Spin Prediction Techniques

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A rotary balance facility located in the Langley spin tunnel was developed to rapidly identify an airplane's aerodynamic characteristics in a rotational flow environment. The generation of on-line rotary balance data plots and predicted steady spin modes concurrent with data acquisition permit the designer to develop, on site, a configuration highly resistant to spins, or one exhibiting desirable spin characteristics if it is to be used for aerobatics or training. The rotary balance data are also used to compute time histories of a spin's incipient, developed, and recovery phases. These spin analysis techniques, i.e., evaluation of rotary balance data, predicted steady spin equilibrium, and large angle, six-degree-of-freedom time history calculations, are presented and discussed.

Nomenclature

b	= wing span
$\bar{c}$	= mean aerodynamic chord
g	= acceleration of gravity
m	= mass
p	= body-axes roll rate
q	= body-axes pitch rate
r	= body-axes yaw rate
C_D	= drag coefficient
C_L	= lift coefficient
C_l	= rolling-moment coefficient
C_m	= pitching-moment coefficient
C_n	= yawing-moment coefficient
I_X, I_Y, I_Z	= moments of inertia about the X, Y, and Z body axis, respectively
R_s	= spin radius measured from spin axis to airplane center of gravity
S_w	= wing area
V	= freestream velocity
α	= angle of attack
β	= angle of sideslip
ρ	= air density
σ	= inclination of the flight path to vertical, $\tan^{-1} R_s\Omega/V$
Ω	= angular velocity about spin axis
$\Omega b/2V$	= spin coefficient, positive for clockwise spin

Introduction

THE NASA Langley Research Center has responsibility for advancing the state-of-the-art in stall/spin technology. This includes development and validation of experimental and analytical techniques for the prediction of stall/spin characteristics. As a part of this effort, a rotary balance facility was developed to rapidly identify an airplane's aerodynamic characteristics in a rotational flow environment.[1] The influence of spin radius, angle of attack, sideslip angle, rate of rotation, and control settings on the aerodynamics can be measured with this apparatus. Using these data, on-line steady spin modes may be analytically predicted by solving the moment equations for steady equilibrium conditions. The rotary balance data may subsequently be used to compute post-stall motions such as the incipient, developed, and recovery phases of a spin by employing an appropriate, large angle, six-degree-of-freedom computer program. These procedures are discussed herein.

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Historical Background

1915-1945

The need for steady-state rotational flow aerodynamics for spin analysis had been recognized since aviation's early days. For example, Glauert[2] attempted in 1919 to calculate these data theoretically using strip theory. By the early 1920s, a rolling balance was used to obtain some of these data experimentally. Gates and Bryant[3] remarked in 1926, however, that this simple rolling balance must be replaced with an apparatus that actually reproduces, in a tunnel, the conditions of a fast spin. NACA investigators also reasoned that subjecting all components of an airplane to a constant velocity vector during static force tests was unsatisfactory for simulating flow conditions in a spin. This belief was supported by Irving and Batson,[4] who noted, in 1928, that the use of static force test data conduced to erroneous conclusions when applied to the spin.

Consequently, in 1933, Allwork[5] as well as Bamber and Zimmerman[6] reported on rotary balances installed in the British NPL 7-ft wind tunnel and the NACA 5-ft vertical wind tunnel, respectively. The NACA apparatus was capable of measuring the six components of aerodynamic forces and moments as a function of angle of attack, sideslip angle, and rotation rate. A significant number of wing and airplane configurations were tested with this apparatus and documented in NACA publications cited in Ref. 7.

Several years later, Bamber, House, and Zimmerman[8,9] presented a method for solving the three moment equations for steady-state equilibrium spin conditions using rotary balance data. This analytical technique was born of necessity. Solving simultaneously the six equations of motion and other associated mathematical expressions before the advent of analog and high-speed digital computers was a formidable task requiring step-by-step integration procedures laboriously performed by hand.

Clearly, the need for rotational flow aerodynamic data was not only acknowledged at an early date, but the technique for its measurement and its application to spin analysis had been demonstrated prior to 1937.

1945-1975

The effectiveness of the first NACA rotary balance was limited by the relative sizes of the model and tunnel. Also, the six-component balance was mounted external to the model, was large relative to the model, and was of dubious accuracy.

These shortcomings were eliminated with a new rotary balance installed in the Langley spin tunnel in 1945. Because of the limited instrumentation then available, an inordinate amount of time and effort was needed to obtain a very small amount of data, which in many instances was not repeatable. Understandably, the rotary balance again fell into disuse after obtaining data for one airplane configuration, which were applied during subsequent analytical studies.[7,10,11]

By the mid 1950s, the mass of fighters had become heavily concentrated in the fuselage, which led to a concern for the vertical tail loads resulting from inertial coupling during uncoordinated rolling pull-out maneuvers. Fortunately, analog computers were in wide use by this time and many engineers became familiar with large angle, six-degree-of-freedom calculations. Eventually, these "inertial coupling" studies were extended beyond stall to include spins by simply extending the conventional aerodynamic model, consisting of static data and dynamic derivatives, to higher α values. The need for rotary balance data was virtually overlooked by the aerospace industry in this country from the mid-1950s to mid-1970s.

Although NASA updated the rotary balance in the late 1950s, it was used for only one analytical study[12] during this 20-yr period. This study properly employed rotary balance data and, therefore, significantly contributed to the methods available for spin analysis. Nevertheless, the practice of using static data and dynamic derivatives to calculate spinning motions continued because matching some portion of a full-scale, high α time history could be demonstrated. These demonstrations, however, always required arbitrary adjustments in the magnitude of some dynamic derivatives.

Consequently, NASA installed a rotary balance apparatus in the Langley full-scale tunnel[13] and supported large angle, six-degree-of-freedom computer studies in the early 1970s to establish rigorously the aerodynamic models required for spin calculations. For example, several studies[14,15] simulated the motions of a fighter airplane, using both a conventional aerodynamic model and one which included the effect of spin rotation rate. The computed time histories were compared with those obtained with an unpowered, radio controlled, dynamically scaled model. It was shown that the developed spin was duplicated using rotational flow data, whereas this was not the case when the conventional model was used. It was indicated, therefore, that the aerodynamic moments generated in the spin due to rotational flow, as measured by a rotary balance, are indeed significant. It was also shown that the contribution of the dynamic derivatives, obtained from forced oscillation tests, to the computed motion must be limited to the oscillatory component of the total angular body rates, p, q, and r. This, of course, could not be done when the aerodynamic model did not include steady rotational flow data. Clearly, modeling only static data and dynamic derivatives during spin calculations was a pseudotechnique.

1975-Present

In the mid-1970s, NASA modernized the spin tunnel rotary balance by incorporating the latest state-of-the-art instrumentation and computer technology. Valid data were now obtained rapidly and economically. Installation of new rotary balances in France[16] and Italy[17] were also reported during this period. Langley tests demonstrated[1,13] the pronounced nonlinear dependency of the aerodynamic moments on rotational rate at a constant α, and once again illustrated the futility of computing spin equilibrium conditions or time histories without rotary balance data. Consequently, 20 configurations representative of general aviation, fighters, and trainers have been tested in the spin tunnel facility during the past five years.

Data Analysis

The rapid and economical acquisition of rotary balance data permits the development of specific configurations tailored to achieve desired characteristics. Configurations highly resistant to spins or exhibiting desirable spin characteristics, if they are to be used for aerobatics or training, can be specified. This is accomplished in the following manner: First, component buildup tests are conducted and the data examined to determine the contribution of the body, wing, horizontal tail, etc. to the moment characteristics. Then the rotational flow aerodynamics are obtained for the complete configuration with various control settings. Again, examining these data, in most instances, indicates α regions in which the configuration is spin susceptible. As mentioned previously, steady developed spins can be predicted concurrently with wind tunnel tests, using a steady-state analysis technique. Consequently, if steady spin modes are predicted, sufficient insight into the causes will have been established to permit the selection of judicious configuration or control modifications. The effectiveness of these modifications in meeting the desired design objectives is then verified with additional rotary balance tests.

Steady-State Spin Analysis

Predicting steady spin modes is not only required during the configuration definition phase, as indicated above, but also appreciably reduces subsequent spin model testing time. The on-line rotary balance spin prediction capability identifies all possible steady spin modes for specified airplane inertias, center-of-gravity location, control settings, and altitude. The calculated spin modes' sensitivity to these variables can, of course, also be determined.

Method

Analyses[3] as early as the mid-1920s indicate an understanding of the basic equations of motion as applied to the spin. Figure 1 illustrates the airplane's orientation and the forces acting upon it in a spin. A steady spin implies that all accelerations are zero along and about the body axes. For practical purposes, therefore, the force equations reduce to the relationships that side force is zero, drag equals weight, and lift is balanced by centrifugal force:

$$mg = \tfrac{1}{2}\rho V^2 S_w C_D \quad (1)$$

$$mR_s\Omega^2 = \tfrac{1}{2}\rho V^2 S_w C_L \quad (2)$$

The three body axes moment equations reduce to

$$\tfrac{1}{2}\rho V^2 S_w b C_l = (I_Z - I_Y) qr \quad (3)$$

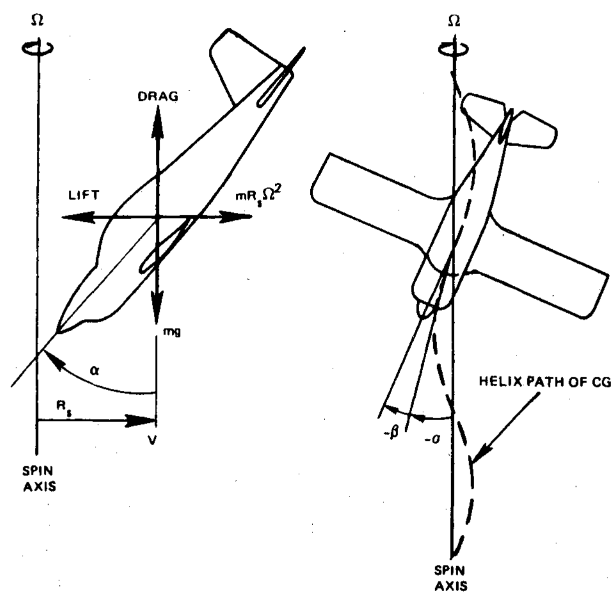

Fig. 1 Illustration of an airplane in a steady spin.

$$\tfrac{1}{2}\rho V^2 S_w \bar{c} C_m = (I_X - I_Z) rp \tag{4}$$

$$\tfrac{1}{2}\rho V^2 S_w b C_n = (I_Y - I_X) pq \tag{5}$$

The angular rates, p, q, and r, are clearly a function of the spin rate, Ω. Various authors[6,18-22] have defined this relationship in different, though generally equivalent, terms depending upon their definition of the airplane's orientation and the order of the axes rotations.

Bamber, Zimmerman, and House[8,9] used a notation that is convenient because the axes rotations are defined in terms of α and β. First, the airplane is considered to be yawed through an angle, $\simeq -(\beta+\sigma)$, where σ is the inclination of the flight path from the vertical, defined as

$$\sigma = \tan^{-1} R_s \Omega / V \tag{6}$$

The airplane is then pitched from the vertical by the angle α. This yields the following for the body axis angular rates:

$$p = \Omega \cos\alpha \cos(\beta+\sigma) \tag{7}$$

$$q = \Omega \sin(\beta+\sigma) \tag{8}$$

$$r = \Omega \sin\alpha \cos(\beta+\sigma) \tag{9}$$

Substituting Eqs. (7-9) into Eqs. (3-5) and solving for the aerodynamic coefficients:

$$C_m = (4/\rho S_w \bar{c} b^2)(\Omega b/2V)^2 (I_X - I_Z) \sin 2\alpha \cos^2(\sigma+\beta) \tag{10}$$

$$C_l = (4/\rho S_w b^3)(\Omega b/2V)^2 (I_Z - I_Y) \sin\alpha \sin 2(\sigma+\beta) \tag{11}$$

$$C_n = (4/\rho S_w b^3)(\Omega b/2V)^2 (I_Y - I_X) \cos\alpha \sin 2(\sigma+\beta) \tag{12}$$

These equations present the necessary requirements for equilibrium of the aerodynamic and inertial terms and must be simultaneously satisfied for a steady spin. Solving Eq. (2) for R_s and substituting in Eq. (6), σ is redefined in terms of $\Omega b/2V$:

$$\sigma = \tan^{-1} \frac{\rho S_w b C_L}{4m(\Omega b/2V)} \tag{13}$$

Consequently, the inertial terms [right-hand side of Eqs. (10-12)] are functions of $\Omega b/2V$, β, and α, as are the aerodynamic coefficients (left-hand side of equations). Thus there are three equations to solve for three unknowns: $\Omega b/2V$, β, and α values required for spin equilibrium.

A spin prediction program was generated, for the NASA spin tunnel rotary balance facility, based on a 45-yr-old method of analysis.[8,9] This method sequentially utilizes the pitching-, rolling-, and yawing-moment equations [Eqs. (10-12), respectively] to determine the $\Omega b/2V$, β, and α spin equilibrium values, respectively, in the following manner.

First, the pitching-moment Eq. (10) is satisfied by locating the $\Omega b/2V$ values that result in equal inertial and aerodynamic moments for each tested α and β. This is demonstrated graphically in Fig. 2 for zero sideslip angle, where both the aerodynamic pitching-moment coefficient and the inertial term are plotted as functions of $\Omega b/2V$ for constant angles of attack. The locus of intersections of the aerodynamic and inertial curves forms the relationship shown in Fig. 3 between α and $\Omega b/2V$ for zero β. The computer program repeats this calculation for each sideslip angle tested, yielding a corresponding $\Omega b/2V$ vs α relationship. It is interesting to note that this relationship is only slightly affected by sideslip, since the aerodynamic pitching-moment coefficient is not a strong function of β for most airplanes, nor is the inertial term for any airplane. Consequently, the $\Omega b/2V$ relationship presented in Fig. 3 for $\beta = 0$ deg is shown to be very closely approximated for $\beta = \pm 10$ deg values. The pitching-moment

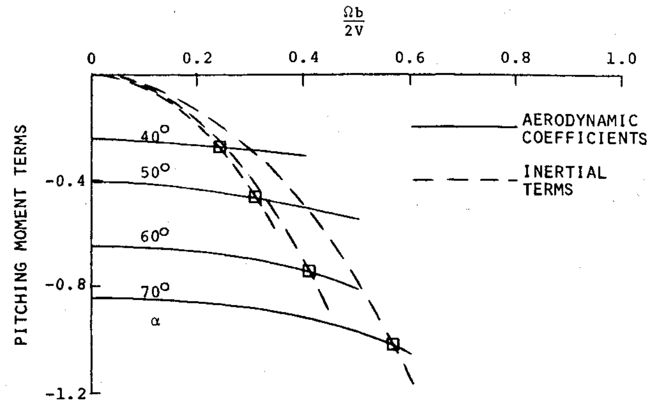

Fig. 2 Pitching-moment coefficients and inertial pitch terms vs $\Omega b/2V$ for selected α's and zero β.

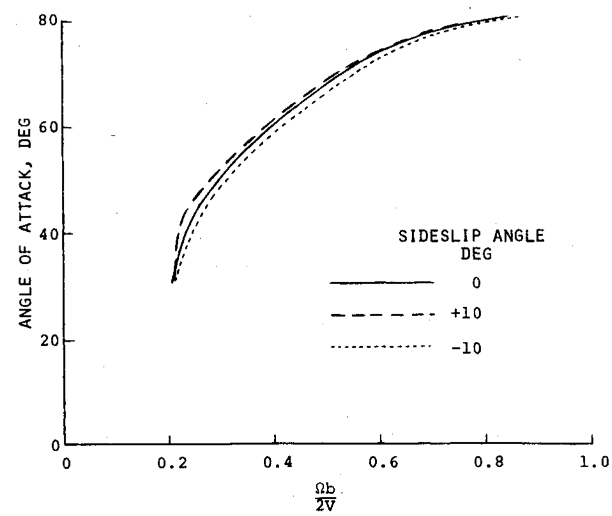

Fig. 3 Locus of α vs $\Omega b/2V$ resulting in pitch equilibrium for constant β values.

Eq. (10) is, however, a strong function of $\Omega b/2V$ and α and, therefore, is used to calculate the $\Omega b/2V$ relationship.

The roll equation, on the other hand, is used to determine equilibrium β's because the aerodynamic rolling moment does have a strong functional dependency on β for most airplanes at high α's. Consequently, the inertial value, right-hand side, of the rolling-moment Eq. (11) is calculated for the $\Omega b/2V$ relationship values found to satisfy the pitch equation at each of the tested β values. The aerodynamic rolling-moment coefficient is, of course, extracted from the rotary balance data at these same $\Omega b/2V$, β, and α values. From these data, the sideslip angles required to satisfy the rolling-moment equilibrium Eq. (11) are determined as a function of angle of attack. This procedure is demonstrated graphically in Fig. 4, which presents the aerodynamic rolling-moment coefficients and the inertial terms plotted as functions of sideslip angle for several angles of attack. Their intersections yield the required β's for equilibrium of the roll equation at each α. The resulting locus of equilibrium sideslip angles as a function of angle of attack is plotted in Fig. 5. The equilibrium rotation rate, previously determined as a function of α and β (Fig. 3), can now be reduced to a function of α alone, as shown in Fig. 6, by evaluating the $\Omega b/2V$ relationship in Fig. 3 at the β values satisfying the rolling-moment equation. At this point, the $\Omega b/2V$ (Fig. 6) and β (Fig. 5) values that are required to satisfy both the pitch and roll equation at each tested α have been determined. It remains only to use these values in the yawing-moment Eq. (12) to find any angles of attack for which the inertial and aerodynamic terms are equal.

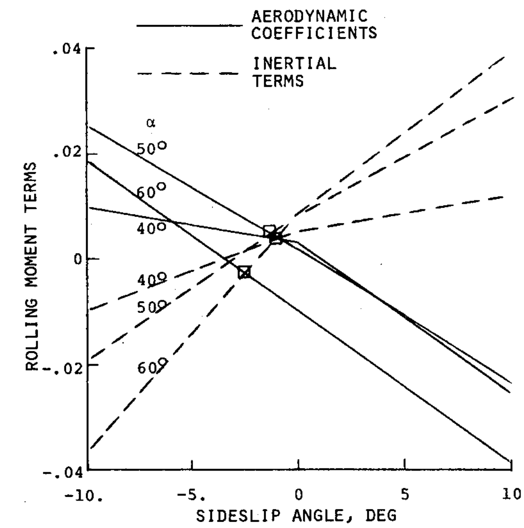

Fig. 4 Rolling-moment coefficients and inertial roll terms vs β for selected α's.

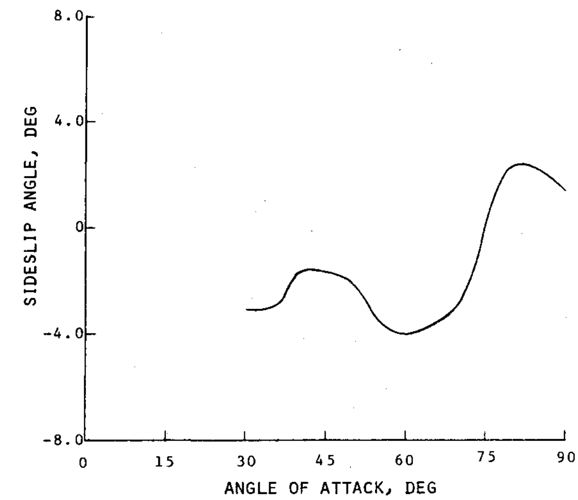

Fig. 5 Sideslip angles required for pitch and roll equilibrium vs α.

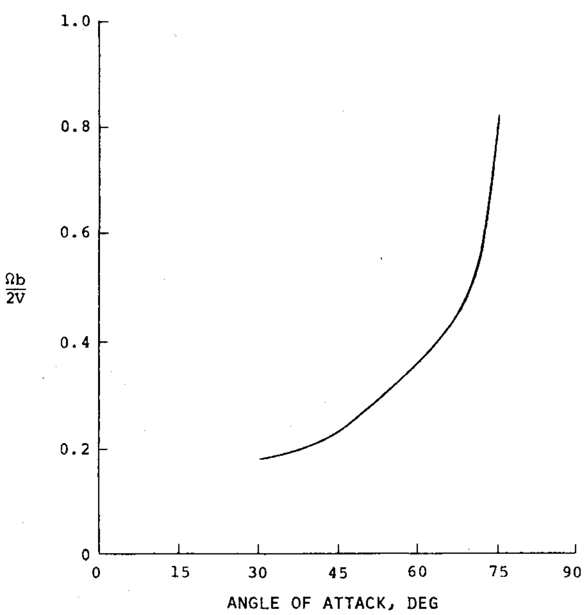

Fig. 6 $\Omega b/2V$ values required for pitch and roll equilibrium vs α.

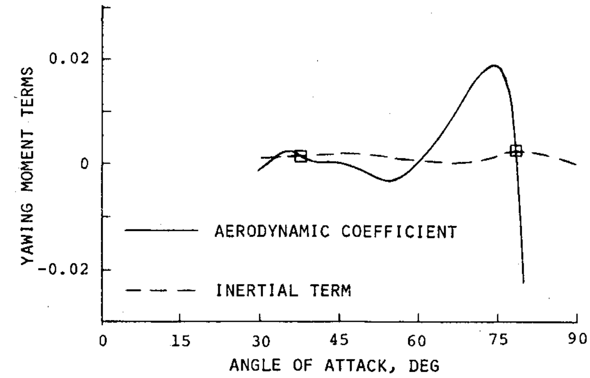

Fig. 7 Yawing-moment coefficient and inertial yaw term vs α curves identifying spin equilibrium α's.

The inertial term in the yaw Eq. (12) is calculated, therefore, at each tested angle of attack, using the β and $\Omega b/2V$ values from Figs. 5 and 6; the aerodynamic yawing-moment coefficient is, likewise, extracted at these same values. Plots of these inertial and aerodynamic values vs angle of attack are shown in Fig. 7.

Intersections of the aerodynamic and inertial curves identify angles of attack at which all three moment equations are in equilibrium. Because of the mechanism of the spin, only the intersections where the aerodynamic curve has a negative slope (indicated by squares) can result in spins. This occurs because a longitudinally stable airplane cannot maintain pitch equilibrium at a somewhat higher or lower α than the predicted value without a corresponding increase or decrease in $\Omega b/2V$ (Fig. 6). At the indicated intersections, however, this $\Omega b/2V$ change is prohibited by the presence of restoring lateral-directional moments about the spin axis.

The spin $\Omega b/2V$ and β value is then obtained from Figs. 6 and 5, respectively, at the spin α identified in Fig. 7. The drag and lift coefficients are then extracted from the rotary balance data for these equilibrium α, β, and $\Omega b/2V$ values. Equations (1) and (2) can then be solved for the descent velocity and spin radius.

Significance of Predicted Steady Spin Modes

Over the past few years, it has been observed that for each predicted steady spin mode, three possibilities exist in the "real world": the steady spin will be duplicated, oscillatory about the steady spin values, or nonexistent. The latter two conditions reflect the underlying spin mode's level of instability. In no instance, however, has a spin occurred in flight for which a steady spin mode has not been calculated.

An indication of recoverability from a predicted spin can also be obtained from these equilibrium calculations. For example, if a spin is predicted for a pro-spin control setting and none for neutral or recovery control settings, the spin is assumed to be recoverable, although its acceptability cannot be foretold. However, an examination of the rotational aerodynamic moments obtained with recovery controls can give an insight into the ease of recovery. This is accomplished by determining the existence of damping or autorotative moments and their variation with α and $\Omega b/2V$ below the predicted spin α.

In 1981, spins obtained with spin tunnel free-spinning models and full-scale airplanes were correlated with those predicted analytically.[23] It was found that the steady-state equilibrium spins were in excellent agreement with the spin tunnel and flight results. Poorer correlation with flight test was noted, however, for general aviation configurations exhibiting very steep spin modes. This was attributed to a significant Reynolds number effect relative to the wing aerodynamics.

Large Angle, Six-Degree-of-Freedom Analysis

Six-degree-of-freedom computer solutions identify the degree of stability or instability of developed spins, the ease or difficulty of entering and recovering from a spin, as well as high α departure, roll reversal, and post-stall gyration motions. Unfortunately, this analytical technique does not lend itself to configuration analysis during rotary balance data acquisition because a large volume of data must be modeled and dynamic derivatives must be obtained prior to running the program.

Method

Six-degree-of-freedom spin analysis utilizes standard large angle, nonlinearized equations of motion.[24] The aerodynamic model, as mentioned previously, incorporates dynamic derivatives and rotary balance data. It is necessary to use the data in the same manner in which it was measured. Rotary balance data, for example, is measured with the airplane model performing a steady rotation about an axis aligned with the freestream velocity vector. Therefore the Ω used to extract rotary balance data is defined as the roll rate about the wind axis, filtered to remove nonsteady components. The dynamic derivatives, on the other hand, are measured or calculated for small oscillations about each of the body axes and are, consequently, multiplied only by the oscillatory components of the body axes rates, as mentioned previously. These oscillatory components are calculated as the total body rates less the steady rotational components about each axis.

$$p_{\mathrm{osc}} = p - \Omega\cos\beta\cos\alpha \tag{14}$$

$$q_{\mathrm{osc}} = q - \Omega\sin\beta \tag{15}$$

$$r_{\mathrm{osc}} = r - \Omega\cos\beta\sin\alpha \tag{16}$$

High-angle-of-attack simulations using this aerodynamic modeling technique may not completely match all phases of a spin time history for several reasons. For example, Reynolds number differences between the model- and full-scale airplane can lead to significant aerodynamic differences in the immediate post-stall α range, and thereby alter a very steep spin mode or modify the incipient spin time history. Another possible source of error may be the dynamic derivatives, which are normally measured while forcing a model to oscillate about a nonrotating reference. A more proper representation for spin analysis would be to superimpose the forced oscillation onto a steady rotating motion. Dynamic derivatives, estimated for this latter condition, have indicated that values so derived can differ from the conventionally obtained values. These differences may be significant because certain dynamic derivatives, specifically C_{m_q} and C_{l_p}, have been shown[14,15,25] to significantly affect the stability of the spin modes. Unfortunately, no apparatus currently exists in this country that is capable of measuring dynamic derivatives in this manner.

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References

[1] Bihrle, W. Jr. and Bowman, J.S. Jr., "Influence of Wing, Fuselage, and Tail Design on Rotational Flow Aerodynamics Beyond Maximum Lift," *Journal of Aircraft*, Vol. 18, Nov. 1981, pp. 920-925.

[2] Glauert, H., "The Investigation of the Spin of an Aeroplane," R&M 618, British A.R.C., 1919.

[3] Gates, S.B. and Bryant, L.W., "The Spinning of Aeroplanes," R&M 1001, British A.R.C., 1926.

[4] Irving, H.B. and Batson, A.S., "Experiments on a Model of a Single Seater Fighter Airplane in Connection with Spinning," R&M 1184, British A.R.C., 1928.

[5] Allwork, P.H., "A Continuous Rotation Balance for the Measurement of Yawing and Rolling Moments in a Completely Represented Spin," R&M 1579, British A.R.C., 1933.

[6] Bamber, M.J. and Zimmerman, C.H., "The Aerodynamic Forces and Moments Exerted on a Spinning Model of the 'NY-1' Airplane as Measured by the Spinning Balance," NACA TR 456, 1933.

[7] Stone, R.W. Jr., Burk, S.M. Jr., and Bihrle, W. Jr., "The Aerodynamic Forces and Moments on a 1/10-Scale Model of a Fighter Airplane in Spinning Attitudes as Measured on a Rotary Balance in the Langley 20-Foot Free Spinning Tunnel," NACA TN 2181, 1950.

[8] Bamber, M.J. and Zimmerman, C.H., "Spinning Characteristics of Wings. I.-Rectangular Clark Y Monoplane Wing," NACA TR 519, 1935.

[9] Bamber, M.J. and House, R.O., "Spinning Characteristics of the XN2Y-1 Airplane," NACA TR 607, 1937.

[10] Scher, S.H., "An Analytical Investigation of Airplane Spin Recovery Motion by Use of Rotary-Balance Aerodynamic Data," NACA TN 3188, 1954.

[11] Burk, S.M. Jr., "Analytical Determination of the Mechanism of an Airplane Spin Recovery with Different Applied Yawing Moments by Use of Rotary-Balance Data," NACA TN 3321, 1954.

[12] Anglin, E.L. and Scher, S.H., "Analytical Study of Aircraft Developed Spins and Determination of Moments Required for Satisfactory Spin Recovery," NASA TN D-2181, 1964.

[13] Grafton, S.B. and Anglin, E.L., "Static and Dynamic Aerodynamic Characteristics of a 0.15-Scale Model of the YF-17 Airplane at Spin Angles of Attack—Coord. No. AF-AM-407 (U)," NASA TM SX-3217, 1975.

[14] Bihrle, W. Jr. and Barnhart, B., "Effects of Several Factors on Theoretical Predictions of Airplane Spin Characteristics," NASA CR 132521, 1974.

[15] Bihrle, W. Jr., "Correlation Study of Theoretical and Experimental Results for Spin Tests of a 1/10-Scale Radio Control Model," NASA CR 144995, 1976.

[16] Verbrugge, R., "Balance Rotative De L' I.M.F. Lille et Techniques Experimentales Associees," I.M.F. Lille No. 79/63, 1979.

[17] Bazzocchi, E., "Stall Behavior and Spin Estimation Method By Use of Rotary Balance Measurements," AGARD-CP-199, 1975.

[18] Babister, A.W., *Aircraft Stability and Control*, Pergamon Press, New York, 1961.

[19] Crow, J.H., "An Elementary Study of the Spin," *Aircraft Engineering*, Vol. XI, Feb. 1939, pp. 39-43; March 1939, pp. 111-114; April 1939, pp. 158-160; May 1939; pp. 203-208; July 1939, pp. 273-278.

[20] Bazzocchi, E., "Etude Analytique de la Vrille en Utilisant des Donnees a la Soufflerie Horizontale et Methode d' Essai des Modeles a l' Air Libre," *Proceedings of the Second European Aeronautical Congress*, Scheveningen, The Netherlands, 1956, pp. 5.1-5.43.

[21] Tischler, M.B. and Barlow, J.B., "Application of the Equilibrium Spin Technique to a Typical Low-Wing General Aviation Design," AIAA Paper 79-1625, Aug. 1979.

[22] McCormick, B.W., "Equilibrium Spinning of a Typical Single-Engine Low-Wing Light Aircraft," *Journal of Aircraft*, Vol. 18, March 1981, pp. 192-199.

[23] Bihrle, W. Jr., "Prediction of High Alpha Flight Characteristics Utilizing Rotary Balance Data," *Proceedings of the 13th ICAS Congress/AIAA Aircraft Systems and Technology Conference*, Seattle, Wash., Aug. 1982.

[24] Etkin, B., *Dynamics of Flight*, John Wiley and Sons, Inc., New York, 1966.

[25] Klinar, W. and Grantham, W., "Investigation of the Stability of Very Flat Spins and Analysis of Effects of Applying Various Moments Utilizing the Three Moment Equations of Motion," NASA Memo 5-25-59L, 1959.