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MEMORANDUM REPORT ARBRL-MR-03052

SPIN JET DAMPING OF ROCKET-ASSISTED PROJECTILES

Charles H. Murphy

August 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)* (jah)

A theory is developed to predict the spin-up of a rocket-assisted projectile during burning. The percentage change in spin is shown to be proportional to the percentage change in the spin moment of inertia. Observed 2% increments in spin are about half the predicted maximum increment.

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I. INTRODUCTION

The thrust of a rocket is produced by the high-speed discharge of gases to the rear of the rocket. In effect, the rearward linear momentum of the rocket gases is balanced by an increased forward momentum of the rocket. In the case of a rocket with pitching and yawing motion, these gases also possess angular momentum in pitch and yaw and a careful dynamics analysis shows a damping of the pitching and yawing motion associated with this gaseous angular momentum. This pitch jet damping is usually fairly small. For Army rocket-assisted projectiles (RAPs), it is completely negligible.

A spinning RAP ejects gases with spin angular momentum and the effect of this lost angular momentum should be considered. In this report an expression for the spin jet damping of a rocket is derived and the size of this effect is computed for two Army RAPs: the 155mm M549 and the 8-inch M650. The predicted change in spin will then be compared with actual flight measurements made by sunsondes with onboard telemetry transmitters[1-2].

II. THEORY

We will use the usual nonrolling aeroballistic x, $\tilde{y}$ $\tilde{z}$ axes with the x-axis along the rocket's axis of symmetry and the $\tilde{z}$-axis selected to be initially downward-pointing. If the rocket is flying at zero angle of attack, the only aerodynamic force acting on the rocket is the drag force $\vec{F}_D$. For small angles of attack and sideslip, the x-component of this force is $F_D = |\vec{F}_D|$. The x-component of the linear momentum of the rocket body plus propellant at time t will be denoted by $A_x(t)$. The derivative of A_x will then be equal to $-F_D$ plus the x-component of the gravity force.

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1. *William H. Mermagen, "Measurements of the Dynamic Behavior of Projectiles over Long Flight Paths," Journal of Spacecraft and Rockets 8, April 1971, pp. 380-385. (See also Ballistic Research Laboratories Memorandum Report No. 2079, November 1970, AD 717002.)*

2. *Charles H. Murphy, "Effect of Large High-Frequency Angular Motion of a Shell on the Analysis of Its Yawsonde Records," Ballistic Research Laboratories Memorandum Report No. 2581, February 1976, AD B009421L.*

$$\dot{A}_x = - F_D + m\, g_x \tag{1}$$

It is very important to note that the derivative in Equation (1) is the rate of change of linear momentum for the constant-mass system of rocket plus propellant and must be calculated with care. At time $t_0 + \Delta t$ the rocket has a mass $m + \Delta m$ (where Δm is negative) and an x-component of velocity, $u + \Delta u$. A mass of propellant gas, $- \Delta m$, has separated from the rocket and is traveling away from the rocket in the exhaust jet with a velocity x-component u_J relative to the rocket. The new linear momentum is, therefore,

$$A_x(t_0) + \Delta A_x = (m + \Delta m)\,(u + \Delta u) + (- \Delta m)\,(u + u_J) \tag{2}$$

where

$$A_x(t_0) = m\, u$$

Equation (2) is divided by Δt and the limit as $\Delta t \rightarrow 0$ is taken to obtain $\dot{A}_x$. This result can be substituted in Equation (1) to yield

$$m\, \dot{u} = F_T - F_D + m\, g_x \tag{3}$$

where

$F_T = \dot{m}\, u_J$ is the x-component of the thrust of the rocket.

This simple derivation of rocket thrust has been done so that we can see the proper way to estimate the jet effect on the angular motion of the rocket. If the components of the angular momentum of the rocket are $(H_x, H_{\tilde{y}}, H_{\tilde{z}})$, the angular motion must satisfy the following vector differential equation:

$$(\dot{H}_x, \dot{H}_{\tilde{y}}, \dot{H}_{\tilde{z}}) + (0, \tilde{q}, \tilde{r}) \times (H_x, H_{\tilde{y}}, H_{\tilde{z}}) = (M_x, M_{\tilde{y}}, M_{\tilde{z}}) \tag{4}$$

We will assume that the rocket grain burns symmetrically so that the x-axis remains an axis of mass symmetry and the transverse moments of inertia remain equal. The angular momentum of the solid part of the rocket is then

$$\vec{H}_S = (I_x\, p,\ I_t\, \tilde{q},\ I_t\, \tilde{r}) \tag{5}$$

and at time t_0

$$\vec{H} = (H_x,\ H_{\tilde{y}},\ H_{\tilde{z}})$$

$$= (I_x\, p + h_x,\ I_t\, \tilde{q} + h_{\tilde{y}},\ I_t\, \tilde{r} + h_{\tilde{z}}) \tag{6}$$

where the h_J's are the angular momentum components of the gas in the rocket motor.

At time $t_0 + \Delta t$, the angular momentum of the solid part has slightly changed and some propellant gas of mass $-\Delta m$ has been emitted from the nozzle, but the small change in the angular momentum of the gas in the motor will be neglected.

The angular momentum $\vec{h}_J$ of the emitted gas can be expressed as a sum of volume elements:

$$\vec{h}_J = \sum (\vec{R}_J \times \vec{V}_J)\, \rho_J \quad \Delta(\mathrm{Vol}) \tag{7}$$

where $\vec{R}_J$, $\vec{V}_J$ and ρ_J are, respectively, the position, velocity and density of the jet of propellant gas in the particular volume element:

$$\vec{R}_J = (x,\ R\cos\theta,\ R\sin\theta) \tag{8}$$

$$\vec{V}_J = (u_J,\ \tilde{v}_J,\ \tilde{w}_J) \tag{9}$$

$$\Delta(\mathrm{Vol}) = R\ \Delta R\ \Delta\theta\ \Delta x \tag{10}$$

and where R and θ are polar coordinates. In the time interval Δt, the emitted gas forms a disk of thickness $\Delta x = u_J \Delta t$ and radius equal to that of the rocket nozzle exit, R_n, located a distance X_n from the projectile c.m.

$$\therefore \vec{h}_J = \rho_J \Delta x \int_0^{R_n} \int_0^{2\pi} \Big(R(\tilde{w}_J \cos\theta - \tilde{v}_J \sin\theta) , \quad R u_J \sin\theta - X_n \tilde{w}_J , \quad X_n \tilde{v}_J - R u_J \cos\theta \Big) R \, dR \, d\theta \tag{11}$$

The transverse motion of the exhaust gases is assumed to be the sum of the pitching motion of the nozzle and a rotationally symmetric circumferential motion due to projectile spin.

$$\tilde{v}_J = \tilde{r} X_n - p R_n f(\hat{R}) \sin\theta \tag{12}$$

$$\tilde{w}_J = - \tilde{q} X_n + p R_n f(\hat{R}) \cos\theta \tag{13}$$

where

$$\hat{R} = R/R_n$$

$$f(0) = 0, \; f(1) = 1 \; .$$

Equations (12-13) allow the angular momentum of the gas emitted in the time interval Δt to be written in a very simple form.

$$\vec{h}_J = (R_n^2 F p, \; X_n^2 \tilde{q}, \; X_n^2 \tilde{r}) \; (- \Delta m) \tag{14}$$

where

$$F = 2 \int_0^1 \hat{R}^2 \, f(\hat{R}) \, d\hat{R}$$

Equation (14) now allows us to compute the change in angular momentum of the system.

$$H_x + \Delta H_x = (I_x + \Delta I_x)(p + \Delta p) + h_x - (R_n^2 \, F \, \Delta m) p \tag{15}$$

$$H_{\tilde{y}} + \Delta H_{\tilde{y}} = (I_t + \Delta I_t)(\tilde{q} + \Delta\tilde{q}) + h_{\tilde{y}} - (X_n^2 \, \Delta m)\tilde{q} \tag{16}$$

$$H_{\tilde{z}} + \Delta H_{\tilde{z}} = (I_t + \Delta I_t)(\tilde{r} + \Delta\tilde{r}) + h_{\tilde{z}} - (X_n^2 \, \Delta m)\tilde{r} \tag{17}$$

Equations (15-17) can be simplified by Equation (6), divided by Δt, and the limit taken as Δt → 0 to yield the derivatives of the angular momentum components. Then Equation (4) becomes

$$I_x \, \dot{p} + \tilde{q} \, h_{\tilde{z}} - \tilde{r} \, h_{\tilde{y}} = J_p \, p + M_x \tag{18}$$

$$I_t(\dot{\tilde{q}} + i \, \dot{\tilde{r}}) - i \, (I_x \, p + h_x)(\tilde{q} + i \, \tilde{r}) = J_q(\tilde{q} + i \, \tilde{r}) + (M_{\tilde{y}} + i \, M_{\tilde{z}}) \tag{19}$$

where

$$J_p = \dot{m} \, R_n^2 \, F - \dot{I}_x$$

$$J_q = \dot{m} \, X_n^2 - \dot{I}_t$$

The small terms in the angular momentum of the motor gas are usually neglected so that the only effects of the propellant gases on the angular motion of the rocket are the time-varying moments of inertia, the spin jet damping, $J_p\, p$, and the pitch jet damping, $J_q\, (\tilde{q} + i\, \tilde{r})$.

III. DISCUSSION

J_q is the derivative of the change in pitch moment of inertia of the propellant gases and is negative. Thus this term damps the pitching motion, producing the well-known pitch jet damping effect. As we shall see, for Army RAPs the pitch jet damping moment is much smaller than the aerodynamic damping moment and has no measurable effect on the pitching motion.

If we assume that the radial variation in circumferential velocity is linear like that of a spinning rigid body, then $f(\hat{R}) = \hat{R}$ and $F = 1/2$. For this case, J_p is the derivative of the change in spin moment of inertia of the propellant gases. Since J_p is positive, this term represents a spin jet undamping. Since it is unreasonable to expect the spin angular momentum of the emitted gases to drop to the low value associated with $f(\hat{R}) = \hat{R}$, this value yields a maximum value of J_p and we would expect the actual value to be less.

$$J_p = \varepsilon\, (J_p)_{\max} , \quad 0 \leq \varepsilon \leq 1 \qquad (20)$$

where

$$(J_p)_{\max} = \dot{m}\, (R_n^2/2) - \dot{I}_x$$

The aerodynamic moment contains a spin damping term in p and a pitch damping term in $\tilde{q} + i\, \tilde{r}$. In order to compare the aerodynamic terms with the jet damping terms we will nondimensionalize the jet damping moments in the same way that the aerodynamic moments are nondimensionalized[3] .

---

[3] *Charles H. Murphy, "Free Flight Motion of Symmetric Missiles," Ballistic Research Laboratories Report No. 1216, July 1963, AD 442757.*

$$J_p = \left(\frac{1}{2}\right) \rho \; V \; S \; \ell^2 \; C_{J_p} \qquad (21)$$

$$J_q = \left(\frac{1}{2}\right) \rho \; V \; S \; \ell^2 \; C_{J_q} \qquad (22)$$

In Table 1 the average values of $\dot{I}_x$, $\dot{I}_t$, $\dot{m}$ and other appropriate parameters are given for two rocket-assisted projectiles, the 155mm M549 and the 8-inch M650. According to this table, the pitch jet damping coefficient is much smaller than the aerodynamic pitch damping coefficient and can be neglected, but the spin jet damping coefficient is the same size as the aerodynamic spin damping coefficient. We would therefore expect the spin to be affected by this term during burning.

Another way to estimate the effect of the spin jet damping is to consider Equation (18) for no aerodynamic moment and neglecting $h_{\tilde{y}}$ and $h_{\tilde{z}}$.

$$\frac{\dot{p}}{p} = - \varepsilon \gamma \left(\frac{\dot{I}_x}{I_x}\right) \qquad (23)$$

where

$$\gamma = - \left(J_p\right)_{\max} / \dot{I}_x$$

γ can be computed from the table and is 0.90 and 0.87 for the M549 and M650, respectively. Thus the percentage change in spin during burning can be approximately related to the percentage change in the spin moment of inertia.

$$\frac{\Delta p}{p} = - \varepsilon \gamma \left(\frac{\Delta I_x}{I_x}\right) \qquad (24)$$

$$= \begin{cases} 0.046\varepsilon & \text{(M549)} \\ 0.033\varepsilon & \text{(M650)} \end{cases}$$

TABLE 1. PARAMETERS FOR TWO ROCKET-ASSISTED PROJECTILES

	155mm M549	8-inch M650
burn-time (s)	2.68	2.95
$\dot{m}$ (kg/s)	- 1.12	- 1.86
$\dot{I}_x$ (kg-m^2/s)	- .00285	- .00714
$\dot{I}_t$ (kg-m^2/s)	- .0379	- .0803
R_n (m)	.0222	.0317
X_n (m)	.326	.365
V (m/s)	481	603
C_{ℓ_p}	- .0112	- .0113
$C_{M_q} + C_{M_{\dot{\alpha}}}$	-13.2	-11.9
$\left(C_{J_p}\right)_{max}$	.019	.012
C_{J_q}	- .61	- .34

IV. EXPERIMENTAL RESULTS

Recently yawsonde data have been obtained[4-5] for the spin during burning of both the M549 and the M650. Sample spin histories for each RAP are given in Figure 1. The spin curve before burning was extended through burning and the percentage change in spin during burning was determined. It was 1.9% for the M549 and 1.7% for the M650. These values correspond to ε values of 0.41 and 0.52, respectively.

V. SUMMARY

1. The derivation of rocket thrust and pitch jet damping has been reviewed.

2. A theoretical model for spin jet damping has been derived which predicts a percentage increase in spin proportional to the percentage decrease in the spin moment of inertia.

3. Experimental results show approximately 2% increase in spin, which is about half the predicted maximum increase.

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[4] *Anders S. Platou, "Yawsonde Flights of 155mm Non-Conical Boattail Projectiles and the 155mm M549 Projectile at Tonopah Test Range--October 1977," USA ARRADCOM Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-02881, November 1978, AD A065356.*

[5] *Vural Oskay, Wallace H. Clay and Martin Klawa, "8-Inch PXR 6263 (Temperature Instrumented M650 RAP) Tests at Yuma Proving Ground," USA ARRADCOM Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-03037, August 1980.*

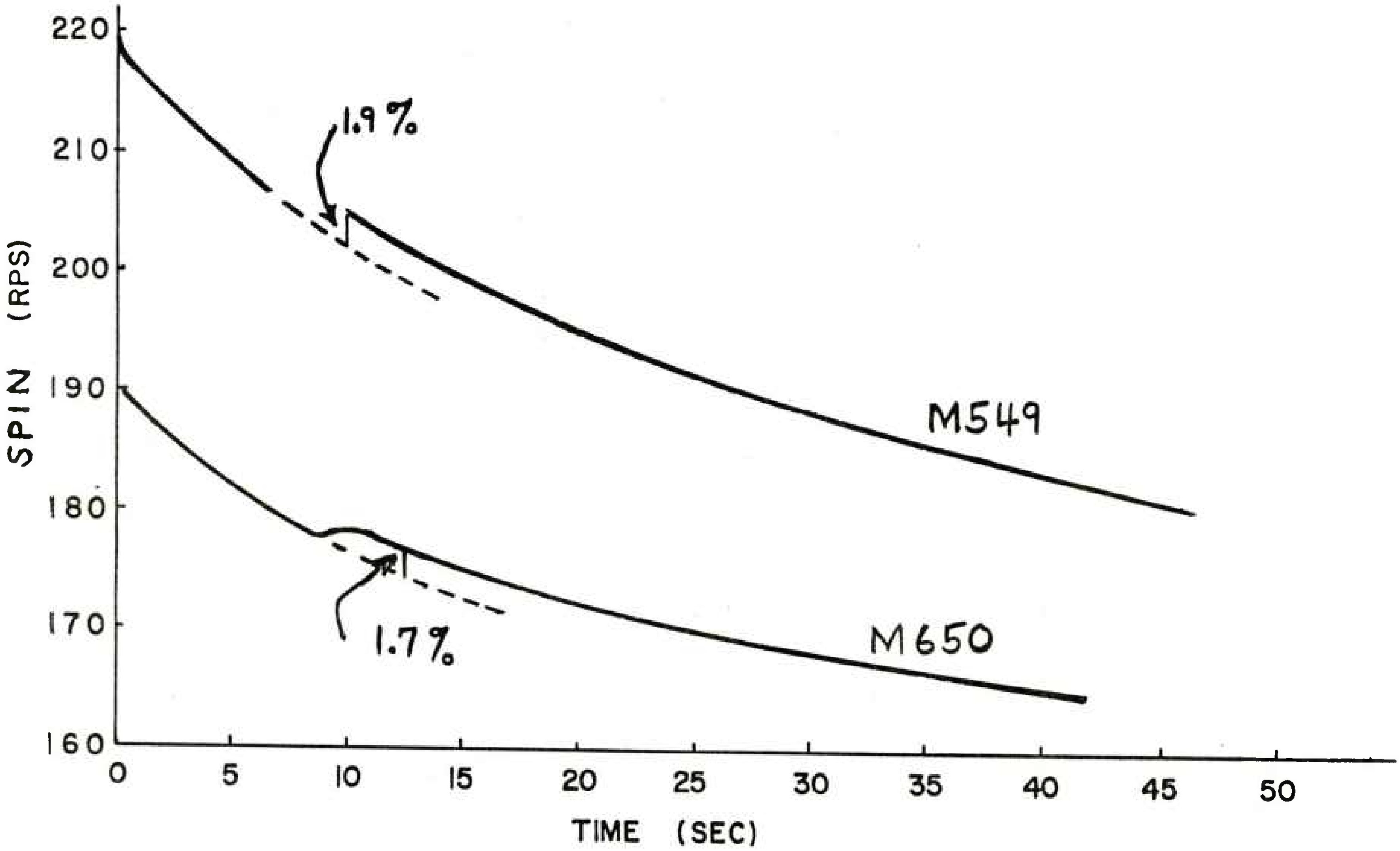

Figure 1. Measured spin histories for two rocket-assisted projectiles, showing the percentage spin-up during burning.

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1. William H. Mermagen, "Measurements of the Dynamic Behavior of Projectiles over Long Flight Paths," *Journal of Spacecraft and Rockets* 8, April 1971, pp. 380-385. (See also Ballistic Research Laboratories Memorandum Report No. 2079, November 1970, AD 717002.)

2. Charles H. Murphy, "Effect of Large High-Frequency Angular Motion of a Shell on the Analysis of Its Yawsonde Records," Ballistic Research Laboratories Memorandum Report No. 2581, February 1976, AD B009421L.

3. Charles H. Murphy, "Free Flight Motion of Symmetric Missiles," Ballistic Research Laboratories Report No. 1216, July 1963, AD 442757.

4. Anders S. Platou, "Yawsonde Flights of 155mm Non-Conical Boattail Projectiles and the 155mm M549 Projectile at Tonopah Test Range--October 1977," USA ARRADCOM Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-02881, November 1978, AD A065356.

5. Vural Oskay, Wallace H. Clay and Martin Klawa, "8-Inch PXR 6263 (Temperature Instrumented M650 RAP) Tests at Yuma Proving Ground," USA ARRADCOM Ballistic Research Laboratory Memorandum Report No. ARBRL-MR-03037, August 1980.

LIST OF SYMBOLS

A_x	x-component of the linear momentum of the rocket body-plus-propellant system
C_{J_p}	$\dfrac{J_p}{(1/2)\ \rho\ V\ S\ \ell^2}$
C_{J_q}	$\dfrac{J_q}{(1/2)\ \rho\ V\ S\ \ell^2}$
C_{ℓ_p}	roll damping moment coefficient
$C_{M_q} + C_{M_{\dot{\alpha}}}$	$\dfrac{\text{sum of the damping moments}}{(1/2)\ \rho\ V^2\ S\ \ell\ (\tilde{q}^2 + \tilde{r}^2)^{\frac{1}{2}}}$
F	$2 \int_0^1 \hat{R}^2\ f(R)\ d\hat{R}$
F_D	$\lvert \vec{F}_D \rvert$
$\vec{F}_D$	drag force
F_T	$\dot{m}\ u_J$, x-component of the rocket thrust
$f(\hat{R})$	differentiable function of $\hat{R}$, where $f(0) = 0$, $f(1) = 1$.
g_x	x-component of gravity acceleration
$\vec{H}$	angular momentum of the rocket
$\vec{H}_S$	angular momentum of the solid part of the rocket
H_x, $H_{\tilde{y}}$, $H_{\tilde{z}}$	aeroballistic system components of $\vec{H}$

LIST OF SYMBOLS
(Continued)

$\vec{h}_J$	angular momentum of the gas in the exhaust jet
h_x, $h_{\tilde{y}}$, $h_{\tilde{z}}$	aeroballistic system components of the angular momentum of the gas in the rocket motor
I_x, I_t	axial and transverse moments of inertia
J_p	$\dot{m} R_n^2 F - \dot{I}_x = (\ell/V) \cdot$ spin jet damping moment
J_q	$\dot{m} X_n^2 - \dot{I}_t = (\ell/V) \cdot$ pitch jet damping moment
ℓ	reference length
M_x, $M_{\tilde{y}}$, $M_{\tilde{z}}$	aeroballistic components of the aerodynamic moment
m	mass of the rocket body-plus-propellant system at time t_0
p, $\tilde{q}$, $\tilde{r}$	rocket spin, pitch and yaw rates in the aeroballistic system
R	polar distance coordinate, $0 \leq R \leq R_n$
$\hat{R}$	R/R_n
$\vec{R}_J$	position vector of the gas in the exhaust jet
R_n	radius of the rocket nozzle exit
S	reference area
t	time
u	x-component of the velocity of the rocket body-plus-propellant system at time t_0

LIST OF SYMBOLS
(Continued)

u_J, $\tilde{v}_J$, $\tilde{w}_J$	aeroballistic system components of $\vec{V}_J$
V	magnitude of the velocity vector
$\vec{V}_J$	velocity of the gas in the exhaust jet relative to the rocket
x, $\tilde{y}$, $\tilde{z}$	nonrolling aeroballistic axes, with the x-axis along the rocket's axis of symmetry and the z-axis initially downward
X_n	distance from the rocket c.m. to the rocket nozzle exit
γ	$-\left(J_p\right)_{max} \Big/ \dot{I}_x$
Δm	the change in mass of the rocket body-plus-propellant system in the time interval Δt
ε	a nondimensional constant in the range 0 to 1 .
θ	polar angular coordinate
ρ	air density
ρ_J	density of the gas in the exhaust jet

Subscript:

$(\ )_{max}$	value at $f(\hat{R}) = \hat{R}$, $F = 1/2$

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