THE SPIN MANOEUVRE

by C.A. Martin and D.J. Pilkington

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Summary

Aircraft spinning is an important area of design for general aviation and military aircraft, and has been so since the early days of aviation. In many of the major aeronautical laboratories in the world, aircraft spinning has been the subject of intensive periods of research. However, the resulting design criteria are still only adequate for predicting gross trends in aircraft spin behaviour. The aircraft designer has to decide upon an appropriate level of spin model testing or risk a flight development program with the prospect of major modifications. In this paper, the nature of the spin manoeuvre is discussed, the information currently available for predicting aircraft spin behaviour is summarized and two methods of spin model testing are described.

1. Introduction

Aircraft spinning is an important area of design for general aviation and military aircraft, and has been so, since the early days of aviation. In many of the major aeronautical laboratories in the world, aircraft spinning has been the subject of intensive periods of research. However, the resulting design criteria are still only adequate for predicting gross trends in aircraft spin behaviour. This information has to be augmented by extensive scale model testing, usually of a qualitative nature, to enable flight testing and development to proceed with confidence. In this paper, these features of the subject will be emphasized.

Following a discussion of the nature of the spin, the methods currently available to the aircraft designer for spin prediction are discussed. The need to interpret pilot experience of aircraft spin behaviour in terms of aircraft characteristics is presented.

2. The nature of the spin

2.1 Spin phases

The spin manoeuvre has traditionally been divided into four stages (Figure 1). Spin entry, incipient spin, steady spin, and spin recovery. Spin entry from unstalled flight may be deliberate, usually as a training rather than an operational manoeuvre, or inadvertent, occurring usually during low speed manoeuvres.

A deliberate spin is initiated by slowing the aircraft towards the stall speed and then applying full rudder deflection. The resulting yawing velocity increases the lift on the forward travelling wing, and reduces that on the rearward travelling one; the differential lift produces a rolling moment in the direction of the rearward travelling wing, and initiates the spin manoeuvre. As this wing goes down, its incidence increases and goes beyond the stall, resulting in classical auto rotation with a large rate of roll.

Aircraft with high spin resistance generally require vigorous and precise control movements to initiate the spin. In contrast, inadvertent spin entry can result with aircraft which are susceptible to spinning, either during steep turns at low speeds, or during the low speed portions of aerobatic manoeuvres such as at the top of a loop or barrel roll.

The incipient spin is the transition between spin entry and the steady spin. Recovery from an inadvertent spin is most effectively achieved in this phase, so it is important for pilots to be able to recognize the manoeuvre and to apply appropriate recovery action. The incipient phase is considered to end when the airspeed has become steady and a vertical trajectory has been reached. For practical purposes, the steady spin is reasonably well established after two to three turns.

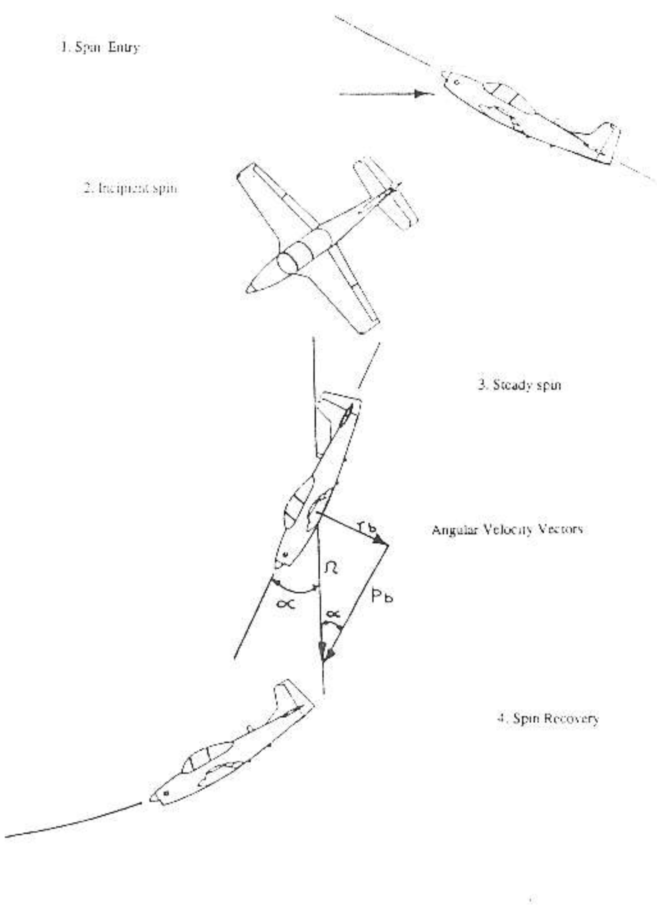


FIG. 1 THE SPIN MANOEUVRE

During the incipient spin the aircraft flight path changes from horizontal to vertical, the angle of attack increases to well beyond the stall value, and the rotation in yaw increases to match or frequently exceed that in roll.

In the steady spin or equilibrium spin, the aircraft describes a steep spiral motion about a vertical axis, in which spin rate, angle of attack, sideslip angle and vertical velocity are approximately constant. In many cases, the motion does not reach a steady state, but may exhibit an oscillation about the nominal equilibrium point, with a frequency higher than the spin rate.

Spin recovery for most configurations is achieved primarily by use of full rudder deflection to arrest the large rate of yaw. Often, the elevator and aileron, if applied correctly, can increase the speed of recovery. For certain aircraft, their use is essential, while in others, they are sufficiently capable of stopping the spin even with full pro-spin rudder deflection maintained.

2.2 The steady spin

The steady spin phase is of particular importance, since it represents a stable equilibrium flight condition from which recovery may be impossible. Because the motion is more or less steady, it is also more tractable to analysis than the other phases.

Some aircraft exhibit more than one steady spin condition or mode, in which case the sequence of control movements applied during the entry and incipient phases will determine which of the modes is reached. However, the characteristics, of the mode depend only on the aircraft aerodynamic and inertia characteristics and on the control settings. There is also a dependency on air density and hence altitude, but this will not be discussed here.

From stability considerations, the steady spin may be referred to as a point of stable equilibrium similar to a trimmed condition in level flight. Figure 2 shows this condition and also another stable equilibrium, the deep stall.

All these cases are in equilibrium since in each there is a balance of forces and moments about all axes; the steady spin is the most complex in that the balance occurs in the presence of large angular rotations about the roll and yaw axes.

The key to spin recovery is to design the aircraft with sufficient control power to unlock this stable condition.

The dynamics of the steady spin were understood and described in detail many years ago. A comprehensive description is given by Gates and Bryant in Reference 1 in 1926. As with other branches of flight dynamics, the difficult problems associated with an analysis of the spin arise not from the system dynamics, but from the complexity of the aerodynamic forces. The more important aerodynamic forces acting in the steady spin are briefly described below.

2.3 The balance of forces and moments

Figure 3 from Reference 1 shows that the balance of forces in a steady spin is such that the drag is equal to the weight and the lift is equal to the centrifugal force. In the steady spin, the spin radius is only of the order of a few feet, the resultant force is almost normal to the wing and acts approximately at the wing semi-chord, and the normal acceleration is low.

In practice, the actual balance is slightly more complex in that aerodynamic sideforces exist, such that the lateral axis is not necessarily horizontal but may be tilted. The amount of tilt is directly related to the spin helix angle and to the angle of sideslip adopted in the spin. The sideslip is determined primarily by the rolling moment characteristics as explained later.

To illustrate the balance of moments in a steady spin, the primary aerodynamic contributions will be discussed. Rotary balance data measured on an aircraft with standard layout will be used to illustrate the discussion. The moments are referred to aircraft body axes. Because of the large variation in onset flows over a spinning aircraft, the choice of axis system has little significance. The less important aerodynamic contributions are neglected in this discussion but are described in detail in Reference 1.

Equilibrium of pitching moments is reached when the nose-down aerodynamic moment is equal to the large nose-up inertia moments, as shown in Figure 4. The aerodynamic contributions are from the wing normal force which, for a stalled wing, acts at the wing semi-chord and from the tailplane normal force. The inertia moment is proportional to the square of spin-rate and reaches a maximum at 45 degrees angle-of-attack. Movement of the elevator adds an increment to the aerodynamic moment, but normally this is not of sufficient magnitude to unlock the balance of pitching moments.

Of prime importance for roll equilibrium, is the balance of the aerodynamic contributions due to roll rate and to sideslip. The inertia moment may be positive or negative, depending

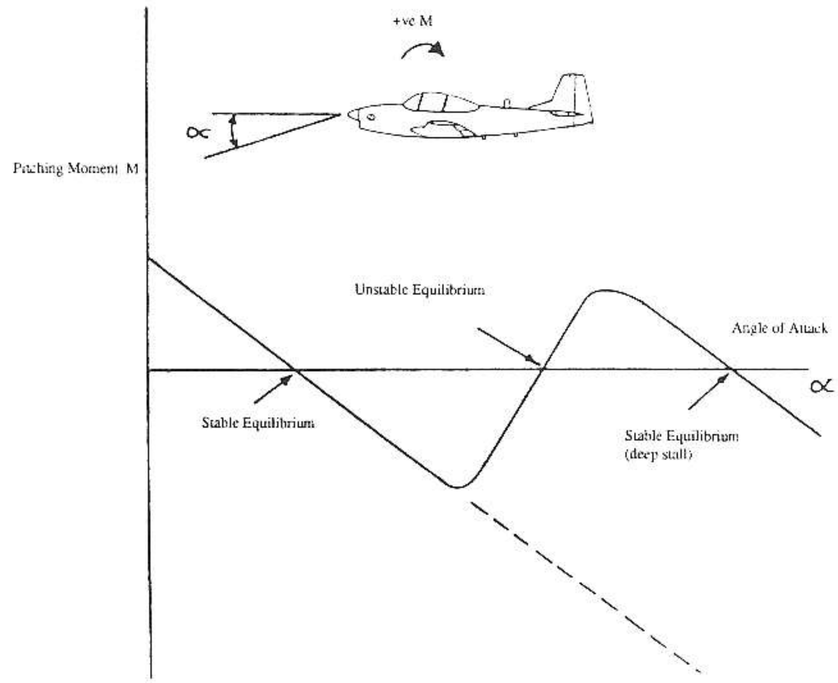


FIG. 2 LONGITUDINAL TRIM CONDITIONS

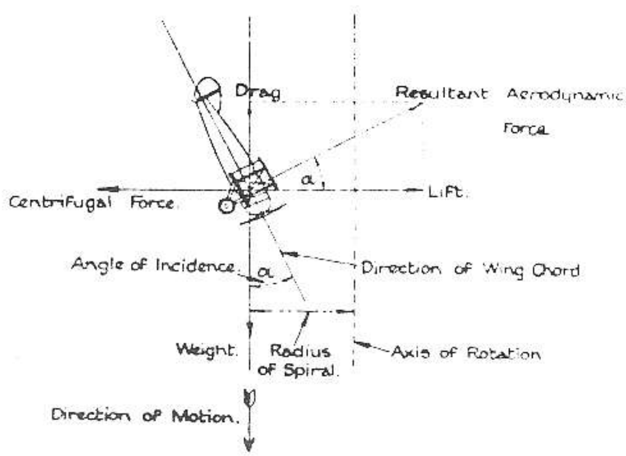
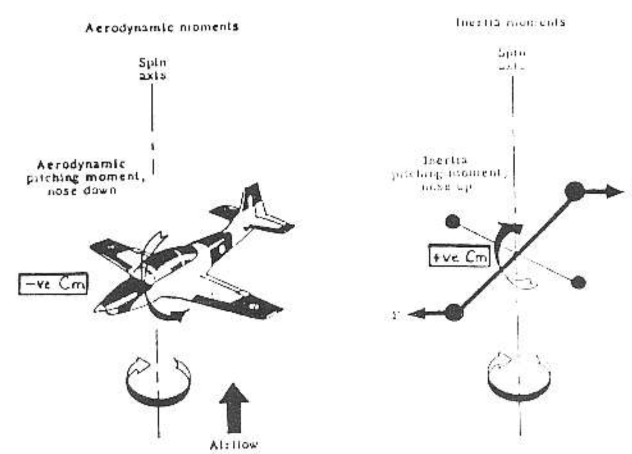
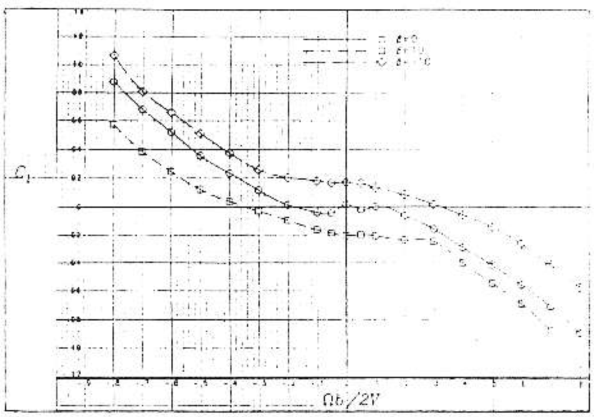


FIG. 3 BALANCE OF FORCES



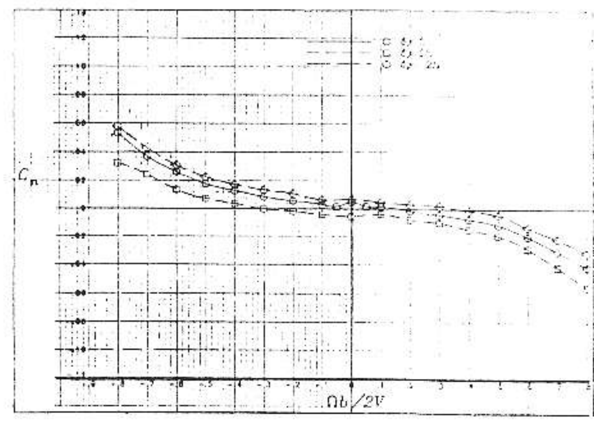
$$\underbrace{C_m}_{\text{AERODYNAMIC}} - \underbrace{(4/\rho S_w \bar{c} b^2)(\Omega b/2V)^2 (I_x - I_z)\sin 2\alpha\cos^2(\alpha+\beta)}_{\text{INERTIA}} = 0$$

FIG. 4 BALANCE OF PITCHING MOMENTS



$$\underbrace{C_{\ell}}_{\text{AERODYNAMIC}} - \underbrace{(4/\rho S_w b^3)(\Omega b/2V)^2(I_z - I_y)\sin\alpha\sin 2(\phi+\beta)}_{\text{INERTIA}} = 0$$

FIG. 5 BALANCE OF ROLLING MOMENTS



$$\underbrace{C_n}_{\text{AERODYNAMIC}} - \underbrace{(4/\rho S_w b^3)(\Omega b/2V)^2(I_y - I_x)\cos\alpha\sin 2(\phi+\beta)}_{\text{INERTIA}} = 0$$

FIG. 6 BALANCE OF YAWING MOMENTS

on wing tilt angle, having a zero value for zero tilt. Figure 5 shows the typical variation of aerodynamic rolling moments with spin rate and sideslip for a given angle-of-attack. Note that, for a significant change in spin-rate, the rolling moments can be balanced by a modest change in sideslip angle. As with the pitching moment balance, movement of the aileron adds an increment to the rolling moment curve, but the magnitude is normally insufficient to unlock the balance of rolling moments.

The two largest aerodynamic yawing moment contributions for the example configuration are due to spin-rate and rudder deflection, as shown in Figure 6; by comparison the contribution due to sideslip is small, and, as with the rolling moment equation, the inertia contribution is zero for zero wing tilt. Since the rudder can alter the yawing moment curve appreciably, the key to unlocking the balance of moments in a spin is, therefore, to generate a large yawing moment with the rudder.

In order to emphasize the major contributions, the wing tilt and hence rolling and yawing inertia contributions have been assumed to be zero. Tilt angles, usually leading wing down, of five degrees can occur in a steady spin. Consequently, the rolling and yawing moment balance will be modified and so, in any detailed analysis, these terms must be included.

Further consideration of the balance of moments would show that the spin rate and spin angle-of-attack are closely related and are determined essentially by the pitching moment; that the sideslip is determined by the balance of rolling moments, and that although all three control surfaces may be effective in changing the balance of moments, and hence spin conditions, the rudder is the most effective means of unlocking this balance. For aircraft of substantially different inertia loading and layout this emphasis may change.

2.4 Incipient spin and spin recovery

These two phases are characterized by the transition between two extremely different flight conditions. Upon entry the aircraft has low angular velocity, moderate linear velocity, constant potential energy, and is flying at low angles-of-attack. The transition through to the steady spin involves an initial increase in roll rate followed by an increase in yaw rate giving a large resultant angular rotation; a decrease in linear velocity and a constant reduction in potential energy, with the angle-of-attack increasing to large values.

The aerodynamic changes are equally dramatic and involve changes from attached to unattached flow over large areas of the aircraft surfaces, with consequent unsteady flow behaviour. During spin recovery these changes are reversed with additional transients occurring due to the dissipation of angular momentum.

Although some progress has been made towards understanding the aerodynamic behaviour occurring during the spin, reliable methods for spin prediction do not yet exist. Even the methods for the prediction of steady spin behaviour only yield gross trends and so extensive scale model testing is required to reduce project risks and provide a basis for the flight development phase. For many aircraft projects, including gliders, access to spin model test facilities may not be possible or may be too costly. For these projects extensive flight development may be necessary.

3. Spin design techniques

3.1 Initial design processes

The extent to which spinning characteristics are considered in the initial design phase will depend largely on the intended role of the aircraft. For example, a two-seat glider will be required to have an unrestricted spin clearance for training purposes. In this case, the designer would obviously start by looking at the spin characteristics of existing designs with an attempt to relate these characteristics to particular aspects of each design. There are several empirical criteria which are useful aids in this process.

One of these was developed by Kerr (2) and is a very simple method requiring only knowledge of the shape of the aircraft and the relative inertia distribution. The aerodynamic rolling moments in a spin of 45 degrees incidence are calculated using the simple expressions given. As it is a spin recovery criterion the moments are calculated for anti-spin rudder. The wing contribution to the rolling moment was derived from NACA rotary balance test data using a rectangular wing. The contributions due to the body fin and rudder are given as a function of the first moment of profile area about the center of gravity combined with a weighting factor. The relative merits of different fuselage shapes and fin/tailplane combinations are reflected in the assigned value of these weighting factors shown in Table 1.

TABLE I.

KERR'S WEIGHTING FACTOR FOR SPIN DAMPING

BODY CROSS-SECTION	WEIGHTING FACTOR
Circular	0.6
Rectangular	1.5
Elliptical	2.1
Round top & flat bottom	1.1
Round top, flat bottom & strakes	1.7
Round bottom & flat top	2.5
Round bottom, flat top & strakes	3.5
Free fin	1.5
Fin in tailplane wake	-0.4
Fin under tailplane	3.0
Free rudder	1.5
Rudder in Tailplane wake	-0.25
Rudder under tailplane	2.0

Note that an adverse tailplane and fin interaction can produce a propelling moment in the spin, hence the negative weighting factors. The extent of this adverse interaction is dependent on elevator position and so this should be included as a variable in the analysis. It was noted before that the wing contribution was derived from isolated wing test data, so an obvious omission in this method is the interference between the wing and other components of the aircraft.

The total aerodynamic anti-spin rolling moment is plotted against the ratio of pitch to roll moment of inertia on a graph upon which empirical boundaries of spin recovery characteristics have been drawn. The designer should perform these calculations for a number of existing configurations similar to his new design, to refine the location of these boundaries for his own application.

Another empirical method was developed by Bowman (3) as a guide for the design of tails to ensure good spin recovery. Figure 7 shows the results of a series of spin tunnel tests, where a number of design changes to the tail of a representative light aircraft were made. The original design, tail num-

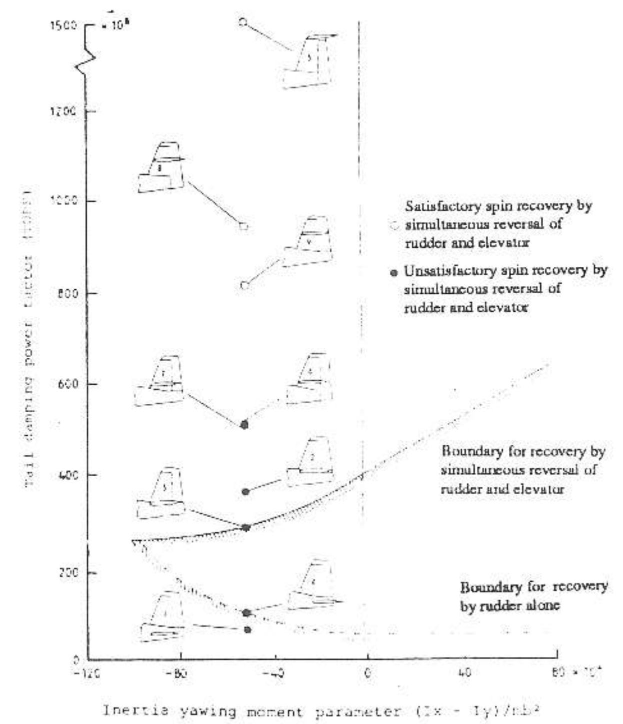


FIG. 7 TAIL DAMPING CHARACTERISTICS FOR VARIOUS DESIGNS

ber 1, has a low value of the tail damping power factor, with correspondingly poor spin recovery characteristics. At the other extreme, tail number 5 has the highest value of the tail damping power factor and gave the quickest recoveries.

Bowman also commented on the influence of wing position on spin characteristics. The higher dihedral effect of the high wing plus the absence of any adverse interaction with the tail because of the higher wing wake leads to some improvement when compared with low wing aircraft.

Both of these empirical methods can also be used as a guide in the flight development of gliders to improve their spinning characteristics as they cover the two common modifications, tailplane strakes and ventral fins. Both of these provide increased damping in the spin, causing the aircraft to spin more steeply and so enable an easier recovery.

Much of the design data base for spinning is derived from light aircraft or military fighters and in its application to glider design the following two points must be remembered:

(i) a glider has a much higher ratio of roll inertia to pitch inertia, which increases the importance of the elevator as a recovery control, and also increases the possibility of the spin being oscillatory.

(ii) as with military fighters, the nose of the glider fuselage can influence the spin, and so there is additional scope for design improvements. A flat elliptical cross-section which might result from a side-by-side cockpit can provide a propelling moment in a spin. Fitting horizontal strakes on the nose at maximum width can be very beneficial as they:

(a) significantly increase the spin damping by retarding the flow around the nose

(b) provide a nose-up pitching moment, which tends to reduce the rate of rotation.

So, in the design of conventional gliders, there is a large

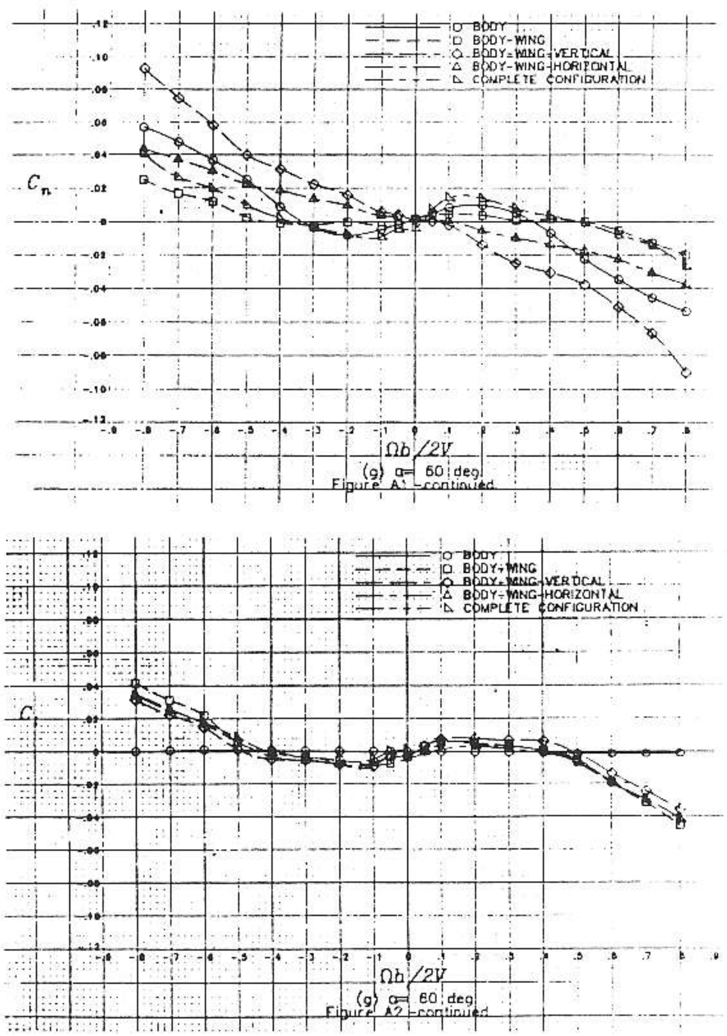


FIG. 8 ROTARY BALANCE DATA

amount of data to assist the designer in the development of satisfactory spin and recovery characteristics. However, if a novel configuration is contemplated, or if other design requirements lead to a configuration which is likely to have poor spinning characteristics, then some model spin tests should be conducted.

Rotary balance model tests can provide a reliable prediction of steady state spin modes, as well as providing a good data base for design and development. Dynamic model spin tests provide information on the recovery characteristics as well as the steady spin modes.

3.2 Rotary balance testing

The obvious disadvantages of these tests are, first, like most model tests there are the problems and unknowns of scaling and, secondly, little information on recovery characteristics is produced. However, the method has one big advantage in that basic aerodynamic data on the complete configuration and several permutations of partial configurations indicate exactly where any potential problem areas exist.

For example, Figure 8 shows some typical results from a rotary balance test series and even without the computer analysis, we can make a number of useful observations. First, the complete model is autorotative with a stable spin mode indicated at $\Omega b/2V = 0.4$. We can also see that without the tailplane, the damping is high leading to the conclusion that there is adverse interference between the tailplane and the fin.

A complete test series would include a number of different control deflections, so from a quick scan of the results, we would get a good indication of the control effectiveness for recovery.

With a complete matrix of rotary balance data, a range of angle-of-attack, spin rate and sideslip angle, as well as, an estimate of the moments of inertia, it is possible to solve the equations of motion for a steady spin.

The solution for the pitching moment equation is shown in Figure 9, and is a plot of angle-of-attack against spin rate, for which the aerodynamic moment equals the inertial moment. It clearly indicates the well-known relationship between fast, flat spins and slow, steep spins. Gliders usually spin steeply, and hence with low $\Omega b/2V$; however, the rate of rotation is often quite high because V is low, three seconds per turn is

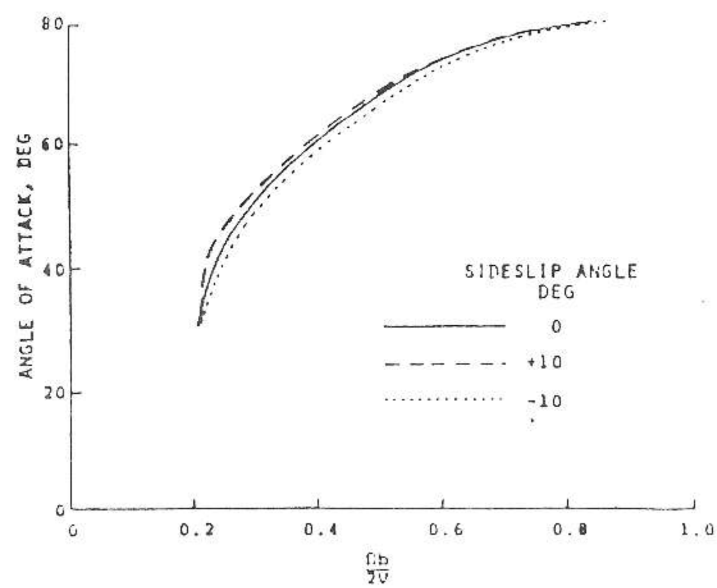


FIG. 9 ANGLE-OF-ATTACK AND SPIN RATE FOR PITCHING MOMENT BALANCE

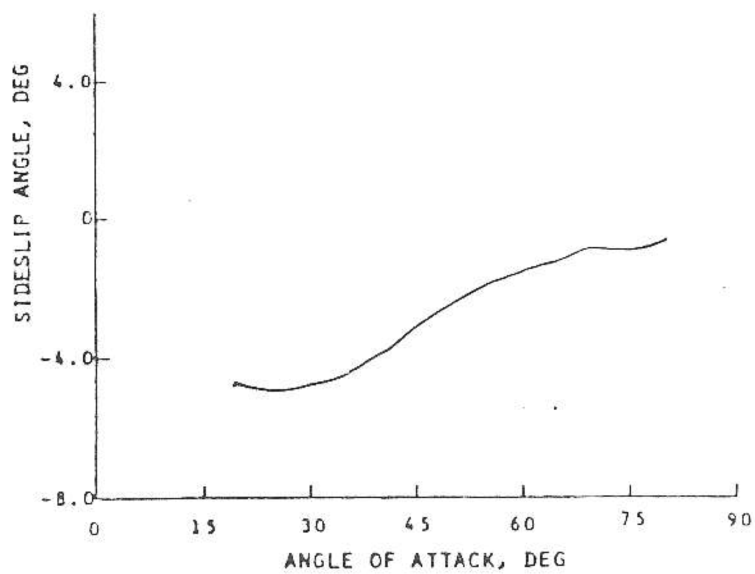


FIG. 10 SIDESLIP ANGLE FOR ROLLING MOMENT BALANCE

not unusual.

Figure 10 shows the solution of the rolling moment equation.

The final curve in this series, Figure 11, is the solution of the yawing moment equation indicated by each intersection of the aerodynamic and inertia terms. Only stable solutions, as shown here, represent a spin mode. This particular example has a steady spin with an angle of attack of about 40 degrees, a spin rate $\Omega b/2V$ of 0.2 and a sideslip angle of -4 degrees. From a balance of forces with drag equal to the weight we can calculate the vertical velocity, and also determine the rate of turn in the spin.

One of the important results in these tests, is the effect of controls. For example, in a trainer we would be looking for a strong intersection of the curves with pro-spin controls and a wide separation with anti-spin controls.

With such testing techniques, it is possible to find out a great deal about the mechanisms of the spinning behaviour of any design in a very short time and at a reasonably low cost.

Dynamic model tests

The concept is very simple, a dynamically scaled model made to spin in a vertical current of air in a spin tunnel will provide the complete steady state spin characteristics. With provision for activation of the controls then the recovery characteristics are also readily determined. Test runs occupy little time, and so a variety of control positions and loading conditions can be assessed very quickly. Minor design changes can also be easily accommodated, and so the dynamic model tests represent a very powerful aid in a development program.

As with the rotary balance tests, there are problems associated with scale effects. Another problem, associated with the separated airflow, is the possibility of cliff-edge effects where a series of changes may have no effect up to a certain point beyond which even a slight change may have drastic consequences. These two problems in particular require experienced interpretation of the test results.

The use of these two model test techniques on the one project is most effective, but is likely to be beyond the budget of a small aircraft company. Rather than neglect model spin tests completely, it is worth considering the use of a miniature spin tunnel as built by Robelen (4). The tunnel has only a 0.6 m diameter working section, so the models are very small and this has raised serious questions about the validity of the results. The tunnel has been used for one test series of modifications to the Victa Aircruiser, and the results appeared quite satisfactory. As the technique is very inexpensive there is merit in further testing to develop comparisons with other spin tunnels, as well as full-scale results so that its limitations can be defined.

4. Interpretation of pilot experience

Considerable knowledge of aircraft spin behaviour exists as undocumented pilot experience. In particular, in the area of spin entry and spin recovery, there are no theoretical or experimental techniques for defining correct control deflections and control sequencing for optimum entry and recovery. These techniques are determined during flight test development and may be refined during operational use.

One particularly sensitive area during spin recovery of a conventional aircraft is the sequencing of anti-spin rudder movement with forward movement of the elevator control to regain flight trim conditions. If the elevator control is moved forward too soon, two adverse effects can occur: first, as the aircraft is pitched down, the radius of gyration is momentarily reduced and because of the conservation of momentum, this will lead to an increase in spin rate; second, as elevator control is moved downwards, the area of effective rudder may be

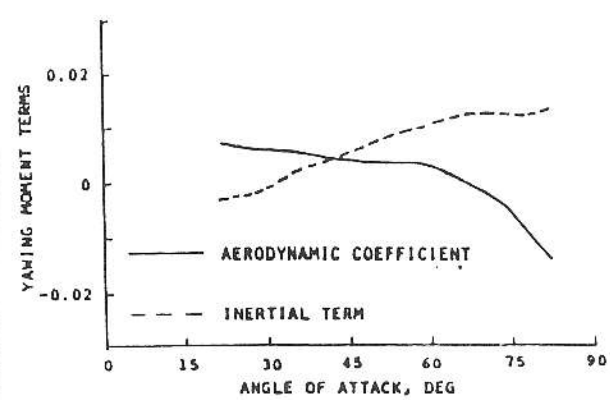


FIG. 11 AERODYNAMIC AND INERTIA YAWING MOMENTS IN A STEADY SPIN

reduced, resulting in a reduction in available anti-spin yawing moment. Alternatively, if the elevator control is moved forward too late, the aircraft may enter a spin in the opposite direction.

For aircraft with poor spin recovery characteristics, correct pilot technique becomes critical and the subtle nuances of particular aircraft give rise to much pilot discussion. Accurate flight dynamic models of aircraft spinning are required to enable this pilot knowledge to be interpreted in terms of the aircraft aerodynamic, inertia and control characteristics.

5. Concluding remarks

Since the early days of flying, both stalling and spinning have been major causes of aircraft handling accidents, and an economic design solution to the problem of spinning has not yet been found.

The characteristics of the spin manouevre have been described in this paper and a brief outline has been given of the design techniques and spin test methods available to the aircraft designer.

The limitations of current design prediction methods are indicated and the need to interpret pilot experience of aircraft spin behaviour in terms of aircraft characteristics is presented.

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Notation

b,	wing span
$\bar{c}$,	wing mean aerodynamic chord
Cm,	pitching moment coefficient
Cl,	rolling moment coefficient
Cn,	yawing moment coefficient
Ix, Iy, Iz,	moments of inertia about the X,Y,Z body axes
m,	aircraft mass
Sw,	wing area
V,	free stream velocity
α,	angle-of-attack
β,	sideslip angle
ρ,	air density
σ,	inclination of flight path to vertical
Ω,	rate of rotation about the vertical axis