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Technical Notes

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Aerodynamically Controlled Expansion Nozzle for Short Takeoff and Vertical Landing Aircraft

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Introduction

THE propulsion system of a short takeoff and vertical landing aircraft, such as the F-35 Joint Strike Fighter, must operate over a wide range of conditions, provide good fuel efficiency at cruise, and deliver high thrust in augmented mode for transonic acceleration and supersonic operation. The propulsion system must be efficient for both high-speed flight and during hover, while addressing the mechanical complexity required for conversion of the thrust stream from horizontal to vertical.

A situation where the desire for mechanical simplicity and high propulsion performance are at odds arises in the exhaust system. The exhaust flow conditions in hover are dramatically different from that in transonic acceleration, yet the nozzle provides the same flowpath in both cases (Fig. 1). Specifically, the nozzle provides an internal expansion ratio of 1.3 to give good performance for the critical transonic acceleration portion of the mission. The same expansion ratio is present in hover and produces overexpansion of the flow, resulting in thrust loss. Reduction of the nozzle expansion ratio to 1.1, however, will increase the gross thrust coefficient C_{fg} at hover from roughly 0.92 to at least 0.96 (Ref. 1). For the three mission points of cruise, transonic acceleration, and hover, nozzle pressure ratio (NPR) values are NPR = 3–4, 6–8, and 2, respectively. The total temperatures are 780 K for cruise and hover and 2000 K for transonic acceleration.

An aerodynamic approach appears feasible for the provision of nozzle expansion control. The underlying principle is to displace the primary airflow away from the divergent flap to achieve an effectively smaller nozzle expansion area ratio. Examples of such techniques include the use of slots or vents to admit secondary air[2] and the use of ejectors or injectors.[3–5]

Greathouse and Beale[5] showed that the gross thrust coefficient increases with increasing secondary ejector flow, particularly at low NPR, with its severe overexpansion, indicating the effectiveness of ejectors in the reduction of overexpansion losses. The study provides clues to a relatively unexplored approach for the relief of overexpansion loss. It shows that without secondary flow, C_{fg} falls off rapidly with decreasing NPR due to overexpansion. However, at a critical NPR, C_{fg} abruptly returns to a relatively high value. This yields a C_{fg} at low NPR that is higher than would be predicted.[1] Without secondary flow through the ejector slot, the configuration is essentially an aft-facing step just downstream of the nozzle throat. Thus, it can be postulated that the step separates the boundary layer from the divergent flap, thereby relieving overexpansion loss through an aerodynamic tailoring effect. Depending on NPR, the flow downstream of an aft-facing step may remain separated to the nozzle exit or reattach on the divergent flap.[6]

Analysis

Ejector data from the literature show that there is a minimum slot (or step) size to assure boundary-layer separation at a given NPR. For the JSF hover condition with NPR = 2, the minimum slot area ratio to achieve separation is approximately $A_s/A_8 = 1.1$. Whereas the step induces boundary-layer separation at low NPR and increases thrust, the drag on the step produces a thrust loss. The thrust loss at peak NPR due to step drag can be estimated by a comparison of peak C_{fg} for ejector nozzles with no secondary mass flux, that is, $\dot{m}_s/\dot{m}_p = 0$, with that predicted for similar nonejector nozzles by the use of a quasi-one-dimensional analysis.[1] This comparison predicts that, at a minimum effective step size of $A_s/A_8 = 1.1$ for the JSF hover condition, C_{fg} is reduced by 0.5% at the design NPR. Thus, a practical approach for the reduction of overexpansion loss at low NPR is a simple mechanical step that induces boundary-layer separation.

A numerical study was performed with the Falcon code developed at Lockheed Martin Aeronautics Company. Falcon is a Reynolds-averaged Navier–Stokes solver that uses a finite volume approach on a multiple-block structured grid and that uses a two-equation k–kl turbulence model with wall functions.[7] There were 33 cases studied, comprising eight nozzle configurations at NPR = 2–8; nozzle area ratios of 1.1, 1.3, and 1.5; and step area ratios A_s/A_8 of 1–1.2, where $A_8 = 0.484$ m^2, covering the potential design space for the JSF application. The baseline configuration is that without the step and with a nozzle area ratio of $A_9/A_8 = 1.1$. Inflow total pressure was specified to simulate hover at NPR = 2.0 to supersonic afterburning acceleration at NPR = 8.0. The exit boundary condition was specified at sea-level standard atmospheric conditions of $P = 101.3$ kPa and $T = 294$ K. The external flow was specified at Mach 0.05.

The computed values of gross thrust coefficient for the baseline nozzle are compared in Fig. 2 with experimental results.[1] The

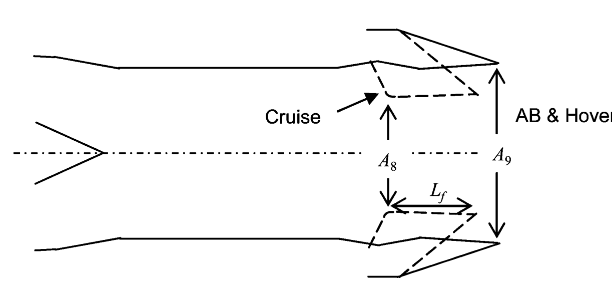

Fig. 1 JSF convergent–divergent nozzle, L_f = flap length = 41 cm.

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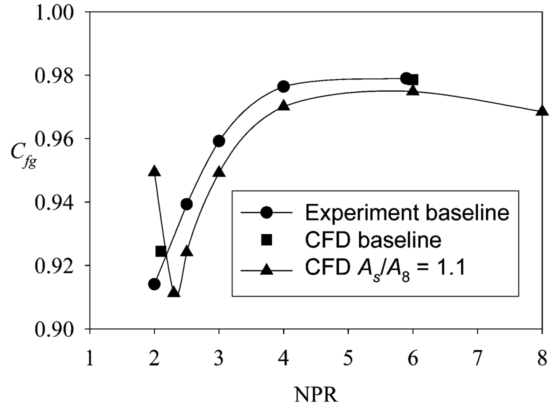
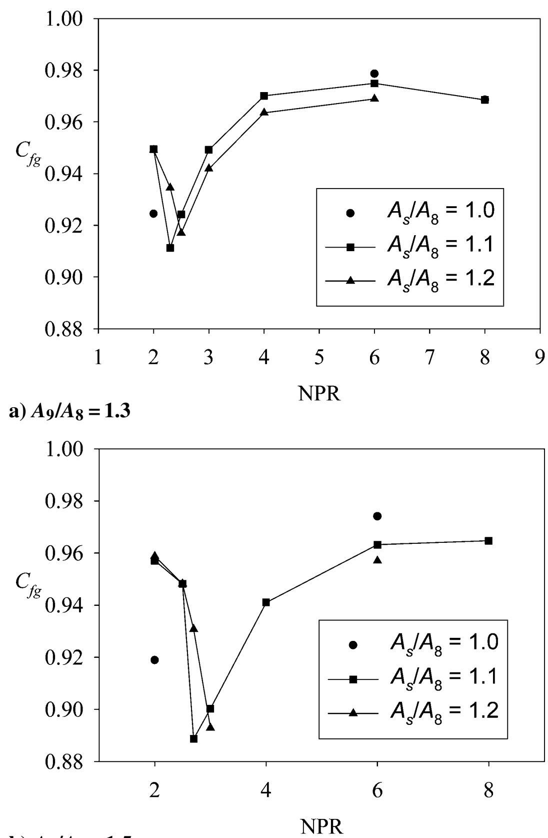


Fig. 2 Comparison of numerical and experimental values of gross thrust coefficient (lines for visual aid).



a) $A_9/A_8 = 1.3$

b) $A_9/A_8 = 1.5$

Fig. 3 Gross thrust coefficients for various nozzle configurations (lines for visual aid).

numerical values show excellent agreement with test data and illustrate the overexpansion thrust loss at low NPR. (Data repeatability is better than ±0.25%, whereas the error in C_{fg} is less than ±0.2%.) Moreover, Fig. 2 shows a potential for improvement in hover gross thrust coefficients of about 2.5% with the $A_s/A_8 = 1.1$ configuration relative to the baseline.

The effect of different step sizes and nozzle expansion ratios are shown in Fig. 3. The $A_9/A_8 = 1.3$ configuration with the larger slot size of $A_s/A_8 = 1.2$ also produces separation at NPR = 2, giving results similar to the $A_s/A_8 = 1.1$ case (Fig. 3a). At the transonic acceleration condition (NPR = 6), the flow reattaches just downstream of the step as in the $A_s/A_8 = 1.1$ case, but low pressures in the separated region act on the larger aft-facing step, producing a higher thrust loss of about 1%.

Qualitatively similar flow features were observed for the $A_9/A_8 = 1.5$ configuration. At NPR = 2, the step induces a boundary-layer separation that reattaches on the divergent section. The lower divergent section pressures exacerbate the overexpansion loss at hover. A highly overexpanded flow exhibits a large region of separated flow as it approaches the trailing edge. This boundary-layer separation is due to the adverse pressure gradient imposed by the ambient pressure. However, at NPR = 6, an open separation was observed. Figure 3b shows that the presence of the step improves the C_{fg} at NPR = 2.

The results indicate that for a given value of A_9/A_8 an increase in step size will induce separation at higher NPR. For a nozzle with $A_9/A_8 = 1.3$, a step size of $A_s/A_8 = 1.1$ will induce separation at NPR < 2, and the flow will reattach at NPR = 2.3 and higher. With a step size of $A_s/A_8 = 1.2$, the separation occurs at a higher value of NPR = 2.3. The NPR at which separation occurs is also a function of A_9/A_8, with separation onset occurring at higher NPR with increasing A_9/A_8. For a nozzle with $A_9/A_8 = 1.5$ and $A_s/A_8 = 1.1$, the onset of separation occurs at NPR = 2.5, compared with NPR = 2.3 for the $A_9/A_8 = 1.3$ and $A_s/A_8 = 1.1$ case.

Conclusions

The aerodynamically configured expansion nozzle concept featuring a boundary-layer control step is able to provide a thrust increase relative to the baseline at the JSF hover condition. The results of this study indicate that a minimum step size of $A_s/A_8 = 1.1$ will induce flow separation and relieves overexpansion loss at the hover condition of NPR = 2 for the JSF nozzle with $A_9/A_8 = 1.3$, which results in a 2.5% improvement in thrust. A larger step size of $A_s/A_8 = 1.2$ produces undesirable step drag at higher NPR conditions.

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