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EFFECT OF NEAR-ZERO SPIN ON INSTABILITY OF CONTROLLED PROJECTILES IN ASCENDING OR DESCENDING FLIGHT

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May 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Lloyd and Brown have shown that constant-amplitude horizontal and vertical side forces applied to a spinning projectile can cause dynamic instability. A subsequent ARRADCOM report removed some of the limitations of the Lloyd-Brown work and gave somewhat more general results. Unfortunately, these results were applied in the report to a case for which they were unsuitable: a nonspinning statically stable missile. The present report derives correct results for the zero-spin case and shows that the results of the earlier report are valid for spin rates greater than about five times the resonant spin value.

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I. INTRODUCTION

In 1977, Lloyd and Brown[1] investigated the feasibility of controlling a 105mm spinning projectile by means of horizontal and vertical forces. Their numerical calculations yielded the surprising result that an applied constant-amplitude yaw moment could cause dynamic instability. This result was then explained theoretically by the influence of a nonlinear term in $\dot{\phi}_{FP}$, the fixed-plane coordinate system spin rate.

The Lloyd and Brown work was limited to large stability factors, neglected spin and density variations and incompletely considered gravity. Reference 2 removed these limitations and thereby gave somewhat more general results as well as a more elegant derivation. Unfortunately, the relations of Reference 2 were applied there to the case of a nonspinning statically stable missile. Although these relations are valid for statically stable missiles with spin rates that are large in comparison with the resonance spin, they are definitely invalid for zero and "near-zero" spin. It is the purpose of this memorandum report to give a more rigorous derivation of the relations of Reference 2 and to obtain the correct equations for a statically stable missile with zero spin.

II. GENERAL THEORY

Equation (3.8) of Reference 2 can be written in the form:

$$\hat{\xi}'' + (H - i\,P)\hat{\xi}' - (M + i\,PT)(\hat{\xi} - \hat{\xi}_e)$$

$$= -2\,i\,E[\hat{\beta}'' + (H - i\,P)\hat{\beta}'] \qquad (2.1)$$

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1. *K.H. Lloyd and D.P. Brown, "Influence of Gravity and Applied Side Forces on the Stability of a Spinning Projectile," Weapons Research Establishment TR 1906(W), South Australia, November 1977, AD A053648. (See also "Instability of Spinning Projectiles During Terminal Guidance," Journal of Guidance and Control 2, January-February 1979, pp. 65-70.)*

2. *C.H. Murphy, "Effect of Horizontal and Vertical Side Forces and Moments on Stability of a Symmetric Missile in Ascending or Descending Flight," USA ARRADCOM Ballistic Research Laboratory Memorandum Report No. 02915, April 1979, AD A072808.*

where

$$E = (a/2)\hat{\xi}_e \tan\theta_e$$

$$\hat{\xi}_e = - C/(M + i\ P\ T)$$

$$a = [\gamma_e + \hat{\alpha}_e \tan\theta_e]^{-1}$$

and the other symbols are defined in the List of Symbols.

The right-hand side of Equation (2.1) is the forcing function due to $\dot{\phi}_{FP}$, linearized with respect to the equilibrium angle $\hat{\xi}_e$ produced by the control moment. Since

$$\hat{\beta} - \hat{\beta}_e = (1/2)[\hat{\xi} - \hat{\xi}_e + \bar{\hat{\xi}} - \bar{\hat{\xi}}_e] \qquad (2.2)$$

$\hat{\beta}$ can be eliminated from Equation (2.1). The result has a quite simple form if $\hat{\xi}_e$ is assumed to be constant:

$$\hat{\xi}'' + (H - i\ P)\hat{\xi}' - (1 - i\ \tilde{E})(M + i\ PT)(\hat{\xi} - \hat{\xi}_e)$$

$$= - i\ \tilde{E}[\bar{\hat{\xi}}'' + (H - i\ P)\bar{\hat{\xi}}'] \qquad (2.3)$$

where

$$\tilde{E} = E/(1 + i\ E)$$

Equation (2.3) is a second-order complex equation with constant coefficients, but it involves $\bar{\hat{\xi}}$ as well as $\hat{\xi}$. Equations of this kind were solved in Reference 3 by assuming a solution of the form:

$$\hat{\xi} = \hat{\xi}_e + k_1 e^{\Psi_1 s} + k_2 e^{\Psi_2 s} + k_4 e^{\bar{\Psi}_1 s} + k_5 e^{\bar{\Psi}_2 s} \qquad (2.4)$$

where k_j and Ψ_j are complex constants:

$$k_j = K_{j0}\ e^{i\phi_{j0}}$$

$$\Psi_j = \lambda_j + i\ \phi_j'$$

3. *C.H. Murphy, "Angular Motion of Spinning Almost-Symmetric Missiles," Journal of Guidance and Control 2, November-December 1979, pp. 504-510. (See also USA ARRADCOM Ballistic Research Laboratory Technical Report No. 02121, November 1978, AD A063538.)*

If Equation (2.4) is substituted in Equation (2.3) and the coefficients of the four exponentials are set equal to zero, there results

$$\left.\begin{aligned} \frac{\bar{k}_{j+3}}{k_j} &= \frac{F_j + i\,M_e}{-\,i[\tilde{E}\,F_j + M_e]} \\ &= \frac{i\left\{\bar{\tilde{E}}[F_j + 2\,i\,P(\Psi_j + T)] + \bar{M}_e\right\}}{F_j - i\,\bar{M}_e + 2\,i\,P(\Psi_j + T)} \end{aligned}\right\} \quad (2.5)$$

$$j = 1,\ 2$$

where $F_j = \Psi_j^2 + (H - i\,P)\Psi_j - M - i\,P\,T$.

$$M_e = \tilde{E}(M + i\,P\,T)$$

For $E = 0$, $k_4 = k_5 = 0$ and the equation $F_j = 0$ is the usual quadratic equation for the epicyclic frequencies and damping rates. We wish to find the effect of small nonzero E. Equation (2.5) can be written in the following form, where $\Psi_j + T$ has been approximated by $i\phi_j'$.

$$F_j + i\,M_e = \frac{\left[\bar{\tilde{E}}(F_j - 2\,P\,\phi_j') + \bar{M}_e\right](\tilde{E}\,F_j + M_e)}{F_j - 2\,P\phi_j' - i\,\bar{M}_e} \qquad (2.6)$$

A first approximation for F_j can be obtained by setting the small right side of Equation (2.6) equal to zero.

$$F_j = -\,i\,M_e \qquad (2.7)$$

A better approximation for F_j now follows from Equation (2.6) by replacing F_j on the right side by $-\,i\,M_e$ and neglecting E^2 terms compared to E terms.

$$F_j = M_e \left\{ -i + \frac{\bar{\tilde{E}}\,[2\,P\,\phi'_j - M + i\,PT]}{2\,P\,\phi'_j + i\,(M_e + \bar{M}_e)} \right\} \qquad (2.8)$$

For this approximation,

$$\frac{k_{j+3}}{\bar{k}_j} = \frac{-i\,\tilde{E}\,(2\,P\,\phi'_j - M - i\,PT)}{2\,P\,\phi'_j - i\,(M_e + \bar{M}_e)} \qquad (2.9)$$

III. SOLUTION FOR SMALL SPIN

For small spin, the PT term in Equations (2.8 - 9) can be omitted and these equations reduce to

$$F_j = \tilde{E}\,M \left[-i + \frac{\bar{\tilde{E}}\,(1 - R_j)}{1 + i\,(\tilde{E} + \bar{\tilde{E}})\,R_j} \right] \qquad (3.1)$$

$$\frac{k_{j+3}}{\bar{k}_j} = \frac{-i\,\tilde{E}\,(1 - R_j)}{1 - i\,(\tilde{E} + \bar{\tilde{E}})\,R_j} \qquad (3.2)$$

where $R_j = M/(2\,P\,\phi'_j)$.

The iterative process that produced Equation (3.1) is valid only if the absolute value of the second term in that equation is smaller than the absolute value of the first term. For small $|\tilde{E}|$, this is the case if $|R_j|$ is less than, say, unity (a conservative upper bound):

$$|R_j| < 1 \qquad (3.3)$$

This condition is always satisfied for the rapidly spinning shell of Reference 1, but its applicability to a slowly spinning finner must be analyzed by use of the concept of resonance spin.

Resonance spin, ϕ'_{reson}, is defined by the relations

$$\phi'_{reson} = \phi'_1 = -\,\phi'_2 = \sqrt{-M} \qquad (3.4)$$

Relation (3.3) assumes a very simple form in terms of resonant spin.

$$\phi'/\phi'_{reson} > \frac{I_y}{2I_x} \quad (3.5)$$

Moment of inertia ratios can be as high as 10:1. Thus, relation (3.5) would be satisfied for spins in excess of five times resonance.

When condition (3.5) is satisfied, the magnitudes of k_4 and k_5 are given in terms of k_1 and k_2 by Equation (3.2) and are small for small $|\tilde{E}|$. For a trim of 12° and a maximum climb or descent angle of 45°, $|\tilde{E}|$ would be about 0.2. For these conditions, k_4 and k_5 could be neglected and the motion approximated by a tricycle. This is what was done in Reference 2 and Equation (2.7) yields the frequencies and damping rates of that report.

For spin rates lower than five times resonant spin, Equation (2.7) loses validity and should be used with caution. This was not done in Reference 2 and erroneous results were given for zero spin.

IV. SOLUTION FOR ZERO SPIN

For P = 0, Equation (2.5) requires that

$$(F_j - b\ M)F_j = 0 \quad (4.1)$$

where

$$b = (\hat{\alpha}_e \tan \theta_e)/\gamma_e$$

If $\hat{\alpha}_e$ is not zero, Equation (4.1) has two distinct roots:

$$F_j = 0,\ b\ M \quad (4.2)$$

The four roots of these two quadratic equations are the Ψ_1, $\bar{\Psi}_1$, Ψ_2, $\bar{\Psi}_2$ of Equation (2.4). If we identify Ψ_1 and $\bar{\Psi}_1$ as the roots of the first of these quadratic equations and Ψ_2 and $\bar{\Psi}_2$ as roots of the second, then

$$F_1 = 0,\ F_2 = b\ M \quad (4.3)$$

For these roots, Equation (2.5) reduces to

$$k_4 = - \bar{k}_1 \tag{4.4}$$

and

$$k_5 = - (\hat{\xi}_e/\bar{\hat{\xi}}_e)\bar{k}_2 \tag{4.5}$$

Hence the solution to Equation (2.3) for P = 0 and $\hat{\alpha}_e \neq 0$ is

$$\hat{\xi} = \hat{\xi}_e + K_1 \left(e^{i\phi_1} - e^{-i\phi_1}\right) + K_2 \left[e^{i\phi_2} - (\hat{\xi}_e/\bar{\hat{\xi}}_e)e^{-i\phi_2}\right] \tag{4.6}$$

where, from Equation (4.3)

$$K_j = K_{jo} \exp(-Hs/2)$$

and (ignoring a small H^2 term)

$$\phi_1' = [-M]^{\frac{1}{2}}$$

$$\phi_2' = - [-(1 + b)M]^{\frac{1}{2}}$$

For the special case $\hat{\alpha}_e = 0$ (which occurs when the fixed-plane transverse control moment has no horizontal component), Equation (4.1) has repeated roots: $F_1 = F_2 = 0$. Equation (2.4) is inadequate to handle this situation. Instead, we must assume a solution of the form

$$\hat{\xi} = \hat{\beta}_e + (k_1 + k_4 s)e^{\psi_1 s} + (k_2 + k_5 s)e^{\bar{\psi}_1 s} \tag{4.7}$$

Direct substitution in Equation (2.3) yields the relations:

$$k_4 = -\bar{k}_5 = -\left(\frac{M\,\hat{\beta}_e \tan\theta_e}{4\,\gamma_e\,\phi_1'}\right)(k_1 + \bar{k}_2) \qquad (4.8)$$

Hence, for $P = 0$ and $\hat{\alpha}_e = 0$, we have

$$\hat{\xi} = \hat{\beta}_e + K_1 e^{i\phi_1} + K_2 e^{i\phi_2} - \left(\frac{i\,M\,\hat{\beta}_e \tan\theta_e}{2\,\gamma_e\,\phi_1'}\right)(K_1 \sin\phi_1 - K_2 \sin\phi_2)s \qquad (4.9)$$

where

$$\phi_1' = -\phi_2' = [-M]^{1/2}$$

We see that in both zero-spin solutions, (4.6) and (4.9), $\hat{\xi}_e$ has no effect on the damping rates and $\hat{\beta}_e$ has no effect on the frequencies. A nonzero $\hat{\alpha}_e$ will effect just one of the frequencies; zero $\hat{\alpha}_e$ will cause secular terms to appear in the solution.

V. SUMMARY

1. The relations given in Reference 2 are valid for gyroscopically stable missiles for $1 < s_g \ll \infty$ and for statically stable missiles for which $\phi'/\phi'_{reson} > 5$.

2. For statically stable missiles with lower spin rates, the motion is quite complex and should be studied by numerical simulation.

REFERENCES

1. K.H. Lloyd and D.P. Brown, "Influence of Gravity and Applied Side Forces on the Stability of a Spinning Projectile," Weapons Research Establishment TR 1906(W), South Australia, November 1977, AD A053648. (See also "Instability of Spinning Projectiles During Terminal Guidance," *Journal of Guidance and Control* 2, January-February 1979, pp. 65-70.)

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LIST OF SYMBOLS

a	$[\gamma_e + \hat{\alpha}_e \tan \theta_e]^{-1}$
b	$\hat{\alpha}_e \tan \theta_e / \gamma_e$
C	$i \gamma k_t^{-2} (m V^2)^{-1} \times$ (fixed-plane system complex control moment)
C_D	$\dfrac{\text{drag force}}{(1/2)\rho S V^2}$
C_{L_α}	$\dfrac{\text{lift force}}{(1/2)\rho S V^2 \delta}$
$C_{M_{p\alpha}}$	$\dfrac{\text{Magnus moment}}{(1/2)\rho S \ell V^2 \phi' \delta}$
$C_{M_q} + C_{M_{\dot\alpha}}$	$\dfrac{\text{sum of the damping moments}}{(1/2)\rho S \ell^2 V (q^2 + r^2)^{1/2}}$
C_{M_α}	$\dfrac{\text{static moment}}{(1/2)\rho S \ell V^2 \delta}$
E	$(a/2) \hat{\xi}_e \tan \theta_e$
$\dot{E}$	$\dfrac{E}{1 + i E}$
F_j	$\Psi_j^2 + (H - i P)\Psi_j - M - i P T \qquad (j = 1, 2)$
H	$\dfrac{\rho S \ell}{2m} \left[\gamma C_{L_\alpha} - C_D - \dfrac{m\ell^2}{I_y} (C_{M_q} + \gamma C_{M_{\dot\alpha}}) \right]$
I_x, I_y	axial and transverse moments of inertia
K_j	$K_{j0} e^{\lambda_j s}$, the magnitude of the j-th modal arm $(j = 1, 2)$
K_{j0}	$\lvert k_j \rvert \; (j = 1, 2, 4, 5)$

k_j	$K_{j0}\, e^{i\phi_{j0}}$, the j-th modal arm at s = 0 (j = 1, 2, 4, 5)
ℓ	reference length
M	$\gamma \left(\frac{\rho S \ell^3}{2 I_y} \right) C_{M_\alpha}$
M_e	$(M + i\, P\, T)\tilde{E}$
P	$(I_x / I_y)\phi'$
p, q, r	missile spin, pitch and yaw rates in a missile-fixed system
R_j	$M/(2P\phi_j')$
S	reference area
s	nondimensional arc length along the trajectory
s_g	$P^2/4M$, the gyroscopic stability factor
T	$\gamma \frac{\rho S \ell}{2m} \left[C_{L_\alpha} + \frac{m\ell^2}{I_x} C_{M_{p\alpha}} \right]$
t	time
u, v, w	velocity components in a missile-fixed system
V	magnitude of the velocity
$\hat{\alpha}, \hat{\beta}$	angles of attack and side-slip in a fixed-plane system
$\hat{\alpha}_e, \hat{\beta}_e$	imaginary and real parts of $\hat{\xi}_e$

LIST OF SYMBOLS
(Continued)

γ_e	equilibrium value of (u/V)
δ	$\lvert\hat{\xi}\rvert$
θ_e	equilibrium value of the angle between the missile's axis and the horizontal
λ_j	$K_j'/K_j \qquad (j = 1, 2)$
$\hat{\xi}$	$\left(\frac{v + i\,w}{V}\right) e^{i(\phi - \phi_{FP})} \doteq \hat{\beta} + i\,\hat{\alpha}$
$\hat{\xi}_e$	-C/(M + i P T), the equilibrium value of $\hat{\xi}$
ρ	air density
ϕ_j	$\phi_{j0} + \phi_j' s \qquad (j = 1, 2)$
ϕ'	$p\ell/V$
ϕ_j'	turning rate of the j-th modal arm (j = 1, 2)
ϕ'_{reson}	resonance value of ϕ'
$\dot{\phi}_{FP}$	spin rate of the fixed-plane coordinate system
Ψ_j	$\lambda_j + i\,\phi_j' \qquad (j = 1, 2)$

<u>Superscripts</u>

$\dot{(\ )}$	d( )/dt
$(\ )'$	d( )/ds = $\dot{(\ )}\ell/V$
$\hat{(\ )}$	fixed-plane value of ( )
$\bar{(\ )}$	complex conjugate

LIST OF SYMBOLS
(Continued)

Subscript

$(\ )_e$	steady-state equilibrium value due to control moment

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