Effect of Nonuniform Nozzle Flow on Scramjet Performance

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Introduction

HYDROCARBON-FUELED scramjet propulsion appears to offer promising performance at hypersonic speeds. For example, Fig. 1 shows performance, measured by thrust coefficient and specific impulse, as functions of nozzle efficiency based on one-dimensional calculations provided in Ref. 1. However, up to the present time, the potential performance indicated by these predictions has not been demonstrated experimentally. Perhaps the sensitivity to nozzle efficiency provides a clue to the difficulty in actually achieving high propulsive efficiency. Possible sources of loss in nozzle efficiency include errors in nozzle design or manufacture, nonuniform entrance flow, shear in nonuniform streams, wall friction, separation, nonequilibrium flow, incomplete expansion, and shock waves.

Some of these potential losses, such as errors in design or manufacture, can be avoided or minimized. The question addressed in this note is, to what extent might nonuniform flow entering a scramjet nozzle result in unavoidable loss of exit momentum? To answer this question, the following procedure has been adopted:

1) Specify a form of inlet nonuniformity. In this investigation, a so-called fictitious or average uniform axial entrance flow is subdivided into two adjacent streams having the same pressure, the same total momentum, and the same total energy as the average uniform stream, but different initial Mach numbers.

2) Approximate the nozzle flow by a model that will exhibit the effects of the entrance nonuniformity isolated from other flow parameters. To this end, the two streams, depicted in Fig. 2, are assumed to be nonmixing and inviscid. Then the unrecoverable loss will be measured by the difference between the exit momentum achieved when the average stream is expanded isentropically to exit pressure and the total combined exit momenta of the two adjacent streams when they are isentropically expanded to the same exit pressure.

3) Calculate the exit momenta by one-dimensional isentropic ideal gas formulas. This approximation would be inappropriate for the design of a scramjet nozzle, or the accurate analysis of the nozzle flow, but by treating each of the streams on the same approximate basis, the unrecoverable loss resulting from the specified entrance nonuniformity can be estimated as a function of chosen inlet parameters. Effects of nonuniform flow in convergent–divergent nozzles have been examined,[2] using a one-dimensional model. The one-dimensional predictions show surprisingly good agreement with a three-dimensional analysis and with wind-tunnel tests. Decher[3] also estimated the effects of flow nonuniformities on nozzle exit momentum for convergent–divergent nozzles. Initial conditions are prescribed in the subsonic part of the flow, and the analysis is linearized by assuming relatively small variations in initial profiles. In Ref. 4, the theory is applied to nozzle performance calculations and includes mixing effects. Decher's analysis is more general than the one given here, allowing, for example, for the effects of a nozzle throat. The method applied in the present paper, however, yields a simpler interpretation of results for scramjets.

Analysis

With the average stream characterized as having the same total momentum and energy as the sums of the two adjacent streams, along with the assumption of isentropic expansions of ideal gases, the loss of nozzle efficiency can be calculated in a straightforward manner as a function of the following parameters: the Mach number of the average stream, the Mach number of one of the adjacent streams, the pressure ratio of the expansion, the ratio of the mass flow of one of the adjacent streams to that of the average stream, and the ratio of specific heats of the exhaust gases.

For the example previously extracted from Ref. 1, the appropriate values are Mach number of average stream = 2.15,

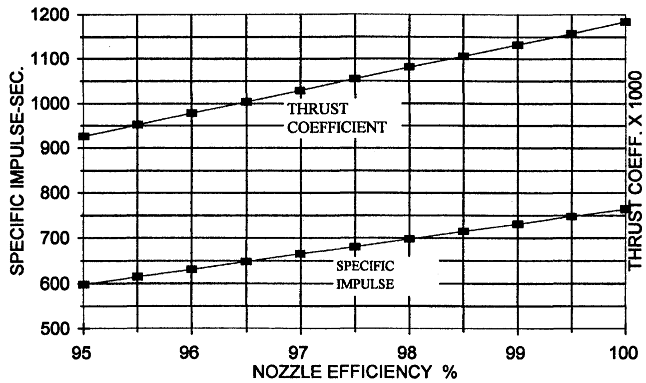

Fig. 1 Effect of nozzle efficiency on scramjet performance.

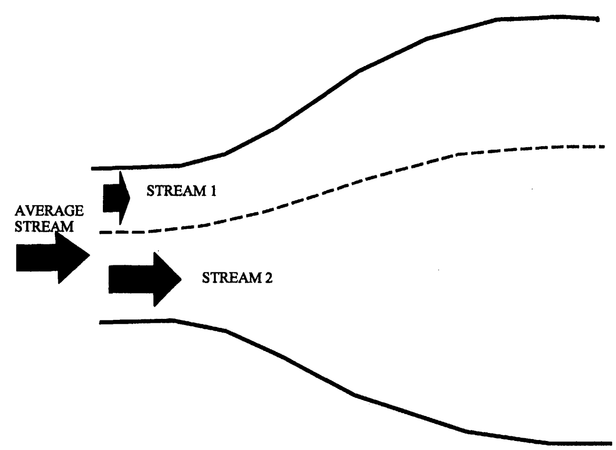

Fig. 2 Subdivision of average stream into two adjacent streams.

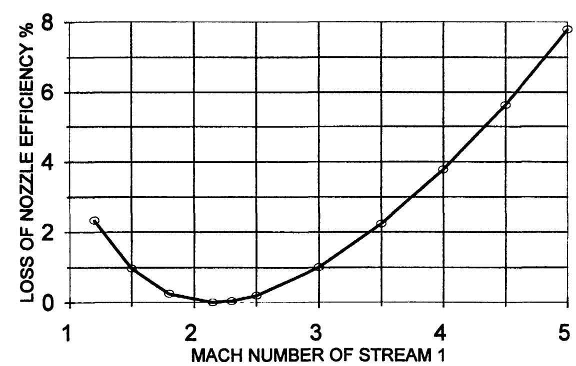

Fig. 3 Loss of nozzle efficiency as a function of the entrance Mach number of one of the adjacent streams.

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pressure ratio of expansion = 0.15, and ratio of specific heats = 1.33.

The loss in nozzle efficiency (loss of exit momentum) is plotted in Fig. 3 as a function of the Mach number of one of the adjacent streams (designated stream 1). In this computation the mass flow is assumed to be divided equally between the two adjacent streams.

Conclusions

It would appear that the unrecoverable loss in thrust resulting from nonuniform velocity at the nozzle entrance is not likely to exceed about 1%, unless large variations in velocity are encountered. However, some reservations should be noted. For this example, the loss in thrust is about four times as great as the loss in nozzle efficiency. Also, the thrust in this example is quite high. In more marginal engines, a small loss in exit momentum could be much more significant. In addition, it is important to recall that it has been assumed here that the nonuniform inlet conditions are known and have been taken into account in the nozzle design. If the design is faulty, then larger losses are possible, and may be inevitable in a flight environment involving changes of angle of attack, altitude, and Mach number.

References

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Multimode Control of Axial Compressors via Stability-Based Switching Controllers

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I. Introduction

A FUNDAMENTAL development in compression system modeling for low-speed axial compressors is the Moore–Greitzer model given in Ref. 1. Specifically, utilizing a one-mode expansion of the disturbance velocity potential in the compression system and assuming a cubic characteristic for the compressor performance map, the authors in Ref. 1 developed a low-order three-state nonlinear model involving the mean flow in the compressor, the pressure rise, and the amplitude of the rotating stall. However, a shortcoming of the low-order three-state Moore–Greitzer model and, as a consequence, the control design methodologies based on the model, is that only a one-mode expansion of the disturbance velocity potential in the compression system is considered. Because the second and higher-order disturbance velocity potential harmonics strongly interact with the first harmonic during stall inception, they must be accounted for in the control-system design process. A notable exception to the low-order three-state model is given in Ref. 2, where a discrete Fourier transform formulation is used to obtain a distributed nonlinear model for axial compression systems.

Using Lyapunov stability theory, in this paper a novel switching nonlinear globally stabilizing control law for a multimode axial flow compressor model, based on equilibria-dependent Lyapunov functions with converging domains of attraction, is developed. The locus of equilibrium points on which the equilibria-dependent, or instantaneous, Lyapunov functions are predicated, is characterized by the axisymmetric pressure-flow equilibria of the compression system. The proposed switching nonlinear controller is directly applicable to compression systems with actuator amplitude and rate saturation constraints while providing a guaranteed domain of attraction.

II. Fluid Dynamic Equations for Axial Compression Systems

In this section, we extend the single-mode Moore–Greitzer model for rotating stall and surge in axial flow compressors given in Ref. 1 to the multimode case. Specifically, we consider the basic compression system consisting of an inlet duct, compressor, outlet duct, plenum, and control throttle.

From an analysis of the flow in the entrance duct, the inlet guide vane entrance, the compressor, and the exit duct, we obtain the expression for the pressure rise between the upstream reservoir and the exit duct discharge given by[1]

$$\Psi = \psi_C(\phi) - l_C\frac{d\Phi}{d\xi} - m\left.\frac{\partial\tilde{\varphi}}{\partial\xi}\right|_{\eta=0} - \frac{1}{2a}\left[2\frac{\partial^2\tilde{\varphi}}{\partial\eta\partial\xi} + \frac{\partial^2\tilde{\varphi}}{\partial\eta\partial\theta}\right]_{\eta=0} \quad (1)$$

where η, θ, and ξ are the nondimensional axial, circumferential, and time coordinates, respectively; m is a parameter such that $m = 1$ for a very short exit duct and $m = 2$ otherwise; $\phi(\xi, \theta)$ is the axial flow coefficient at $\eta = 0$; $\Phi(\xi)$ is the circumferential-averaged component of $\phi(\xi, \theta)$; and $\tilde{\varphi}(\xi, \theta, \eta)$ is the perturbation velocity potential. Furthermore, $\Psi \triangleq (p_S - p_T)/\rho U^2$, $l_C \triangleq l_E + l_I + (1/a)$, are, respectively, the rise between the static pressure, p_S, and the total pressure, p_T, normalized with respect to the dynamic pressure, ρU^2, and the effective flow-passage length through the compressor [pseudolength $(1/a)$] the inlet and exit ducts (length l_I and l_E, respectively), all measured in radii of the compressor wheel. Finally, $\psi_C(\phi)$ is the quasisteady axisymmetric compressor characteristic pressure-flow map, and represents the compressor performance in the case where the flow through the compressor is circumferentially uniform and steady, even in a stalled condition.

Assuming that the velocity field is unperturbed at the entrance, we obtain that the perturbation velocity potential satisfies $\nabla^2\tilde{\varphi} = 0$ with

$$\left.\frac{\partial\tilde{\varphi}}{\partial\eta}\right|_{\eta=-l_I} = 0$$

whose solution can be written as

$$\tilde{\varphi}(\xi, \theta, \eta) = \sum_{k=1}^{\infty}[a_k(\xi)\sin(k\theta) + b_k(\xi)\cos(k\theta)] \times \frac{\cosh[k(\eta + l_I)]}{k\sinh(kl_I)}, \qquad \eta \le 0 \quad (2)$$

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