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# Estimation of the Moment Coefficients for Dynamically Scaled, Free-Spinning Wind-Tunnel Models

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## Nomenclature

| | | |
|---|---|---|
| $b$ | = | wingspan, ft |
| $\bar{c}$ | = | mean aerodynamic chord, ft |
| $I_x$, $I_y$, $I_z$ | = | model moments of inertia about the $X$-, $Y$-, or $Z$-body axis, respectively, slug-ft$^2$ |
| $I_{xz}$, $I_{yx}$, $I_{yz}$ | = | model products of inertia, slug-ft$^2$ |
| $l$ | = | total aerodynamic rolling moment about c.g., coefficient $C_l = l/\hat{q}Sb$ |
| $m$ | = | total aerodynamic pitching moment about c.g., coefficient $C_m = m/\hat{q}S\bar{c}$ |
| $n$ | = | total aerodynamic yawing moment about c.g., coefficient $C_n = n/\hat{q}Sb$ |
| $p$ | = | angular rate about $X$-body axis, rad/s |
| $q$ | = | angular rate about $Y$-body axis, rad/s |
| $\hat{q}$ | = | freestream dynamic pressure, $\frac{1}{2}\rho V^2$, lb/ft$^2$ |
| $R$ | = | spin radius: distance from model c.g. to spin axis, ft |
| $r$ | = | angular rate about $Z$-body axis, rad/s |
| $S$ | = | wing area, ft$^2$ |
| $V$ | = | vertical wind-tunnel freestream velocity, ft/s |
| $\alpha'$ | = | angle between $X$-body axis and vertical in vertical wind tunnel, deg or rad |
| $\rho$ | = | air density, slugs/ft$^3$ |
| $\psi$, $\theta$, $\phi$ | = | Euler angles: azimuth, pitch, and roll angles, respectively, deg or rad |
| $\Omega$ | = | spin rate, i.e., angular velocity about vertical axis, deg/s or rad/s |

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## Introduction

AERODYNAMIC forces and moments on a model undergoing steady rotation at a constant attitude can currently be measured using the rotary balance technique.[1,2] These data are used to predict potential steady spin modes and for building up data bases for the spin portion of flight simulations. However, rotary balance data alone cannot be used to predict oscillatory spins since the measured forces and moments are constant for a given set of conditions. In contrast, dynamically scaled free-spinning models can predict the oscillatory nature of an airplane's spin.[1]

Free-spin tests of dynamically (Froude) scaled models have been performed in the NASA Langley 20-ft Vertical Spin Tunnel since 1941.[1] In all of these tests, model attitude and angular rate data were obtained from high-speed motion picture film or video tape records, read frame-by-frame, to quantify spin modes. Historically, this method has been used successfully to predict full-scale results. However, 6-degree-of-freedom time histories of model motions have recently become available via a computerized, optically-based data acquisition system known as the Spin Tunnel Model Space Positioning System (MSPS).[3] Using the equations of motion coupled with these time histories, a simple procedure for estimating the moment coefficients about all three body axes during a spin that may or may not be oscillatory is developed. The method used in this Note is similar to that proposed by Neihouse et al.[1] for determining the moments of a spinning airplane from flight-test data.

## Estimation of Moment Coefficients

For a true equilibrium spin mode to exist (i.e., a "steady" spin in which the angular accelerations are equal to zero), the external (aerodynamic) moments and inertial moments about all three axes must balance simultaneously. In many cases, assuming that a spin is steady is reasonable since the angular accelerations are small and can be ignored. In reality, however, no spin is perfectly steady and, in fact, some may be quite oscillatory. Free-spin tests with dynamically scaled models provide a unique opportunity to determine the moments produced during an oscillatory spin.

In terms of the equations of motion for a rigid body (assuming a body axis system is used in which $I_{yx} = I_{yz} = 0$), the moment balance, including angular accelerations, can be written as

$$l = I_x\dot{p} - I_{xz}\dot{r} + (I_z - I_y)rq - I_{xz}pq \tag{1}$$

$$m = I_y\dot{q} - (I_z - I_x)pr + I_{xz}(p^2 - r^2) \tag{2}$$

$$n = I_z\dot{r} - I_{xz}\dot{p} + (I_y - I_x)pq + I_{xz}rq \tag{3}$$

where a superscript dot over a variable represents differentiation with respect to time. Assuming with $\psi = R = 0$ and rewriting the body-axis angular rates in terms of the Euler angles and the spin rate yields

$$p = -\Omega \sin\theta \tag{4}$$

$$q = \Omega \cos\theta \sin\phi \tag{5}$$

$$r = \Omega \cos\theta \cos\phi \tag{6}$$

Differentiating Eqs. (4–6) with respect to time, substituting into Eqs. (1–3), and nondimensionalizing the moments results in

$$C_l = \frac{1}{\hat{q}Sb}\Bigg([I_x(-\Omega\cos\theta\dot{\theta} - \dot{\Omega}\sin\theta)] + \Bigg\{I_{xz}\Bigg[\Omega\cos\theta\sin\phi\dot{\phi} - \cos\phi(\dot{\Omega}\cos\theta - \Omega\sin\theta\dot{\theta}) + \frac{\Omega^2}{2}\sin\phi\sin 2\theta\Bigg]\Bigg\} + \Bigg[(I_z - I_y)\frac{\Omega^2}{2}\sin^2\theta\sin 2\phi\Bigg]\Bigg) \tag{7}$$

$$C_m = \frac{1}{\hat{q}S\bar{c}}\Bigg(\{I_y[\Omega\cos\theta\cos\phi\dot{\phi} + \sin\phi(\dot{\Omega}\cos\theta - \Omega\sin\theta\dot{\theta})]\} - \Bigg[(I_z - I_x)\frac{\Omega^2}{2}\cos\phi\sin 2\theta\Bigg] + [I_{xz}\Omega^2(\sin^2\theta - \cos^2\theta\cos^2\phi)]\Bigg) \tag{8}$$

$$C_n = \frac{1}{\hat{q}Sb}\Bigg(\{I_z[-\Omega\cos\theta\sin\phi\dot{\phi} + \cos\phi(\dot{\Omega}\cos\theta - \Omega\sin\theta\dot{\theta})]\} - \Bigg[(I_y - I_x)\frac{\Omega^2}{2}\sin\phi\sin 2\theta\Bigg] + \Bigg[I_{xz}\Bigg(\Omega\cos\theta\dot{\theta} + \dot{\Omega}\sin\theta + \frac{\Omega^2}{2}\cos^2\theta\sin 2\phi\Bigg)\Bigg]\Bigg) \tag{9}$$

Equations (7–9) allow the aerodynamic moment coefficients produced during a spin to be calculated if the inertial and geometric parameters are known and a time history of a model's attitude is available. Evaluation of the moment coefficients is accomplished by measuring a model's $I_x$, $I_y$, and $I_z$, calculating $I_{xz}$ (given the principal axes), converting full-scale values of $S$ and $b$ to model scale, measuring $\hat{q}$ during the test, and using MSPS to obtain $\psi$, $\theta$, and $\phi$. The quantities $\Omega$, $\dot{\Omega}$, $\dot{\theta}$, and $\dot{\phi}$ are obtained by numerically differentiating the motion time histories.

## Results

A dynamically scaled model of a typical, modern high-performance fighter was used to obtain data for this test. In Fig. 1, time histories of the predicted (i.e., full-scale) nominal angle of attack $\alpha' = \theta + \pi/2$, $\phi$, and $\Omega$ during a "flat" (high angle-of-attack) spin are shown. The time (abscissa) in both figures and $\Omega$ in Fig. 1 were converted to full scale using the model's geometric scale factor of 1/30 (time is scaled by the square root of the scale factor). Angles such as $\alpha'$ and $\phi$ correspond directly from model to full scale. The end of each complete turn during the spin is marked on the upper horizontal axis of Fig. 1. Note the oscillations in the angle of attack and roll angle and that the spin rate was not constant. A spin with $\alpha'$ and $\phi$ variations of this magnitude ($\approx \pm 5$ deg) would be categorized as "mildly" oscillatory. While the values of $\alpha'$ and $\phi$ in Fig. 1 are the actual raw numbers from MSPS, the $\Omega$ curve is a locally weighted least-squares curve fit through the raw spin rate data. In this way, "noise" in the data introduced by sampling over small time steps and then differentiating is minimized. Resolution of the spin rate is not compromised by curve fitting since $\Omega$ is typically a relatively slowly varying quantity. The other quantities obtained by differentiation ($\dot{\Omega}$, $\dot{\theta}$, $\dot{\phi}$) were also treated in this manner to reduce noise.

The calculated moment coefficients are presented in Fig. 2. Aerodynamic moments measured using a similar model on a rotary balance are used as a basis for comparison. These plotted coefficient values, obtained by linearly interpolating the rotary balance data between $\alpha' = 80$ and 90 deg, correspond to the average $\alpha'$ and nondimensional spin rate $\Omega b/2V$ recorded during the free-spin test. Although there is good agreement between the average values of the free-spin-derived coefficients and the rotary balance results, it can be seen that there were oscillations in the moments produced

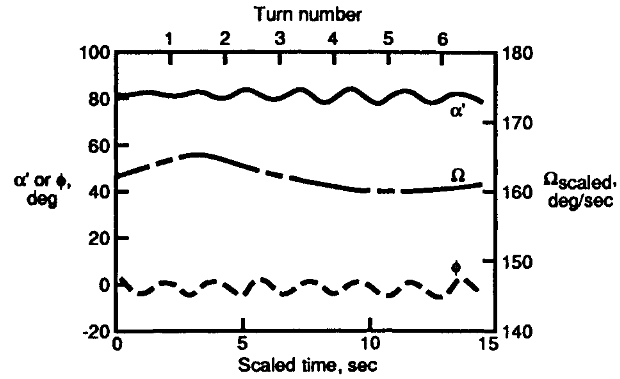


**Fig. 1 Full-scale nominal angle of attack, roll angle, and spin rate obtained using MSPS and a 1/30-scale model of a typical fighter configuration in an oscillatory, flat spin.**

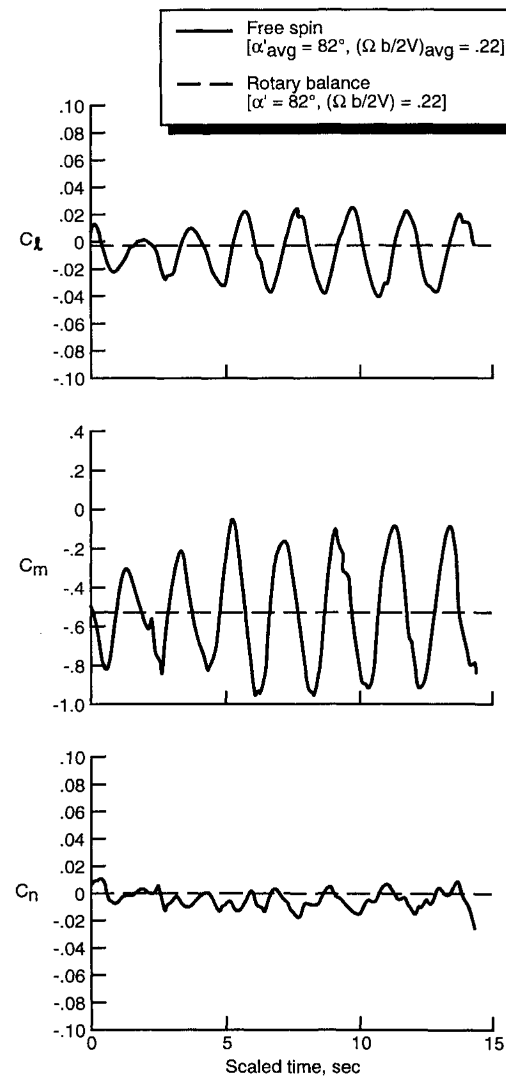


**Fig. 2 Comparison of predicted moment coefficient values for a typical fighter configuration in a flat spin.**

during the spin. The rolling-moment and yawing-moment coefficient variations were relatively small, and thus, the steady-spin assumption is reasonable for these quantities. In contrast is the large amplitude of the pitching moment coefficient trace. The maximum and minimum values of the free-spin results are approximately equal to the rotary balance coefficient ±90%. Clearly, the steady-state results do not capture the true nature of the moment coefficient in this case. This trend would obviously be more exaggerated if the spin became more oscillatory.

## Conclusions

Estimates of aerodynamic moment coefficients for a dynamically scaled, free-spinning wind-tunnel model have been shown to be easily obtained using the equations of motion and a time history of a model's attitude during a flat spin. Experimentally derived moment coefficients from free-spin tests have not been previously available. Their availability will be especially helpful for cases in which the spin is oscillatory. The method will be useful for comparison to flight test and simulation results, as well as a diagnostic tool, e.g., for examining the impact of configuration changes on an airplane's spin aerodynamics.

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# Validation of a Multipoint Approach for Modeling Spin Aerodynamics

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## Nomenclature

$a'_k$ = force parameters to be estimated
$b_j$ = length of $j$th aircraft component
$d'_k$ = moment parameters to be estimated
$F_{ij}$ = $i$th force component on $j$th aircraft component
$M_{ij}$ = $i$th moment component on $j$th aircraft component
$P$ = body axis roll rate
$\bar{q}_j$ = local dynamic pressure
$S_j$ = area of $j$th aircraft component
$V$ = aircraft speed
$\alpha_j$ = locally defined angle of attack
$\beta_j$ = locally defined sideslip angle
$\eta$ = spanwise distance parameter

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## Introduction

A NEW aerodynamic model for the analysis of spin flight-test data has been developed and reported.[1,2] The model results from a unique reformulation of an established aerodynamic theory and leads directly to a natural set of aerodynamic state variables. Unlike conventional estimation models that define the aerodynamic state only at the c.m. (single-point), the multipoint approach defines this state at several points on the aircraft. The preliminary results reported herein indicate a strong correlation between the new set of variables and the aerodynamic forces and moments during spins. More generally, these results indicate that the multipoint approach is a valid and viable approach for aerodynamic modeling in difficult flight regimes.

## Aerodynamic Functions

As shown in Refs. 1 and 2, Eqs. (1) and (2) express the $i$th force and moment component respectively produced by the $j$th aircraft component (i.e., right wing, left wing, fuselage, etc.). The aircraft's $i$th force or moment component is the sum over the $j$ parts:

$$F_{ij}/S_j = a'_1\bar{q}_j + \tfrac{1}{2}[a'_2\delta\bar{q}_j + \bar{q}(a'_3\delta\alpha_j + a'_4\delta\beta_j)] + \tfrac{1}{3}[a'_5\delta^2\bar{q}_j + \delta\bar{q}_j(a'_6\delta\alpha_j + a'_7\delta\beta_j) + \bar{q}_j(a'_8\delta^2\alpha_j + a'_9\delta^2\beta_j + a'_{10}\delta\alpha_j\delta\beta_j + a'_{11}\delta\alpha_j^2 + a'_{12}\delta\beta_j^2)] + \cdots \tag{1}$$

$$M_{ij}/S_jb_j = \tfrac{1}{2}d'_1\bar{q}_j + \tfrac{1}{3}[d'_2\delta\bar{q}_j + \bar{q}_j(d'_3\delta\alpha_j + d'_4\delta\beta_j)] + \tfrac{1}{4}[d'_5\delta^2\bar{q}_j + \delta\bar{q}_j(d'_6\delta\alpha_j + d'_7\delta\beta_j) + \bar{q}_j(d'_8\delta^2\alpha_j + d'_9\delta^2\beta_j + d'_{10}\delta\alpha_j\delta\beta_j + d'_{11}\delta\alpha_j^2 + d'_{12}\delta\beta_j^2)] + \cdots \tag{2}$$

In the previous equations, the variables are determined from functions that describe the spanwise variation of a set of locally defined basic aerodynamic variables. Spanwise derivatives, which comprise the majority of the new variables, are multiplied by an appropriate length parameter as shown in Eqs. (3):

$$\delta\bar{q}_j \equiv b_j\frac{\mathrm{d}\bar{q}}{\mathrm{d}\eta_j}, \qquad \delta^2\bar{q}_j \equiv \frac{b_j^2}{2}\frac{\mathrm{d}^2\bar{q}}{\mathrm{d}\eta_j^2}$$

$$\delta\alpha_j \equiv b_j\frac{\mathrm{d}\alpha}{\mathrm{d}\eta_j}, \qquad \delta^2\alpha_j \equiv \frac{b^2}{2}\frac{\mathrm{d}^2\alpha}{\mathrm{d}\eta_j^2}, \qquad \delta\alpha_j^2 \equiv \frac{b_j^2}{2}\left(\frac{\mathrm{d}\alpha}{\mathrm{d}\eta}\right)_j^2 \tag{3}$$

$$\delta\beta_j \equiv b_j\frac{\mathrm{d}\beta}{\mathrm{d}\eta_j}, \qquad \delta^2\beta_j \equiv \frac{b^2}{2}\frac{\mathrm{d}^2\beta}{\mathrm{d}\eta_j^2}, \qquad \delta\beta_j^2 \equiv \frac{b_j^2}{2}\left(\frac{\mathrm{d}\beta}{\mathrm{d}\eta}\right)_j^2$$

## Comparison Between Key Model Variables

Figure 1 compares the time history of $P/V$ with the angle-of-attack gradient calculated at the midpoint of the right wing during a spin. The comparison is worthwhile because the nondimensional roll rate $Pb/2V$ is an important variable in conventional models, and $P/V$ closely approximates the gradient of angle of attack in normal flight regimes. The plot shows the correlation between the variables steadily diminishing as the spin progresses. Eventually, the correlation is lost because the gradient of angle of attack depends on the general state of translation and rotation, not on the roll rate alone.