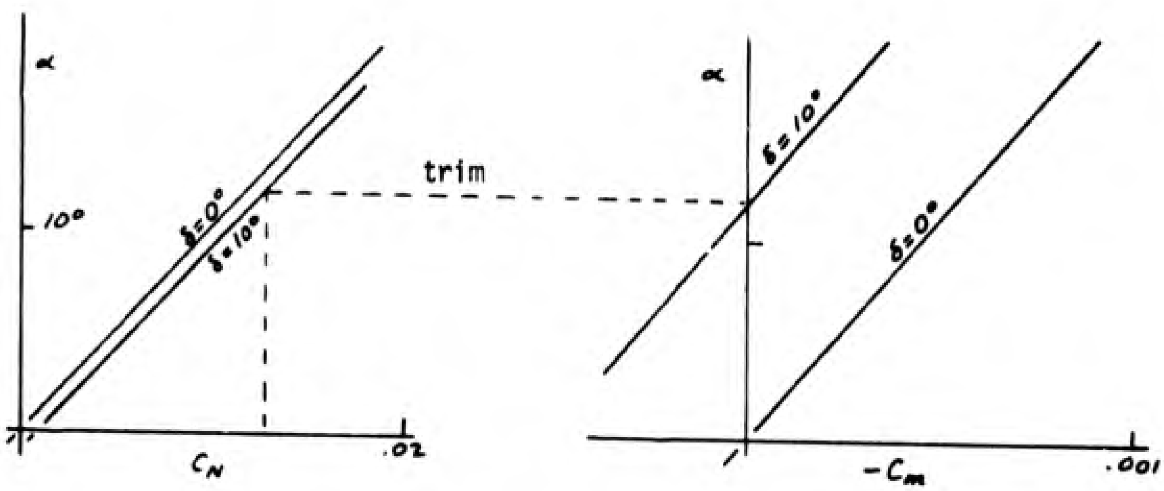
Induced roll effects can be severe for tail control since the relatively high missile trim angles of attack can cause the tail fins to move out of the wing downwash field at relatively low missile maneuvering rates. A final disadvantage of tail control systems is the packaging problem associated with the small amount of space available in the tail regions of rocket-propelled missiles. Since minimum diameter and maximum maneuverability are premium characteristics of tactical missiles, it is difficult to establish that tail control methods are the most desirable of the available aerodynamic control schemes.

3. Canard Control

Canard control is used in tactical missiles when maneuverability levels are not sufficiently high to lead to a demand for large wing surfaces. In order to obtain sufficient control moments with reduced wing surfaces, the controls are placed at a large distance forward of the center of gravity, and the resulting small forward-located surfaces are called canards (see sketch).



The qualitative aerodynamic characteristics of canard control are the same as those for wing control. The aerodynamics of canard control are considerably simplified because of their small size and their relatively large displacement from downstream stabilizing surfaces. The only major effect of the canard surfaces is to create a turning moment upon deflection.



Canard Control Characteristics

As shown in the sketch, canard controls rely heavily upon missile angle of attack in order to develop normal forces necessary to change the missile flight path. For this reason canard-controlled missiles develop relatively large trim angles of attack and are sluggish relative to wing-controlled configurations. The load factor capability of canard-controlled missiles is reduced below that of wing control due to the negligible contribution of C_{N_c} to the total missile turning force.

Roll control is not feasible with the canard configuration because of the extremely short moment arm for roll and the induced roll created by canard downwash at tail surfaces.

Perhaps one of the most attractive features of the canard control is the availability of space for locating the control mechanisms in forward stations of the missile. Forward location is additionally advantangeous because of its close proximity to missile seeker and guidance components.

C. FLUID INTERACTION CONTROLS

A characteristic common to the aerodynamic control methods discussed above is that they all involve the rotation of an external panel in the flow surrounding the missile. This flow is often complex, and predictions of control performance based upon simplified models can lead to considerable error. The class of control methods discussed in this section depends upon the momentum of a control fluid to alter the missile pressure distribution. In most cases (with the exception of JI) the interaction of the control fluid with the surrounding stream is not a decisive factor and predictive modeling is, therefore, simplified. In all cases discussed here, the control device sets up a steering force that is tail-located and, therefore, the qualitative effects of these systems are similar to those of the tail-controlled missile. Forward located fluid interaction controls have been studied (see bibliography) but these systems so complicate the flow over downstream surfaces that it is difficult to identify improvements over more conventional aerodynamic methods.

In obviating the need for large external control surfaces, fluid interaction controls can lead to improvements in total drag, interference effects (especially induced roll), and control effectiveness. However, the systems discussed here are only different ways of establishing a value of C_{m_c}. The overall maneuverability and stability of the missile will, of course, depend upon the missile aerodynamic configuration exclusive of the control system. Fixed wings may be needed for lift and fixed (or free-to-rotate) tail fins may be needed for stability. Control systems utilizing fluid interaction techniques suffer from new problems in design and performance. These are outlined below for fluid interaction control methods falling into two categories: (1) thrust vector control (TVC), and (2) external fluid controls.

1. Thrust Vector Controls

The basic effect of thrust vector control devices is to deflect the main rocket exhaust jet so as to purposely misalign the thrust vector with the missile axis. The resulting off-axis thrust component can be estimated in terms of the asymmetric pressure distribution on internal nozzle surfaces. The asymmetric pressure distribution can subsequently be related to the equivalent exhaust jet deflection. Jet deflection angles in the range of 10 to 20 degrees are commonly required depending, of course, upon mission requirements and main engine thrust levels.

Areas of difficulty common to TVC systems are: (1) the operation of the system depends upon the level of the main thrust (thereby causing loss of control at motor burnout), (2) the development of control moments is relatively ineffective at low thrust deflection angles, (3) the control force is developed at the expense of main engine total impulse, (4) TVC systems are invariably associated with the control of high temperature erosive gases, (5) the necessary hardware is tail-located with the associated problems in packaging, and (6) roll control is not available. On the positive side, TVC devices require no additional power fluid other than the main rocket exhaust gas (although control fluid is required), the analytical prediction of control moments is relatively simple and accurate, and, as previously mentioned, reduction in system inertias indicate an advantage for missions requiring high maneuverability.

Thrust vector control is generally achieved by either fluid or mechanical means. These categories are illustrated in Fig. 4 and discussed separately below.

a. Fluid Injection TVC

The commonly accepted fluid interaction method of TVC is to inject a gas or a liquid into the main rocket exhaust nozzle in a direction transverse to the crossing supersonic flow. Although not completely understood, the basic control force mechanism is the upsetting of the crossing stream (with associated shock phenomena) and a resulting distribution of relatively high pressure in the vicinity of the jet. Because of the enhancement of the interaction that results, the fluid is injected through slots or a series of orifices and, if possible, an upstream injection angle is utilized. In fluid injection TVC systems the jet itself contributes a minor portion of the side force and thus a liquid is normally used because of its relatively high volumetric storage efficiency. Liquids that are easily vaporized are used in order

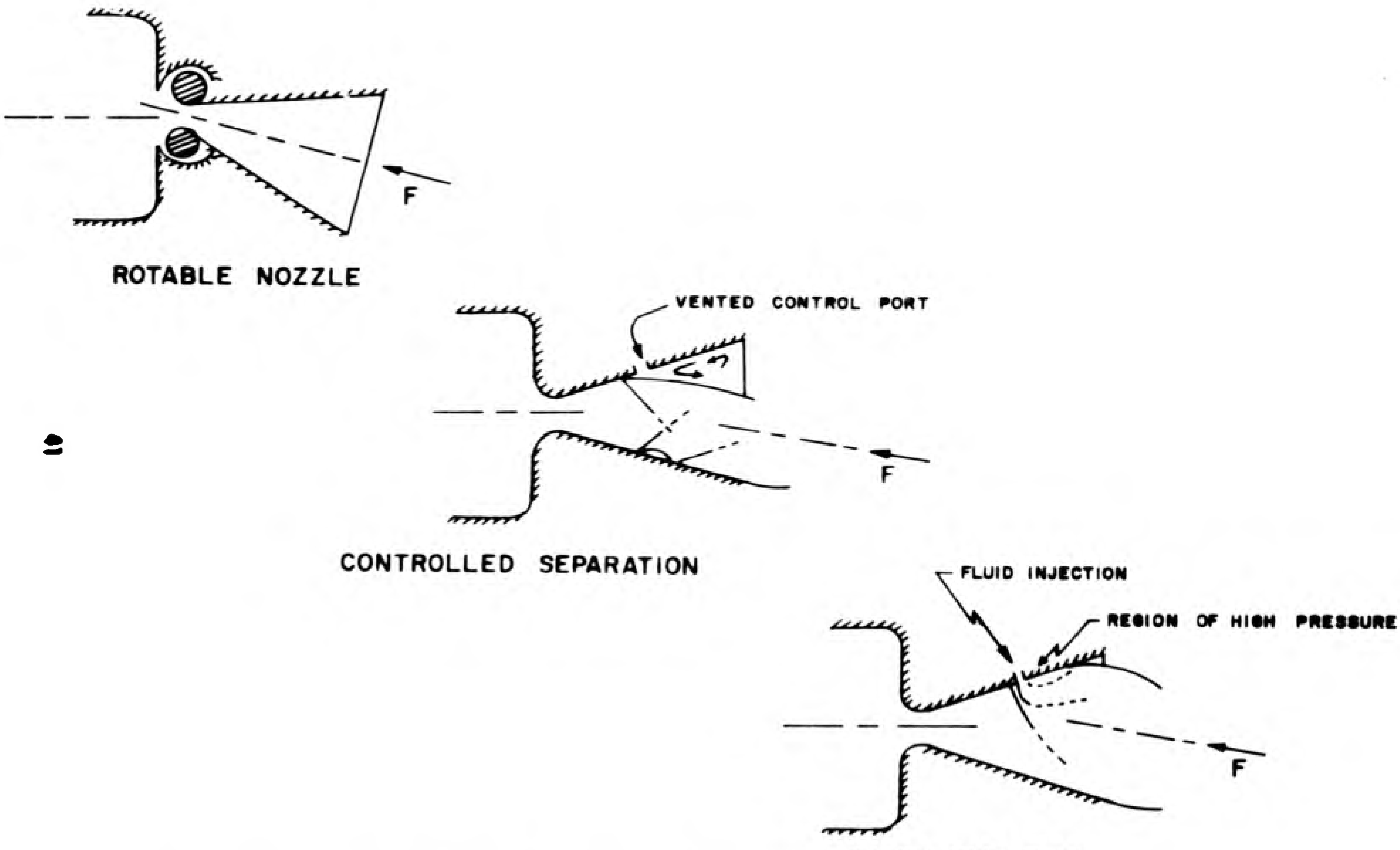


FIGURE 4. THRUST VECTOR CONTROL METHODS

to achieve increased interaction due to vaporization of the liquid after injection.

As a class of TVC the fluid injection methods are generally difficult to package and, of course, require a separate source of TVC fluid and associated plumbing and controls. For these reasons fluid injection TVC is a doubtful contender for tactical missile control.

A novel and relatively new concept of TVC involves the exploitation of the well-known Coanda effect on a large scale; that is, for the control of a main rocket exhaust jet. The method employs the control of the location of separation of a purposely overexpanded exhaust. Control is obtained by selectively venting to atmosphere a region on the nozzle wall that is at subatmospheric pressure due to the entrainment associated with separation. Under the proper conditions the resulting relatively high pressure on the vented side of the nozzle will cause adherence of the jet to the opposite side with resulting thrust vector rotation.

The controlled separation technique has only reached the laboratory demonstration stage. Several important questions have yet to be answered concerning the fluid mechanics of the process (conditions for stable separation, response times, effects of altitude and geometry) and the feasibility of the system (losses in performance and other problems due to overexpansion, effectiveness with propellant gases, and nozzle integrity under hot erosive conditions). The advantages of the system, if feasible, are the same as those that are claimed for smaller fluidic devices. These include simplicity (proportional to cost and reliability) and a vast improvement in packaging efficiency.

It is apparent that this method of fluidic TVC has the potential to provide all of the advantages of TVC systems over conventional aerodynamic controls while suffering few offsetting disadvantages.

b. Mechanical TVC

Although this method of TVC is not a fluid control device, it is considered here since recent technology advances have made this technique a strong competitor in the family of tactical missile control methods. Although a variety of mechanical methods (gimbaled nozzles, jet vanes, and jetavators) have been used for the TVC of large missile systems, these devices have required a volume and mass of hardware that have precluded their utilization in tactical missiles. Recent development and perfection of methods of fabrication and bonding of elastomeric materials have led to systems that are suitable for the small packaging envelopes of tactical missiles.

Progress that has led to the development of the elastomeric joint for rotable nozzles has not, however, been accompanied by advances of equal magnitude in small and lightweight servo-actuators. The present status, therefore, depends upon the proof of cost and packaging effectiveness of actuator systems for the elastomeric nozzle.

In general, the control effectiveness of rotable nozzle systems is somewhat less than that of corresponding fluid systems with equal thrust vector angles. This is due to the additional control moment that can be generated in carefully designed fluid TVC systems by creating an axial thrust component on the surface of the nozzle wall near the point of injection. Because this force is located off of the missile axis an additional turning moment is developed that adds to the thrust vectoring effect. Thus, the effective TVC angle for fluid injection (and controlled separation devices) can be somewhat greater than the measured angle of the exhaust jet.

Since rotable nozzle systems require the acceleration of relatively large masses, it is to be expected that the speed of response of these systems will be somewhat less than that of the fluid TVC devices. This statement must be qualified by a current uncertainty as to the rise times that elapse between control valve actuation and the establishment of the disturbance pressure field in fluid TVC systems. In terms of solid masses, however, the rotable nozzle system is clearly less responsive.

2. External Fluid Controls

Several of the drawbacks inherent in TVC controls can be avoided by the use of fluid reaction controls that interact with the external rather than the internal flow. The basic candidate system is known as Jet Interaction (JI) and is basically an external version of fluid injection TVC. Essential differences are (1) the thrust of the control jet alone is a significant part (on the order of 30%) of the side force developed, (2) the control effectiveness neither depends upon nor affects the main motor thrust, and (3) significant jet thrust amplification (on the order of 2 to 1) can be obtained at supersonic vehicle Mach numbers. From aerodynamic and simplicity considerations, the JI method appears to be very promising for tactical missile controls. Jet interaction systems have been successfully tested in considerable depth in connection with exploratory development programs but their acceptance as a potential operational systems has been delayed by the existence of "lower risk" systems. Perhaps the major source of uncertainty concerning these systems lies in the problem of packaging the gas supply and ancillary hardware. For missions requiring extensive maneuvers the amount of jet gas required may be excessive, requiring the use of main propulsion gases and an attendant approach to similarity with TVC systems and their problems.

Jet interaction ports are normally slot-shaped and directed upstream in order to enhance the interaction with the crossing external flow. Although the control moment advantages make forward located jets attractive, the uncertain and generally adverse effects of the flow downstream of the point of injection have led to a widespread opinion in favor of aft located jets. Other than the body location, the main factor affecting JI performance is the geometry and mass flow rate of the jet at injection. With a given body boundary layer condition at injection, the effects of Reynolds number, freestream Mach number, slot width, and injection Mach number are secondary for a supersonic freestream. For subsonic and transonic missile velocities there is little or no jet thrust amplification, and this factor may prove to be a serious deficiency if the weapon mission calls for extensive low speed high-g maneuvers. Comprehensive tests of JI systems at high (up to 45°) angles of attack have indicated that little or no degradation of interaction effectiveness occurs. This observation has, to date, defied analytical explanation.

The nature of JI systems invites the application of fluidic autopilot techniques. The elimination of the usual electro-pneumatic or electro-hydraulic interface should prove to be a considerable improvement in simplicity and response. Many conceptual fluidic control systems have been proposed in connection with external jets and the few that have been tested have proved feasibility. The problem of roll control, present in all systems previously discussed, with the exception of aerodynamic wing control, can be relatively easily solved in JI systems by designs that take advantage of the already existent pneumatic hardware and supply. The marriage of JI concepts with fluidic control techniques, although promising, will require sophisticated methods for interfacing fluidic sensors and circuitry with seeker and guidance electronics.

IV. SUMMARY

Without detailed mission requirements and extensive preliminary analysis it is impossible to recommend any one specific method of control for tactical missiles. As previously emphasized, the goal of this report has been to identify, explain, and qualitatively assess the characteristics of various methods and to point out those aerodynamic features that are beneficial or detrimental to the performance of tactical missiles. Many important factors have not been considered in any detail. These include cost, reliability, producibility, development time, aeroelasticity, and accuracy. In addition, control methods have been discussed only with respect to their properties as components in the total guidance and control loop. Since tactical missiles are typically controlled by means of electronic autopilots, control configurations that are unstable or bistable in open loop operation may be feasible when incorporated with sufficiently sophisticated autopilot capabilities.

Table I below is an attempt to list some of the relative advantages and disadvantages of the control methods discussed in the previous sections. This information is presented here only as a guide to missile system designers and as an annotated listing of those areas that should receive special attention in the initial selection of candidate control methods. Each method is rated on a scale of from 1 (best) to 3(worst), for the various factors under consideration.

TABLE I. Comparative Ratings

	Interference effects	Response time	Control Effectiveness	Hinge moment	Load factor (1)	Trim α	Simplicity (linearity)	Packaging	Remarks
Aerodynamic									Low development cost
Wing	3	1	3	3	1	low	3	2	
Tail	1	2	2	1	3	hi	1	3	Poor roll control
Canard	2	3	2	1	2	hi	2	1	No roll control
Fluid Interaction (2)									Clean external aerodynamics no roll control
Fluid TVC	1	2	2	2	3	hi	1	3	
Mechanical TVC	1	3	2	2	3	hi	1	3	
JI	2	2	1	2	3	hi	1	3	Control after burnout

Notes: (1) Per unit deflection - Eq. (7)

(2) Aft locations only

A. CONCLUSIONS

A careful examination of Table I will reveal that, on the basis of the rating factors given, there is no dramatic advantage of any of the six systems under consideration. If equal weighting is given to all rating factors, the table will indicate a slight preference for tail or canard control over wing control systems, with the fluid interaction techniques being somewhere in between. However, if low trim α is important (for airbreathing propulsion or seeker considerations, say) wing control may prove most beneficial. If maneuverability (load factor) and response time are of particular importance, as is usually the case in tactical missiles, the wing system again becomes competitive in spite of the other associated drawbacks.

An interesting conclusion can be drawn with respect to fluid interaction systems, That is, these systems are sufficiently promising to warrant continued interest and development. These systems seem to suffer seriously in comparison with tail control systems, only with respect to development costs. Since all fluid interaction systems have the potential of considerably simplifying the external missile configuration, they are promising for future generation weapons. Particular attention should be given to the packaging of these systems with the implication that fluidic techniques may prove especially effective for these devices.

The problem of roll control is seen to be common to all systems with the possible exception of wing control. When roll control (and not merely passive roll stabilization) is necessary, it would appear that a separate system is necessary within the present state-of-the-art. Since reaction jets are especially effective as roll control devices (where missile diameters are sufficient to permit adequate moment arms), systems requiring roll control may become those in which fluid interaction techniques are most feasible. An additional factor favoring fluid interaction control methods is the "aerodynamic cleanliness" of such methods. The elimination of external surfaces, especially control surfaces, is seen as a significant advance in missile design. Such an advance may be extremely beneficial in missions requiring great maneuverability because at the associated high angles of attack, conventional aerodynamic surfaces are at best unpredictable. Until justifications such as these are developed and emphasized, fluid interaction methods will be slow to develop due to their relatively high-risk status.

More detailed specific conclusions, such as those given above, can be developed based upon the choice of weighting of the various rating factors given in Table I. Some general conclusions can, however, be noted here. These are:

(a) Maneuverability will always come at the expense of stability. Highly maneuverable missiles will require advanced and sensitive guidance and control systems.

(b) Missiles with forward located controls will always respond faster and develop side forces more rapidly for a given control input. Aft located controls will require higher angles of attack both from an aerodynamic point of view (to yield the same load factor) and in order to develop higher load factors (and hence turning rates) in order to compensate for the time lost in reaching the trim state.

(c) Aerodynamic controls are relatively "messy" from an interference point of view. In this respect, internal TVC control methods are especially promising.

(d) Roll control is never easy. Guidance laws and autopilot capabilities that do not require roll control should receive special preference in the design of missile systems.

(e) The choice of control method is strongly dependent upon mission requirements and it is unlikely that an optimum method exists for both short and long range missions. Thus, a TVC controlled missile with high thrust may be the best method for satisfying a short range (dogfight) trajectory. But the same TVC missile would clearly be unsuitable for ranges beyond which the propulsion system is no longer operable. It is felt that continuous searching for missiles suitable for all missions (short and long range) is futile and will inevitably lead to systems that are marginal at both extremes.

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Although only a few basic references have been cited, a considerable amount of literature, much of it classified, has been reviewed in the preparation of this report. A bibliography has, therefore, been included to guide the reader in pursuing a greater depth in the general subject area. As noted in the bibliography, several of the works listed contain extensive bibliographies in themselves.

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13. ABSTRACT

Methods in use or proposed for the control of tactical missiles are identified, described, and compared. A brief and simplified discussion of missile response and flight dynamics is presented in order to illustrate the primary factors affecting control system performance. Aerodynamic (wing, tail, canard) controls are discussed as well as fluid interaction devices (thrust vector control, jet interaction, and others). Considering various performance factors, a rough comparison is made in an attempt to identify the most promising control methods for highly maneuverable missiles.

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