Performance Analysis of STOVL Aircraft Nozzle in Hover

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A quasi one-dimensional analysis of a STOVL aircraft nozzle in hover is performed to estimate the gross thrust coefficient as a function of nozzle pressure and nozzle area ratios. The analysis is supported by subscale, cold flow test results. The nozzle performance was found to be less than desirable in hover due to the overexpansion arising from the geometrical constraints of the existing nozzle.

Nomenclature

A	cross-sectional area
C_{div}	divergence loss coefficient, Eq. (10)
C_{exp}	expansion coefficient, Eq. (9)
C_{fg}	gross thrust coefficient, Eq. (4)
C_{vel}	velocity coefficient, Eq. (11)
F	thrust
k	specific heat ratio
L_f	secondary flap length (Fig. 3)
$\dot{m}$	mass flux
M	Mach number
NPR	nozzle pressure ratio
P	pressure
q	dynamic pressure
R	gas constant
T	temperature
V	velocity
ρ	density

subscripts

g	gross
id	ideal
t	total
0	far upstream
8	nozzle throat
9	nozzle exit

Introduction

FOR many years, aeronautical engineers have explored concepts that seek to exploit the advantages of both fixed and rotary wing concepts in a single vehicle. Nowhere have these efforts received more interest than in military aviation. The military challenge is to develop an aircraft that combines the basing flexibility of rotary wing vehicles while achieving the range, payload, speed, and maneuver performance of fixed wing aircraft. Most designers have approached the dilemma by providing some mechanical feature that directs thrust from the horizontal to the vertical direction as necessary for conventional and hover operation. Design approaches range from physically rotating the entire vehicle to a vertical position for landing and takeoff, to rotating the propulsion system and nacelle, and to employing a variable geometry nozzle system to deflect the thrust stream.

The fundamental technical challenge in designing a STOVL vehicle lies in the propulsion system. The difference in horizontal and vertical thrust generation involves two distinct principles. First, and most obvious, is the physical orientation of the thrust vector. Less obvious is that the thrust stream conditions required for efficient thrust is substantially different in these two cases. For air-breathing systems, the ideal propulsive efficiency is given by[1]

$$\eta_p = 2V_0 / (V_0 + V_9) \qquad (1)$$

This equation reveals that the propulsive efficiency approaches unity as the exhaust velocity approaches flight velocity. Therefore, efficient high-speed flight dictates a high velocity thrust stream. On the other hand, efficient hover operation is achieved by propelling a large mass of air at relatively low velocity. This difference is readily obvious in a cursory examination of fixed and rotary wing propulsion systems. This difference also dictates that STOVL design must be able to accommodate the disparate mass and velocity requirements of the thrust stream in high-speed flight and in hover while maintaining good propulsive efficiency.

Obviously, the design of STOVL propulsion systems must address the mechanical complexity required for converting the thrust stream from horizontal to vertical. Regardless of the approach taken to accommodate this requirement, significant weight, complexity and cost are

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incurred in the air vehicle. The STOVL propulsion system must accommodate both flight regimes and must be capable of providing controlled transition between modes. A propulsion system designed for efficient hover performance will tend to require a high airflow, low velocity thrust stream that will be inefficient in conventional flight. On the other hand, an efficient conventional propulsion system will tend toward a low airflow and high velocity thrust stream that will prove inefficient in hover.

The JSF STOVL Propulsion System

The Joint Strike Fighter (JSF) or F-35 program is a multi-national effort to develop a common fighter design that meets the needs of conventional land-based, carrier-based, and STOVL operators. The JSF propulsion system is based on the Pratt and Whitney F-119 turbofan engine. The engine is well matched for transonic fighter operation. It provides good fuel efficiency at cruise, and high thrust in augmented mode for transonic acceleration and supersonic operation. In conventional cruise operation, this engine operates as a standard fighter engine with a typical nozzle pressure ratio of 3–4 and thermodynamic characteristics that provide good propulsive efficiency.

The JSF STOVL variant shown in Fig. 1 retains a high degree of commonality with the conventional take-off and landing configuration. The primary difference lies in the propulsion system. The common engine is fitted with an articulated exhaust duct that allows vectoring from axial to 105 degrees off axial for STOVL operation. In addition, a lift fan system is mounted just aft of the cockpit. The lift fan is powered by a mechanical drive shaft connected to the main engine through a clutch mechanism. The main components of the STOVL propulsion system are shown in Fig. 2.

Figure 1. JSF STOVL design.

In the STOVL mode, the lift fan balances the thrust of the aft nozzle. In addition, small nozzles in each wing provide roll control. These four thrust posts provide the lift and control for STOVL operations. The JSF is de-

signed to accommodate these components with minimal modification to the common airframe structure. The unique JSF propulsion system accomplishes the two key STOVL propulsion challenges by physical vectoring the thrust stream and by effectively providing a variable thermodynamic cycle to achieve good propulsive efficiency in both horizontal and vertical modes.

JSF Nozzle Operating Conditions

The JSF STOVL propulsion system operates over a wide range of conditions. Achieving efficient performance over this range requires variability in the flow-path geometry of the inlet and nozzle systems as well as the engine itself. Traditional variable geometry systems can be quite complex, heavy and expensive. The emphasis on weight savings and affordability in the JSF program makes it highly desirable to minimize mechanical complexity.
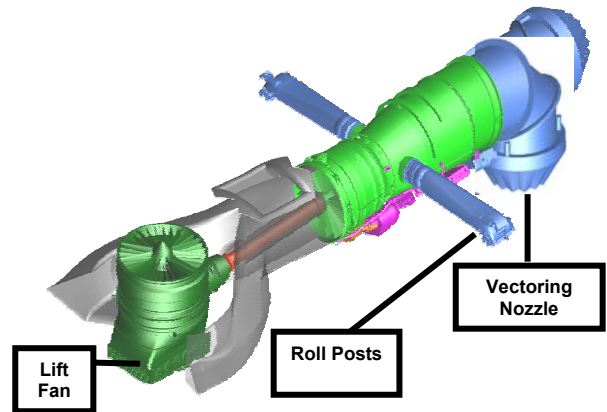

Figure 2. JSF STOVL propulsion system.

One particular case where the desire for mechanical simplicity and high propulsion performance are in direct conflict is the exhaust system. The exhaust flow conditions in hover are dramatically different from those in transonic acceleration, yet the mechanical geometry of the nozzle provides the same flow-path in both cases. Specifically, the nozzle mechanical arrangement is scheduled to provide an internal expansion ratio of 1.3 to give good performance for the critical transonic acceleration portion of the mission. The nozzle expansion ratio of 1.3 is also presented in the hover case but produces over-expansion of the flow at this condition, resulting in significant thrust loss.

The JSF STOVL variant mission segments include three stressing conditions: transonic cruise, transonic acceleration and STOVL including hover. The engine exhaust's thermodynamic conditions are unique for each of these cases. One of the primary variables that characterize exhaust flow conditions is the ratio of nozzle total