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A RELATIONSHIP BETWEEN LIQUID ROLL MOMENT AND LIQUID SIDE MOMENT

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
BALLISTIC RESEARCH LABORATORY
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Spinning projectiles carrying liquid payloads and performing large coning motion have uniformly been observed to experience rapid despin. For linear fluid mechanics, it has been shown that the ratio of the magnitudes of the liquid roll moment to the liquid side moment is the tangent of the coning angle. The validity of this relationship is demonstrated by gyroscope data obtained by M.C. Miller and flight data for twelve projectiles analyzed by R.L. Pope.

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I. INTRODUCTION

In the summer of 1974, a 155mm shell with a liquid payload was fired with a yawsonde telemetry unit and this projectile developed a large amplitude coning motion. When the coning motion exceeded forty degrees, the telemetry record showed a very rapid despin of forty percent in less than five seconds.[1] Since 1974, ten more observations of liquid-filled projectiles with large coning motions and large despin rates have been made.[2-4] In addition, thirty-six observations have been made of large coning motions and despin moments for projectiles with payloads of liquid-solid mixtures.[5] Indeed, all observed flights of projectiles with liquid or liquid-solid payloads that performed large coning motion also experienced large losses in spin.

This characteristic association of a large despin moment with a large coning motion for a projectile with a moving payload can become a diagnostic tool. Miller[6] suggested using this tool to determine the existence of small-amplitude unstable liquid-induced side moments. Spin measurements made during coning motion on a gyroscope predicted flight pitch instabilities caused by very viscous liquids, and these were observed in flight.[7]

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1. *D'Amico, W. P., Oskay, V., and Clay, W. H., "Flight Tests of the 155mm XM687 Binary Projectile and Associated Design Modification Prior to the Nicolet Winter Test 1974-1975," US Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-2748, May 1977. (AD B019969).*

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6. *Miller, M. C., "Flight Instabilities of Spinning Projectiles Having Nonrigid Payloads," Journal of Guidance, Control, and Dynamics, Vol. 5, March-April 1982, pp. 151-157.*

7. *D'Amico, W. P., and Miller, M. C., "Flight Instability Produced by a Rapidly Spinning, Highly Viscous Liquid," Journal of Spacecraft and Rockets, Vol. 16, January-February 1979, pp. 62-64.*

The linear liquid-induced side moment was first computed by Stewartson[8] for an inviscid liquid payload by use of eigenfrequencies determined by the fineness ratio of the cylindrical container. Wedemeyer[9] introduced boundary layers on the walls of the container and was able to determine viscous corrections for Stewartson's eigenfrequencies, which could then be used in Stewartson's side moment calculation. Murphy[10] then completed the linear boundary layer theory by including all pressure and wall shear contributions to the liquid-induced side moment.

The first theoretical work on liquid-induced roll moments was done by Vaughn[11] in 1978. Although fair agreement with Miller's data was obtained, the work was marred by some hard-to-justify algebraic steps. Recently Vaughn et al[12] developed an impressive numerical capability to compute roll moments for very high viscosity liquids and obtained excellent agreement with Miller's data. In Reference 5 the linearized Navier-Stokes equations were used to develop a relationship between the liquid side moment and the liquid roll moment. It is the purpose of this note to give the results of this analysis and illustrate its predictions with yawsonde data recently analyzed by Pope.[13]

II. LIQUID ROLL MOMENT

The pitching and yawing motion of a symmetric spinning projectile can be represented as the sum of two rotating exponentially growing two-dimensional vectors. In terms of complex variables, this relationship assumes the form

$$\hat{\xi} \equiv \hat{\beta} + i\,\hat{\alpha} = K_1 e^{i\phi_1} + K_2 e^{i\phi_2} \tag{2.1}$$

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8. *Stewartson, K., "On the Stability of a Spinning Top Containing Liquid," Journal of Fluid Mechanics, Vol. 5, Part 4, September 1959, pp. 577-592.*

9. *Wedemeyer, E. H., "Viscous Correction to Stewartson's Stability Criterion," US Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Report 1325, June 1966. (AD 489687).*

10. *Murphy, C. H., "Angular Motion of a Spinning Projectile with a Viscous Liquid Payload," US Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-03194, August 1982. (AD A118676). (See also Journal of Guidance, Control, and Dynamics, Vol. 6, July-August 1983, pp. 280-286.)*

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13. *Pope, R. L., "Further Analysis of Yawsonde Data from Some Liquid Payload Projectiles," US Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report 03329, December 1983. (AD A137256)*

where $\ln (K_j/K_{j0}) = \varepsilon_j \tau_j \dot{\phi} t$

$\phi_j = \phi_{j0} + \tau_j \dot{\phi} t$

$\dot{\phi}$ is the roll rate and is assumed to be positive.

Two coordinate systems will be used in this note: the nonrolling aeroballistic $\tilde{X}\tilde{Y}\tilde{Z}$ system whose $\tilde{X}$ -axis is fixed along the missile's axis of symmetry and the inertial XYZ system whose X-axis is tangent to the trajectory at time zero. Both coordinate systems have origins at the center of the cylindrical payload cavity, which is assumed to be at the center of mass of the projectile.

The transverse moment exerted by a liquid payload was expressed in Reference 10 in the following form.

$$M_{L\tilde{Y}} + i\, M_{L\tilde{Z}} = m_L\, a^2 \dot{\phi}^2 \left[\tau_1\, C_{LM_1}\, K_1 e^{i\phi_1} + \tau_2\, C_{LM_2}\, K_2 e^{i\phi_2} \right] \qquad (2.2)$$

where

m_L = mass of liquid in fully filled container

and

a = maximum radius of liquid container.

For linear fluid motion, C_{LM_1} should depend on τ_1, ε_1, time, Reynolds number, fill ratio, and shape of cavity. A similar remark applies to C_{LM_2}.

The C_{LM_j} are complex quantities whose imaginary parts represent in-plane moments causing rotation in the plane of exp $(i\phi_j)$ and whose real parts represent side moments causing rotation out of the plane of exp $(i\phi_j)$. Thus, C_{LM_j} can be written as

$$C_{LM_j} = C_{LSM_j} + i\, C_{LIM_j} \qquad (2.3)$$

where C_{LSM_j} are liquid side moment coefficients and C_{LIM_j} are liquid in-plane moment coefficients.

The liquid roll moment can now be defined in a similar way. Symmetry considerations imply an even dependence on coning amplitudes.

$$\therefore M_{L\tilde{X}} = m_L a^2 \dot{\phi}^2 [C_{LRM_0} + \tau_1 K_1^2 C_{LRM_1} + \tau_2 K_2^2 C_{LRM_2}] \tag{2.4}$$

where C_{LRM_j} are functions of Reynolds number, fill ratio, shape of cavity, and time. In addition, for j = 1 and 2, the C_{LRM_j} may be functions of τ_j, ε_j and K_j^2. C_{LRM_0} is the roll moment coefficient exerted by the liquid during spin-up and is zero when steady state is reached. For the steady-state coning motion considered in the Stewartson-Wedemeyer theory ($C_{LRM_0} = K_2 = 0$), only one roll moment coefficient is present and we will omit the subscript on τ_1 and C_{LRM_1}:

$$M_{L\tilde{X}} = m_L a^2 \dot{\phi}^2 \tau K_1^2 C_{LRM}. \tag{2.5}$$

Throughout this note, we will consider only roll moments that can be approximated by the one-term Eq. (2.5) rather than the more complete three-term Eq. (2.4). Similarly, the transverse liquid moment will be approximated by the first term of Eq. (2.2).

$$M_{L\tilde{Y}} + i M_{L\tilde{Z}} = m_L a^2 \dot{\phi}^2 \tau (C_{LSM} + i C_{LIM}) K_1 e^{i\phi_1} \tag{2.6}$$

Since $\dot{\phi}^2 \tau$ is $\dot{\phi}\dot{\phi}_1$, we are explicitly assigning equal weights to the spin rate and coning rate. As the moment is a response to the coning motion, the appearance of $\dot{\phi}_1$ is natural. The primary characteristic of the high Reynolds number Stewartson-Wedemeyer theory is the existence of a dominant inertia wave mode. This resonance mode is caused by an interaction of the <u>spinning</u> liquid with the coning motion and, thus, the spin rate is as important as the coning rate. At very low Reynolds numbers, these inertia waves are strongly damped and the influence of spin on the liquid moment should be much weaker. Indeed, Miller[8] found no dependence of the roll moment on spin for $\tau < .3$ and very low Reynolds numbers. If the roll moment is independent of spin, the liquid roll moment coefficient is proportional to τ ($C_{LRM} = \tau C_R$).

The frozen liquid value (Re = 0) of the liquid in-plane moment coefficient for constant amplitude coning motion is[10]

$$C_{LIM} = 1/2 - \tau [1/4 + c^2/3a^2] \tag{2.7}$$

Thus the in-plane moment must always be strongly dependent on spin. The side-moment coefficient, however, for $\tau < .3$ and low Reynolds number is probably proportional to τ ($C_{LSM} = \tau\ C_S$) and for these conditions both C_S and C_R may be more appropriate non-dimensional forms of these moments. (These new coefficients may, of course, be functions of τ.)

III. ROLL/SIDE MOMENT RELATION

In Reference 5, it is shown that

$$C_{LRM} = -C_{LSM} + (\tau\varepsilon/2)\ [1 - (4/3)\ (c/a)^2] \tag{3.1}$$

or

$$C_R = -C_S + (\varepsilon/2)\ [1 - (4/3)\ (c/a)^2] \tag{3.2}$$

These equations are valid for linear fluid mechanics and state that for the simple case of constant amplitude motion ($\varepsilon = 0$) the liquid roll moment is the negative of the liquid side moment. Since no boundary layer assumptions were used to obtain Eqs. (3.1-3.2), they should apply to the numerical results of Reference 12. If the complete nonlinear fluid equations are used, additional significant contributions to the quadratic liquid roll moment may be present. It is interesting to note that Eq. (3.1), for constant amplitude coning motion, is the linear condition for the liquid moment about the trajectory to be zero.

$$M_{LX} = M_{L\tilde{X}} \cos \alpha_t + M_{LSM} \sin \alpha_t \doteq M_{L\tilde{X}} + M_{LSM}\, K_1 = 0 \tag{3.3}$$

Thus the ratio of the magnitudes of the roll moment to the side moment is $\tan \alpha_t$.

Recently Pope[13] very carefully analyzed the yawsonde records of twelve unstable liquid-filled projectiles. All projectiles showed a growing coning motion and a rapid despin. Two of these missiles carried low viscosity liquids ($Re \sim 10^6$), four carried silicon oil ($Re \sim 40$), five carried corn syrup ($Re \sim 10$), and one had felt wedges impregnated with liquid white phosphorus.

Since the aerodynamic roll damping is easily measured, Pope was able to obtain liquid roll moment coefficients. He was unable to separate the aerodynamic and liquid side moments in the observed motion and, therefore, obtained "equivalent" side moment coefficients (C_{SMEQ}) containing both contributions. He was able to make estimates of the aerodynamic side moment coefficients (C_{SMA}). These three coefficients are given in Table 1 for the twelve yawsonde records. The rough agreement of C_{LRM} and C_{SMEQ} with Eq. (3.1) is very gratifying.

Finally, Miller's liquid roll moment data[6] for spinning cylinders coning at a constant cone angle of 20° are plotted in Figure 1 as open circles. C_{LSM}'s are computed by the linear boundary layer theory of Reference 10 and plotted as solid circles. The qualitative agreement for the boundary layer theory at such low Reynolds numbers is quite encouraging.

Table 1. Pope's Results

Yawsonde	Re	τ	C_{LRM}	C_{SMEQ}	C_{SMA}
404 [a]	2×10^6	0.090	-0.05	0.05	<0.01
1339	1.8×10^6	0.090	-0.02	0.04	-0.005
1866	45.2	0.123	-0.055	0.050	-0.004
1867	45.2	0.123	-0.055	0.050	-0.004
1868	45.2	0.123	-0.060	0.053	-0.004
1955	20	0.087	-0.04	0.04	-0.010
1293	10	0.090	-0.03	0.02	-0.008
1313	10	0.088	-0.02	0.025	-0.008
1585	10	0.091	-0.025	0.02	-0.008
1587	10	0.093	-0.04	0.02	-0.008
1588	10	0.095	-0.03	0.02	-0.008
1693 [b]		0.094	-0.025	0.025	-0.005

[a] Fill ratio for 404 was 87%, all others were 100%.

[b] This projectile contained white-phosphorus-impregnated felt wedges.[14]

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14. *D'Amico, W. P., "Aeroballistic Testing of the XM825 Projectile: Phase III, High Muzzle Velocity and High Quadrant Elevation," US Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, BRL Memorandum Report ARBRL-MR-03196, September 1982. (AD B068511)*

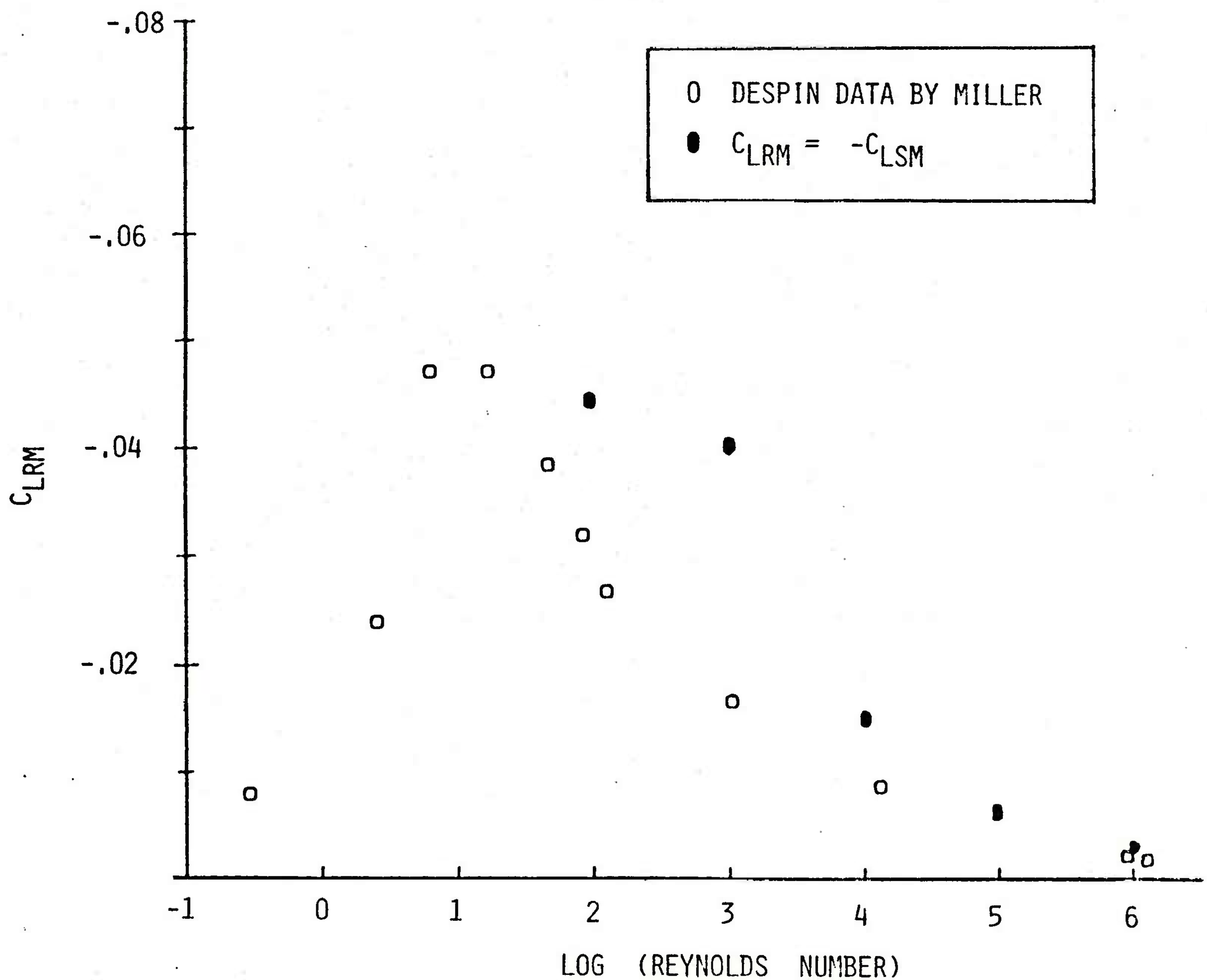

Figure 1. C_{LRM} From Gyroscope Tests (Ref. 6), c/a = 4.291.

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