

Numerical Investigation of Roll Torque Induced by Solid Rocket Motor Internal Flow

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To understand the mechanism of the generation of large roll torque in an operating solid rocket motor with axially slotted propellant grain and a narrow nozzle-submergence region, fully three-dimensional Navier–Stokes numerical simulations are conducted. Several grain configurations are computed, and it is found that there are at least two groups of quasi-steady-state solutions: one shows large roll torque, and the other shows small roll torque. From the current simulation results, it is observed that large roll torque is generated as a result of the interaction of the circling flow around the nozzle inlet with the slot jet exhausting from the slot end into the aft-end cavity. Although the roll torque evaluated from the computation is one order higher than that observed in real flight, the simulations provide an insight into the qualitative mechanism of real roll-torque generation.

Nomenclature

A, B, C	= inviscid flux Jacobian matrices
c	= specific heat of condensed phase
e	= total energy per unit volume
\bar{I}	= unit matrix
i, j, k	= cell indices
p	= pressure
\mathbf{Q}	= conserved variable vector
\mathbf{q}	= heat flux vector
R	= gas constant
\bar{R}	= effective gas constant
t	= time from ignition
u, v, w	= velocity components in x, y, z directions, respectively
\mathbf{V}	= velocity vector
$\bar{\gamma}$	= effective specific heat ratio
γ_g	= specific heat ratio of gas
Δt	= local time step
$\nu_A, \nu_B,$	= spectral radii of A, B, C
ν_C	
ρ	= density
$\bar{\tau}$	= stress tensor
ψ	= loading ratio

I. Introduction

FROM the pioneering days of modern rocketry, it has been recognized and reported that roll torque is generated around the thrust axis during the firing of a solid rocket without tail fins, especially with relation to acoustic instability in the combustion chamber of a solid rocket motor (SRM) [1–6].

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As in the case of the first launch of the Sergeant missile in 1961 [4], or as in some other cases, the intensity of the roll torque generated is sometimes one order higher than that expected from the aerodynamics and thrust misalignment. This roll torque tends to occur during the early period of the burn and then tends to decline.

The mechanism of roll-torque generation, in general, is categorized into several types, including acoustic instability, grain configuration, nozzle erosion, and jet damping (of a spinning motor) [7]. However, a method has not yet been established to predict the amount of possible roll-torque generation when an individual SRM specification is given. It seems therefore, that, even in recent years, in the system design of launch vehicles (LVs), one cannot help but employ some empirical evaluation [7].

In a situation where a booster is used as the first-stage motor, such as the planned U.S. ARES-1 crew LV [8,9], or where a new launch system is constructed of new SRMs, such as the European VEGA LV [10,11], there is a pressing need in the design phase for an evaluation of the amount of torque. Against such a background, there is a need worldwide for clarification regarding the origin and mechanism of the generation of roll torque of an SRM during its operation.

The Mu-V LV (M-V) [12,13] is a Japanese three-stage, full solid-propellant rocket system, which was launched seven times from 1997 to 2006. As reported recently [14,15], marked roll-torque disturbance was observed during the first-stage motor burn in all M-V flights. The roll-torque disturbance estimated from the attitude-angle measurement is plotted in Fig. 1. The strength of the torque is more than 3 kN · m immediately after separation from the launcher, and it then attenuates gradually. It is a high, but transient, torque, so that the roll-control system can handle it without any problem. As for the direction of the torque, it was observed to have the same direction in six flights out of seven. The peak value of the measured torque is an order of magnitude higher than that estimated from the aerodynamics and thrust misalignment. With regard to this roll torque, a theoretical evaluation has been made and a fully three-dimensional computational fluid dynamics (CFD) simulation of the flow inside the combustion chamber has been reported [14,15].

The major objective of this paper is to investigate the flowfield inside a motor chamber with axial slots and in the aft cavity of the nozzle-submergence region based on CFD simulations. It should be noted that the nozzle treated is not canted. Moreover, we will discuss how roll torque and side thrust change according to grain shape, by comparing numerical solutions for several grain burnback configurations. The grain configuration dealt with in this study is generic as a star-perforated motor, but its shape and size are basically similar to a