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 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 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. There were 33 cases studied, comprising eight nozzle configurations at NPR = 1.1 for the JSF hover condition, Cfg 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.

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 A8/A8 = 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 Cfg for ejector nozzles with no secondary mass flux, that is, m_s/m_p = 0, with that predicted for similar nozzles by the use of a quasi-one-dimensional analysis. This comparison predicts that, at a minimum effective step size of A8/A8 = 1.1 for the JSF hover condition, Cfg 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.

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Fig. 1 JSF convergent–divergent nozzle, Lf = flap length = 41 cm.
Fig. 3 Gross thrust coefficients for various nozzle configurations (lines for visual aid).

![Graph showing gross thrust coefficients for various nozzle configurations.](image)

The effect of different step sizes and nozzle expansion ratios are shown in Fig. 3. The $A_s/A_b = 1.3$ configuration with the larger slot size of $A_s/A_b = 1.2$ also produces separation at NPR = 2, giving results similar to the $A_s/A_b = 1.1$ case (Fig. 3a). At the transonic acceleration condition (NPR = 6), the flow reattaches just downstream of the step as in the $A_s/A_b = 1.1$ 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 $A_s/A_b = 1.5$ 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 $A_s/A_b$ an increase in step size will induce separation at higher NPR. For a nozzle with $A_s/A_b = 1.3$, a step size of $A_s/A_b = 1.1$ will induce separation at NPR < 2, and the flow will reattach at NPR = 2.3 and higher. With a step size of $A_s/A_b = 1.2$, the separation occurs at a higher value of NPR = 2.3. The NPR at which separation occurs is also a function of $A_s/A_b$, with separation onset occurring at higher NPR with increasing $A_s/A_b$. For a nozzle with $A_s/A_b = 1.5$ and $A_s/A_b = 1.1$, the onset of separation occurs at NPR = 2.5, compared with NPR = 2.3 for the $A_s/A_b = 1.3$ and $A_s/A_b = 1.1$ 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 $A_s/A_b = 1.1$ will induce flow separation and relieves overexpansion loss at the hover condition of NPR = 2 for the JSF nozzle with $A_s/A_b = 1.3$, which results in a 2.5% improvement in thrust. A larger step size of $A_s/A_b = 1.2$ produces undesirable step drag at higher NPR conditions.

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**References**