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Determination of the Spin and Recovery Characteristics of a General Aviation Design

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The equilibrium spin technique implemented in a graphical form for obtaining spin and recovery characteristics from rotary balance data is outlined. Results of its application to recent rotary balance tests of the NASA low-wing general aviation aircraft are discussed. The present results, which are an extension of previously published findings, indicate the ability of the equilibrium method to accurately evaluate spin modes and recovery control effectiveness. A comparison of the calculated results with available spin-tunnel and full-scale findings is presented. The technique is suitable for preliminary design applications as determined from the available results and data base requirements. A full discussion of implementation considerations and a summary of the results obtained from this method to date are presented.

Nomenclature

b	= wing span, ft
c.g.	= center of gravity, percent of the mean aerodynamic chord
C_l	= rolling moment coefficient ($L/\frac{1}{2}\rho V^2 Sb$)
C_{l_β}	= rate of change of rolling moment coefficient with sideslip ($\partial C_l/\partial\beta$)
C_m	= pitching moment coefficient ($M/\frac{1}{2}\rho V^2 Sb$)
C_n	= yawing moment coefficient ($N/\frac{1}{2}\rho V^2 Sb$)
C_{n_β}	= rate of change of yawing moment coefficient with sideslip ($\partial C_n/\partial\beta$)
I_{XX}, I_{YY}, I_{ZZ}	= moments of inertia about the X, Y, and Z body axes, respectively, slug-ft^2
L	= rolling moment, ft-lb
M	= pitching moment, ft-lb
N	= yawing moment, ft-lb
p	= rolling angular velocity about X body axis, rad/s
q	= pitching angular velocity about Y body axis, rad/s
R	= steady spin radius, measured from spin axis to aircraft c.g., ft
r	= yawing angular velocity about Z body axis, rad/s
S	= wing planform area, ft^2
V	= rate of descent, ft/s
W	= aircraft weight, lb
X	= body axis aligned with the fuselage reference line, positive in the forward direction
Y	= body axis aligned with wing through the c.g., positive axis extends outward from the right wing
Z	= body axis orthogonal to X and Y axes taken positive in the downward direction
α	= approximate angle of attack at c.g., deg
β	= approximate angle of sideslip at c.g., positive when relative wind comes from right of plane of symmetry, deg
γ	= spin helix angle [$\gamma = \tan^{-1}(\omega R/V)$], deg
λ	= spin parameter ($\omega b/2V$)
ρ	= air density, slug/ft^3
χ	= wing tilt angle measured about the Z body axis, in the X-Z plane between the X axis and radial direction, positive for a nose clockwise rotation, deg
ω	= aircraft angular velocity about the vertical spin axis, positive for a right spin, rad/s

Subscripts

i	= inertial moment designation
aero	= aerodynamic moment designation

Introduction

In the last several years, NASA has been intensively studying the spin behavior of light general aviation aircraft. Wind-tunnel and spin-tunnel facilities at Langley Research Center are being utilized along with theoretical studies and free-flight model methods. Early emphasis has been focused on the definition of the spin modes of existing aircraft and derivative configurations by means of spin-tunnel, radio-controlled model, and full-scale flight tests.[1] Analytical efforts have been centered on the refinement of the six degree-of-freedom methods. A review of these current techniques may be found in Refs. 2 and 3. The available techniques need improvement so that designers can obtain reliable information on spin behavior in the preliminary design phases of aircraft development.

Early studies of airplane spin phenomena were based on concepts of force and moment equilibrium under steady conditions. These studies, as documented by the British scientists Gates and Bryant[4] and Irving [5] in the early 1930s, focused on the conditions when an aircraft had reached a condition of constant angular velocity and attitude orientation. The objective was to identify those factors that most affect the balance of forces and moments during a steady spin. The dynamic behavior of the aircraft with a state near a steady spin was investigated by the classical linearized approach. These early attempts at dynamic spin simulation suffered from inaccuracies and incompleteness of the aerodynamic data base, and the inability of the linearized theory to predict the highly nonlinear sideslip effects. However, calculated moment equilibrium at observed steady spin rates and attitudes showed close correlation in some reported cases.[6]

A spin prediction method suitable for the preliminary design phase must provide early information on spin modes and recovery characteristics, as well as control authority requirements, center of gravity, inertial loading, and configuration effects (strakes, wing fillets, etc.). It is desirable that a minimal aerodynamic data base be required and that dynamically scaled models not be required. Such a method

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could conceivably be supported by extensions to current preliminary design wind-tunnel test programs through utilization of rotary balance tests. A rotary balance is an instrument which measures the forces and moments on a model under steadily rotating conditions simulating a range of possible steady spin conditions.

During the 1950s and 1960s, the Italian Aeronautica Macchi developed several horizontal rotary balances. The director of the Macchi, Ermanno Bazzocchi, documented a sequential equilibrium search procedure in a 1956 publication[7] which yielded precise information on the location of spin modes and aircraft attitudes. This method utilizes data from the static and horizontal rotary balances.

In a publication by the AGARD in 1975, Bazzocchi[8] showed good correlations between analytical results and full-scale flight data of a Macchi aircraft. These results demonstrated an accurate prediction of full-scale characteristics obtained from rotary balance data with the equilibrium spin method. The Macchi horizontal rotary balance[8] attains a Reynolds number of $6\text{-}7.5 \times 10^5$ (based on mean aerodynamic chord). This is an order of magnitude above the 5×10^4 Reynolds number typical in the NASA free-spin-tunnel tests.[9] The NASA vertical rotary balance can attain a Reynolds number of 1.3×10^5. This Reynolds number improvement could be important in the prediction of full-scale spin characteristics,[11] a regime where Reynolds numbers are of the order of 2.5×10^6. Extensive rotary balance tests of the NASA low-wing general aviation airplane have been conducted at the Langley Research Center.[10,14]

The present authors have conducted an extensive study of the spin and recovery characteristics of the NASA low-wing general aviation aircraft.[12,13] The purpose of the study was to assess the ability of the equilibrium spin technique to predict the locations of spin modes and evaluate recovery control effectiveness of general aviation configurations.

The equilibrium spin technique, as employed in this study, is developed and discussed in detail in Ref. 12. The preliminary results of its application to the rotary balance tests of the NASA aircraft with tail configuration 3 are presented in Refs. 12 and 13. Those results indicate the ability of the equilibrium technique to predict the location of steep and flat spin modes to within 10 deg of the published NASA spin-tunnel test results.[9] The results also indicate the strong effect that sideslip modeling can have on the steep spin and spin recovery analyses.

In the present study, rotary balance sideslip data are incorporated as a refinement to the previously used static derivative data (C_{l_β}, C_{n_β}). The spin modes and recovery characteristics of the NASA aircraft with tail configuration 4 are analyzed and compared with available spin-tunnel and full-scale data.

Equilibrium Spin Technique

The airplane is assumed to be rotating at constant angular velocity about the vertical spin axis (Fig. 1). In many cases, full-scale aircraft will achieve such a steady condition after about three or four turns. If the assumed angular velocity and sink rate represent an equilibrium state, the forces and moments must balance.

Force Equilibrium

Application of force equilibrium constraints require that the aircraft weight be balanced by the vertical aerodynamic force (approximately the drag), and the centrifugal force be balanced by the normal force (approximately the lift). The resultant aerodynamic force is assumed to act perpendicular to the plane of the wing. Therefore, the side force is considered negligible.[15] This assumption is necessary in order to decouple the force equations and to satisfy the constant spin rate condition. Force equilibrium conditions can normally be satisfied for any attitude and spin rate by adjustment of the spin radius and rate of descent. Therefore, the attainment of

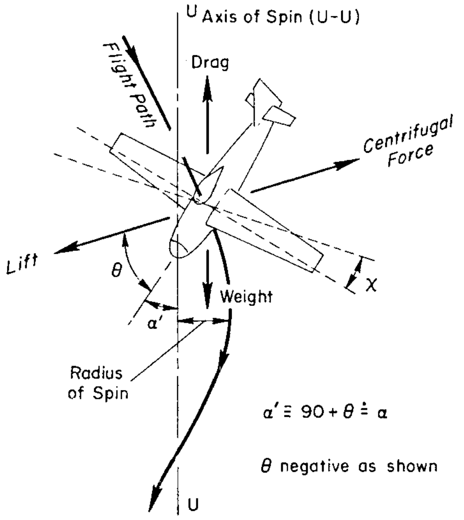

Fig. 1 Balance of forces in a steady spin.

force equilibrium does not impose a limitation on the spin. It is the balance of moments that becomes the essential factor in maintaining a steady spin condition.

Moment Equilibrium

The moment equations for a steady spin condition may be expressed with respect to the principal body axes in scalar form as

$$L + (I_{YY} - I_{ZZ})qr = 0 \tag{1a}$$

$$M + (I_{ZZ} - I_{XX})rp = 0 \tag{1b}$$

$$N + (I_{XX} - I_{YY})pq = 0 \tag{1c}$$

The first terms of the above equations are the applied aerodynamic moments, and the second terms may be considered as inertial moments. These conditions represent a balance of the aerodynamic and inertial moments and must be satisfied in a steady spin condition. In order to express the body angular rates in terms of the constant spin rate, a series of Euler transformations is introduced.

The first standard Euler rotation, yaw angle, is unnecessary because of the assumption of a vertical spin axis. The second rotation, pitch θ, is taken in the negative direction about the wing span Y-Y axis. It can be shown[12] that this rotation is almost equivalent to a rotation of $90 - \alpha$ from the horizontal in the same direction. The last rotation, wing tilt χ, is taken about the body Z-Z axis. This is essential in order to insure that the resultant aerodynamic force (normal to the wing chord) passes through the spin axis and does not generate moments which would unbalance the equilibrium spin rate condition. This rotation constraint is consistent with the assumption of negligible side force. The total transformation matrix from the vertical to the body fixed reference frame is given from Ref. 12 as:

$$L_{BV} = \begin{bmatrix} \cos\chi\sin\alpha & \sin\chi & \cos\chi\cos\alpha \\ -\sin\chi\sin\alpha & \cos\chi & -\sin\chi\cos\alpha \\ -\cos\alpha & 0 & \sin\alpha \end{bmatrix} \tag{2}$$

Adopting the convention of spin parameter ($\lambda = \omega b / 2V$) and nondimensionalizing, we obtain the inertial moment coefficients from Eqs. (1) and (2) as:

$$C_{l_i} = \frac{-4(I_{YY} - I_{ZZ})(\sin 2\alpha)(\sin\chi)\lambda^2}{\rho S b^3} \tag{3a}$$

$$C_{m_i} = \frac{4(I_{ZZ}-I_{XX})(\sin 2\alpha)(\cos\chi)\lambda^2}{\rho S b^3} \tag{3b}$$

$$C_{n_i} = \frac{-4(I_{XX}-I_{YY})(\sin 2\chi)(\cos^2\alpha)\lambda^2}{\rho S b^3} \tag{3c}$$

The final form of the moment equilibrium conditions then becomes:

$$C_{l_{\text{aero}}} + C_{l_i} = 0 \tag{4a}$$

$$C_{m_{\text{aero}}} + C_{m_i} = 0 \tag{4b}$$

$$C_{n_{\text{aero}}} + C_{n_i} = 0 \tag{4c}$$

The implementation of the equilibrium spin technique used here is a graphical search procedure which determines the proper combination of α, χ, and λ in order to produce simultaneous moment equilibrium about all three axes [Eq. (4)].

Solution Algorithm

A FORTRAN program was developed to provide an interactive graphical presentation of the equilibrium conditions over a range of aircraft attitudes. A typical variation of the inertial yawing moment coefficient [Eq. (3c)] with spin parameter ($\omega b/2V$) and wing tilt angle χ at a fixed angle of attack is shown in Fig. 2. Superimposed on this figure is the corresponding aerodynamic data curve for zero tilt angle. For illustrative clarity, the family of aerodynamic curves for various tilt angles has not been shown. Intersection points between the aerodynamic and inertial curves for specific tilt angle indicate conditions of moment equilibrium about that axis. The loci of the intersection points produce a single equilibrium curve along which moment balance is maintained for a given angle of attack. A typical three-axes equilibrium diagram is presented in Fig. 3. Each loci curve provides the proper combination of χ and λ, at a specific angle of attack, which is necessary to maintain the equilibrium condition about that axis only.

A common intersection indicates the simultaneous solution of all three equilibrium conditions for a specific combination of α, χ, and λ. This condition indicates a steady spin mode. Such a result is shown in Fig. 4. In many cases, an exact simultaneous intersection does not occur at a spin mode location. This is commonly caused by the coarseness of the grid variation of the angle of attack used in the search. A simultaneous crossing might occur at an intermediate value of α. In other cases, this may be a result of aerodynamic or inertial data inaccuracies, or the nonexistence of a perfect steady spin condition. A "close crossing," as in Fig. 5 (shaded region), does indicate the strong likelihood of a steady spin at an attitude within the region defined by the three intersection points. The definition of "close crossing" could be made precise with the addition of an error analysis of the data for the aerodynamic and inertial moments.

Sideslip Effects

The inertial rolling and yawing moment coefficients, small under influence of the $\sin\chi$ and $\sin 2\chi$ terms of Eqs. (3a) and (3c), will have their sense (positive or negative) determined by

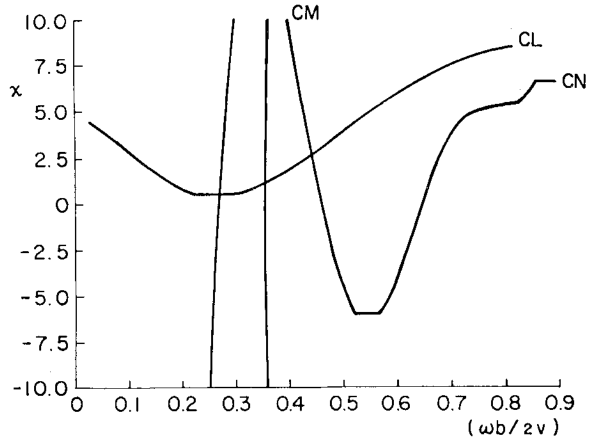

Fig. 3 Typical three-axes equilibrium diagram.

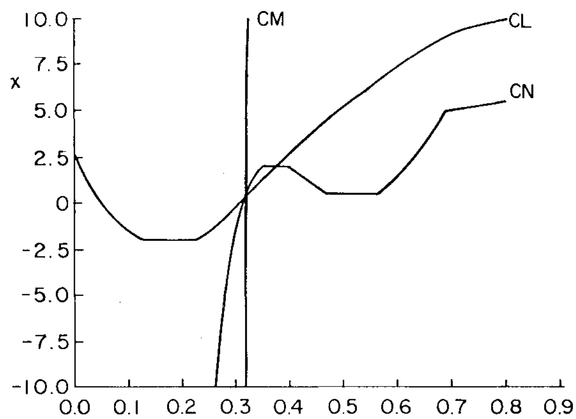

Fig. 4 Common point of intersection of three equilibrium curves indicating steady spin mode.

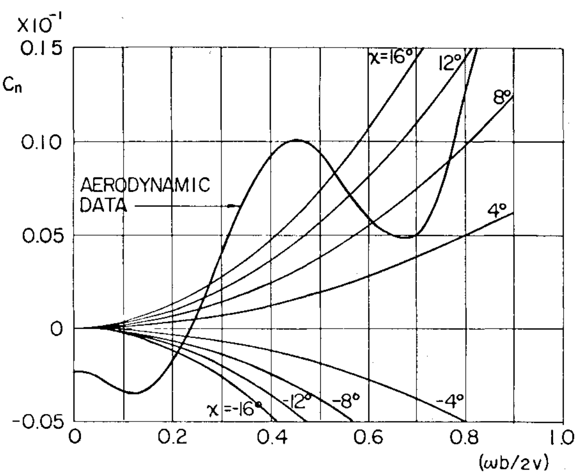

Fig. 2 Typical variation of inertial and aerodynamic yawing moment coefficients with spin parameter ($\omega b/2V$) and yaw angle χ).

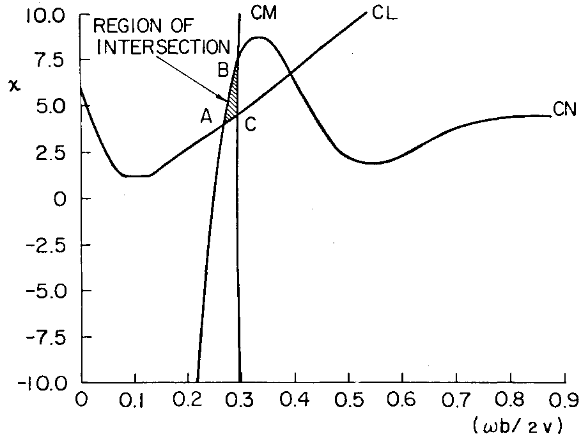

Fig. 5 "Close crossing" equilibrium diagram indicating steady spin mode.

the sense of χ. In addition, variations in wing tilt χ will directly affect the aerodynamic sideslip,[12] which has a significant effect on the aerodynamic rolling and yawing moment coefficients. Therefore, small adjustments in the wing tilt angle can significantly change the conditions of equilibrium about these axes. The accuracy of the equilibrium technique in assessing spin modes and especially recovery characteristics is largely dependent on the accuracy to which the highly nonlinear sideslip effects are known.

The earlier studies of Refs. 12 and 13 incorporated the conventional static derivatives (C_{l_β}, C_{n_β}) to extend the zero sideslip data base. This method of extending the data is inadequate beyond a small sideslip range. In a steep spin (25-40 deg), an aircraft may typically experience 6-10 deg of outward (prospin) sideslip. At such attitudes, the static corrections, which assume sideslip linearity, may produce misleading results. In the flat spin (60-90 deg), the aircraft will tend to orient itself wings level and travel down a virtually vertical path. It will typically have less than 3 deg of sideslip. The steep spin results are therefore considerably more sensitive to sideslip corrections than are the flat spin results. Previous studies also indicated that recovery conditions could not be accurately evaluated from a data base extended with the static corrections.

For the present study, rotary balance data at sideslip angles of ± 10 deg with no control deflections were available.[14] These data were linearly interpolated for the desired sideslip angle and the correction was applied to the basic data base by superposition. This method proved to be far superior to the static correction technique of the previous studies. The results presented in this paper show the capability of the equilibrium spin technique with adequate sideslip data to accurately assess spin and recovery characteristics.

Technique Implementation

A series of equilibrium plots over angles of attack of 30-90 deg provide the locations of spin modes for a specific control setting. Repeating the sequence for a variety of control configurations yields the combination(s) of control settings (if any) which result in the aircraft maintaining a flat spin attitude. Although this technique does not guarantee that an aircraft can reach the flat spin condition, it does assert that should it be achieved, the flat spin (located by this technique) will be an equilibrium condition. In addition, results presented in this paper and Refs. 12 and 13 correlate with the spin behavior of existing aircraft, confirming the stability of the predicted modes. Had one of the predicted modes been unstable, the mode would not have been found to exist in the spin tunnel.

By application of this technique, the aircraft's ability to spin against intended recovery controls can be determined, thereby providing information on minimum control authority requirements. A series of equilibrium curves for a specific control setting which did not exhibit any steady spin attitudes would indicate a successful recovery control configuration. Further analyses could indicate the effects of configuration additions such as strakes, wing fillets, and empennage locations on spin and recovery characteristics. After the aerodynamic data base is completed, additional studies on the effects of center of gravity and inertial loading changes could be conducted by adjusting the associated computer inputs.

The equilibrium method also has the distinct feature of separating the influences of the configuration effects with respect to the equilibrium conditions about each axis. The visualization of the individual equilibrium states allows a designer to isolate those configuration factors contributing to an equilibrium condition about a specific axis. In this way, a more quantitative basis for studying such configuration effects might be adopted to augment the currently used model and simulation techniques. Such analyses would indicate, for example, how a flat spin mode could be corrected, or what controls would be necessary to break an equilibrium condition to effect recovery.

The equilibrium spin technique requires a data base which is obtainable entirely from a rotary balance test. Dynamically scaled or instrumented models are not needed.

Application to NASA Rotary Balance Data

In order to correlate the results of a test case to spin-tunnel and full-scale data results, the NASA low-wing general aviation aircraft was selected. Recent rotary balance test results over a range of attitudes, control settings, and tail configurations for this aircraft are provided in Refs. 10 and 14. As noted earlier, sideslip data at ± 10 deg (no control deflections) was used to extend the basic data base to the desired sideslip angles. A complete discussion of calculation of the sideslip angle for a specified combination of α and χ is given in Ref. 12. A brief discussion is presented below.

Sideslip Corrections

From geometric considerations,[12]

$$\beta = -\chi\cos\alpha - \gamma \tag{5}$$

which gives the small angle dependence of sideslip β on the attitude angles χ and α and the helix angle γ. Wing tilt and angle of attack are treated as the independent variables. The helix angle, which directly affects sideslip, must be estimated as a function of angle of attack. From Fig. 1,

$$\tan\gamma = \frac{\omega R}{V} \tag{6}$$

where R is the spin radius and V the vertical descent rate.

If the assumption of a small value of χ is made, a functional relationship of the form

$$\lambda = C_0 + C_1\alpha + C_2\alpha^2 \tag{7}$$

can be developed from the pitch equilibrium conditions. The constants C_0, C_1, and C_2 are evaluated for each horizontal tail configuration and control setting. The constants do not have to be re-evaluated for each aileron setting. The use of the second-order form of Eq. (7) is a substantial refinement over the first-order form used in Refs. 12 and 13.

Estimates of the values of ω and R in Eq. (6) are obtained as a function of α and λ [Eq. (7)] from the force equilibrium conditions, following the development presented in Ref. 12. A typical plot of the resulting helix angle as a function of angle of attack is given in Fig. 6. We note from this figure and Eq. (5) that for small incidences, the helix angle can produce substantial prospin (outward) sideslip. As the aircraft incidence becomes large, this effect is diminished. From these considerations, the sideslip angle can be evaluated for any specified tilt angle and angle of attack. Sideslip corrections

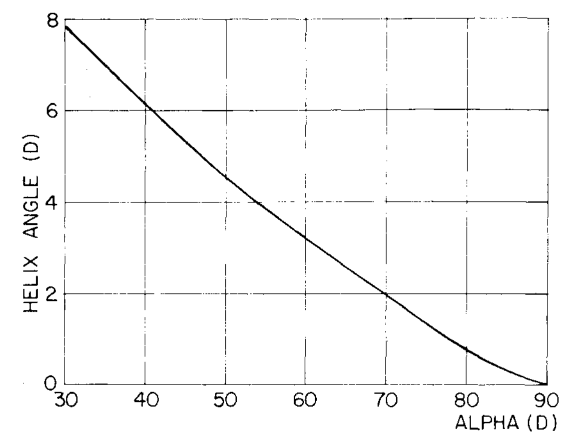

Fig. 6 Typical variation of equilibrium helix angle γ with angle of attack.

Table 1 Comparison of spin mode results of tail configuration 4

Prospin controls	Ailerons neutral[a] (c.g 25.5%)				Ailerons against (c.g. 25.5%)				Ailerons neutral (c.g. 14.5%)			
	Mode 1		Mode 2		Mode 1		Mode 2		Mode 1		Mode 2	
	α	λ[b]	α	λ	α	λ	α	λ	α	λ	α	λ
Spin tunnel	38	0.233	77	0.823	42	0.242	78	0.880	35	0.251	73	0.546
Full scale	51	0.283	68	0.455	52	0.309	NA[c]	NA	NA	NA	NA	NA
Equilibrium spin technique[a]	30	0.150	72	0.600	52	0.310	68	0.500	30	0.215	69	0.600

[a] All spins are with prospin rudder (rt) and elevator (up). [b] $\lambda = (\omega b)/(2V)$, spin parameter (all spins are to the right). [c] Not available.

are then applied by superposition from the relation

$$\text{coef}(\alpha,\lambda,\beta,\text{ controls}) = \text{coef}(\alpha,\lambda,\text{ controls}) + \text{coef}(\alpha,\lambda,\beta) - \text{coef}(\alpha,\lambda) \tag{8}$$

In order to analyze intermediate attitudes between those that were available from Ref. 14, linear interpolation was used. The data base was extended a maximum of 5 deg. For future applications, a uniform attitude test grid of 3 deg in angle of attack and wing tilt angle would be desirable.

Equilibrium Analysis Results and Discussion

The spin modes of the NASA single-engine low-wing general aviation aircraft with and without recovery controls have been determined from rotary balance data and compared to spin-tunnel and full-scale flight results. Tail configuration 4 was studied. A set of equilibrium curves was developed over an angle of attack range of 30-90 deg and a spin parameter range of 0.0-0.9 for each of a series of control settings and center-of-gravity locations. The results of these analyses will now be discussed in detail. A tabular summary and comparison to the published spin-tunnel results[9] and full-scale tests[11] is given in Tables 1-3.

Aircraft Spin Modes

Analyses were conducted for a right spin with prospin rudder (rt) and elevator (up). Aileron positions neutral and against (lt) for the rearward c.g. location (25.5%) and neutral for the forward c.g. location (14.5%) were studied. Presented in Table 1 is a comparison of the calculated results to the spin-tunnel and full-scale flight results.

The spin modes of the aircraft configuration were divided into two groups. Those spins designated "mode 1" (steep spin) exhibit an angle of attack less than 60 deg. Those classified "mode 2" (flat spin) have an angle of attack greater than 60 deg. The classification of the spins as adopted in this paper is neither essential nor especially standard. It simply provides a reasonable categorization of results. A more selective system is used by NASA for some of their tests.[9]

The equilibrium analysis indicated the existence of both steep and flat spin modes for the rearward c.g. with ailerons-neutral-and-against, and the forward c.g. with ailerons-neutral control settings. Spin-tunnel angle-of-attack results were within 10 deg of the calculated values. Full-scale data, where available, correlated well with the spin-tunnel and calculated results. The ailerons-neutral full-scale flat spin (c.g. 25.5%) was found to be unrecoverable without the use of the emergency spin parachute. As a result, the ailerons-against full-scale flat spin was not explored, although it was found to exist in spin-tunnel tests and was confirmed by the equilibrium analysis.

The correlation differences between the three sets of results may be attributed to two primary causes. First, the full-scale data has not, as yet, been corrected for wing upwash effects at the angle-of-attack vanes. These effects are thought to cause an angle-of-attack error of up to +10 deg for the steep spin case. A second possible source of variability between results is scale difference. Effects of Reynolds number variation are not well understood. This area is currently under study by NASA.

The results presented in Table 1 indicate the ability of the equilibrium method to accurately predict the existence of both steep and flat spin modes. As stated earlier, the accuracy of results could be improved with the use of a finer wind-tunnel test grid, especially in sideslip variation. There is a greater difference between the spin-tunnel and equilibrium results of the ailerons-against spin (c.g. 25.5%) than for the other cases. This is probably due to the use of neutral control sideslip data applied by superposition to the zero sideslip ailerons-against data base. A study of the improved accuracy that a more complete sideslip data base would provide is needed to help clarify data base requirements in an optimum test program.

Basic Recovery Results

A study was completed to determine the ability of the equilibrium method to predict basic recovery control effectiveness. Recovery from each of the spin modes (steep and flat) of the three control positions of Table 1 was attempted by full-rudder reversal. This maneuver is the basic spin-tunnel recovery technique. The results of this analysis, which was presented in Table 2, are organized according to the prospin aileron control settings of Table 1. Recovery was considered satisfactory, by the equilibrium method, if no prorecovery steady spin was located at any attitude less than, or 12 deg greater than, the initial prospin mode location.

The application of rudder reversal will normally cause a spinning aircraft to slow its angular rate. This effect will produce a reduction in the "nose-up" inertial pitching moment [Eq. (1b)]. If no other spin modes exist below the initial prospin attitude, the aircraft will nose down and recover. However, should a spin mode be formed as a result of the recovery controls at an attitude less than the initial angle of attack, the aircraft will settle into the new mode. This indicates a failure of the intended recovery controls to terminate the spinning motion. Should a prorecovery spin mode exist at an attitude somewhat greater than the initial prospin location (say within 12 deg), a transient generation of additional prospin sideslip or blanketing of the vertical tail could cause the aircraft to pitch up initially. This would again cause a transition to the new spin mode which would, as before, indicate recovery control failure. The 12 deg upper limit criterion was based on a bank of correlated results compiled to date. This criterion could be refined with further correlation studies.

NASA, in their spin-tunnel tests, considers a specific recovery technique to be satisfactory if it terminates the spinning motion within 2¼ turns or less from the time of recovery control application. For the purposes of presentation, this criterion was applied to both spin-tunnel and full-scale results. The reader is cautioned, however, against drawing specific conclusions from a comparison between spin-tunnel and full-scale results on the number of turns for recovery.[15] The important comparison presented is the equilibrium method's predictions of recovery control failure with the results of the other test techniques. In the case of the spin-tunnel and full-scale tests, recovery failure (when it occurred) was clear. The aircraft continued to spin steadily, usually at an attitude different from that of the initial spin mode.

Based on the above criteria, attempted recovery using the rudder reversal maneuver was rated satisfactory or unsatisfactory (S/U) in Table 2. Satisfactory recovery is denoted by an "S" and the number of turns for recovery noted for spin-tunnel and full-scale results only. An infinity sign indicates that the aircraft continued to spin steadily after recovery controls were applied (prorecovery spin modes). Equilibrium results for this condition provide the prorecovery mode angle of attack and spin parameter.

Rudder reversal recovery from the steep spin mode was predicted to be satisfactory for each of the prospin aileron positions. This was confirmed by the spin-tunnel and available full-scale results (Table 2). The equilibrium results of the recovery from the steep mode of the ailerons against spin (c.g. 25.5%) are marginally satisfactory as defined by the adopted criterion. However, as mentioned earlier, the spin modes of the ailerons-against case tended to be less accurate than the other cases as a result of the sideslip corrections. Based on the spin-tunnel results, the calculated prospin mode of 52 deg should probably be somewhat lower, nearer to the 42 deg value. This would make the result of "satisfactory" more conclusive.

Recovery from the flat spin mode was calculated to be unsatisfactory for all prospin cases. The flat spin mode attitude was reduced an average of 6.3 deg for the three cases. These results indicate that a flat spinning aircraft subjected to rudder reversal will have its attitude and rotation rate reduced slightly but continue to spin steadily so recovery fails. These findings were confirmed by spin-tunnel and available full-scale results.

Information obtainable by the equilibrium spin technique, such as has been presented in this section, could be provided in the early phases of preliminary design and wind-tunnel test programs. The incorporation of this method as a viable preliminary design tool would prove invaluable in the assessment of configuration effects and control authority requirements.

Alternate Control Techniques for Recovery from an Ailerons Neutral Spin

A study of the effectiveness of three alternate recovery techniques was completed using the equilibrium method. The results of Table 3 indicate the ability of simultaneous elevator and rudder reversal, elevator reversal, and neutral controls to provide recovery from a neutral-ailerons spin. These results are compared with the full-scale tests of Ref. 11.

The simultaneous control reversal and the neutral control movements both provided satisfactory recovery from the neutral-aileron steep spin as determined by the equilibrium method and full-scale results. The use of elevator reversal, in the absence of rudder reversal, has been shown to cause a steeply spinning aircraft to spin flatter or at increased rotation rates, or both.[16,17] This was indicated by the equilibrium results of Table 3 for elevator reversal recovery. Upon application of elevator reversal, the steady spin mode of $\alpha = 30$, $\lambda = 0.150$ shifts to the flatter prorecovery mode of $\alpha = 42$, $\lambda = 0.370$, thus indicating recovery failure. The inability of the elevator reversal technique to terminate the steep spin was confirmed by the full-scale results (Table 3).

None of the alternate recovery control techniques investigated in this study satisfactorily terminated the neutral-aileron flat spin mode, as determined from the equilibrium and full-scale results. A 20% decrease in both attitude and spin parameters was caused by the elevator and rudder simultaneous reversal technique. As indicated by the full-scale results, the aircraft will then continue to spin against the recovery controls at the new spin mode.

The use of the elevator reversal and controls neutral techniques for flat spin recovery caused the generation of an oscillatory flat spin condition with an angle-of-attack variation amplitude of 3 deg (4.3%) and 8 deg (11.9%), respectively. The spin parameter variation had an amplitude of 0.14 (18.7%) for the elevator reversal method, and 0.24 (37.5%) for the controls neutral method. The generation of a flat spin oscillatory condition in response to the application of forward stick movement, in the absence of full-rudder reversal, has been demonstrated in previous studies.[12] Those

Table 2 Comparison of basic recovery results of tail configuration 4

Prospin controls	Ailerons neutral[a] (c.g 25.5%)				Ailerons against (c.g. 25.5%)				Ailerons neutral (c.g. 14.5%)			
	Mode 1		Mode 2		Mode 1		Mode 2		Mode 1		Mode 2	
	S/U[c]	No. turns	S/U	No. turns	S/U	No. turns	S/U	No. turns	S/U	No. turns	S/U	No. turns
Spin tunnel[a]	S	1,½,½	U	∞	S	1,1,1¼	U	∞	S	1,1	U	9
Full scale[b]	S[a]	1¼,1⅝	U[a]	∞	S	1½,1⅝	NA[d]	NA	NA	NA	NA	NA
Equilibrium	S	–	U	∞	S	–	U	∞	S	–	U	∞
spin technique[a]	α	λ	α	λ	α	λ	α	λ	α	λ	α	λ
	–	–	64	0.430	–	–	65	0.440	–	–	61	0.520

[a]Recovery attempted by full-rudder reversal. [b]Recovery attempted by full-rudder reversal followed by forward stick movement unless otherwise noted. [c]S = satisfactory recovery, U = unsatisfactory recovery. [d]Not available.

Table 3 Comparison of alternate control techniques for an ailerons neutral spin

Recovery controls[a]	Elevator and rudder simultaneous reversal				Elevator reversal				Neutral controls			
	Mode 1		Mode 2		Mode 1		Mode 2		Mode 1		Mode 2	
	S/U[b]	No. turns	S/U	No. turns	S/U	No. turns	S/U	No. turns	S/U	No. turns	S/U	No. turns
Full scale	S	1⅛	U	∞	U	∞	H	∞	S	1¼,1⅜,2	U	∞
Equilibrium	S	–	U	∞	H	∞	U	∞	S	–	U	∞
spin technique[a]	α	λ	α	λ	α	λ	α	λ	α	λ	α	λ
	–	–	57	0.480	42	0.370	68	0.680	–	–	63	0.52
							71	0.820			71	0.76

[a]Prospin controls for all spins in ailerons neutral, prospin rudder (rt) and elevator (up). [b]S = satisfactory recovery, U = unsatisfactory recovery.

results indicated the transition from a steady flat spin to an oscillatory flat spin with an attitude variation of 5.5 deg (7.9%) and a spin parameter variation of 0.18 (27.3%). Further research is necessary to determine the stability characteristics of both oscillatory equilibrium points.

Conclusions

The study of the spin and recovery characteristics of the NASA low-wing general aviation aircraft has produced the following conclusions for this class of aircraft:

1) Spin modes can be accurately determined by the equilibrium spin technique from rotary balance data. For each control setting studied, both high and low angle-of-attack modes were predicted to within 10 deg of spin-tunnel results.

2) The calculated recovery characteristics showed close correlation to available spin-tunnel and full-scale test data. These results indicate that the effectiveness of the basic and alternate control techniques in producing recovery from steep and flat spin modes can be accurately determined by the equilibrium method.

3) The use of forward stick movement to produce flat spin recovery, in the absence of full-rudder reversal, may cause the generation of an oscillatory flat spin condition in some cases. Complete recovery from the flat spin modes of this aircraft is not possible with the control techniques analyzed in this study.

4) The analyses reflect the strong influence of sideslip modeling on the accurate prediction of spin and recovery characteristics. This underscores the importance of including complete sideslip sweeps in future rotary balance test programs.

5) Information obtainable by the equilibrium spin technique, such as has been presented in this paper, could be provided in the early phases of preliminary wind-tunnel test programs. The incorporation of this method as a design tool would prove valuable in the early determination of spin mode locations and the assessment of control authority requirements.

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