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Transient Three-Dimensional Side-Load Analysis of a Film-Cooled Nozzle

Ten-See Wang* and Mike Guidos†
NASA Marshall Space Flight Center, Huntsville, Alabama 35812

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Transient three-dimensional numerical investigations on the side-load physics of an engine encompassing a film-cooled nozzle extension and a regeneratively cooled thrust chamber were performed. The objectives of this study are to identify the side-load physics and to compute the associated aerodynamic side load. The computational methodology is based on an unstructured-grid pressure-based computational fluid dynamics formulation and a transient inlet history based on an engine system simulation. Computations simulating engine startup at ambient pressures corresponding to sea level and three high altitudes were performed. In addition, computations for both engine startup and shutdown transients for a stub nozzle operating at sea level were also performed. For engine startups with the nozzle extension attached, computational results show that the dominant side-load physics are the turbine-exhaust-gas-assisted asymmetric Mach disk flow and the subsequent jump of the separation line, which generated the peak side load that decreases as the ambient pressure decreases. For the stub nozzle operating at sea level, the peak side load reduces drastically. The computed side-load physics and the associated peak side load for the sea-level cases agree reasonably well with those of available data from the tests of a similar engine.

Nomenclature

C_1, C_2, C_3, C_μ = turbulence modeling constants 1.15, 1.9, 0.25, and 0.09.
C_p = heat capacity
D = diffusivity
F_{yz} = integrated force in the lateral direction
H = total enthalpy
K = thermal conductivity
k = turbulent kinetic energy
p = pressure
Q = heat flux
T = temperature
t = time, s
u = mean velocities
V^2 = $\sum u^2$
x = Cartesian coordinates or nondimensional distance
α = species mass fraction
ε = turbulent kinetic energy dissipation rate
θ = energy dissipation contribution
μ = viscosity
μ_t = turbulent eddy viscosity, $\rho C_\mu k^2/\varepsilon$
Π = turbulent kinetic energy production
ρ = density
σ = turbulence modeling constants 0.9, 0.9, 0.89, and 1.15 for Eqs. (2) and (4–6).
τ = shear stress
ω = chemical species production rate

Subscripts

r = radiation
s = solid
t = turbulent flow
w = wall
∞ = ambient

I. Introduction

STRUCTURAL damages caused by the transient nozzle side loads during testing at sea level have been found for almost all rocket engines during their initial development [1–5]. For example, the J-2 engine gimbal block retaining bolts failed in tension, and the space shuttle main engine (SSME) liquid-hydrogen feed line or steer horn fractured from low cycle fatigue during the shutdown transient [2,5]. More recently, the Japanese LE-7A engine cooling tubes broke [4]. As a final example, during its maiden flight, the European Vulcain engine failed by a leak in coolant pipes allowing the nozzle to overheat; although the side loads were not the root cause, they exacerbated the problem [6]. As a result, whether during sea-level testing or in flight, transient nozzle side load has the potential of causing real system-level failures and are therefore considered to be a high-risk item and a design issue during any new engine development.

The J-2X engine, the Ares I upper-stage engine under development, is an evolved variation of two historic predecessors: the powerful J-2 engine that propelled the upper stages of the Apollo-era Saturn IB and Saturn V rockets, and the J-2S, a derivative of the J-2 that was developed and tested but never flown. Because the asymmetric shock evolutions inside the nozzle, or the origins of the transient nozzle side loads, occur naturally during the nozzle fillup or evacuation processes, it can be safely assumed that the J-2X engine will experience side forces, just like its predecessors such as J-2 and J-2S, or engines similar in design such as the LE-7A and Vulcain engines. It should be noted though that the hardware failures caused by side forces are all fixable or avoidable, once the effect of the side load is understood and the structure is strengthened. For example, the steer horn of the SSME was redesigned to reduce the stress level [2,7]. The strategy is therefore to understand the physics and properly predict the peak side load and its impact on the components during the design phase and before the tests, such that the risk of expensive hardware failures may be avoided or reduced.

Currently, three approaches are available to predict the peak side loads for J-2X: the empirical or skewed-plane approach [5], cold-

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*Aerospace Engineer, Mail Stop ER42, Fluid Dynamics Branch, Propulsion Structure, Thermal, and Fluids Analysis Division. Senior Member AIAA.

†Aerospace Engineer, Mail Stop ER21, Liquid Engine and Main Propulsion Systems Branch, Propulsion Systems Design and Integration Division.