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THE AERODYNAMICS OF JET THRUSTER CONTROL FOR SUPERSONIC/HYPERSONIC ENDO-INTERCEPTORS: LESSONS LEARNED

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The Aerodynamics of Jet Thruster Control for Supersonic/Hypersonic Endo-Interceptors: Lessons Learned

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ABSTRACT

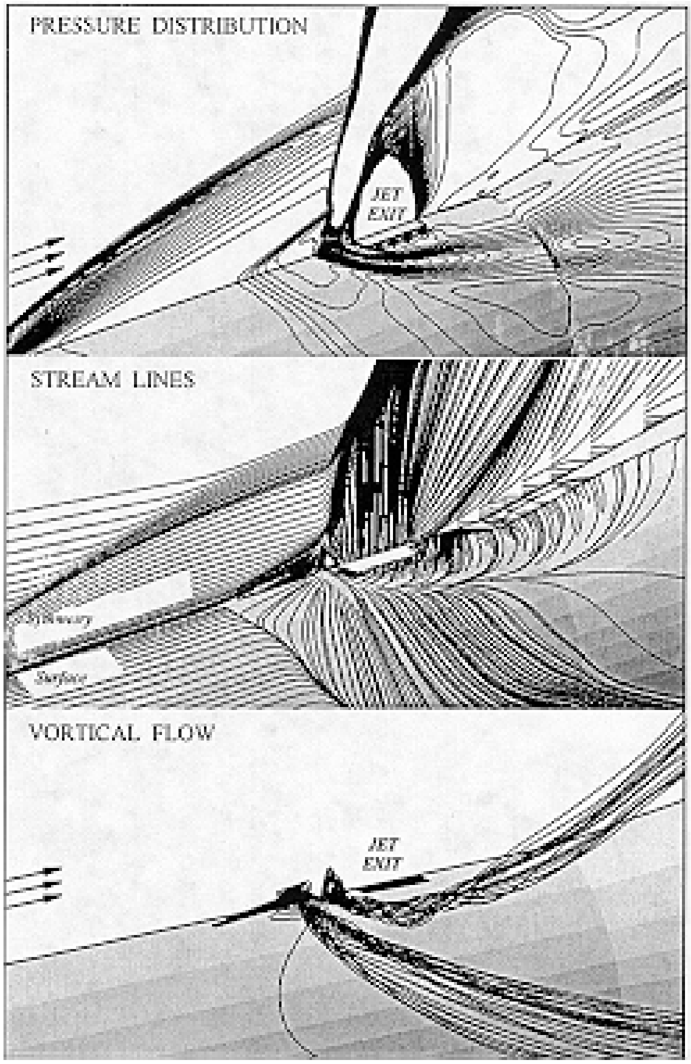
Nearly fifty years of flight and wind tunnel tests have shown jet thruster control for supersonic/hypersonic interceptors to be effective. It is less vulnerable to the blast environment of MX defense and less sensitive than aerodynamic controls to the lower dynamic pressures expected for higher altitude defense scenarios. Thruster control effectiveness is configuration dependent and is determined by the fluid dynamic interaction between the jet and the freestream. Factors affecting the interaction are itemized.. The problem of scaling wind tunnel tests results to flight environments in a complex one. Scaling involves issues of geometric scaling, jet composition, jet/freestream chemical reactions, and wind tunnel wall interference. A methodology or process definition is called for to guide testing for new interceptor concepts. The methodology should address scaling issues and provide direction for testing/analysis approaches that should work and to those that will not for generic system configurations.

INTRODUCTION

The Jet Interaction

Driven principally by the requirements that hypersonic interceptors for ballistic missile defense be lighter and more agile, surface mounted jet thrusters have emerged as a popular means of providing the desired maneuver control capability. This is so because jet thruster control has been found to be capable of delivering several thousand pounds of thrust in less than 10ms. When used at very high altitudes the forces involved are fundamentally of the action-reaction type in the usual Newtonian sense. However, at the lower altitudes the jet interacts with the atmosphere flowing past the missile and can produce additional forces on the missile that are very different from the high altitude counterpart.

The fluid dynamic interaction created by a surface mounted jet firing transversely into a supersonic stream parallel to the surface is now relatively well understood. Numerous wind tunnel tests, missile flight tests, and analytical and numerical studies[1-169] over more than forty-seven years have provided input to our current view of this complex jet-interaction (JI) phenomenon. Included in the references sited are studies in which both JI and external burning (EB) or base burning were investigated as possible reactive controls for hypersonic interceptors. This has been done for historical reasons, but also because the influence of fuel rich JI[39,76] is still under investigation.. Extensive testing in the 1960's and 1970's eliminated EB as a candidate system for endo-homing interceptors because control performance was found to decrease rapidly with decreasing dynamic pressure, i.e. a serious altitude and/or Mach number limitation.



Details of the JI flow physics are made clear through application of computational fluid dynamics (CFD). Predictions performed over the past nineteen years[120-169] have provided invaluable insight into the interaction flowfield. Features of the interaction can be seen in the predictions[147] displayed in Figure 1. The Mach 10 nitrogen freestream in Figure 1 is directed from left to right. The large rectangular divert thruster Mach 3 jet is exiting normal to the surface of the second conic section of a tri-conic configuration. Dominant features, evident in the top two parts of Figure 1, are drawn and labeled in the schematic shown in Figure 2. The jet plume itself is

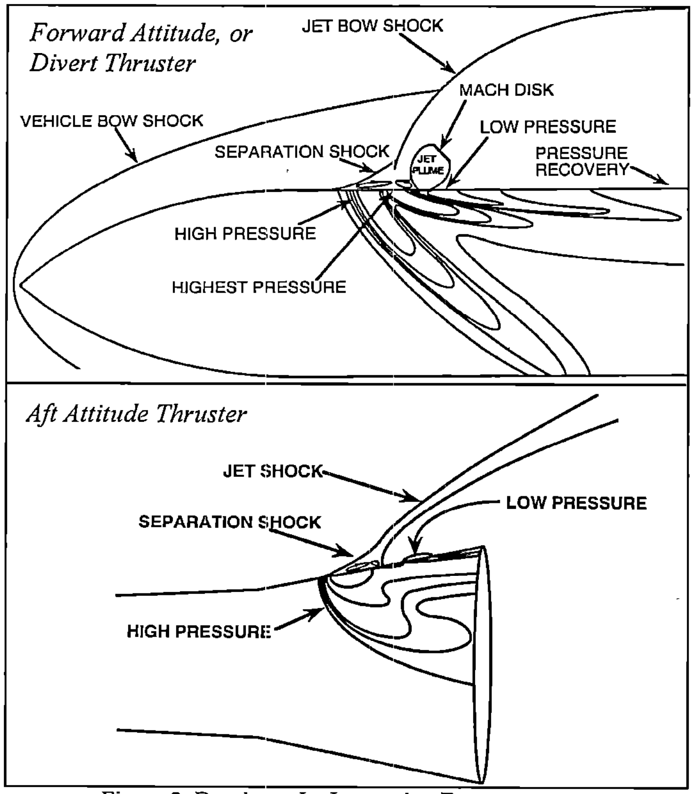


Figure 2. Dominant Jet Interaction Features

housed in a shock envelope composed of a strong interaction shock or jet bow shock and a weak boundary layer separation shock. The pressure footprint of this three-dimensional structure on the missile surface imposes (i) elevated pressures in front of the jet, which wrap around the surface, and (ii) a very low pressure region directly behind the jet with an eventual pressure recovery. A barrel shaped structure immediately surrounds the jet which terminates in a Mach disk. The upstream separated region normally contains two characteristic horse-shoe vortical flow patterns (see Figure 1 bottom) which wrap around the jet and proceed downstream just above the missile surface. Evidence of these vortices can be seen in the surface stream flow pattern in the middle of Figure 1 and in many photographs of surface oil flow patterns obtained in wind tunnel tests.[28,43] The shock structures are also evident in test shadowgraph photographs, as displayed in Figure 3.

All jet interaction flows created from surface mounted thrusters firing into a supersonic cross-flow contain these features, no matter what the size of the jet.

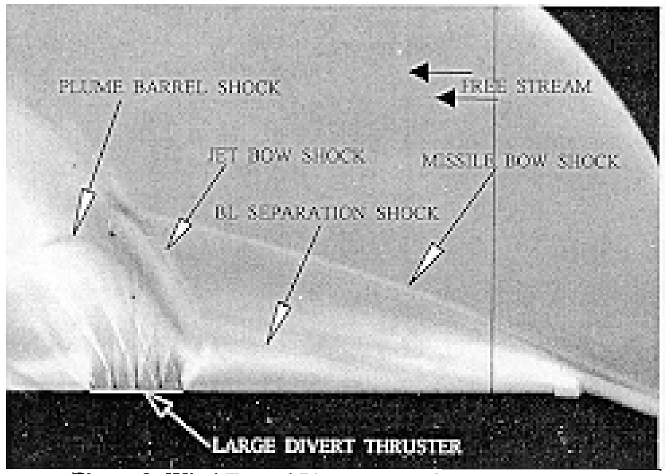


Figure 3. Wind Tunnel Photograph of Jet Interaction

The CFD results[148] presented in Figure 4 show that even a small jet on a large missile produces these same characteristics.

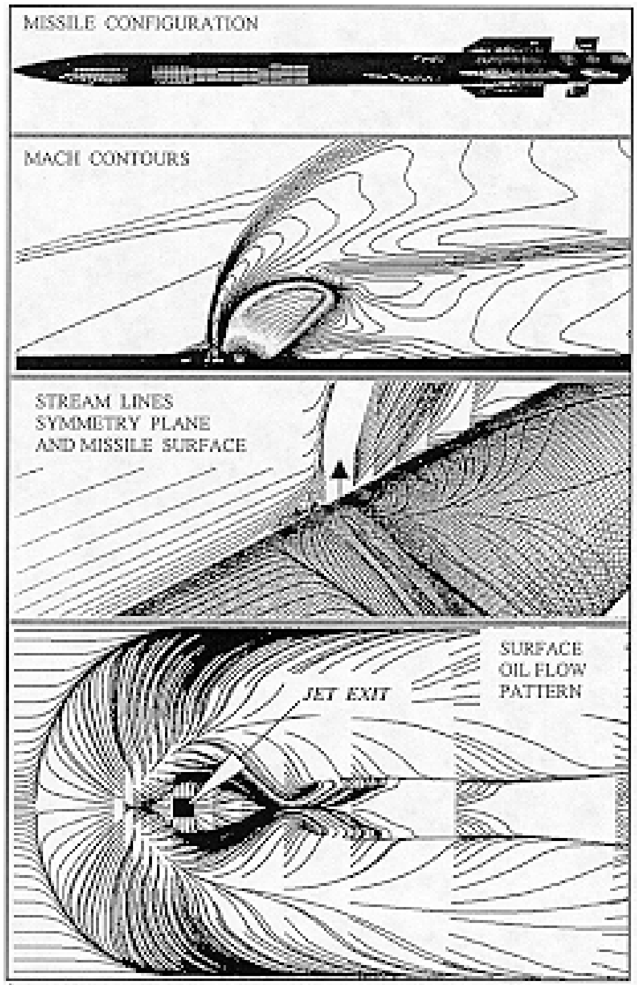


Figure 4. CFD Predictions For Small Attitude Jet Long Missile

Thus are the highlights of the jet interaction.

Important Factors

Of importance to the missile autopilot is the net force and/or moment imparted to the missile when a thruster is activated. Typically this is provided as an amplification factor. The **normal force amplification factor, K_F**, is usually defined as the total normal force imparted to the missile with the freestream present to the jet vacuum thrust. **The moment amplification factor, K_M**, is similarly defined as the ratio of the total moment imparted to the missile with the freestream present to the vacuum moment.

The name of the game, and the reason for the majority of all research on jet interaction, has been to relate the amplification factors to the 'performance' of the jet including all factors that influence that performance. The search has been for one or more similarity or scaling parameters which characterize the interaction and which can be used to extend wind tunnel test results to tactical flight environments. Thruster *control effectiveness* can be thought of as the accuracy with which the autopilot knows the relationship between the amplification factors and the JI environmental factors; i.e. how the missile will respond when the thruster control is activated. The more accurate the relationship between the amplification factor and the JI environmental factors are known the more effective will be the thruster maneuver control of the vehicle. Factors which influence control effectiveness are:

- freestream Mach number,
- altitude,
- angle of attack (AoA),
- jet momentum/vacuum thrust,
- jet fuel-air combustion,
- thruster nozzle configuration,
- jet Mach number,
- missile cross section at thruster location,
- position of the jet exit,
- jet injection angle relative to missile surface, and
- Protuberances on the missile surface (strakes, fins, ...etc.).

Because of the last four of these, the effectiveness of a control thruster, and thus how the amplification factors depend on any scaling parameters, is missile configuration dependent.

BACKGROUND

Many attempts have been made to 'correlate' the amplification factors to relevant nondimensional parameters for various missile configurations. An extensive review of test data for aft-injection attitude control on axisymmetric configurations was conducted by Munson and Garbrick[52] in 1969. Dimensional parameters characterizing jet pressure, jet exit width and aspect ratio, jet and freestream Mach numbers, jet exhaust injection angle, interaction wrap-around effects, and jet position were employed. A linear multiple regression analysis produced the following correlation equation as the best fit to the data for a single jet injecting at zero or windward angles of attack:

$$K_F = \exp^{n1} \bullet (P_{oj}/P_{oL})^{n2} \bullet \left[\frac{\bar{w}/\theta_L}{1+(\bar{w}/\theta_L}\right]^{n3} \bullet \left[\frac{1.5+8.78(\bar{w}*/s*)}{1+9.19(\bar{w}*/s*)}\right]^{n4} \bullet (M_L^2-1)^{n5}$$

$$\bullet [\sin(s*/D)]^{n6} \bullet [L_a/D)\exp^{-L_a/D)}]^{n7} \bullet M_j^{n8} \bullet [1-(P_{oj}/P_{oL})^{0.286}]^{n9}$$

where exponents are found based on injection angle, θs:

θ_s (deg)	n1	n2	n3	n4	n5	n6	n7	n8	n9
40	2.41254	-0.50991	-0.12051	0.48689	0.22183	-0.18685	0.12466	0.12778	1.48171
60	0.21196	0.19623	-0.18702	1.99446	0.16125	-0.36437	0.12466	-0.09983	0.28160
90	-0.01811	0.09719	-0.10631	1.51188	0.08596	-0.18611	0.12775	-0.08071	-0.26397

For lee side injection the best fit was obtained with the following expression, which contains the injection angle explicitly:

$$K_F = \frac{\left[\frac{1.5+8.78(\overline{w}*/s*)}{1+9.19(\overline{w}*/s*)}\right]^{1.51188} (M_L^2-1)^{0.08596}\left[1-\left(\frac{L_s}{D}\right)\exp(-L_a/D\right]^{0.12775}}{\exp^{4.414498}\left(\frac{P_{oj}}{P_\infty}\right)^{0.1608}\left[\sin\left(\frac{S*}{D}\right)\right]^{0.12687}\left[1-\left(\frac{L_a}{D}\right)\exp(-L_a/D)\right]^{1.2038}(\sin\theta_s^{0.27752})\exp\left(\frac{\pi\alpha/180}{D/L_f}\right)^{0.08917}}$$

where for both expressions

$\overline{w}^*$	-	nozzle slot exit width
S^*	-	arc length subtended by the nozzle
L_a	-	length from jet to vehicle base
L_f	-	length from nose to nozzle
θ_L	-	approach flow momentum thickness
D	-	body diameter at the jet
α	-	angle of attack in degrees
θ_s	-	nozzle injection angle.

The windward equation was correlated using 325 data points and resulted in a multiple correlation parameter of 0.959. The lee side equation used 100 data points, with a multiple correlation parameter of 0.881. The ranges of nondimensional parameters for these two relationships are:

$$M_L = 2.4 \text{ to } 7.6$$

$$M\infty = 2.8 \text{ to } 10.3$$

$$P_{oj}/P_L = 2.9 \text{ to } 3{,}270$$

$$P_{oj}/P_\infty = 47 \text{ to } 5{,}880$$

$$\alpha = \pm 30 \text{ deg}$$

$$\overline{w}^*/\theta_L = 0.44 \text{ to } 12.1$$

$$\overline{w}^*/s^* = 0.0024 \text{ to } 0.79$$

$$S^*/D = 0.026 \text{ to } 0.78$$

$$L_a/D = \begin{cases} 0.026 \text{ to } 0.625 \text{ (windward)} \\ 0.036 \text{ to } 0.090 \text{ (leeward)} \end{cases}$$

$$M_J = \begin{cases} 1\text{-}2 \text{ (windward)} \\ 1\text{-}3 \text{ (leeward)} \end{cases}$$

$$L_f/D = 3.2 \text{ to } 5.4$$

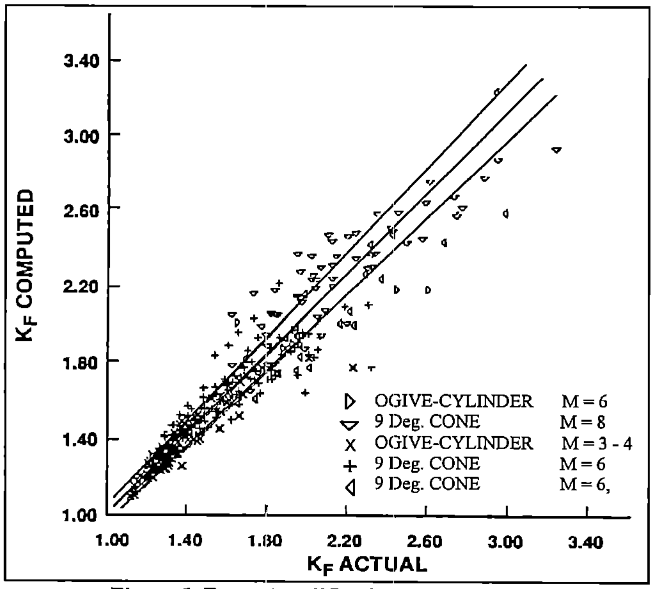


Figure 5. Force Amplification Factor Correlation

Figure 5 contains a plot of the 90-deg injection equation at windward angles of attack as a function of the actual data. The majority of the data used was produced on simple sphere-cone configurations.[33,48] The effect on force amplification factor due to changes in jet Mach number for three cant angles is provided in Figure 6. The effect on force amplification factor due to changes in AoA is also included as Figure 7.

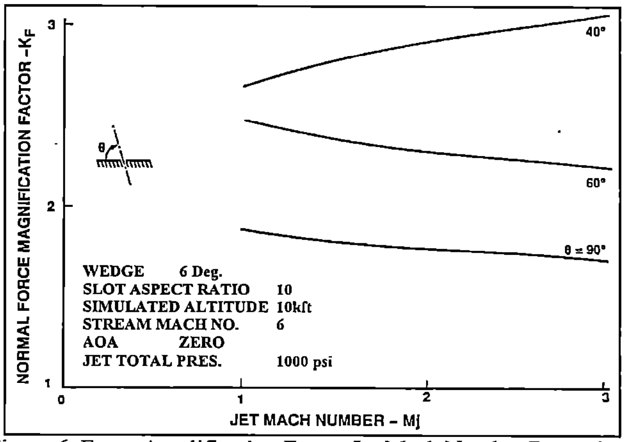


Figure 6. Force Amplification Factor Jet Mach Number Dependence

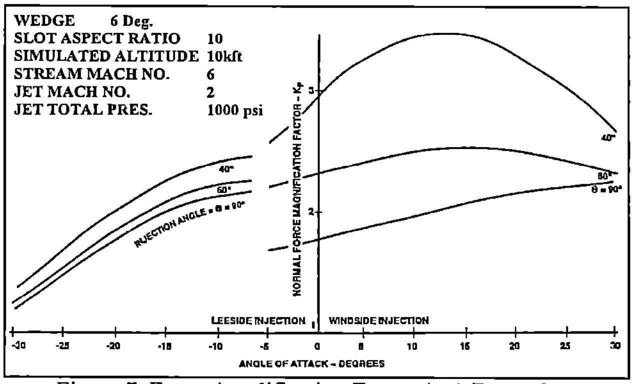


Figure 7. Force Amplification Factor AoA Dependence.

Trends deduced from these two figures are:

- A jet canted upstream produces larger amplification factors than one exiting normal to the surface;
- For a jet exiting normal to the surface, there is essentially no change in amplification factor on jet Mach number;
- A jet canted 50 deg. upstream from the vertical to the surface produces a larger amplification by exiting at Mach 3 jet than sonic.

From additional wind tunnel and flight tests conducted in the late 1960's and early 1970's[65,70,72] evolved a 'scaling parameter', **H**, for aft attitude control of circular and elliptical cone configurations. The pertinent amplification factors were expressed as functions of **H**. This early H parameter was defined as:

$$H_L = \frac{P_{oj} \cdot A_j^*}{q_L \cdot R_c \cdot b} \tag{3}$$

where P_{oj} is the jet total pressure, A_j^* is the thruster throat area, q_L is the local dynamic pressure just upstream of the jet exit, R_c is the local radius of curvature at the position of the jet, and b is the thruster nozzle exit span normal to the fee stream flow. A plot of the moment amplification factor verses this local **H** parameter is shown in Figure 8. In the early 1980's further

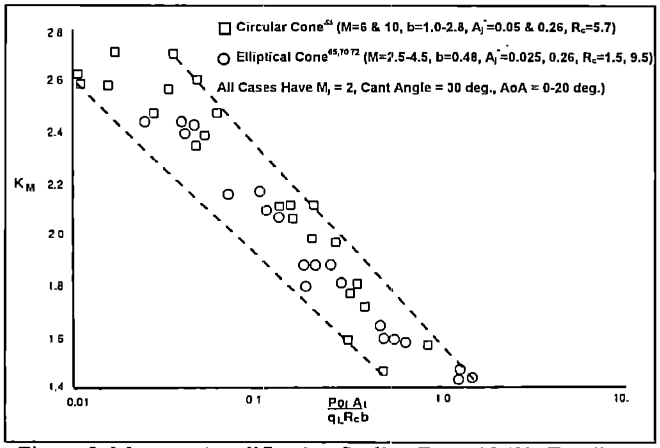


Figure 8. Moment Amplification Scaling From 1970's Test Data.

testing on aft attitude control thruster designs on axisymmetric conic section configurations produced correlations using this same local H parameter, with the model base area in place of the product R_c b. A sketch of the correlation is included as Figure 9.

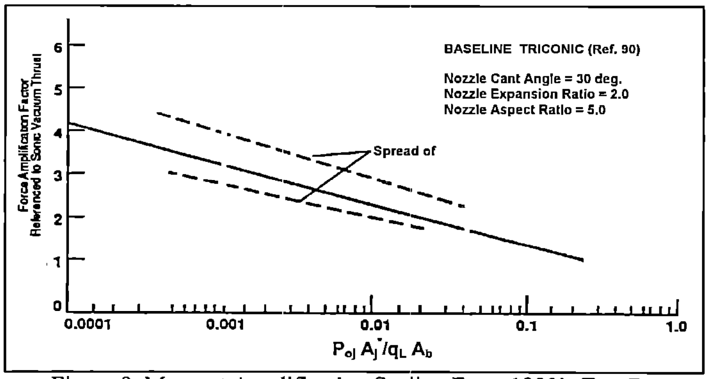


Figure 9. Moment Amplification Scaling From 1980's Test Data.

It seems clear that for these configurations:

$$K \sim \ln H + const. \tag{4}$$

Most of the studies through the early 1980's were performed on conic section interceptor terminal stage configurations. For completion a selection of schematics of configurations studied is included as Figures 10 and 11.

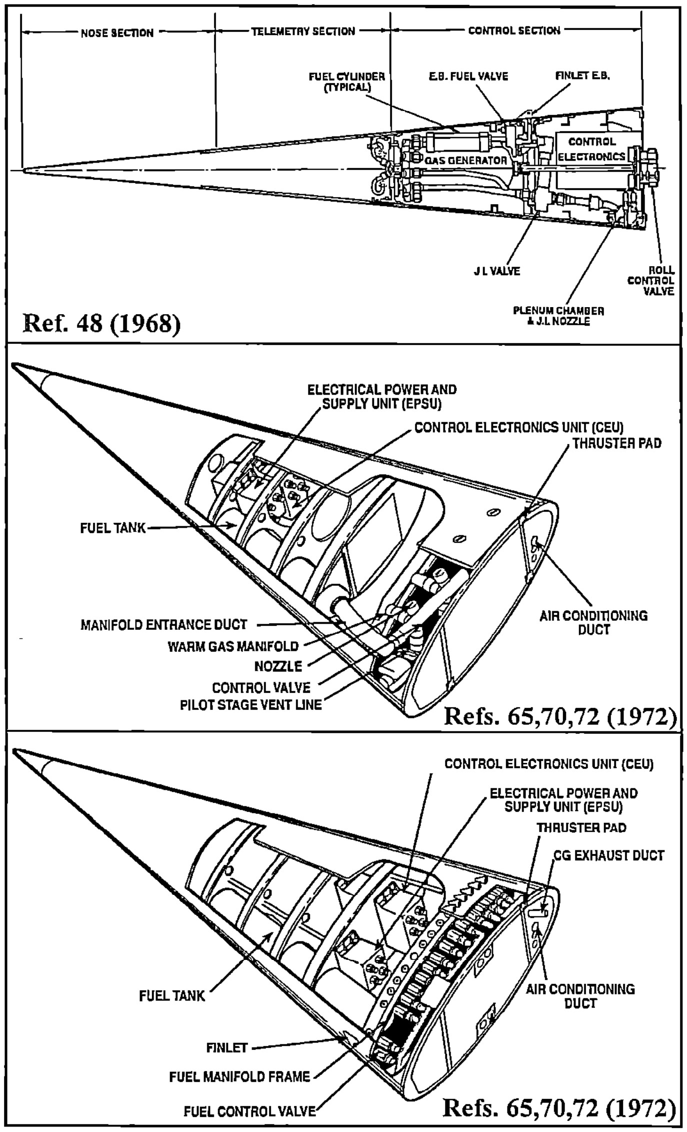


Figure 10. Terminal Stage Configurations Studied in 1970's.

In the late 1980's a series of JI wind tunnel tests[101] were conducted on a triconic configuration in a Mach 10 freestream. Both divert/lateral control and aft attitude control was investigated. A sketch of the configuration including definitions of force and moment amplification factors is displayed in Figure 12. The interceptor was designed to only use the lateral thrusters at higher altitudes where the jet interaction effects would be a minimum. JI performance models were developed separately for the attitude and lateral thrusters. The attitude thruster performance was

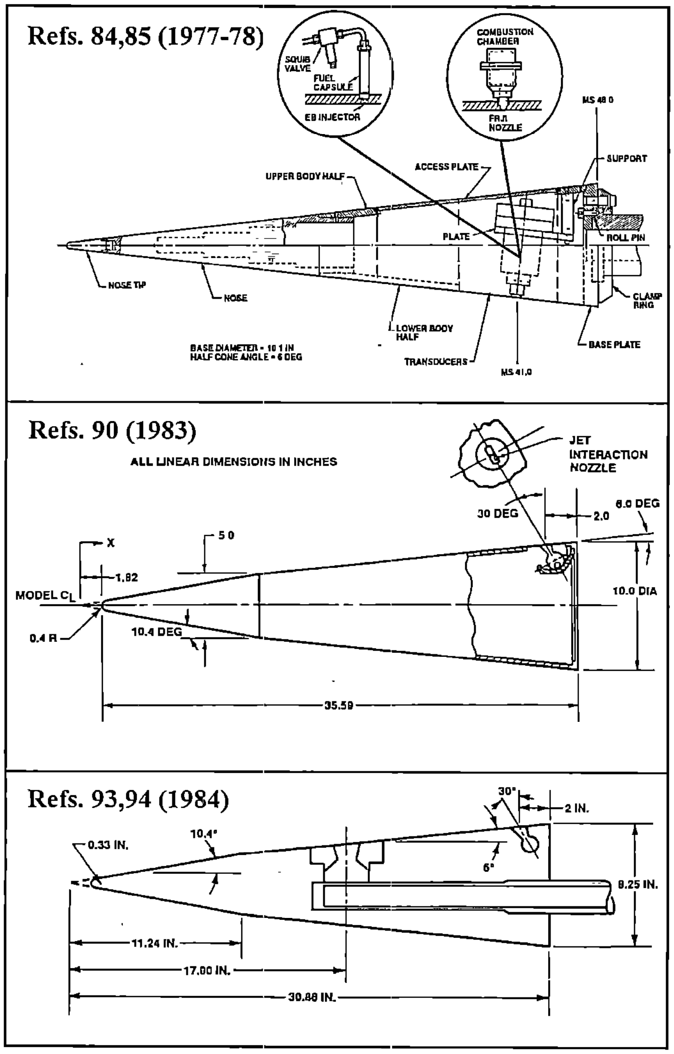


Figure 11. Terminal Stage Configurations Studied in 1980's.

correlated using a local AoA, α_L, and the local scaling parameter, $\mathbf{H}_L$, given by

$$H_L = \frac{P_{oj} \cdot A_j^{*}}{q_L \cdot A_B} \qquad (5)$$

where A_B is the base area of the model. Both force and moment amplification factors are expressed as:[104]

$$K = A\,(\ln H_L)^3 + B\,(\ln H_L)^2 + C\,(\ln H_L) + D \qquad (6)$$

where

$$\begin{aligned} A &= a_o + a_1\,\alpha_L + a_2\,\alpha_L^2 + a_3\,\alpha_L^3 + a_4\,\alpha_L^4 \\ B &= b_o + b_1\,\alpha_L + b_2\,\alpha_L^2 + b_3\,\alpha_L^3 + b_4\,\alpha_L^4 \\ C &= c_o + c_1\,\alpha_L + c_2\,\alpha_L^2 + c_3\,\alpha_L^3 + c_4\,\alpha_L^4 \\ D &= d_o + d_1\,\alpha_L + d_2\,\alpha_L^2 + d_3\,\alpha_L^3 + d_4\,\alpha_L^4 \end{aligned} \qquad (7)$$

and

$$\tan \alpha_L = \tan \alpha \cos \psi \qquad (8)$$

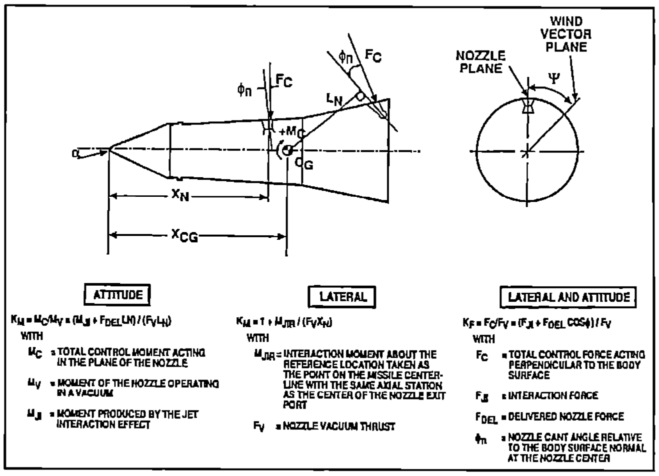


Figure 12. Triconic Configuration Studied in Late 1980's.

where ψ is defined in Figure 12. The coefficients a_o, a_1, ... etc. are classified. The lateral thrusters are correlated using the freestream AoA and the **H** parameter based on the freestream dynamic pressure. The expressions are identical to those in Eqs. (6) and (7). A control moment correction term for simultaneous operation of both lateral and attitude thrusters was also developed, and can be found in Ref. 104. Sketches of the force and moment correlations cannot be presented here. However, general trends can be stated:

- Both force and moment amplification factors show large dependence on local AoA;
- Windside amplification is larger than leeside;
- Attitude moment amplifications factors are always positive and can be larger than three;
- Lateral amplification factors can be negative.

Even though the lateral thruster is located near the center of mass of the kill vehicle/terminal stage of an interceptor, there is a significant amount of the airvehicle aft of its location. It is the interaction with this down stream portion which can cause the moment amplification to be negative. This phenomenon has been seen in other investigations[97,105,154,155] involving forward mounted control thrusters.

JI programs/studies in the 1990's, whether in the technology development phase[117,156,158-160,162], the demonstration/validation phase[155], or the production phase[148,154,157] are employing some variation of the **H** scaling parameter. Much of the wind tunnel test results using conic section configurations show a good correlation between H and the jet penetration height, h, which is expressed as

$$H \propto \left(\frac{h}{D_B}\right)^2 \qquad (9)$$

where h is measured from the missile surface along the normal from the jet center, and D_B is the base diameter.

At this point pertinent previous testing results on *fuel rich JI*[39,76] are injected. These studies found:

- External ignition to be feasible for systems operating at Mach 4 or greater;
- An extra 20 to 30 percent performance increment was achieved over non-reacting jets, everything else being constant;
- The altitude limit for the combusting jets was noted at 110,000 feet or about 1 psia local surface pressure.
- For solid propellants, the performance of a nonaluminized propellant was generally better than for an aluminized propellant.

SCALING

Understanding The H Parameter

If H is expressed relative to whatever reference quantities are relevant, i.e.

$$H = \frac{P_{oj} \cdot A_j^*}{q_{ref} \cdot A_{ref}}. \tag{10}$$

and if the jet momentum ratio is similarly expressed as

$$MR_j = \frac{(\rho \cdot U^2)_j \cdot A_j^*}{(\rho \cdot U^2)_{ref} \cdot A_{ref}} \tag{11}$$

a little algebra leads to the result that

$$MR_j = f'(\gamma_j, M_j) \cdot H \tag{12}$$

The H parameter is essentially the same as the ratio of the jet momentum to that of the stream into which the jet is firing. If the jet Mach number is unchanged but the gamma changes from 1.2 to 1.4 the function f only differs by 6%. *Thus it is the jet-to-freestream momentum ratio which is facilitating the scaling*

Defining a dimensionless thrust, $\mathcal{T}$, as

$$\mathcal{T} = \frac{Thrust}{q_{ref} \cdot A_{ref}} \tag{13}$$

a little more algebra leads to the result

$$\mathcal{T} = f'(\gamma_j, M_j) \cdot H. \tag{14}$$

Thus the dimensionless thrust and the **H** parameter differ only by the function f'. Again if the jet Mach number is unchanged but the gamma changes from 1.2 to 1.4 the function f' only differs by 6%. So, using **H** or $\mathcal{T}$ should accomplish the same result[157]. In fact if a thrust coefficient, C_T, is defined as

$$C_T = \frac{Thrust}{P_{oj} \cdot A_j^*} \tag{15}$$

then

$$\mathcal{T} = C_T\, \mathbf{H} \tag{16}$$

Important Scaling Issues

Preliminary design of JI controls has been based on amplification factors determined from cold flow wind tunnel tests on geometrically scaled models. Performance from tunnel to flight is 'scaled' matching jet momentum and plume shape (using **H** and Eq. (9)). Rarely are the wind tunnel freestream conditions the same as those expected in flight. At the current state of development of thruster controlled hypersonic interceptors it is not clear how well this process will work in practice for a hit-to-kill interceptor. Particularly since a successful intercept using thruster control alone has not yet been achieved. Accurate guidance processing is required for precise guidance, and can occur only with a detailed description of the JI performance.

The important scaling issues that should be addressed are:

- The geometric scaling issue (can test results on a 0.25 to 0.1 scale model be scaled to full scale, even for wind tunnel conditions);
- The jet cold flow/hot flow issue (is it even possible to scale jet cold flow wind tunnel results to hot flow flight conditions);
- The external burning issue (how different are the JI effects when a fuel rich jet chemically reacts with the post shock freestream and what are the altitude boundaries of external burning for proposed fuels to be used);
- The wind tunnel boundaries issue (what influence do the walls of the test section have on the test measurements).
- The jet-on jet-off transients issue (what transients are imposed on the control moment by the finite rise and fall time of the jet itself);
- Flight duplication issue (can flight environments be duplicated prior to actual flight for spot calibration of performance models).

DISCUSSION

Because of the dependence of JI control effectiveness on the interceptor configuration, currently a shotgun approach is adopted by each new proposed interceptor design team; i.e. test for everything and see what is relevant. A ***methodology*** to determine JI performance for modern hit-to-kill designs is lacking. This methodology should address the above issues and provide a road map for any system designer. The road map should point to testing/analysis approaches that should work and to those that will not for generic system configurations.

An attempt to begin to define such a methodology was initiated in 1998 supported by the Ballistic Missile Defense Organization (BMDO). The first phase of a planned five year JI risk mitigation program[169] was funded. The phase one plan called for test planning and CFD computations to help guide testing and test planning efforts for the remaining four phases of the program. Reported herein will be a summary only of what was addressed by the phase one CFD effort. Computations were performed to address the geometric scaling issue, the external burning issue, the tunnel wall issue, and the transients issue. Predictions from two of these[164,168] will be presented at this meeting. The essential findings from the study are summarized here:

- It appears that geometric scaling can be accomplished using the nondimensional thrust scaling parameter;
- There are definite transient issues for configurations with fins near or down stream of the jet exit;
- A thruster using nonaluminized solid propellant to deliver several thousand pounds of thrust can exhibit appreciable external burning at moderate freestream Mach numbers an altitudes in the mid-sixty thousand foot range; with an accompanying large difference in control moment
- Force and moment measurements can be affected if the jet plume interacts with the wind tunnel wall boundary layer.

SUMMARY

Nearly fifty years of experience has resulted in an extensive database on thruster maneuver controls for supersonic/hypersonic interceptors. Flight and wind tunnel tests have shown it to be an effective control which should be less vulnerable to the blast environment of MX defense and less sensitive than aerodynamic controls to the lower dynamic pressures expected for higher altitude defense scenarios.

Thruster control effectiveness is interceptor configuration dependent and is determined by the interaction between the jet and the freestream. Factors affecting the interaction were itemized.. The problem of scaling wind tunnel tests results to flight environments in a complex one. Scaling involves issues of geometric scaling, jet composition, jet/freestream chemical reactions, and wind tunnel wall interference.

A methodology or process definition is called for to guide testing for new interceptor concepts. The methodology should address scaling issues and provide direction for testing/analysis approaches that should work and to those that will not for generic system configurations.

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