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Jet Flap Diffuser: A New Thrust Amplifying Device

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A jet sheet is proposed as an alternative to a rigid diffuser for a momentum propulsor. This appears attractive technically since the diffuser shape can be tailored by modulating jet momentum and angle and can be switched off in forward flight, its main function being to increase thrust-power ratio at static speeds. Theoretical global analysis for a steady inviscid incompressible flow predicts impressive thrust amplifications, showing effects of blowing coefficient, angle and jet thickness. Taking into account the energy required to feed the jet sheet, the propulsor thrust/power ratio is generally increased. The device can be applied to ducted fans, jet engines and seems particularly attractive for ejector thrust systems. To determine flow details, a linearized solution of the planar problem is given. A mapping transforms it into a half-plane boundary value problem of the Riemann-Hilbert-Poincare type. It is solved by combining Hilbert Transforms, asymptotic expansion, and a digital computer program.

I. Introduction

THE thrust performance of static propulsion systems is measured in terms of the thrust to power ratio (T/P), which, regardless of the details of the particular device employed, depends on the effective disk loading T/S as shown in Fig. 1.

For high thrust-power ratios the disk loading should be low. This can be achieved by expanding the stream tube by means of a rigid diffuser shroud. As is well known, the diffuser angle is limited by flow separation and there may be other practical difficulties of weight and complexity. In addition, the shroud becomes a drag producing element when

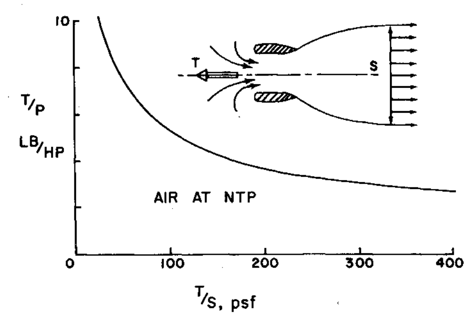

Fig. 1 Thrust/power ratio.

the propulsor is in flight and it would be desirable to remove it at high speeds.

A new approach to this is to replace the solid diffuser by a high-energy air sheet—this is called the jet flap diffuser. Substantial thrust amplification can be achieved by this device (even taking into account the energy required to feed the jet sheet). In addition, the thrust can be readily modulated in direction and magnitude simply by varying the jet flap strength or angle. Thus one has, in effect, a continuously varying diffuser of zero weight. An additional advantage is that because there is no solid wall, large diffusion rates can be achieved without boundary-layer separation. Thus the jet flap diffuser concept has important implications for V/STOL application, both for propulsion and control.

No theoretical analyses of the problem are known, although there exists a simplified approach using the rheoelectric analog (Luu[1]). Nor are controlled experimental data available, and indeed there may be technical obstacles involved in achieving the flow geometry required. In the following analyses it is assumed that such flows can exist and in Sec. IV

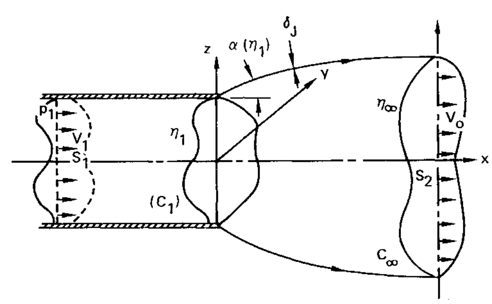

Fig. 2 Generalized geometry of jet flap diffuser.

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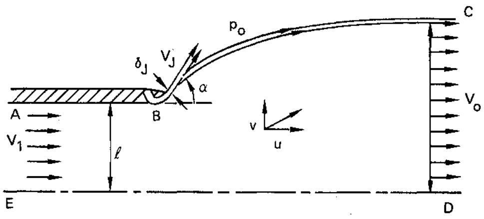

Fig. 3 Axisymmetric or planar jet flap diffuser.

some arguments and experiments supporting this assumption are cited.

II. Global Approach

In this section the performance of a jet flap diffuser as a thrust amplifying device is analyzed on the basis of global momentum considerations. The results obtained are then applied to determine the performance of various momentum generators equipped with jet flap diffusers.

II.A General Momentum Analysis

For this approach one considers the incompressible, inviscid flow in a jet flap diffuser of arbitrary shape (Fig. 2). The flow inside the semi-infinite cylinder of cross section S_1 is initially at subatmospheric pressure and expands or diffuses to the ambient pressure p_0. It is assumed that the velocities in the far upstream and downstream sections are uniform, and have magnitudes V_1 and V_0, respectively. At the exit of the cylinder a high-velocity jet is blown at an angle $\alpha(\eta_1)$ which forms a jet sheet around the main flow. The jet curvature is directly related to the pressure difference across it, in this case due only to the internal pressure since there is no flow external to the jet.

The momentum along the X axis of the external jet sheet at the exit of the cylinder is

$$\int_{C_1} I_1(\eta_1) \cos\alpha(\eta_1) d\eta_1$$

where η_1 is the coordinate along the perimeter C_1 and $I_1(\eta_1)d\eta_1$ is the elementary momentum $\rho_J V_J{}^2 \delta_J$ of the external jet there. Similarly this momentum becomes $\int_{C_\infty} I_\infty(\eta_\infty) d\eta_\infty$ for conditions far downstream.

We define a mean value $\bar{\alpha}$ by the following expression:

$$\bar{\alpha} = \cos^{-1}[\int_{C_1} I_1(\eta_1) \cos\alpha(\eta_1) d\eta_1 / \int_{C_1} I_1(\eta_1) d\eta_1]$$

Assuming that there is no variation of the absolute momentum in the jet sheet between section (1) and (∞)

$$\int_{C_1} I_1(\eta_1) d\eta_1 = \int_{C_\infty} I_\infty(\eta_\infty) d\eta_\infty$$

Conservation of momentum along the X axis, the Bernoulli and continuity equations, give the following system of equations:

$$(p_1 + \rho V_1{}^2) S_1 - (p_0 + \rho V_0{}^2) S_2 = (1 - \cos\bar{\alpha}) \int_{C_1} I_1(\eta_1) d\eta_1) + p_0(S_1 - S_2)$$

$$p_0 + (\rho/2) V_0{}^2 = p_1 + (\rho/2) V_1{}^2$$

$$S_1 V_1 = S_2 V_0$$

To normalize the results, we define a diffusion coefficient $\sigma = S_2/S_1$ and the external momentum coefficient

$$C_J = \int_{C_1} I_1(\eta_1) d\eta_1 / (\rho/2) V_0{}^2 S_1$$

Then the solution of this system gives the diffusion coefficient

$$\sigma = 1 + [C_J(1 - \cos\alpha)]^{1/2}$$

The total thrust of the jet flap diffuser is

$$T_J = \rho S_2 V_0{}^2 + \int_{C_1} I_1(\eta_1) d\eta_1$$

and the total required power

$$P_J = (\rho/2) S_2 V_0{}^3 + \int_{C_\infty} P_\infty(\eta_\infty) d\eta_\infty$$

where $P_\infty(\eta_\infty) d\eta_\infty = \frac{1}{2} \rho_J V_J{}^3 \delta_J d\eta$, the elementary power of the external jet in an infinite downstream section.

For zero blowing, if the total head of the main flow is $H_0{}^* = p_0 + (\rho/2) V_0{}^{*2}$, the thrust becomes $T_0{}^* = \rho S_1 V_0{}^{*2}$, whereas the power is $P_0{}^* = (\rho/2) S_1 V_0{}^{*3}$.

We now compare the performance of this system to one with no blowing but of the same power and physical exit area. For compactness, we define $\bar{V}$ as the ratio of the mean jet velocity to V_0 by

$$\bar{V} = \bar{V}_J / V_0 = \int P d\eta / (\rho/4) S_1 V_0{}^3 C_J$$

where $\bar{V} = V_J/V_0$ for uniform blowing. To compare the system with an unblown one, it is necessary to account for both the thrust and additional energy of the jet sheet. For the same power applied to each system, defining T_J as the total thrust of the blown system and T_0 that of the unblown system we get

$$T_J/T_0 = (\sigma + C_J/2)/[\sigma + C_J/2\bar{V}]^{2/3} = A_P$$

Here A_P is the thrust amplification at constant power. We note that the theoretical analysis is entirely inviscid, neglecting ejector effects due to entrainment and that A should not be confused with the augmentation of an ejector system.

For the axisymmetric case (Fig. 3) with $\delta = \delta_J/l$, we obtain

$$A_P = (\sigma + \delta \bar{V}^2)/[\sigma + \delta \bar{V}^3]^{2/3}$$

and if we define C_J as $\rho_J V_J{}^2 \delta_J / \rho_2 V_0{}^2 l$, an identical result for the planar case is obtained.

Typical results for A_P are shown in Fig. 4. Note that fairly moderate values of C_J give the maximum amplification. Figure 5 shows the effect of variation in slot width.

It is noted that for small slot widths there is a reduction of A for higher C_J. Increases in C_J always increase thrust, but at an increasing power cost, so that eventually A_P (being effectively the thrust/power ratio) diminishes. However, this introduces the idea of the thrust amplification for a system where power consumption is of secondary concern to thrust. We might think, for example, of a V/STOL control device where the exhaust area is limited, but the power available is very large, so that the system is always able to provide a flow of head H_0, regardless of the jet power demands. For this case, we define an amplification factor A_{H_0} as the ratio of thrust with and without the jet flap, subject only to the constraint that the primary power source is always capable of delivering a flow of head H_0. We now get

$$A_{H_0} = \sigma + C_J/2$$

II.B Applications to Propulsors

It is possible in principle to couple the jet flap diffuser to any momentum source, for example, the ducted propeller, the

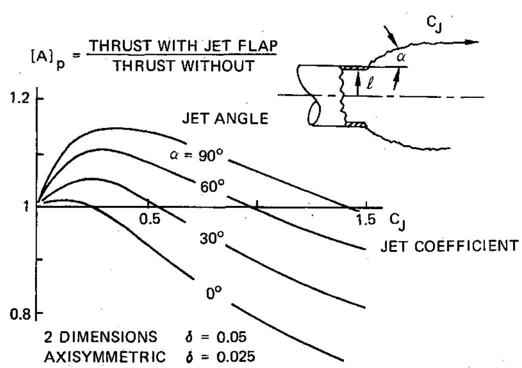

Fig. 4 Amplification of jet flap diffuser.

turbojet, or the ejector. The performance may be calculated by standard analysis, and examples are given in Ref. 2. Typical results for ducted fans at constant power are thrust increases of the order of 18%. An ejector coupled with a jet flap diffuser shows very impressive thrust increases. These may be of the order of 60% for constant power inputs. It should be noted however that this improvement is in part due to the generally poor efficiency of a simple ejector.

No controlled experimental data on the jet flap diffuser are available, and it is clear that the effects of viscosity may possibly be significant. However, the experimental results reported by Lazareff[3] on a standard propeller with a blown diffuser have shown thrust increases of about 18% at constant power. This is in the range of the values predicted by the aforementioned simple inviscid theory.

III. Analysis of the Flow

III.A General

The previous analysis is global, so that details of the slope of the jet surface, and internal flow velocity profiles, cannot be determined. Here we consider theoretically some aspects of the details of the flowfield. The analysis is done for the simplified case of planar incompressible, inviscid flow. While this may not be a sufficient model for the real flow, even this idealized potential case is of considerable mathematical difficulty because of the unknown boundary and the nonlinear boundary conditions to be met on it. Two simplified models can, however, be solved; the nonlinear one-dimensional analysis (see Morel[4]) and the linearized two-dimensional analysis, which is described here.

III.B Linearized Planar Potential Analysis

III.B1 Definition of boundary conditions

The geometry of the physical problem is shown in Fig. 6. A flow of subatmospheric pressure and uniform velocity V_1 in the upstream section of the channel is expanded downstream to a velocity V_0 at ambient pressure. At B, a thin high-energy jet sheet is blown at an angle α. This sheet serves as the diffuser wall. The jet sheet represents an unknown flow boundary where the shape of the boundary dictates the internal pressure field, while the local pressure itself dictates the curvature and hence the shape of the boundary. This is the typical source of an integro-differential equation.

Equilibrium of the jet sheet, of local curvature R, gives

$$P - P_0 = \rho \delta_J V_J^2/R = 2C_J \tfrac{1}{2}\rho V_0^2/(R/l)$$

If the velocity of the flow is given by $(V_1 + u', v')$, we find after normalization with respect to V_1 and l; and linearization, that the dynamic boundary across BC is

$$u = -\alpha(C_J/2)^{1/2} - (\alpha C_J/2)\, dv/dx$$

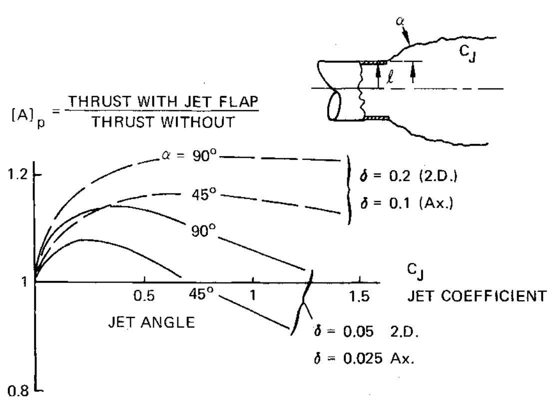

Fig. 5 Effect of slot width on amplification.

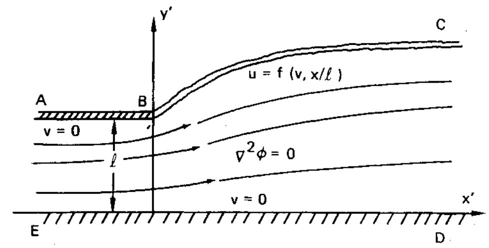

Fig. 6 Geometry in physical plane.

whereas the kinematic boundary condition is

$$v = dy/dx$$

where $u = u'/V_1$, $v = v'/V_1$, $z = z'/l$.

We observe that irrotationality and incompressibility are satisfied if the complex conjugate velocity $q = u - iv$ is analytic with respect to $z = x + iy$.

Thus, the problem reduces to that of finding the analytic function of z subject to the boundary conditions

$$v = 0 \text{ on } AB, ED; \quad u = v = 0 \text{ on } EA$$

$$u = -\alpha(C_J/2)^{1/2}, \quad v = 0 \text{ on } DC$$

$$u = -\alpha(C_J/2)^{1/2} - (\alpha C_J/2)dv/dx \text{ on } BC$$

Consistent with the linearization we assume that the diffusion is not very large so that BC may be taken as the line $y = 1$.

In this form the problem becomes very similar to that of the jet flap in ground effect.[6] It involves the solution of the so called Riemann-Hilbert-Poincare (RHP) problem, since the dynamic boundary condition requires finding a function having a defined relationship to the derivative of its own harmonic conjugate.

III.B2 Mapping to Z plane

It is convenient to map the physical domain into the auxiliary Z plane ($Z = X + iY$) by the transformation

$$z = -(1/\pi)\ln Z + i$$

Under this mapping q is conserved so that the kinematic boundary conditions are unchanged, but the dynamic BC is modified by the mapping derivative.

This now becomes the problem of determining a field in the upper half plane, $Y > 0$ subject to the appropriate conditions on $Y = 0$. We note that this mapping converts the problem to that sketched in Fig. 7 with the new boundary conditions

$$v = 0 \text{ on } ED$$

$$u = -\alpha(C_J/2)^{1/2} + (\alpha\pi C_J/2)X dv/dX \text{ on } CB$$

$$v = 0 \text{ on } BA$$

In this plane C, B are singular points. The transformation greatly simplifies the geometry of the boundary conditions but, of course, cannot remove the characteristic RHP nature of the dynamic condition.

In the auxiliary plane, we have only to determine the V distribution on CB.

Now, using the fact that $v = 0$ on ED, BA, the harmonic conjugate is given by the Hilbert Transform of v so that u is expressed by

$$u(X) = \frac{1}{\pi}\int_0^1 \frac{v(\xi)d\xi}{X - \xi}$$

thus we obtain the integro differential equation for v as

$$-\alpha\left(\frac{C_J}{2}\right)^{1/2} + \alpha\pi\left(\frac{C_J}{2}\right)X\,\frac{dv}{dX} = \frac{1}{\pi}\int_0^1 \frac{v(\xi)d\xi}{X - \xi}, \quad 0 < X < 1$$

which is the equation we will solve.

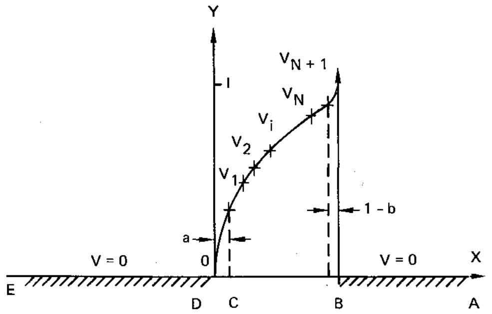

Fig. 7 Geometry in auxiliary Z plane.

In the physical plane we assume that near C the jet boundary y_J is given by

$$y_J = \sigma - A/x + 0(1/x^2) \qquad A > 0$$

then

$$v = A/x^2 + 0(1/x^3)$$

From this, we obtain the asymptotic behavior in the Z plane near $X = 0$ as

$$v = A\pi^2/(\ln X)^2 + \ldots$$

$$u = -\alpha(C_J/2)^{1/2} - AC_J\pi^3/(\ln X)^3 + \ldots$$

At B, we note $v = \alpha$ as $X \to 1$. Thus from Hilbert Transform theory we see that near here

$$u(X) = -(\alpha/\pi)\ \ln(1 - X) + \ldots$$

Utilizing the dynamic boundary condition and integrating gives

$$v(X) = \alpha(1 - 1/3C_J) + [\alpha/\pi(C_J/2)^{1/2}]\ \ln X + 2\alpha/\pi^2 C_J[X + X^2/2^2 + \ldots + X^n/n^2 + \ldots] + \ldots$$

III.B3 Numerical solution

For the numerical solution, the range is divided into three intervals. The singular intervals near $X = 0, 1$ are defined as $0 < X < a, b < X < 1$. We use the truncated expansions for v in these intervals. The interval $a < X < b$ is regular, here we approximate v by N equal linear segments (Fig. 7), using a method developed by Lissaman.[6] The value of v at the end of each interval is designated $V_i (i = 1, \ldots N + 1)$. We now put $\alpha = 1$ and satisfy the integro-differential equation at the midpoints of each interval by the set of N equations

$$u\left[a + (2p + 1)\ \frac{b - a}{N}\right] \equiv \frac{1}{\pi} \int_0^1 \times \frac{v(\xi)d\xi}{a + (2p + 1)(b - a)/N - \xi}$$

$$= -\left(\frac{C_J}{2}\right)^{1/2} + \frac{\pi C_J}{2}\left[a + (2p + 1)\ \frac{b - a}{N}\right] \frac{V_{p+i} - V_p}{(b - a)/N}$$

$$p = 1 \ldots N$$

Here $v(\xi)$ is defined as $V_1(\ln a/\ln \xi)^2$ in the range $0 < \xi < a$; as the trapezoidal function in the range $a < \xi < b$, and in the range $b < \xi < 1$ by

$$v(\xi) = \left(1 - \frac{1}{3C_J}\right) + \frac{\ln \xi}{\pi(C_J/2)^{1/2}} + \frac{2}{\pi^2 C_J} \times \left(\xi + \frac{\xi^2}{2^2} + \ldots\right) = K(\xi)$$

with V_{N+1} defined as $K(b)$. Thus we have N linear equations with N unknowns.

The full expressions, integration routines and solution procedures are given by Morel.[4] In Ref. 4, the influence of the magnitude of a, b and of the accuracy of the integral computation was checked. It was found that provided $a \gtrsim e^{-3}$ excellent accuracy was obtained for a modest number of intervals. For example, a difference of less than 0.08 in V (maximum value of $V = 1$) is found as N was varied from 3 to 15.

It should be noted that the numerical analysis is constrained to recover the global results of Sec. II. Unlike the jet flap airfoil case, the jet flap diffuser performance is determined by the global results, which can be computed without solving the integro-differential equation. The analysis of the preceding section, therefore, is to determine the inviscid shape of the jet sheet and to give details of the internal flow; which could form the basis for a model containing viscous effects.

III.B4 Comparison of planar and one-dimensional theory

One means of checking the above results is by comparison with one-dimensional nonlinear theory. Results of the latter theory (as developed in Ref. 4) are compared with the planar linearized theory in Fig. 8, for the case $C_J = 5$, $\alpha = 10°$. No discernible difference in the jet shape occurs, and it is observed that one-dimensional theory correlates well with the planar theory on the center line, as might be expected. The most significant difference occurs on the edge of the jet, particularly near the end of the duct (B). It should be noted that neither theory can be expected to be correct near B since the boundary conditions of finite angle flow turning require a full nonlinear solution here.

The purpose of the planar solution is to determine the velocity profiles near the duct orifice. It is found that these profiles rapidly approach uniform flow. The internal duct flow is essentially uniform about half a duct width upstream from the exit, while the diffuser flow achieves uniformity about one duct width downstream. The axial flow diffusion takes place quite rapidly too, with about 80% of the diffusion occurring one duct width downstream of the orifice.

IV. Discussion of Viscous Effects

It at first appears surprising that the large turning angles assumed in the jet flap diffuser can actually be achieved. It must be remembered, however, that the surface on which the pressure rise takes place is not rigid (with the no-slip boundary condition) but a high-speed jet sheet having a tangential velocity higher than that of the diffusing flow. Thus, elementary boundary-layer considerations show that conditions associated with classical separation will not occur. In fact, this device has all the characteristics of boundary-layer control by blowing.

No controlled experiments on jet flap diffusion are known; however, numerous experiments on jet flap airfoils exist.[6,7]

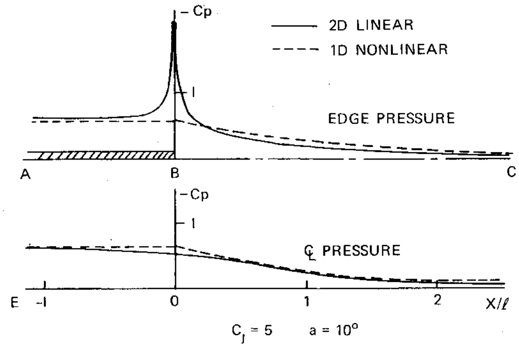

Fig. 8 Comparison of solutions.

These experiments show that the flow on the upper surface will follow a downward directed jet flap, even when the jet flap angle may be as much as 60°. The attached trailing edge flow on the upper (low pressure) surface is quite distinct from that on the lower (high pressure) surface. The jet flap diffuser fluid mechanics near the duct exit are *exactly* those of the low pressure trailing edge flow of a jet flap. Thus it is believed that the many successful jet flap experiments support the jet flap diffuser flow assumptions.

It is clear that entrainment will affect the performance of the jet flap diffuser. However, it is believed that this effect will be small. For the jet flap airfoil it is usual to assume that entrainment occurs with conservation of jet momentum, so that if the jet is thin (compared with the chord) the proper outer inviscid solution is that of a zero thickness jet of constant momentum. The theory developed by Spence[5] uses this assumption and has shown excellent correlation with experiment for a wide range of blowing coefficients and angles. Thus, it is believed that the inviscid analysis employed here is quite representative of the real viscous problem.

V. Summary and Conclusions

It appears that the jet flap diffuser will be a useful device for amplifying the thrust of an actuator, by effectively increasing its exit area. This may be of significance in cases where vehicle design precludes large mechanical diffusers, or where the propulsion system is capable of providing extra power.

Although the global and local analyses are done for the idealized case of the thin, inviscid jet it is believed that the results obtained do represent the dominant effects, and that the effective ranges of blowing coefficient and jet thickness indicated by this theory give the proper parameters for optimal design.

It is clear that experimental studies are the next important step, to assess the significance of turbulent entrainment on the performance of the jet flap diffuser.

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Studies of Engine-Airframe Integration on Hypersonic Aircraft

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Effects of turbo-ramjet exhaust impingement on performance, stability, and control of a Mach 6 transport, and thrust vectoring on a scramjet powered Mach 12 vehicle were investigated. Simplified theories for predicting performance benefits from exhaust interference were in agreement with experimental results for the transport. Scramjet engine integration on a Mach 12 lifting body configuration was studied parametrically, and the effects of engine location, thrust deflection, and altitude were evaluated on the basis of cruise Breguet factor. Losses due to trim penalties could be minimized by careful consideration of engine integration as well as vehicle static margin.

Nomenclature

A_c = inlet capture area
BF = Breguet factor, $V(L/D)I_{sp}$, naut miles
C_p = pressure coefficient $p_l - p_\infty/q_\infty$
D = drag, lb
d_e = nozzle exit diam, ft
F_g = gross thrust, lb
F_N = net thrust, lb
h = altitude, ft
I_{sp} = installed specific impulse, Drag/$\dot{w}_F$, sec
l = pitching-moment reference length (equal body length for lifting body, mean aerodynamic chord for airplane model)
L = lift, lb
M = Mach number
m = moment, ft-lb
p = static pressure, lb/ft^2
q = dynamic pressure, lb/ft^2
R_l = Reynolds number
S = reference area, ft^2
V = velocity, fps
$\dot{w}_F$ = fuel flow, lb/sec
x = longitudinal distance, ft
α = angle of attack, deg
γ = specific heat ratio
θ_{F_g} = thrust vector angle, positive when exhaust is deflected downward from body axis
δ_e = elevon deflection angle, positive trailing edge down

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