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Transient Flow Thrust Prediction for an Ejector Propulsion Concept

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Abstract

A NEW method for predicting transient thrust augmenting ejector characteristics is presented. The transient flow model blends a self-similar turbulent jet description, a mixing region control volume representation, and a primary-to-secondary energy exchange approximation. Since pressure is considered the forcing function in the inlet and diffuser, analysis of those regions is simplified by a quasi-steady flow assumption. The focus of the control volume analysis on the mixing region corresponds with the viscous-dominated phenomenon central to thrust augmentation. A discussion of important modeling assumptions and results from preliminary calculations is given.

Nomenclature

b = jet half-width
B = channel half-width
KE = kinetic energy
t = time
v = velocity
x = transverse coordinate
z = streamwise coordinate

Subscripts

e = entrained stream
m = primary stream centerline
$1s$ = secondary steam at station 1
$1p$ = primary stream at station 1

Contents

Interest in the transient response of an ejector system extends from an effort to develop a **complete** propulsion system simulation for STOVL aircraft.[1] Propulsion system simulations that run in real-time are an important part of research on design methodologies for integrated flight and propulsion control systems. If ejector frequency response is on the same order as the control system design bandwidth, a real-time predictive ejector simulation is required.

Unfortunately, the need to predict transient ejector performance aggravates a more fundamental problem extending from an incomplete picture of steady-state ejector phenomena. Since direct solutions to the Navier-Stokes solution will not meet the real-time simulation objective, a control volume approach is explored. Despite criticism that control volume predictions devoid of empirical correction factors do not rigorously account for mixing, entrainment, and boundary layer effects, this approach has been the foundation for many steady-flow ejector performance predictions exhibiting rapid execution speed and acceptable engineering accuracy.[2] In the present work, an attractive simulation for transient flow ejector performance results when the control volume approach is combined with some basic assumptions about the ejector flowfield.

Several mixing region assumptions are introduced that experience has shown do not unduly compromise the physics of interest. These assumptions simplify the mathematics of the integral form of the mass, momentum, and energy conservation equations. The result is not new nor unusual; details can be found in Ref. 3. Although the next step in steady-state analyses is to drop the time derivatives from the system of equations, the contribution of the present work is the treatment of the *complete* system. There are two facets to this: 1) the assumptions leading to a tractable mathematical treatment, and 2) the kinetic energy exchange model used to link the primary and secondary flows.

Important assumptions about the mixing region flow field are illustrated in Fig. 2. The linear jet expansion is not only mathematically convenient, but has been experimentally shown to be a good approximation. Subdivision of the mixing region into five elements is considered adequate to capture the different flow characteristics. Each control volume is of fixed size, partitioned only in the streamwise direction. (The size of the control volumes are time independent.) As a first approximation to meeting the primary and secondary flow interface condition, the static pressure is assumed uniform in the transverse direction, but *not* in the streamwise direction.

Another important jet feature illustrated in Fig. 2 is the dimensionless self-similar velocity distribution for the mixing region flowfield. Although there are many similarity profiles available,[4] the basic Abramovich[5] self-similar result is used in the present work.

In comparison with the Abramovich freejet approximation, ejectors involve a confined jet in which a streamwise pressure gradient exists. An issue to, therefore, be resolved is the accuracy with which the Abramovich profiles represent the

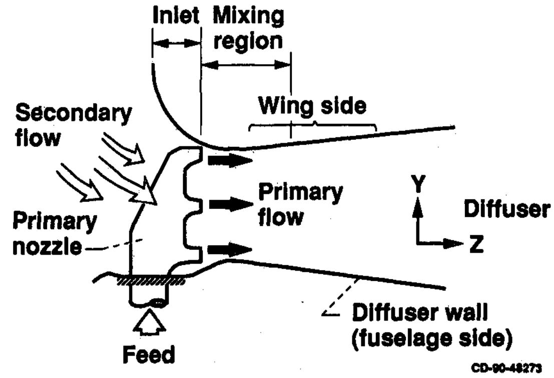

Fig. 1 Ejector configuration for STOVL aircraft.

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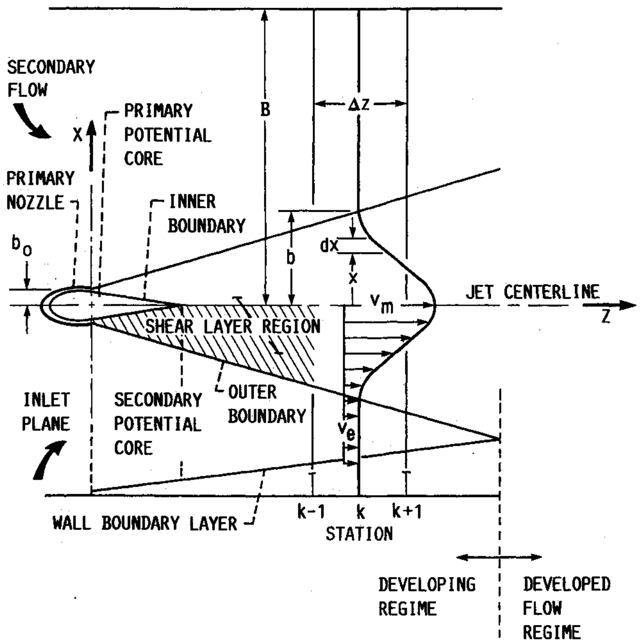

Fig. 2 Mixing region approximation.

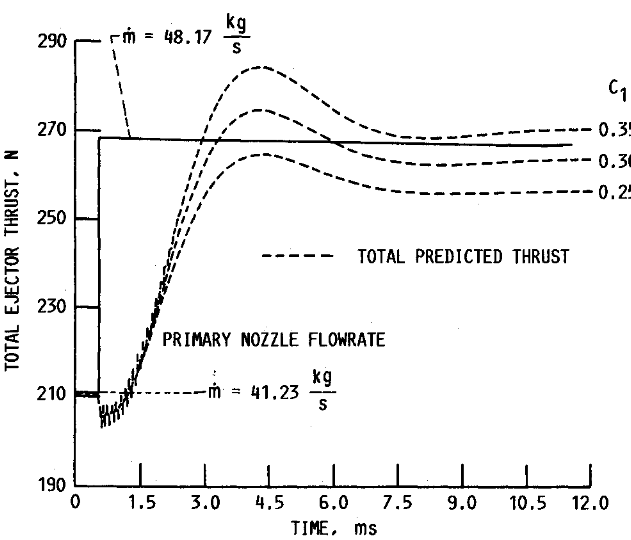

Fig. 3 Thrust prediction for test case.

ejector flow. As a practical matter, these self-similar profiles have been used extensively with acceptable accuracy in fluidized bed gas cleaning applications.[6,7] Although the pressure gradient is in the opposite direction (than that of the ejector), the gradients are significant (up to 100%). This situation encourages the application of Abramovich's profiles outside of his original set of assumptions (as we have done in the present work).

Self-similar profiles define the nondimensional velocity profiles, but in themselves do not prescribe energy transfer from the primary to the secondary in the mixing region. In order to link the stream energies, we assume the kinetic energy gain of the secondary flow is expressible as a function of the kinetic energy loss of the primary flow.

Research has shown the relationship between the change in entrained flow kinetic energy and the total primary flow kinetic energy for a shear layer can be expressed in the functional form:

$$\Delta KE_{1S} = f(KE_{1P}, \sigma/z)$$

where σ is an empirical coefficient. The difficulty with the kinetic energy function as given above is that it represents a quasi-steady constant-pressure flow approximation and, therefore, cannot be used in its present form for the transient flow analysis. To entertain local transport of energy, consider the change in secondary flow to be a combination of changes in primary and secondary flow kinetic energies due to mixing alone

$$\Delta KE_{1S} = f(\Delta KE_{1P,m}, \Delta KE_{1S,m}, \sigma/z)$$

where the subscript m denotes the change in kinetic energy due exclusively to mixing. Numerical experiments suggest the form

$$\Delta KE_{1S}^{t+\Delta t} = \Delta KE_{1S,m}^{t+\Delta t} + \Delta KE_{1P,m}^{t} C_1(\sigma/z)^2$$

This engineering approximation results in the introduction of an undetermined constant C_1, the latter determined by matching transient solution asymptotes with steady-state experimental data.

Again, the centerpiece of the analytic research is the choice of the self-similar profile assumption and the kinetic energy exchange approximation, and subsequent application to the complete form of the control volume equations. Although the analysis is presented in complete detail elsewhere,[3] the result is essentially an initial value problem with three times as many differential equations as there are control volumes. As an exercise for the formulation, a test case for a step-change in primary nozzle flowrate from 41.23 kg/s to 48.17 kg/s is chosen because 1) experimental steady-state data at each of these operating points is available, and 2) this change in primary flowrate is well beyond a "small"-perturbation examination (and exercises the system nonlinearities).

The empirical coefficient in the transient analysis (required for calibration of the primary-to-secondary kinetic energy exchange mechanism), was selected to match the asymptotic transient thrust prediction with the quasi-steady value at the new set point. Figure 3 illustrates the value of the coefficient ranges from 0.25 to 0.35.

A distinctive second-order flavor is displayed by the predicted thrust profile; under a second-order assumption the ejector test case for $C_1 = 0.35$ has approximately a 0.75 damping ratio and a natural frequency on the order of 300 Hz. Although the results seem reasonable, it is necessary to conduct more extensive computational tests before conclusions about the order or linearity (about the perturbation) of the system can be made.

A critical link in the proposed method of analysis lies within the entrained flow prediction by kinetic energy exchange. The one-dimensional flow limitation has required the traditional theoretical analysis of the problem to be modified and the empirical coefficient C_1 introduced. This may mitigate the robust nature of the simulation approach and require fine tuning for a specific ejector configuration and performance window.

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