On the Early History of Spinning and Spin Research in the UK
Part 1: The period 1909 - 1929

B J Brinkworth
Waterlooville, Hants, UK

Abstract

From the beginning of manned flight, spinning was a hazard that has taken many lives. Control actions for recovering aircraft from the spin were soon found by experience, but not all types would respond. A more fundamental understanding of the nature of spinning was gained progressively through directed research over the first decades of the 20th Century. This required the developments of a theoretical base, novel experimental techniques with models, and full-scale tests with instrumented aircraft in free flight.

Part 1 of this study traces a continuous thread of progress from 1917 to the end of the 1920s, despite the financial retrenchment in the period following World War 1. This work remained largely within research programmes at the Royal Aircraft Establishment and the National Physical Laboratory. Though techniques of spin recovery continued to be of an empirical nature, the first steps were taken to convey aspects of what had been learnt about the spin to designers in an increasingly knowledgeable and receptive aircraft industry.

1 Origins
1.1 The general nature of the spin.

Spin is a stable aerodynamic state, in which an aircraft descends at a uniform rate along a helical path with small radius and long pitch, about a vertical axis. The path is accordingly very steep, perhaps inclined at less than $10^\circ$ to the vertical.

What is called the path in this motion is that followed by the centre of mass, or more commonly the centre of gravity $G$. A typical disposition of a spinning aircraft, illustrated by the sketch of Figure 1, is strikingly unlike that of normal flight. The angle of bank is nearly $90^\circ$, and the longitudinal axis is substantially displaced from the path, in pitch and in yaw. These departures are required for the airframe to experience the aerodynamic forces and moments that satisfy the equations of motion in vertical descent and rotation. Since both the aerodynamic effects and the dynamic requirements are dependent on the orientation, for a given aircraft there is often only one attitude in which the motion is steady.

Methods for obtaining a good definition of this situation took many years to be resolved to a good level of certainty. But during the first few decades of the 20th Century it was a new subject of enquiry, that drew out impressive instances of physical insight, mathematical modelling and the development of novel experimental methods. In due course, these established a working level of understanding of the spinning behaviour of aircraft that allowed it to take its place in aeronautics, together with others required for their operational role, generally in the technical area of Stability and Control. But as with those, the spinning characteristics
predicted for a new aircraft would still require verification by model testing and deliberate spinning in flight as a standard part of acceptance testing before entry into service.

Figure 1  An impression of an aircraft in a fully-developed spin

The pitch angle taken up in a spin is invariably such that the incidence of the wings and the tailplane are beyond that of the stall. There is thus a potential to induce a spin in any situation in which an aircraft has been stalled. If this occurs in forward flight, a pilot is trained to lower the nose to build up speed to unstall the wings and pull out, before any significant departures in roll and yaw can occur. But from earliest times, there were situations in which stalled flight quickly developed into a spin. The most dangerous of these was when a turn was being made with only a narrow margin above stalling speed, when the slowing of the inner wing was likely to stall that side first. This wing will then lose lift and drop, more-or-less abruptly, beginning a curving movement towards what is termed the ‘incipient spin’. Without immediate corrective action the subsequent motion will progress quite quickly towards the steady downward path of the fully-developed spin with the unfamiliar and disorientating attitude as sketched in Figure 1. If there is an instinctive reaction by the pilot to move the controls in an attempt to level the wings and raise the nose, that tends instead to deepen the stall, and to accelerate the development of the spin. As this is a stable state, without specific corrective actions by the pilot it can continue, perhaps until the aircraft reaches the ground. From the beginning of manned flight, failure to recover from the spin has been the cause of many fatalities and serious injuries.
1.2 First experiences of spinning

It cannot be stated for certain when spin first occurred, or when it was first observed. In the earliest days of aviation, flights took place not far above ground level. As height was lost in the preliminary stages of entry and incipient spin, aircraft must often have reached the ground before the characteristic stable helical motion of the spin had fully developed and could be recognised. The stall that invariably preceded it was more likely to occur abruptly with the earliest aircraft, which had thin wing sections modelled on those of birds and relatively low inertia to slow the response to the loss of lift. Notes made by the Wright brothers indicate that they experienced stalled turns in their gliding experiments, sometimes followed by crashes, but happily, due to the low speed and good energy absorption of the structure of these early craft, without great injuries to themselves (1).

Attempts to follow the Wrights in powered flight soon led to a rising number of accidents. They repeatedly warned of the dangers of stalling, reckoning that ‘fully 90% of the fatal accidents in flying are due to this cause’, and cautioned that the risk was much greater if a turn was attempted at low airspeed. An early accident of this kind in the UK was the crash in October 1908 that ended Samuel Cody’s first sustained flight (2). Returning to his starting-point, he had managed to negotiate the disturbed air over a clump of trees when he immediately faced another clump and turned sharply to avoid it. This is when the inner wing was likely to stall first, accentuating the wing drop and tightening the turn. For whatever reason in this case, the altitude was low enough for the tip to strike the ground, where it ‘crumpled up like so much tissue paper’. Although his flight had been too low for the descending turn to develop into a spin, its ending was an unfortunately common type, of which it would shortly be said that the pilot had ‘spun in’. As early as 1909, when the Advisory Committee for Aeronautics (ACA) was set up to advise the War Office and the Admiralty on matters relating to flight in military service, a reference to spinning was included in its first annual report, as one of the items it expected to investigate (3).

Airspeed can be misjudged from the relative motion of the ground on the downwind leg of a circuit, and might already be low before turning onto the base leg, where it is often reduced further onto the final approach to land. In the early stages of flight-training, these are critical points where a stall could occur, with insufficient height from which to effect a recovery. In the years leading up to the start of WW1 and in its initial stages, many young men had to begin training when there was little background of practical experience, and the particular combination of motions that characterise spin entry had not yet been appreciated widely. Retrospectively, the Farnborough test pilot Frank Courtney acknowledged that “the spin was there all the same, killing lots of people, only we didn’t recognise it” (4).

It is generally accepted that in the UK the first recovery from a fully-developed spin to be witnessed by informed observers was that experienced by Lt Wilfred Parke RN in August 1912. Participating in the first competitive military trials for the War Office, accompanied by Lt. Le Breton RFC, he was returning from the 3-hour qualifying flight over Salisbury Plain in the Avro G biplane, shown in Figure 2. They arrived over the airfield base at Lark Hill at a height reported variously to have been 600 to 700ft and began to lose height in a tight descending turn to the left with engine at idle. Thinking that his descent had been too steep, Parke tried to raise the nose, and must have stalled the inner wing. From this height there was
enough room for a full spin to develop. After trying various actions to escape from this spiralling descent without success, he finally applied full right rudder and the aircraft recovered smoothly, to be pulled out into level flight, though only at about 50ft above the ground. The events were discussed immediately after he had landed at a meeting of Parke with other experienced pilots who had seen them. Also involved was A E (Algernon) Berriman, then Technical Editor of the magazine *Flight*, who had been on the site to observe the trials. In a significant initiative, Berriman reported the incident and the conclusions of the discussion group about it in *Flight*, just a few days later \(^{(5)}\).

Figure 2   The Avro ‘G’ cabin biplane at the War Office trials, Lark Hill, 1912
(National Aerospace Library Collection)

Berriman also included an account of this event in his book of 1913 \(^{(6)}\), but it seems that it was his magazine article that was more likely to have been read and remembered. Jones \(^{(7)}\) reports a comment from Maj. Smith-Barry of the RFC that

‘Up to the autumn of 1916 not many pilots who had the misfortune to get into a spin in the air had ever regained control. One exception was Maj J A Chamier who, while in France, found himself spinning as he came from a cloud. While he was falling, he recalled an incident on Salisbury Plain before the war when Lt W Parke RN had recovered from a spin near the ground. When people had crowded round to congratulate Lt Parke on his luck, he had explained that he had stopped spinning by doing ‘everything wrong’. Maj Chamier likewise did the opposite of what his experience as a pilot suggested and he also recovered. He subsequently related his adventure to Royal Flying Corps head-quarters.’

‘Parke’s Dive’, as it became known from the heading of Berriman’s article, had been inadvertent, but deliberate spinning was undertaken subsequently by a number of investigators, through which the general features of the spin came to be recognised and the earliest techniques for recovering from it were found. Hadley has assembled a notable collection of accounts of spinning in powered and gliding flight, beginning with around 20 from the period of interest here, and with more from later years \(^{(8)}\). From a thorough review of the primary documentation, Hadley concludes that the first deliberate spin and attempted recovery (having been announced beforehand) could be attributed to Sqn Ldr J C Brooke, an instructor at the
RNAS base at Killingholme in the summer or late autumn of 1915. There followed numerous other reports, which have been widely reviewed in the literature, partly in attempts to establish who could be said to have been the first to arrive at an understanding of the spin that was technically sound. Among those known to have made spins deliberately before 1917 were H G (Harry) Hawker of the Sopwith Aviation Company and Maj F W Goodden, of the Royal Aircraft Factory. Several other pilots at Farnborough followed. These early recoveries were made by methods similar to that found empirically by Parke. It is fitting that his name should be associated with all commentary on spin recovery, so as to form a memorial to this young pilot, whose life, having been saved at the last moment at Lark Hill, had been lost in a flying accident before the end of the year.

Use of the rudder to oppose the rotation subsequently became a standard element in spin recovery, as taught in training. But for some time there was uncertainty as to the sequence of control movements that would be most effective. In some cases recovery could be obtained simply by centralising all controls and then gently moving the stick partially forward. This would always be required at some point to lower the nose and increase speed, so as to un stall the wings before pulling-out to regain normal level flight. But sometimes the nose could not be lowered unless rudder action had been applied first. No doubt this variation was a reflection of the diverse attitudes taken up by the different aircraft involved and the responses to their controls, and so uncertainties of this sort continued to be reported subsequently.

From the earliest days, initial flight-training has always emphasised the primacy of never approaching the stall in the first place. But as more challenging situations were met, accidents due to spinning continued to occur frequently in those years. In a review of 1918 for the ACA, its Accidents Investigation Committee considered 27 crashes involving spinning, nearly all having taken place in the single month of May of that year\(^9\). One make of aircraft (not identified in the report but afterwards thought to have been a Sopwith type) had accounted for more accidents than the four other types in the study, taken together. Flight tests had shown that in its earliest form this type had been basically unstable. Some modifications were suggested, necessarily pragmatic at the time, and it was recommended that pilots for this aircraft should have special additional training, to become accustomed to the sensitivity of its response to the controls. The more general conclusion was a message to designers that ‘an equally good fighting machine can be designed that is stable, and that it is unnecessary and dangerous to design an unstable aeroplane with a view to obtaining great controllability’ (perhaps ‘agility’ would be the term used today).

When pilots who had been engaged in air operations on the Western Front began returning home as instructors they brought with them experience in spin recovery which by the end of the war had become a common occurrence. In the turmoil of air warfare, recovery procedures had been found by trial and error as a necessity for survival. Spinning had commonly followed the disorientation that often occurred when pilots, without guidance from instruments, had to climb through cloud or enter cloud to escape interception, as in the experience of Maj Chamier recounted above. Quite shortly, enough confidence was gained in being able to recover that spinning took its place as a deliberate manoeuvre with uses in air combat\(^10\).

And so the hard lessons learnt for survival in war slowly began to inform the schedules for pilot training. In his popular book *The Aeroplane Speaks* of 1916, Horatio Barber, a serving
officer in the RFC, had described the spin as ‘the worst predicament the pilot can find himself in’. It is notable however that before any significant analysis of the dynamics of the spin had been published, Barber had also given his view of what was happening physically, which, as will be seen later, was remarkably prescient. In *The Aeroplane Speaks* he wrote that the spin was ‘due to the combination of (1) a very steep spiral descent of small radius, and (2) insufficiency of keel surface behind the vertical axis, or the jamming of the rudder or elevator into a position by which the aeroplane is forced into an increasingly steep and small spiral. Owing to the small radius of such a spiral, the mass of the aeroplane may gain a rotary momentum greater, in effect, than the air pressure of (on) the keel-surface or controlling surfaces opposed to it: and, when once such a condition occurs, it is difficult to see what can be done by the pilot to remedy it’.

And yet, concerning the fully-trained pilot just two years later, he felt able to write confidently about recovery, to the extent that ‘a finished pilot could spin down to within about 200ft of the earth in safety’. Others, who were more cautious, remained wary of empiricism, and began to seek a more fundamental understanding of processes taking place in the spin.

### 1.3 Spinning research

A new phase in that development, one of systematic scientific enquiry into spinning, began before the end of WW1, in the first taking of measurements during deliberate spins, made in 1917. This followed the view that resistance to the onset of spinning and/or ease of recovery if one had developed, should be embodied in the design of an aircraft from the beginning. To support that fully would require the many factors involved in spinning and the interactions between them to be recognised, understood and modelled. Initially, it was hoped that it might be possible to establish some simple rules on the subject for designers. But a full understanding of events in the spin would be required eventually, so as to be taken into account in the future as developments in aircraft design led to new configurations and variation in operating conditions that had not been experienced previously.

In Britain, work in this area would continue at Farnborough, in its revised form as the Royal Aircraft Establishment (RAE). In a major reorganisation in 1918, it now operated under the authority of the new Air Ministry, which had central ministerial responsibility for the Royal Air Force, also formed in that year from amalgamating the Royal Flying Corps and part of the Royal Naval Air Service. RAE was to concentrate on aeronautical research, after the design and manufacture of aircraft at the former Royal Aircraft Factory had been ended, following objections from the industry that this amounted to state-sponsored competition. It happened that Britain also had another centre for research in this field, at the Aerodynamics Division established in 1909 at the National Physical Laboratory (NPL) at Teddington, and reporting from 1918 to the Department of Scientific and Industrial Research (DSIR). The Advisory Committee for Aeronautics (ACA) had its secretariat and publishing arm at NPL, so that its advice to the Secretary of State for Air was now based on research communicated by both NPL and RAE. The reports from the establishments were reprinted in a standard form as appendices to the annual Technical Reports of the ACA – from 1920 renamed the Aeronautical Research
Committee (ARC) – and provide a vital insight into the progress of aeronautical research over time. They were also published as the series of Reports and Memoranda of the ACA/ARC (the ‘R&Ms’), made available more widely to researchers at universities and users in industry, as separate documents (the ‘blue books’), obtainable via H M Stationery Office.

The Air Ministry also had overall responsibility for the Aeroplane and Armament Experimental Establishment (A&AEE), which was located at Martlesham Heath in Suffolk in 1924. Its antecedents had been the former Aircraft Testing Flight of the Central Flying School at Upavon, which had moved to Martlesham in 1917, and the Armament Flight that had moved to nearby Orfordness. Its function was to evaluate aircraft that were being considered for potential entry into service with the RAF. (A similar function was performed for naval aircraft at the neighbouring Marine Aircraft Experimental Establishment (MAEE), which moved to Felixstowe in 1924.) From about 1918, spinning and spin recovery were among the characteristics to be investigated as a matter of routine. Reports on this work were not generally circulated, but could be considered by the ACA/ARC when particularly relevant, so key papers from A&AEE also appeared occasionally, reprinted as R&Ms. Other material of technical and historic interest from NPL and RAE is to be found today in The National Archives, the National Aerospace Library and the library of the Farnborough Air Sciences Trust (FAST). In due course, papers reporting original work and overviews of specific developments appeared also in the journals of the professional scientific and engineering institutions, and in the growing body of technical journals and magazines concerned with aviation.

The totality of the canon is therefore very large. At intervals over time, some excellent reviews were compiled and published, which should be consulted when searching for specific details. To keep the present study within a reasonable compass, the aim here will be mainly to trace within this extensive body of work the general thread of the development of understanding of the spin. In due course this provided the perception of spinning that had reached a fairly solid position around the beginning of WW 2. Although further refinements have continued to be required and made subsequently, the period to be covered here extends over the first three decades, of which Part 1 covers about the first half.

A selected catalogue of key sources on spinning, including early papers, was compiled in 1988 by Martin (13), though many more might have been included. Most of the earliest cited were among the R&Ms of the ACA and its successors, which are also drawn upon heavily here. Perhaps the first of relevance involving analysis was that of G P Thomson in 1915 (14). This set out the consequences of making an unbalanced turn in flight, even at a forward speed thought to be clear of the usual stalling speed. Analysis of the unsteady motion in the early stages could be made approximately, but taken only as far as the onset of the stall of the inner wing at that time. However, some representations of the dynamics of the spin itself when fully established were made shortly afterwards. It was soon apparent however that there would be a long path from the initial mathematical formulation to practical applications in design. This was partly because the effect of design features, especially in the empennage, could not be predicted accurately in the absence of reliable values for the relevant aerodynamic forces and moments and the coupling between them. To obtain these would require the development of new facilities and experimental techniques. In the meantime, exploratory modelling continued, accompanied by various programmes of test work, by which some straightforward perceptions began to emerge about overall design features that could be used to ensure as far as possible that new
aircraft could be expected to have acceptable spinning and recovery characteristics. This would be an addition to work taking place in relation to other areas of stability and control, where there was a similar lack of basic data. Analysis of the spin would need to be supplemented by specific testing programmes, both with the basic tool of the wind tunnel model and at full scale with aircraft in flight, as new areas requiring investigation were identified and new methods of measurement were brought into use.

2 First observations on conditions in the spin
2.1 In-flight measurements

Systematic investigation of spinning at full scale began at Farnborough in the summer of 1917, notably in the famous experiments by F A (Frederick) Lindemann (later Lord Cherwell) \(^{(15)}\). There has been some uncertainty about the timing, due to the data obtained having been reported in R&M 411, which was not published until 1918, perhaps a consequence of the reorganisation taking place at that time. Flying Royal Aircraft Factory BE 2E and FE 2B biplane aircraft, Lindemann made a series of deliberate spins directly above a camera obscura on the ground, from which observers could estimate quantities such as the rate and radius of turn. Though he had learned to fly only a few months previously (by some accounts specifically to do these tests), he became sufficiently adept at spinning and recovery that in one of them he was able to move from the spin to a spiral dive and back to the spin during the descent, making clear the distinction between these states, that in the dive the wings are not stalled.

The aircraft types involved in this pioneering work are shown in Figure 3. Like all Service aircraft, they were biplanes at this time, due to a continuing prejudice against monoplanes that had begun with the War Office in 1912, following structural failures in flight which had defied explanation. With these early machines the observed rate of rotation in the spin was moderate. Lindemann reported that for a typical spin with the BE 2E the period was about four seconds per turn and the radius of the turn about 20 feet. He noted that ‘The attitude of the machine was such that the wing struts were horizontal and there was no appreciable sideslip’. On the BE 2E the wings had forward stagger of about 20°, so the implication was that the dives were very steep, with the fuselage axis at about this angle to the vertical.

Instruments on board gave the forward (indicated) speed, normal acceleration and orientation. Most of the observations were made with the basic standard instruments installed in the service aircraft of the time. Thus, the rate of descent was obtained from the aneroid (altimeter) and a stopwatch, and the longitudinal and lateral orientations of the aircraft were inferred from the readings of the standard bubble levels normally used to judge correct alignment in level flight and turn-and-bank manoeuvres. In an open cockpit, sideslip could usually be detected by the pilot from the direction of the airflow felt on his face, but Lindemann considered that his impression of the absence of slipping was supported by the reading of the lateral bubble level. He had noted that the bubble was in fact reading ‘one or two degrees to the left, indicating an outward sideslip’, but had attributed that to the level being positioned in the aircraft somewhat aft of the centre of gravity.
The normal acceleration in the turn was measured with an instrument devised by Lindemann and G F C Searle, mounted in the pilot’s seat. This was described as a ‘spring accelerometer’, though no details were given (23), so probably consisted of a sliding mass that compressed a spring with enough deflection to be easily read off a scale by the pilot. This was the forerunner of RAE standard instruments that were in regular use for many years (16).

After the first flights, when the attitude taken up by the aircraft had been confirmed, it was seen that the standard airspeed indicator could not give a reliable value in the spin. The aircraft were then fitted with additional dynamic pressure heads, pointing forwards and downwards at an angle of 30°, which was typical of the pitch angles being encountered. There had been concern also about the accuracy of the loss-of-height measurements, arising from the lag in the response of the aneroid, but it was hoped that the errors would be similar at the beginning and end of a set of readings, since once established the rate of the descent was seen to be constant.

An attempt was made to measure the angle of incidence of the wings directly. Rods 12ft long were attached to the middle of wing struts of the BE 2E aircraft, projecting forward with a graduated vertical member fixed between them 7ft ahead of the leading strut, within a clear view of the pilot. The direction of the relative wind was indicated by the position of a tape attached to the front of the lower rod, and streaming back past the scale. It was assumed that the flow would be undisturbed at a point so far ahead of the wing, but the tape fluttered too much for the incidence to be determined within better than 2 or 3 degrees.

Though very basic, these novel observations were typical of the emerging tradition of systematic data collection which would characterise the work of RAE, often involving much ingenuity in planning, the devising of new methods of measurement and willingness to take risks with personal safety.
2.2 Autorotation

Lindemann reported subsequently that before undertaking this pioneering test work he had formed a hypothesis about the aerodynamic situation of the wings in the spin\(^{(15)}\). That it was a steady state was shown by the rates of descent and rotation remaining constant, unlike the spiral dive in which the speed became progressively faster. His deduction was that, for the rotation to be steady, the lift of the wings would have to be about equal on both sides, and thereby produce no nett turning moment. He thought that this could be so if the angle of incidence (angle of attack) on one wing was above the value for maximum lift and on the other wing was below it. Lindemann had perhaps felt that his perceptions during his test had been consistent with this hypothesis. However, another RAE test pilot, Maj F W Goodden, had reported earlier on one of his spins that the axis of the path did not pass centrally through the wing – he thought that “The whole aeroplane (an FE 8) was turning about a point mid-way between the right-hand wing tip and the body” (see Glauert later\(^{(23)}\)).

Work on the autorotation of wings had begun at NPL, though the date of that too is uncertain, as it was not published until 1918\(^{(17)}\). It was made specifically in connection with spinning, on the suggestion of Leonard Bairstow, Head of the Aerodynamics Department, who had made measurements as early as 1913 of the rolling, pitching and yawing moments experienced by a wing when set oscillating in an airstream. The idea now was that autorotation was likely to be the driving force for starting and maintaining the spin. As carried out by E F Relf and T Lavender, measurements were first made of the autorotation of model wings of around 18in span, free to rotate about a fixed axis at mid-span, in the 4ft No1 wind tunnel (still called by the earlier term of ‘wind channel’) and these were supplemented by further tests with a scale model aircraft. The specimens were mounted on a pivot with arrangements to adjust the angle at which they were presented to the airstream, as shown in Figure 4. Since aerodynamic moments must be responsible in some way for the spinning of aircraft, this critical experiment is worth noting as an identifiable early step in the history of the subject.

The underlying mechanism of autorotation is the imbalance of aerodynamic forces that first cause the wing to rotate and then to reach equilibrium in a particular combination of the contributions of the angular speed of rotation \(\Omega\) and the speed of the approaching free stream \(V\). This can be illustrated by reference to the variation of lift and drag coefficients with angle of incidence shown in Figure 5. The data are taken from a report on measurements of the lift and drag of the RAF (Royal Aircraft Factory) No 6 aerofoil, made in 1915, that covered the whole range of possible incidence from 0 to 360°\(^{(18)}\). When an aircraft rolls, the incidence of the down-going wing is increased by the addition of a normal component of velocity to the relative wind.

![Figure 4 Autorotation rig at NPL, 1919](National Aerospace Library Collection)
Similarly, that of the up-going wing is reduced. If the incidence on both wings is below that of the stall, the aerodynamic reaction at these small angles consists mostly of lift. Since in that region the wing with the greater incidence has the greater lift coefficient, the lift forces apply a moment to the wings tending to oppose the roll, a factor in the lateral stability of aircraft in normal flight. After the stall, however, the slope of the lift curve is downwards, and in the incipient spin the down-going wing, though having the greater incidence, has the lesser lift coefficient, and the turning moment is in a direction that assists the roll. Relf and Lavender\(^{(17)}\) confirmed that for a model wing (in that case with aerofoil section RAF No 3), autorotation could be obtained only with an initial angle of incidence greater than the ‘critical’ angle (that at maximum lift at the beginning of the stall). Below that angle, if the wing was given a rotation by hand it was damped out very quickly.

![Fig 5](image.png)

Figure 5  Aerodynamic characteristics of the RAF (Royal Aircraft Factory) No 6 aerofoil, for incidence from 0 to 90°

This work established that at a given initial incidence beyond the stall, the speed of autorotation was directly proportional to the tunnel airspeed. Since the resultant angle of incidence \(\alpha_r\) at any radius \(r\) from the centre of rotation is given by \(\tan \alpha_r = \Omega r/V\), the proportionality of \(\Omega\) to \(V\) confirmed that specific angles for the relative wind at the wing were required to sustain the motion.

When tests were made with a light wooden model of a complete aircraft, as seen in Figure 4, it was found that the speed of rotation was again directly proportional to the wind speed. Scaling up the results from the test at 30 ft/s and initial incidence of 30° gave good agreement for the rate of rotation with those of the corresponding test in Lindemann’s experiments. Although perhaps fortuitous, as the aircraft modelled was not of the same type as that used at full scale, it was considered to be an encouraging result.
Relf and Lavender also made an approximate calculation for the equilibrium condition, based on the lift and drag curves of the relevant aerofoil. As the contribution of the rotational component varied with the radius from the central axis of rotation then employed, this required integration across the span to find the condition of a steady state, when the contributions from the two sides had come into balance and the overall turning moment had fallen to zero. For this they assumed that the aerodynamic characteristics at any given radius were the same as those of the aerofoil in a standard fixed test at the same incidence and was unaffected by conditions at neighbouring points. (That is, applying what came to be called 'strip theory', in which the forces and moments were calculated on a series of thin strips across the span, with conditions at a given strip assumed to be independent of those on adjacent strips.) At higher incidence both lift and drag contribute significantly to the turning moments, so at each section, the directions and magnitudes of the two components and the distance from the axis of rotation had to be taken into account in evaluating the turning moments. Although it was well-known already that there was a fall-off of lift towards the tips of wings, no allowance for that could be made on a theoretical basis at that time. Even so, the agreement of the calculated equilibrium state with the wind tunnel measurements in that study was quite close.

2.3 Glauert and the first analysis

The second author of R&M 411 was H (Hermann) Glauert. He had joined RAE in 1916 and quickly began to establish a position that would make him the leading British aerodynamicist of his time. In their comprehensive memoir on his work in this journal, Ackroyd and Riley refer to his deep physical insight and outstanding mathematical ability (19). Covering the wide scope of his contributions, they cite 89 publications under his name, mostly R&Ms, 71 of which were of his sole authorship. This was within a period of only 18 years, due to the tragic shortening of his life in 1934 in a random accident, unconnected with his work.

In R&M 411, Glauert drew together the results of the flight tests by Lindemann with knowledge of the approach to autorotation by Relf and Lavender as the foundation of what is considered to be the first analysis of the motion in a spin. His methods are in the mathematical tradition, in which the equations of motion that govern the problem and procedures for their solution are set out without lengthy explanation, so as to be more expansive in presenting the results. His papers often show the widest implications of the solutions in graph form.

Some particulars of Glauert’s procedures should be noted. The equations of motion that he employed were basically those that had been set out in full by G P Thomson in R&M 211 of 1915, where he had analysed a turn with sideslip, which had the potential to develop into an incipient spin (14). Now Glauert applied them to the steady spin, after it had developed fully. In his treatment there are three coordinate systems that have to be related. The space axes define the helical path of the aircraft centre of gravity at G, with velocity components the vertical rate of descent $V$ and the horizontal circumferential velocity $\Omega R$ around the vertical axis of the spin. The resultant velocity defines the direction of the path, making an angle $\gamma$ to the vertical at all points along it, given by $\tan \gamma = \Omega R/V$. The orientation of the aircraft relative to the space axes is defined in two ways – first by a set of axes GXYZ fixed in it, with GX facing along the path. And secondly by the usual Gxyz coordinates to give the conventional angles of bank $\phi$, pitch $\theta$ and yaw $\psi$ relative to the path, as used in Figure 1.
At this time, the aircraft was considered to be a rigid body, so that in a steady spin there are six basic equations to be formulated, corresponding with the six degrees of freedom, three each for linear and angular motion. The linear equations relate forces to accelerations in the appropriate directions, two accelerations having to be resolved - the vertical one due to gravity \( g \) and the horizontal centripetal acceleration towards the axis of rotation, \( \Omega^2 R \). For the angular motion, in a steady spin the equivalent of acceleration is a rate of change of angular momentum due to the changing directions of the components of spin about the three principal axes of the aircraft. The dynamic interactions between the moments of the forces applied to a body and the rotations around these axes are given in the three standard gyrodynamic expressions known as Euler’s equations. An aircraft does not have a simple shape, but it is generally found that the conventional longitudinal, lateral and normal axes may be regarded as its principal axes of inertia for practical purposes.

Thus the moments of inertia of the aircraft \( I_x, I_y \) and \( I_z \) have to be known for the principal axes \( G_x, G_y \) and \( G_z \) (roll, pitch and yaw axes respectively, see Figure 6). Then suppose that the aircraft is in a steady rotational state, in which the component angular velocities about these axes are respectively \( \omega_x, \omega_y \) and \( \omega_z \). These are represented by vectors in the relevant directions which do not change in magnitude in a steady state, but each is changing in direction due to the rotations about the other two axes. Euler’s equations then give the couples \( T_x, T_y \) and \( T_z \) which are required to be applied about the axes to produce the resulting changes in angular momentum:

\[
T_x = (I_z - I_y) \omega_y \omega_z, \quad T_y = (I_x - I_z) \omega_x \omega_z \quad \text{and} \quad T_z = (I_y - I_x) \omega_x \omega_y
\]  

(1)

In this form, the meanings of the various terms are clear. However, the routine use of Greek characters and so many suffixes was troublesome for the typing of reports and type-setting in print, so a simpler nomenclature began to be adopted, much of which became standardised and continues in use today. In this, the principal moments of inertia about the usual three axes for the aircraft were labelled \( A, B \) and \( C \) for the longitudinal, lateral and normal axes respectively. The rates of rotation about the axes became \( p, q \) and \( r \) respectively, and the couples \( L, M \) and \( N \) respectively. Equation (1) could thus be written

\[
L = (C - B) \, qr, \quad M = (A - C) \, pr \quad \text{and} \quad N = (B - A) \, pq
\]  

(2)

Although there is at first some loss of clarity, the brevity of equation (2) is generally to be preferred. These conventions were not fully formulated at the time of Glauer’s work, but, to encourage uniformity of practice, the ARC later began to print a set of standard definitions and nomenclature of this system on the inside of the covers of all R&Ms issued and sold separately as ‘blue books’. This was done from R&M 1130 onwards, initially as reproduced in Appendix A at the end of this paper. It will be convenient to use the ARC conventions in this account, but with amendments as necessary to avoid confusion with different definitions used today. This arises principally from the divisor used to obtain non-dimensional coefficients for forces and moments. In Appendix A, it is seen that this was then \( \rho V^2 \), rather than \( \frac{1}{2} \rho V^2 \), adopted later by international agreement, as it already had a place in aerodynamics as the dynamic pressure of the flow. There is rarely confusion over the forms used for lift and drag coefficients, as the symbols used for these were originally \( k_L \) and \( k_D \), being changed to \( C_L \) and \( C_D \) when the divisor \( \frac{1}{2} \rho V^2 \) was introduced. However, the symbols for other coefficients were largely unchanged, and different linear dimensions, particularly span \( b \), semi-span \( s \) and mean chord \( c \)
were also used at different times, so that it is vital to establish which conventions are in use when reviewing printed matter from the past.

For quick reference at this point, the nomenclature employed here is illustrated in Figure 6 by a sketch of the aircraft which was shown spinning in Figure 1. Displacement and linear velocity are positive looking along an axis from G, and rotation and applied moment are positive in a clockwise sense when looking in that direction. In Figure 6, the symbols in columns are the standard ARC ones for these quantities, descending in the order just given. The final symbol in each column is for the moment of inertia about the axis concerned.

\[
\begin{align*}
L &= L_1 + L_3, \\
M &= M_1 + M_2, \\
N &= N_1 + N_3
\end{align*}
\] (3)

In this, the suffix 1 indicated moments originating in the wings, 2 in the tailplane and elevators and 3 in the fin, rudder and body. Glauert went on to state, without elaboration, that the quantities \(L_2\), \(M_3\) and \(N_2\) (respectively the rolling moment due to the tailplane, pitching moment due to the fin and yawing moment due to the tailplane) did not appear because they could be neglected to a sufficient approximation. Though later work was to show that this was not always the case, his basic view that moments from forces acting on all parts of the airframe should be considered for each of the axes was an important point to make at this first stage.
Glauert’s method of validating the modelling was not to attempt to solve the equations explicitly, but to insert values of some of the quantities observed in Lindemann’s trials and then to check if other quantities derived from the equations were reasonable and internally consistent for the type of aircraft concerned. The observed quantities were the vertical rate of descent \( V \) and the angular velocity of rotation \( \Omega \). The latter could be obtained reliably from the observations made at the \textit{camera obscura}, though values of the radius of the path \( R \) would be approximate, as they could not be correlated with the height of the aircraft, due to the absence of communication with it, and had to be inferred in relation to the span. Required physical quantities, such as the weight and dimensions of the aircraft were known, though estimates had to be made of the moments of inertia. The unknown value of the mean incidence \( \alpha \) of the wings could be used as a parameter, giving tables of calculated values of other variables, with which the observed results could be compared. It was assumed that the inclination of the fuselage axis could be taken to be \( \alpha \) also, to a sufficient accuracy for the purpose (i.e. neglecting the rigging angles of the wings in comparison with \( \alpha \)).

The form of the force equations used by Glauert for the validation was one for a state of zero sideslip, as reported to be the case by Lindemann. Given the measured value of the normal acceleration, the lift and drag of the wings could be calculated. A constant quantity of 0.03 was added to the drag coefficient to represent the drag of the rest of the airframe, and then the mean effective incidence of the wings and the lift/drag ratio could be obtained. These values were seen to be in good agreement with known wing characteristics (although at that time, values for conditions beyond the stall were available only for the RAF 6 aerofoil section, which was not used in the aircraft tested). With the measured values of the spin rate, the radius of the path \( R \) could be obtained from the radial component of acceleration, and these values were also consistent with those observed from the ground.

When the overall spin rate \( \Omega \) is known, the three components of rotation about the principal axes can be written down for any given orientation of the aircraft relative to the vertical. Then for the angular motions, the required couples were first obtained using the Euler steady-state equations, equation (2). For validation, it was checked whether these couples could reasonably have been applied by the available aerodynamic forces at the wings and empennage, including those produced by the controls. In Lindemann’s trials, the control positions used to start the spin had been held on throughout the period when measurements were being taken. Full left rudder was applied in all cases, in conjunction with various backwards stick positions. It is noted that these positions somewhat resembled those that had been envisaged earlier by Barber to be jammed positions forcing an aircraft into a spin \(^{11}\).

There had been no way of measuring the applied couples on the aircraft, so comparisons had to be made with estimated values of what could be obtained within the given ranges of the control deflections of the particular aircraft involved. Regrettably, no detail is given of the methods by which these were estimated by Glauert. Nothing seems to have been published at this time on the effectiveness of controls located on deeply-stalled primary surfaces, but he refers simply to some unidentified ‘full scale tests on the elevators’. It seems unlikely that he would have based these estimates on data for the hinge moments obtained in normal conditions of unstalled flight, so it appears that test work of some kind had been done on this. For rolling and pitching, the calculated control deflections were then found to be within the scope of the controls on the aircraft, though the agreement was poor in respect of the rudder.
In time, it was realised that the control movements provided in design for ordinary flight manoeuvres could not always produce moments large enough to bring the aircraft back to an unstalled condition. The most dangerous cases were known as ‘involuntary spins’, which continued whatever control actions were applied subsequently.

The ranges of the main results thus deduced by Glauert for the first tests with the BE 2E are summarised below:

- **Flight path** $\gamma$ 18° - 31° to vertical
- **Angle of bank** $\varphi$ 74° - 79°
- **Mean incidence** $\alpha$ 15° - 37°
- **Mean lift/drag ratio** 1.3 - 2.9
- **Period of rotation** 3.8 - 4.9s
- **Normal acceleration** 1.6 - 2.6g

These were the first firm figures to illustrate the aerodynamic conditions in the spin, and in particular to show the orientation taken up by the aircraft. Glauert considered them to be ‘rather surprising’.

The measurements from tests with the FE 2B were more difficult to validate, as this aircraft had a pusher configuration, with the cockpits in the nose, so that the levels and acceleration were being measured at a point some way forward of the centre of gravity $G$. However, making approximate corrections for this, he was able to conclude that results from these tests were again plausible. For this aircraft, he remarked on the small size of the radius of the path – only 7ft, though this was much as had been reported for a test by Gooden (15).

Glauert noted that only the most basic characteristics of the aircraft had been used to obtain results from the force equations, so that it was to be expected that those quantities would not depend strongly on details of the design. This would not be the case for the moment equations, where the characteristics of the empennage and effectiveness of the controls, expected to be major factors, were very specific.

In conclusion, he went on to consider the implications of the results for the stresses experienced in the wings, which had then been a matter of some concern. The loading was different from that assumed in the original design in several respects. The mean angle of incidence was far beyond the stall, and the speed of the relative wind varied along the span due to the rotational component, so that there were substantial torsional and centrifugal loads on the wings. Glauert reports an evaluation of the consequences of these differences, without giving any details of the calculations. The measured normal accelerations in the spin had seldom exceeded 2g, so there was little concern about spar bending stresses. In biplane aircraft, the torsional loading would be distributed by the interplane struts and rigging wires. The spanwise centrifugal loads were well within the capacity of typical spar materials, and in fact would provide some relief to the bending loads. Hence it was indicated that there was no risk of structural failure during spins. But it was necessary to take care in recovering from them. The wings would then have to pass back from the stalled condition through the region of maximum lift coefficient, and the forces could become dangerously high if the speed had been allowed to build up too far during the recovery and pull-out.
In 1918, the Ministry of Munition’s Technical Department - Aircraft Production issued H.B.806, the first *Handbook of Strength Calculations* (20), forerunner of the famous long-running publications AP 970 and AvP 970 *Design Requirements for Service Aircraft*. This contained a reference to the ‘Spinning Nose Dive’ among several other ‘special manoeuvres’. Stating that ‘the values of the forces arising during these evolutions are difficult to get mathematically’, it cites Lindemann’s measured acceleration of around 2g and low forward speed as indications that the loading in a spin was not likely to be excessive. The spin was not about to be considered as one of the basic design cases.

Glauert’s first exercise had not been a full prediction of the behaviour in the spin, since some of the leading quantities had been assumed to be as given in the measurements in Lindemann’s trials. But the basic force and moment equations had been set out for the first time in this context and estimates of the applied aerodynamic forces and moments were found to give results that were reasonably consistent internally and within the range expected of the available control deflections. Considering the number of checks and balances that this involved it was felt to be a significant step forward, on which much could be built. Glauert had also noted a consequence of the lift/drag ratios that were deduced. Over the full range of mean wing incidence encountered in the trials these would mean that the overall aerodynamic reaction had been in a direction close to perpendicular to the plane of the wings. This was very well validated subsequently and has often been the starting-point in later studies and adopted in teaching material and textbooks up to the present day.

### 2.4 Glauert’s further work

At this time, the first textbook reference to the mechanism of spinning appeared in G P Thomson’s *Applied Aerodynamics* of 1919 (21), in which were summarised the material of Glauert’s first presentation and Relf and Lavender’s work on autorotation. To the extent that references in textbooks were likely to be imprinted in the minds of students, some of those who would be entering aircraft design offices in the years that followed would be aware of spinning and its implications from the start.

Glauert went on to examine the process of autorotation in more detail, extending the earlier work and reporting his analysis in R&M 595 (22). For this, he used the set of measurements by Nayler, Bryant and Irving of the aerodynamic characteristics of the RAF 6 aerofoil section, of which a part was shown in Figure 5 (18). Again, strip theory was used, still without representation of the loss of lift at the tips. It was found that with this section, self-starting autorotation would be possible only within a narrow range of initial incidence below 90°, from 15 to 26½°. Outside these limits the aerofoil was stable when at rest, any small disturbance being damped out. However, if given a sufficient angular velocity it could be made to enter an autorotation within a small further range of initial incidence between 26½° and 31½° approximately. In this range, the autorotation was said to be ‘latent’.

To facilitate estimation of the range of mean incidence α within which a wing would autorotate spontaneously, Glauert obtained the simple criterion that this could occur only where the negative of the overall lift-curve slope dC_L/α (which after the stall was itself negative) was
greater than the value of the drag coefficient $C_D$. For the aerofoil sections of the time, this occurred typically over a range extending only 10 to 15° from just after the critical incidence, in line with the wind-tunnel tests made so far. As seen for example in Figure 5, beyond this region the drag coefficient is rising steeply, so autorotation was not to be expected there. However, in some of Lindemann’s spins with whole aircraft the mean incidence had been calculated to be somewhat into this range. There were also occasional reports of spins in which the incidence had been thought to be significantly higher, occurrences yet to be explained.

A further substantial compilation of work on the spin was subsequently prepared by Glauert, which became R&M 618 of June 1919 (23). To the earlier results of the trials by Lindemann he was now able to add others, from flight tests made on six types of service aircraft, including two of the most significant fighters of WW 1, the SE 5A and the Sopwith Camel. With the latter, some further tests were done with enlarged elevators and rudder. The measurements were mainly of the rates of spin and the height lost during spinning and in recovery. Both aircraft were single-seaters, but these quantities could be obtained readily enough by an experienced pilot, counting the number of rotations against a stopwatch and timing the interval between aneroid readings for the height loss to give the vertical velocity of descent. Again, the spins were induced by the application of full rudder and with various combinations of backwards stick movement. These positions were held on during the observations of the spin, and then various control movements were tried in the subsequent recoveries.

It was found to be impossible to spin a Vickers FB 14 aircraft, a type shown in Figure 7. This was thought to be attributable to its large fin, which also extended forward for some way along the top of the rear fuselage. So in a series of tests, the covering fabric was progressively stripped away from the fin, until only the structure remained. When the aircraft still would not spin on every occasion, the fin was removed altogether. Remarkably, the aircraft was flown by Maj R M Hill with only the rudder post and rudder in place, and then could be induced to spin in the usual way, though large control forces were required in the recovery. In the dry language of his report, this required ‘great exertion on the pilot’s part, more than it feels safe to exert under normal conditions.’

Tests on recovery from spins were made with various combinations of movements of rudder and elevator. The standard advice, to centralise the rudder and ease the stick forward, was confirmed. The rotation would usually stop, and the nose could be lowered to un stall the wings and increase the forward speed, allowing the aircraft to be pulled out of the dive. In an emergency, the rudder could first be put across to oppose the spin, but this should be for a short time, as in some cases the response could be rapid and result in a spin in the opposite direction. Failure to recover from a spin when there was ample height in which to do so, was attributed to ‘lack of experience’ on the part of the pilot, or disorientation by physiological effects caused by the acceleration and the rotating field of view.
In R&M 618, Glauert’s account of the theory of spinning is presented more systematically than in his first presentation in R&M 411, but the theory is essentially the same. The relationships between angles, that define the orientation of the aircraft relative to the axes of the spin, are still presented in terms of spherical triangles, with no supporting guidance. There are no changes to the assumptions, in particular that there was no sideslip in the spin. The earlier tables of results and graphs from R&M 411 are given again, together with those for the more recent observations. The principal addition to the analysis is that the aerodynamic forces and moments for the wings are not now represented by those of a wing at the mean effective incidence in the spin, but are calculated by the method developed in Glauert’s R&M 595 on autorotation (22). This used strip theory to integrate across the span, taking account of the large variation of local incidence due to the rotation.

Another change is to express the equations in terms of non-dimensional groups, to facilitate parametric representation of the results. Many more calculated values are then given, with the object of showing the variation of the incidence at the centre-section, the rate of spin and the necessary positions of the controls for a range of characteristics typical of contemporary fighter aircraft. Three generic types are defined, designated ‘A’, ‘B’ and ‘C’, with varied quantities of the wing loading, span, position of cg and moments of inertia. In the absence of any available data, it is assumed that the latter quantities about the longitudinal and lateral axes (A and B) are equal, so that by equation (2) the nett couple N required about the normal axis would be zero (this is often a reasonable assumption). The moments applied by the control surfaces are said to be represented by ‘curves or formulae for different angles of the relative wind and different control positions’. This suggests the existence of a significant body of data, but again the source of these is not identified.
The results of the calculations are presented in tables and figures, showing the effects of variations in the principal parametric groups. Good agreement is found with the observed test flight behaviour, now extending over a wider range of aircraft and test conditions than those in R&M 411. The exception found in the prediction of the rudder angle is still present, all values now reported to have come out with the incorrect sign, though an explanation for this continues to be elusive.

In an Appendix to this R&M, an account is given of some more wind tunnel experiments on autorotation, carried out by L W Bryant at NPL, to explore further the effectiveness of the strip theory approach to calculating the forces on a wing in the spin (24). For this, a model wing was twisted along an axis at the one-third chord line, with a change of incidence from tip to tip of 43°, to correspond with the angles determined by Glauert for the case of the BE 2E aircraft in one of Lindemann’s trials, where the mean incidence had been about 31°. The measured values of lift, drag and moment were compared with calculations and found to agree closely (the least agreement being for the turning moment, which was said to be expected, since this is determined by the difference between contributions of similar magnitude from the parts of the wing on opposite sides of the axis). Tip effects were here represented for the first time, by reference to some existing pressure-plotting results for a model SE 5A aircraft. These observations provided further confidence in the use of strip theory in this situation.

The inclusion of earlier material that was already published, and the general tone of R&M 618, tend to suggest that Glauert considered that the essential theoretical work on spinning had now been done, and that he was here bringing the necessary matter into one document for convenience of reference. Whether or not that was the case, this was the last contribution he made to spinning specifically, as his attention turned thereafter mainly to fundamental aspects of aerodynamic theory and to other problems in stability and control (19). Although in fact there remained much more work to be done, it was remarkable that the subject had been brought to this state of understanding within two years of the start of research. Though other approaches were used later, it will be seen that these early contributions from Glauert formed a solid foundation for what would follow.

3  The early 1920s
3.1  Continuing development

The decade 1920 – 29 was a time of strict economy in public expenditure, which also continued well beyond this period. It was experienced keenly at RAE and NPL, where staff numbers had been reduced to a small fraction of their complements during the war. Fortunately, the work at the two establishments was not seen to be duplication and there continued to be a considerable output of publications relevant to spinning from both establishments.

Glauert, who had accepted an invitation to visit the Institute of Technical Physics at Göttingen, had been deeply impressed by the work of Ludwig Prandtl and others on the development of Lanchester’s circulation theory of lifting surfaces (19). On his return, he applied these ideas to the determination of thrust and torque of propellers (25), later to be developed further and included in his famous book on aerofoil and airscrew theory (26). For this, he again used strip theory, with its assumption that local aerodynamic effects could reasonably be regarded as
independent of those on adjacent sections. The first practical verification of Glauert’s predictions for propellers, which further validated this procedure, was made at NPL by Lock, Bateman and Townend (27), who were also leading contributors to spin research there.

In the later years of the previous decade, the combination of work at RAE and NPL had provided much insight into the dynamic processes at work in the spin. The main approach in the next decade would be the further development that would be needed to enable understanding of the spin to be brought into practical effect by designers. It was apparent that a key direction for this would be to obtain a reliable map of the moments applied aerodynamically around the principal parts of an airframe, when rotating with an attitude that took the lifting surfaces well beyond the stall. First steps had been taken to measure the characteristics of wings when in autorotation and it had been confirmed that simple strip theory was able to give calculated values for the forces in reasonable agreement with those. Glauert had contrived some estimates of control surface moments on lifting surfaces in the conditions of the spin, but no details were given and this remained a largely unknown area.

The ARC Stability and Control Panel had earlier called for an investigation of possibilities for retaining control of aircraft when in a fully-stalled condition in straight flight. Investigation of post-stall control methods would require facilities for testing models at incidence up to 30° or so, but it was seen that if these could operate over a wider range of incidence they would also make a valuable contribution to spinning research. There was a considerable volume of reporting of this work on post-stall control during the first half of the 1920s, accounting for most of the output of R&Ms in the area of stability and control for several years. Within that were parts that could be said to contribute to the continuing thread of development in the understanding of spinning. In particular, new instrumentation and test procedures were introduced for the post-stall investigation that were relevant to spinning research, but might be overlooked through having been reported in that different context.

### 3.2 New wind-tunnel methods

A major step in test procedures was made with various versions of the ‘rotating balance’, in which the moments generated by models of wings could be measured while being rotated about the wind axis. The first of these, designed around an idea attributed to Ronald McKinnon Wood at RAE, is shown in Figure 8 with model wings of the Bristol Fighter in position (28). This was used to measure the rolling and yawing moments as a function of the rate of roll, over a range of incidence. [As an aside, it is noted that the R&M on this pioneering work was presented by Frances Bradfield, a significant contributor to wind tunnel research, and here just identified by her initials in the same way as for her male colleagues].
A similar facility was promptly set to work at NPL (29), and a period of use and development followed, in which the moments could now be measured systematically.

In these balances, the wings and later whole aircraft models were mounted on a sleeve that was free to rotate in bearings on a fixed central member, or between fixed centres. Adjustments could be made so that the required range of incidence, and later yaw, to the free stream could be obtained. Electric motors drove the model support through gears, providing a wide range of the quantity $ps/V$, relating the rotational to the axial components of the relative velocity, which had been introduced as a parameter by Glaubert. In some types, the required moments were measured by mechanical balances, and in others by the deflection of springs registered by the movement of spots of light reflected by small mirrors onto scales mounted on the tunnel wall. Further refinements allowed measurements to be made from which the three moments $L$ in roll, $M$ in pitch and $N$ in yaw could be determined, though at first these could not all be measured at the same time. The suffix $p$ indicated that these moments were measured in rotation about the longitudinal axis (e.g. $M_p$ for the pitching moment due to rate of roll). Since the model was now being actively driven around, the incidence could be taken beyond the rather narrow range in which autorotation had been found to occur spontaneously (30).

Values obtained with wings only could be compared with those calculated by strip theory, showing good agreement. The technique was quickly adapted to allow complete aircraft models to be tested. Reports of this later work contain few illustrations of the mechanisms involved, but one example is shown in Figure 9. With complete models, rapid changes, and even reversal of trends were observed, as the parameter and orientations were varied. These effects were not seen in conventional wind-tunnel testing with stationary models, suggesting that the rotating balance was opening up new fields and was likely to be a significant facility for advancing work on spinning. But proposing explanations for these observations became a challenge, in
view of the current limitations in the understanding of the complex aerodynamic processes involved.

Figure 9  Rotating balance at NPL with Bristol Fighter model

3.3  Progress via tests for particular aircraft

Following a specific request from the ARC, attention was drawn at this time to practical problems in spinning with two aircraft – the Short Springbok, a 2-seat reconnaissance aircraft, one of the first of all-metal construction, and the British Aerial Transport Company (B.A.T.) single-seat Bantam fighter \(^{(31, 32)}\). The first Springbok could not be recovered on the only occasion that it had been spun, and two of the prototypes of the Bantam had been lost similarly. Although, as its name implies, the Bantam was smaller, there were distinct physical similarities between the two types. As shown in Figure 10, both were biplanes with streamlined fuselages, of circular cross-section, having radial engines at the nose. The wings were without stagger and had a narrow interplane spacing (the ‘gap’) due to being mounted in contact with the top and bottom of the fuselage. This limited the number and length of struts exposed to the airflow in the interests of reducing drag, though in both cases it meant that the pilot’s cockpit had to open through the upper surface of the top wing, with effects on the visibility downwards.
It was already known from experience in flight that a combination of zero stagger and small gap led to reduced longitudinal stability, though this had been accepted in return for increased manoeuvrability in close combat. In the case of the Bantam that had been accentuated by the choice of a rearward normal position of the centre of gravity. Significantly, observers had noted that the Bantam had taken up an orientation in the spin in which the fuselage axis was nearer to the horizontal than to the vertical, one of the first of the situation that came to be described as a ‘flat spin’. The high drag in this condition meant that the vertical rate of descent was lower, but as this was accompanied by a higher rate of spin the rotational parameter $ps/V$ was unusually large. The flat spin was an unpleasant experience, with rotation at up to one revolution per second in a path with a radius of just a few feet. It began to gain a reputation that it was also something from which it was particularly difficult to recover.
No further observations with these aircraft at full scale could be made safely, so now the contribution from the rotating balances came to the front. It had been noted earlier that the amount of stagger of two wings had a large effect on both speed of autorotation and the range of incidence over which it occurred. The later versions of rotating balances were made robust enough to carry complete models of a reasonable scale – for the Bantam, for instance, this was 1/7th, which could be accommodated in the largest (7ft) tunnel at NPL. Moveable control surfaces were reproduced in both models, with the correct maximum angular deflections.

Measurements were first made with incidence up to 45°, the highest angle before the model would foul the supports, and with yaw up to the same value. At high values of incidence and yaw, the required pitching moment rose beyond the point at which it could be provided by the tailplane, even with the maximum available elevator deflection. With the empennage deeply stalled, the effect of elevator deflection was greatly reduced and the rudder became completely ineffective. But reference to basic theory could now provide some understanding of the mechanisms at work here, as reviewed shortly.

The model tests showed that with the arrangement of the wings on the Bantam an increase in incidence tended to increase the rate of rotation. As this was accompanied by a decrease in the available elevator moment the process would become self-reinforcing. With the controls set to promote the spin, high values of incidence and rotation would be obtained. When the stick was moved forward to attempt recovery, it was indicated that the aircraft would continue to spin, with perhaps only a somewhat smaller incidence. Attempts were made to increase the control moments by fitting a revised empennage with all surfaces enlarged, with some success, though the trends at the highest available incidence remained problematic.

When tests continued with a Springbok model, a fuller explanation of events began to emerge. This time, comparisons were made between the dependence on incidence for the biplane and for a single wing, termed a ‘monoplane’. As noted previously, it had been found that for a single wing, autorotation was limited to a narrow range of incidence from just after the onset of the stall. But now a biplane model like that of the Bantam ‘took up its station briskly’ and continued to rotate up to the maximum available incidence, even after this had been raised to 70°. Other measurements showed that at high incidence, the lift and drag of the upper wing were both lowered, so that although the lift-curve slope was reduced, autorotation became possible in this region, as predicted by Glauert’s rule. The clear conclusion was that with zero stagger and small gap the spin was being driven to higher incidence and faster rotation as a result of serious interference to the flow over the upper wing from the presence of the lower one. These tests also revealed that, although autorotation of monoplane wings had been noted previously only over a small range of incidence, another, previously unknown, region could be found at very high incidence. It seemed that with biplane wings of small gap and stagger these regions became effectively merged into a continuous one.

It was felt reasonable to claim that the progression up to the flat spin and failure to recover, which had proved so dangerous for these aircraft, was now ‘understood to a large extent’. This work had thus shown in a modest way how studies to investigate the cause of accidents could also lead to advances in research.
Both types were subsequently modified and re-submitted for service trials. The Bantam was fitted with wings of a longer span, an enlarged tailplane and increased rudder fraction, and the centre of gravity was moved forward. It did well in the trials, but only a single batch of nine aircraft was ordered. For the Springbok, the tailplane was enlarged and raised, and the fin and rudder areas both increased. The wing gap, which had been identified as a leading factor in the failure to recover from the spin, was increased in this aircraft, by mounting the upper wing higher, on extended fuselage frames at the pilot’s station. The modified version successfully entered service as the Short S.3a.

At RAE, rotating balance tests were being made with models of aircraft that had been long in service, such as the SE 5A and the Bristol Fighter, shown in Figure 11. The behaviour of these types in all flight conditions, including the spin, was thought to have been well-characterised already at full scale. Now, the rotating balance procedure had become accepted to be a ‘satisfactory’ one for determining the moments due to rolling and the corresponding derivatives with respect to roll rate, $L_p$ and $N_p$ (28). Examples of these aircraft at RAE, particularly the Bristol Fighter, in effect became standard test vehicles for full-scale comparisons of behaviour in flight with results from theory and tests with models. Thus began a comprehensive programme that was to continue for some time before conclusions could be reached. This will be reviewed later, after considering the conclusions of two important surveys of work to date which were made around the middle of the decade.

The first was R&M 1000, the summary report on the very extensive study that had been made of the behaviour of aircraft in conditions immediately beyond the stall (34). As part of this, there was a series of tests, with models and at full scale, to establish as fully as possible the characteristics of the Bristol Fighter over a range of incidence up to 30°. These will not be reviewed here, except where new measurement techniques were employed, or there were possible implications for the behaviour in the spin. For example, when it was required to apply known moments to the aircraft in flight, a rolling moment was produced by carrying a weight on one wing tip, and a yawing moment by attaching a parachute to an outer wing strut (35). Although the type had been long in service, it was known that inexperienced pilots had found it hard to manage, and in the RAE tests it was considered to have too little control power to deal with an incipient spin following engine failure at low speed near the ground. Their aircraft was modified, first with an enlarged tailplane and elevators and later with an enlarged fin and rudder (36). When the latter also produced too large a rolling moment when in sideslip, due to the fin area being above the aircraft’s centreline, a novel cambered fin was made and fitted, to provide an aerodynamic moment to cancel this effect. The controls were now considered to be better harmonised, and the aircraft could be more firmly controlled at low speeds and in the stall. It could also be recovered more quickly from a spin. As it was said to be ‘very much liked by all who have flown it’ the recommendation was made that the changes should be made to aircraft in service use.
Concerning control in roll, it was clear that the effectiveness of ailerons was reduced when they were operating in the largely-separated flow in the stall. But since the patenting of the Handley-Page slot in 1919, it had been joined by a variety of other devices for re-energising the flow over the top of the leading edge of the wing, so as to delay the onset of separation and to reduce the disturbance to the flow. Among these were leading-edge slats of various forms, both fixed and retractable, and occupying part or all of the semi-span. These had effects of considerable utility, by increasing the incidence at which stalling began, and so, for a given wing-loading, lowering the stalling speed. Experience with these devices in various forms began to be reported in R&Ms from 1924, including rotating balance testing.

In the course of this work, it was also perceived that if roll control could be maintained well beyond the stall, it might make it possible to prevent a transition from a sharp turn at a slow speed into an incipient spin. One of the variants that was thought to be promising for this was a retractable slat positioned ahead of the spanwise location of the aileron, and mechanically linked to it, so as to open the slat when the aileron was deflected upwards. A more complicated version
included an ‘interceptor’, a small plate that could be raised from the top of the wing in certain conditions, which had the effect of varying the flow of air though the aperture formed between the slat and the leading edge. Model tests had been encouraging, and others at full scale with this arrangement fitted to an Avro 504K aircraft were considered to have provided ‘greatly increased safety of flight in the region of the stall’, without measurable loss of performance in normal flight conditions (37). However, investigation of the possibility that high-lift devices might help to prevent inadvertent entry into the incipient spin did not materialise. The further prospect, that they might assist in the recovery from a spin, if that had not been avoided, would require tests extending over a much larger range of incidence, but was to be raised later.

Some step-by-step numerical calculations of post-stall behaviour, made at Cambridge at this time by Melvill Jones revealed some limiting effects of increasing the size of the fin (38). Somewhat along the lines used by Thomson a decade earlier (14) it was argued that although the processes were non-linear beyond the stall, they could be followed sufficiently well by calculations if these were made at small time-intervals. Increments of 0.1s were used, and the behaviour obtained over periods that were generally not more than a few seconds. This was a forward-looking approach, but as some 80 different conditions were examined, some very tedious computation would have been required with the facilities available then. [It is notable that the co-author of this R&M, who was probably the one to undertake the calculations, and at that time would have been called a ‘computor’, was a Miss Trevelyan. This indicates that procedures in academia had not yet caught up with those at RAE, where Frances Bradfield was not now distinguished by name from her male colleagues.]

It was found in this work that if no control actions were taken, the usual outcome of a small disturbance in the stall was that the aircraft started the usual spin entry. For fin size above a certain point, however, that became a steady oscillation in roll, tending towards a definite amplitude. This behaviour had been observed also in tests at full scale for the case of an Avro biplane with a large fin and rudder in some new trials on control actions (39). In that study, the effects were checked of abandoning the controls when a full spin had developed, a procedure advocated by some service pilots. This was found to be effective in recovering the other aircraft tested, though a quick resumption of forward stick was required to avoid developing a further spin, in the opposite direction.

Questions from readers of technical magazines had shown that there was a lively interest in spinning and spin recovery. But as early as 1920, an editorial article in The Aeroplane had stated that ‘since pre-war days, very little has been publicly printed on the subject, though much has been learnt’ (40). As seen above, that was not strictly justified, though it would probably be correct that published material in the ARC R&Ms was too scattered and uncoordinated to be readily assimilated by designers and others in the industry. An authoritative summary of the various actions taken up to this point was certainly desirable. This could bring together advances in the modelling of the dynamics of the spin with the work with rotating balances, that had built up a new body of information on the aerodynamic moments that sustained the motion. This was to be provided in the form of R&M 1001 - ‘The Spinning of Aeroplanes’ - the most significant source within one cover up to this point in the account.
4 The mid-20s

4.1 A timely review: R&M 1001

A collaboration by S B Gates of RAE and L W Bryant of NPL, this R&M was published separately from those reproduced in the Annual Reports, in the form of a bound hardback volume of 130 pages in 11 chapters. The material was presented progressively at different levels of complexity, probably intended in part to make the subject more accessible to newcomers than it had been hitherto. Comprehensive coverage of the leading work on spinning that had gone before was accompanied by summaries of the views of the authors on the aerodynamic actions that were important for understanding the mechanisms at work. On the title page is the statement ‘This Monograph has been carefully criticised and endorsed by the Stability and Control Panel’ (of the ARC).

When this work is brought together, the scope of what had been achieved in a little short of a decade since scientific investigation began is striking. Nevertheless, the authors emphasise that many uncertainties remain, and cautionary statements about inadequacy of the data base are frequent. R&M 1001 is in effect a book, with a layout that would assist it to be an essential resource for researchers and perhaps to arouse interest by designers. Only a summary of so much detail is possible here, and it is principally that potential value to designers that will be brought out below.

The approach is different from that of Glauert in R&Ms 411 and 618. The theoretical development had begun there by providing two figures showing how the three sets of coordinates that would be used were related by arcs on the surface of a sphere. This was a standard procedure in one branch of spherical geometry, but as it was presented largely without explanation, it must have been assumed that the reader would be familiar with the routine of the relevant angular transformations required to relate them. Then the six basic equations of motion were set out briefly with the manipulations required for the solution. This compact presentation was fine for fellow researchers, but could have a somewhat forbidding aspect for the general reader. For design staff, aiming to gain an understanding of this unfamiliar condition of flight, the earlier presentations on theory would perhaps have reinforced the impression that the situation in the spin is difficult to comprehend, an unfortunate view that has continued to present times. That could probably have been countered right at the beginning by including more explanation, maybe with some free-body diagrams that are the usual starting-points for analysis by aeronautical engineers.

It seems puzzling that Gates and Bryant too had begun their introduction by stating that the problem of spinning was ‘extraordinarily complex’, since in what followed they worked from the simplest representation that would give a reasonable impression of the actions of the forces and couples in a spin, which can be followed readily. The case used for this, as shown in Figure 12, was called the ‘prototype spin’. It provides a good approach to the subject, and has often been the example used at the start of others made subsequently. In view of its significance at the time, and so that comparisons can be made more readily with later treatments, some detail of the assumptions and procedures in the analysis of this study seems appropriate here.

From the results of Lindemann’s spin experiments and others, Glauert had deduced that the angle of bank had been more than 70°, so the aircraft would almost be presenting its upper
surface inwards towards the axis of the spin. It is shown in that position in side view in Figure 12, defining the prototype spin, in which the positions of the aircraft axes are immediately apparent in relation to the wind axes. The latter are given by the vertical descent at a rate $V$ and the horizontal velocity $\Omega R$ due to the rate of rotation about the vertical axis. At its centre of gravity $G$ the path of the aircraft along its downward spiral is not actually vertical, but makes the angle $\gamma$ to that, where $\tan \gamma = \Omega R/V$. Crossing the page at this angle in Figure 12, Glauert found that this angle could be small enough to be alarming to an unprepared pilot, who was unlikely ever to experience so steep a descent in normal diving flight. However, some of the paths reported subsequently were to be even steeper. At this time, the aircraft considered were biplanes, with interplane struts and rigging wires, fixed undercarriages, uncowled engines, open cockpits, and other drag-producing features. Manufacturers were now making efforts to lower the drag, and later, more streamlined monoplane aircraft were to follow, so that there would be a progressive reduction over time. This would lead to higher rates of descent and smaller path angles to the vertical.

![Diagram of forces on an aircraft](image)

Figure 12  Forces on an aircraft in the ‘prototype spin’, according to Gates and Bryant, reference 41

If there was no sideslip in the spin, as asserted by Lindemann, the path would have to lie in the aircraft’s plane of symmetry. In that case, it would not be shown exactly in side view, as for the prototype spin. This point will be considered later, but that representation was a reasonable initial assumption for Gates and Bryant to make, when the path was already known to be steep, and was likely to be more so in the future.

An outline of the theory now follows, as obtained for the prototype case of Figure 12.
a) The force equations  It could be assumed that the resultant aerodynamic force on the aircraft F acted in the vertical plane, perpendicular to the chord as noted by Glauert, and can be divided into its usual components lift L and drag D. Then in the simplest force balance for a steady rotation, D equals the weight W, and L provides the centripetal acceleration $\Omega^2 R$ of the aircraft for the path of G at radius R about the vertical axis. (It will be seen in Figure 12 that the approach used was actually via the concept of equilibrating a ‘centrifugal force’, which would be familiar to readers at the time).

Since, as will be shown below, the determination of $\Omega$ was still problematic, we can proceed by noting that a measured value for the normal acceleration $a_n$ was about 2g. If the resultant force F from the wings is close to the normal direction, F would be about 2W, and resolving that, the lift L would be $2W \cos \alpha$ and the drag D would be $2W \sin \alpha$. As D was equal to the weight W, $\alpha$ is found to be 30° and the L/D ratio around 1.7, figures consistent with the range of these values as determined by Glauert from the measurements by Lindemann.

Neglecting the rigging angle by comparison, this would also give an approximation to the inclination of the fuselage axis to the vertical. Thus, to a first approximation, the pitch attitude of an aircraft in the spin, the most noticeable feature of its orientation, could be determined approximately from the lift and drag characteristics of the wings.

At an incidence of 30° most, if not all, of the wing would be in a condition beyond the stall. Reference to the autorotation calculations or measurements would give the mean values of the lift and drag coefficients at this incidence, which in this attitude would originate mainly in the wings. Then equating the drag to the weight would give the approximate value of the rate of descent V, from the definition of drag coefficient,

$$V^2 = \frac{2W}{C_D \rho S}$$  \hspace{1cm} (3)

showing that in the spin, V is proportional to the square root of the wing loading $W/S$ and inversely to the square root of the air density $\rho$. A mid-range value of the wing loading for the BE 2E would be about 5.5 lb/ft$^2$, and the overall $C_D$ of the aircraft corresponding with the L/D ratio of 1.7 in the post-stall region would have a value of about 0.65, giving a descent velocity V of around 85 ft/s near the ground, as typically observed.

For the centripetal acceleration we have that

$$\Omega^2 R = a_n \cos \alpha$$  \hspace{1cm} (4)

or about 1.7g in this case. It is remarkable that so many aspects of the aircraft’s behaviour in a spin can be determined so simply from just the balance of forces. But to evaluate the other key values, the rate of rotation $\Omega$ and the radius of the path R, these quantities would have to be separated. For this, it is necessary to consider the moment equations to obtain the components of rotation about the principal axes and the couples applied by aerodynamic forces required to maintain them.

b) The moment equations  In the analysis of flight, it is usual to resolve the aerodynamic actions on an aircraft along each of its three principal axes into a resultant force passing...
through the centre of gravity \( G \) and a couple, equal to the moment applied by the forces about that point. (Because of this origin, in the aeronautical literature the term ‘couple’ and ‘moment’ have been widely used interchangeably, especially in the earlier work, and the distinction between them had been almost lost now).

The principle being followed in the representation of the spin was that the rotation is driven by the aerodynamic couples, initially thought to arise principally from autorotation of the wings, together with others, often of the opposite sign, arising from the empennage as the fin and tailplane are carried around the spiral path. For there to be a state of steady rotation, the resultant of the applied aerodynamic couples must equal the rate of change of angular momentum of the aircraft about each of its principal axes, as given by the Euler equations, equations (1) and (2). The supposition is that although the motion is unsteady in the entry and incipient stages of the spin, the rotation and the attitude of the aircraft quickly become adjusted so that these steady-state equations are satisfied. It was accepted that couples from all parts of the airframe should be included, as had first been put forward by Glauert in 1918.

The component angular velocities \( p, q \) and \( r \) of the aircraft about its principal axes combine to give the overall rate of rotation \( \Omega \). This is represented by a vertical vector which, if the spin is right-handed for example, points downwards, so in reference to Figure 12, resolving \( \Omega \) in the directions of the axes gives

\[
p = \Omega \cos \alpha \quad q = 0 \quad \text{and} \quad r = \Omega \sin \alpha
\]

(5)

Here, \( q \) is zero because in the side view of Figure 12 the \( y \)-axis about which the aircraft pitches is horizontal and so has no component in the downward direction. Since \( q \) appears as a multiplier in the first and third parts of equation (2), only the second part has a non-zero magnitude, which with values from equation (5) would give the remaining required couple in pitch \( M \) as

\[
M = (A - C) pr = (A - C) \Omega^2 \cos \alpha \sin \alpha
\]

(6)

about the lateral \( y \)-axis.

It is seen that this is proportional to the square of the rate of spin. And since \( \cos \alpha \sin \alpha \) is identically equal to \( \frac{1}{2} \sin 2\alpha \), it also varies symmetrically with \( 2\alpha \), increasing with \( \alpha \) at first, reaching a maximum value at \( 45^\circ \) for a given \( \Omega \). Since the moment of inertia \( C \) in yaw about the normal axis is invariably greater than \( A \) in roll about the longitudinal axis, the direction of the required couple \( M \) is negative, i.e. clockwise as looking at Figure 12, where the positive direction for rotation about the lateral axis points out of the page.

The source for the values used by Glauert for the couples such as \( M \) was not given, but now work with rotating balances had begun to measure these over a wide range of operating conditions. This was showing that significant cross-coupling occurred in rotation, especially at high angles of incidence and yaw. For example, the rolling of the wings generated both pitching and yawing moments, varying with the rate of roll. Results for these were summarised later in the book. As measurements accumulated the set of moments acting in a given spin state could be estimated more accurately so that in principle there was progress towards being able to obtain solutions to the moment equations such as equation (6) more confidently. Much more material would be
needed to provide enough for a solution in all cases, but in time that would allow $\Omega$ to be found, by equating the applied couple to the required value $M$ and then the path radius $R$ could be obtained from equation (4), to complete the analysis.

c) ‘Equilibrium’ in pitch  Gates and Bryant did not at first cite the Euler equations when determining the effects in pitch, but gave a figurative representation of the situation in terms of the concept of centrifugal force. Their illustration of that is reproduced as Figure 13, which for some reason showed the aircraft on the opposite side of the axis of rotation from that of Figure 12 (probably an existing figure was used for this). No doubt the centrifugal force representation was chosen again here in the expectation that it would be familiar.

![Figure 13](image)

Figure 13  Origin of the ‘inertial moment’ in pitch, according to Gates and Bryant, ref 41

There are other aspects of the representation of Figure 13 that might not have been so helpful to newcomers to the subject. It labels the ‘axis of rotation’ as passing through the centre of gravity $G$, though the same term had been used correctly for the axis of the spin in Figure 12. Since the aircraft makes one turn about the axis through $G$ while it makes one about the spin axis, the representation might be fair, but when Bryant and Gates gave a presentation of this work to the RAeS in March 1927, the approach was questioned immediately in the discussion (42).
Figure 13 was intended to show the distribution of component centrifugal forces along the body of the aircraft due to the rotation, but actually only the parts that contribute to the couple about G are represented there. The reply given to the question was a reminder that any set of forces acting on a body can be reduced to a resultant force acting though a given point plus a couple about that point. In this case G had been the chosen point and the resultant was the overall centrifugal force, which had already been used in deriving the result equivalent to equation (4). To find the couple, what remained to be represented was the effect of variation of the radius of the path at points on the body away from the centre of gravity G compared to the value R at G, due to the inclination of the body to the spin axis.

For an elementary mass \( m \), distant \( x \) along the body from G, the centrifugal force contributing to a couple would be \( m \Omega^2 (x \sin \alpha) \) and its moment about the lateral axis \( m \Omega^2 (x^2 \sin \alpha \cos \alpha) \). Summing this over the length of the aircraft gave the estimated centrifugal couple to be

\[
\text{Centrifugal couple} = B\Omega^2 \sin \alpha \cos \alpha = B \, pr
\]  

where \( B \) is the moment of inertia in pitch, and the couple is positive because in this view along the y-axis, the positive direction is clockwise. Using this approach, the applied aerodynamic couple required to equilibrate this ‘centrifugal’ moment would be

\[
M = -B\Omega^2 \sin \alpha \cos \alpha
\]  

(8)

negative when using the standard sign convention for the lateral axis.

Readers would find it reasonable that the moment of inertia appearing in the moment equation in pitch equation (8) should be the value \( B \) about the lateral axis. However, if the corresponding expression from the Euler equations equation (6) had been given here, the moment of inertia part is \( (A - C) \). Without taking a step back to see how the Euler equations are formed, it would be legitimate to wonder how the moments of inertia \( A \) and \( C \) about the longitudinal and normal axes could have any influence on equilibrium about the lateral axis. This might have been part of the choice by Gates and Bryant of the process leading to equation (8). (The two forms come about because for something the shape of an aircraft, the moments of inertia closely satisfy the square-law relation that leads to the expression \( C = (A + B) \). Then for the case of an aircraft the magnitude of \((-B)\) is a good approximation to \((A - C)\), making equation (8) closely equivalent to equation (6) for practical purposes).

The presentation in this R&M had been ‘carefully criticised’ by the Stability & Control Panel of the ARC before endorsing it. Its members would have been familiar with the approach to dynamics using centrifugal forces and must have found it acceptable. However, there is a well-recognised problem that sometimes accompanied this usage, arising from its very familiarity. The regular inclusion in the analysis of forces shown acting in the opposite direction to the acceleration (as in Figures 12 and 13) could lend them a kind of reality, as if real forces had somehow been brought into existence by the motion itself. Though Gates and Bryant were researchers of good standing, they were not immune to this, remarking at one point that the ‘inertia couple’ due to the fictitious forces shown in Figure 13 ‘tended to raise the nose’, and on another occasion to it ‘holding the machine at a high incidence’ (42).
By whatever method, values of the rate of rotation $\Omega$ could not be calculated without the availability of data for the aerodynamic couple $M$ that could be applied in the spin. To proceed, Gates and Bryant introduced a result from observations suggesting that values of the dimensionless quantity $\Omega s/V$ lay within a certain range in the spin. A series of calculations could then be made beginning with assumed values of this quantity as a parameter. Typical dimensions and weights were used, representing fighter-type aircraft. Observations in flight seemed to show that in practice the range of values of $\Omega s/V$ for spins of this type of aircraft was narrow, typically around 0.4 to 0.5. Among the conclusions reached from calculations using these values was that a high incidence in the spin was associated with a fast rate of rotation and a small radius of the path, providing useful support for the limited observations of these quantities then available.

4.2 The effects of yaw

If a quantity such as $\Omega s/V$ was a significant parameter, it would imply that the effects of the vertical and horizontal components of the relative wind were more closely coupled than in the simplified presentation of the prototype spin. To move on, it would be necessary to see the implications of this.

Lindemann had said that his impression that there had been no sideslip in his tests was seemingly confirmed by the absence of any significant deviation of the bubble in the lateral level used as the turn indicator on the aircraft. But the only orientation in which there would be no deviation of the bubble would have been that of the prototype spin, in which the plane of symmetry $xGz$ was vertical, as shown in Figure 12. In that position, the two governing accelerations, the centripetal and the gravitational, both lie in that plane. With no transverse components, there would be no sideways movement of the lateral bubble. But in moving along its helical path, the aircraft would experience the horizontal component of air velocity coming from one side. It would then be sideslipping, at an angle equal to the path angle $\gamma$, but Lindemann did not mention feeling any component of wind from the side.

For there to have been no slip or skid, the plane of symmetry of the aircraft would have been inclined so as to contain the instantaneous path of $G$, requiring a rotation from the prototype position, about the z-axis. The lateral bubble would then show a substantial reading, so there was the paradox that Lindeman had reported neither sideslip nor bubble deflection.

In the condition of no sideslip, with rotation about the z-axis (rotation in yaw) the wings would not be level, and if the path angles had been up to 31° as reported by Glauert, this would surely have been noticed by the pilot and perhaps by observers on the ground. Having looked laterally, and reporting that the struts between the wings were horizontal, Lindemann could hardly fail to notice if the wings had not been level. It must be supposed that in those tests the aircraft had happened to remain close to the attitude of the prototype spin, despite the tests having been made with various aileron deflections that produced a wide range of incidence in the pitching plane. As these were the first spins on which measurements of any kind were taken, it is no criticism to point out that on this occasion the opinion that there had been no sideslip must be questionable.
Gates and Bryant made no reference to Lindemann’s observations, but now began to look at the implications of yaw more closely. Subsequent observations of spins had shown that the wings were often deflected from the horizontal, displacements in both directions being observed. The attitudes in various key situations were illustrated in the lecture to the RAeS by Bryant and Gates by photo-montages similar to that reproduced as Figure 14 (41). Others had been given in R&M 1001, including the first representations noted of the inverted spin. An aircraft was sufficiently symmetrical that an inverted spin was in principle just as likely as the more usual upright one if the aircraft entered it in that position. However, one significant difference is that in the inverted position, the fin and rudder are not blanketed by the wake from the rear fuselage and tailplane, so that they are able to exert full moments about the normal and longitudinal axes. Nevertheless, pilots are warned of an inverted spin being a possible consequence of the fall-off near the top of a loop, if begun with insufficient speed to keep the wings beyond the stall throughout the whole manoeuvre.

Figure 14 Photomontage of spinning aircraft, Bryant and Gates, reference 41. Left to right; ‘prototype spin (steep), zero sideslip (steep), ‘prototype’ spin (flat), zero sideslip (flat)

From their own calculations, Gates and Bryant could now assert that, far from being a negligible factor in the spin, yawing was of the first importance. They cite the results from wind tunnel tests that showed that the rolling moment due to sideslip greatly increased at incidences beyond the stall, and could be ‘of such magnitude as to remove the rate of roll in the spin far beyond the autorotative rate’. Further, they were aware that yaw angles of up to 20° had been measured during spins of the Bristol Fighter, which are reported later. From these considerations, Gates and Bryant concluded that yaw was to be expected in most spin situations, and account should be taken of that, even in the simplest representation.
If there had been a yawing rotation $\psi$ around the normal or z-axis of the aircraft, the lateral axis $y$ would acquire a component $q$ of the overall rotation $\Omega$, at a rate $\Omega \sin \psi$ for small angles. The other components $p$ and $r$ would be changed also by that, though their values as given in equation (6) would still be reasonable approximations when $\psi$ was small.

Equation (2) shows that with all three components of rotation $p$, $q$ and $r$ now in action, nett applied couples would be needed about all of the aircraft’s principal axes. The two further ones, not required previously, are

$$L = (C - B) qr, \quad \text{and} \quad N = (B - A) pq$$

(9)

The first of these, for the equation in roll, was invariably the larger of the two, as it involves the substantial difference between the moments of inertia $C$ and $B$ about the normal and lateral axes (i.e. in yaw and pitch) respectively. The second expression, for the equation in yaw, involves the difference between the inertias for the lateral and longitudinal axes, which for most aircraft at the time were of a similar magnitude. The difference between them was not only likely to be small, but could also be of either sign or even zero, so the aerodynamic actions that provide the yawing moment $N$ must also have a corresponding range of value.

That the response to the moment about the longitudinal axis should involve the difference between the moments of inertia $C$ and $B$ about the other two axes was again resolved by use of the approximation $C = A + B$, equating $(C - B)$ to the moment of inertia $A$ about the same axis as that of the applied couple $L$. As with the pitch equation, this would seem reasonable. However, the scope for puzzlement was not entirely removed by it, since the second expression in equation (9) (for yaw about the normal axis) is not simplified similarly by the same substitution.

In expressing the requirements for couples about the longitudinal and normal axes, Gates and Bryant now proceeded to use the Euler equations only, though still referring to the couples through a concept similar to that of centrifugal force. The equivalent of such an ‘inertial force’ in the force equations is an ‘inertial couple’ in the moment equations. Just as the first is a fictitious force acting in the opposite direction to the acceleration, the second is a fictitious couple acting in the opposite direction to the rate of change of angular momentum. The applied couples were then considered to be required to oppose these. The inertial moments thus had to be given the opposite sign to those of the Euler equations, as given in equation (1). Regrettably, as this reversal became routine, the negative sign became absorbed into the term for the moment of inertia differences at the beginning of the Euler equations, which were then reversed in order, for example $(C - B)$ becoming $(B - C)$. But these modified equations were still being called the Euler equations, so that two different forms of those were found in different parts of the literature, becoming a significant ground for confusion.

Work with rotating balances had now shown the multiple actions that were at work. For instance, for a complete model sideslip could generate significant contributions to both $L$ and $N$. The contribution to the rolling moment from the forces in yaw arose in part because the side-forces on the fin and rudder are usually located above the fuselage centre-line. This was possibly one of the factors responsible for the continuation of rotation beyond the limits of autorotation found in earlier studies, which had at first been puzzling when tests had been made with wings only.
The influence of the moments of lateral and normal surface areas, in the form of ‘tail volume coefficients’ was now becoming familiar to designers from the consideration of longitudinal and directional stability. These are non-dimensional forms of the moment of the presented areas of the tailplane and fin/rudder about the centre of gravity (so named because the product of an area and a length had the form of a volume). Minimum values for these coefficients were being adopted, though alone they are only damping coefficients and would not ensure more than an eventual return to straight flight after a disturbance by, say, a gust. Gates and Bryant point out that usually the capacity of lateral areas and control surfaces based on these requirements would also be sufficient to provide the modest moments implied by equation (9), and an enlargement of those could be readily obtained if that capacity should prove to be inadequate. However, it was already clear that in practice aerodynamic effects on these surfaces could be seriously reduced in the spin if the fin and rudder were enveloped by the wakes from the tailplane and under-surface of the rear fuselage. It had been found in rotating balance tests that on the whole Springbok and Bantam models the rudder became virtually ineffective when the incidence reached about 40°, and it was concluded that this alone was ‘almost sufficient to account for their failure to pull out of spins’ at full scale.

e) Completing the picture

Gates and Bryant went on to set out the full dynamical equations of motion for the general case, with deviations of the aircraft’s principal axes from the relative wind axes in all three directions, without limitation of the yaw displacement to small angles. To aid the angular transformations a global diagram was again shown, similar to those given earlier by Glauert, though its use was more thoroughly explained. At first it was found that in the general equations of motion symbols with three suffixes would be needed, so a new and less elaborate notation was introduced. However, this would probably have further deterred many readers from following the analysis of the general case, and it will also not be detailed in that form here.

The later parts of R&M 1001 consist of extensive calculations of theoretical relationships in the spin, using a comprehensive review of the data now available from wind tunnel measurements. In the calculations the quantity $ps/V$ is used as the independent variable or as a parameter. The presentation of the results and of the wind-tunnel measurements is comprehensive, taking the number of figures in this work up to a total of 76. While all of these contribute to the general canon of knowledge at the time, some which were subsequently cited more than others are shown by two adjacent pages reproduced from R&M 1001 as Figure 15. The part on the right shows the connection between this spin parameter and the incidence for conditions of spontaneous autorotation, observed in the wind tunnel tests cited earlier. This indicated how, with complete aircraft models, autorotation could occur over a much wider range of incidence than had previously been supposed. Experiments with bare wings, backed up by calculations using strip theory, had shown that autorotation typically began at a mean incidence just beyond the stall and extended only as far as 30° or so. This was found also in measurements with a model of the wings of the Bristol Fighter biplane (28). However, with models of the Bantam and Springbok biplanes, which had been found to be prone to flat spinning, spontaneous autorotation continued to occur up to incidences of 60° or so.

Using strip theory for the two cases of monoplanes and biplanes, Gates and Bryant obtained the calculated values shown in the parts on the left of Figure 15, suggesting that fair agreement
was now being found with the general form of results from model tests and some limited ones at full scale. They had also re-derived and used the expression devised by Glauert to make predictions of the regions in which autorotation could occur. It was indicated that the characteristics in monoplanes would usually mean that autorotation would not extend to high values of incidence. This was so for biplanes also, unless the stagger and gap ratios were low. The model tests for the Bristol Fighter and the Springbok were consistent with this, and backed up by the observations in flight at full scale. With zero or negative stagger and a low gap ratio, the rule had indicated that autorotation could occur up to $90^\circ$ incidence, which had previously been thought to be impossible. These results were further publicised in the RAeS lecture\(^{42}\), giving a clear indication that progress continued to be made in widening the understanding of the characteristics of aircraft that were relevant to the spin, and in presenting them in fairly straightforward terms.

![Figure 15](image.png)

**Figure 15** Variation of the rotation parameter $ps/V$ with incidence $\alpha$.

Left, by calculation; right, from model tests and at full scale.

Gates and Bryant, reference 41

At the end of R&M 1001 is an extensive bibliography, which lists not only all the relevant R&Ms, but also the numerous Current Papers relating to spinning submitted to the Stability and Control Panel that had not been selected subsequently for publication. This large resource provides an insight into finer details of the work in progress than is summarised in the overall view given here.
4.3 Conclusions from R&M 1001

Gates and Bryant ended their comprehensive R&M with a summary of their conclusions. The first was a confirmation that in the force equations on an aircraft in a spin there was little room for variation. There had to be a vertical component to balance the weight and a horizontal one to provide the centripetal acceleration (or equilibrate the centrifugal force) in rotation. Hence the aircraft must take up an attitude in which it faces substantially towards the axis of the spin. And so the disposition of the components of lift and drag for any case could not depart greatly from those indicated for the simplified one of Figure 12. This seems to have been largely accepted, and there is little reference to the force balance in subsequent work. When in 1924 the Handbook of Strength Calculations had been reissued (for the first time with its long-term designation of AP 970), the reference to spinning was omitted, presumably on the grounds that it was now clear that the spin did not present a significant stressing case.

It was also certain that the requirements of the moment equations determined the rate of rotation in a spin and the angles of pitch and yaw by which the principal axes of the aircraft deviate from the wind axes. Since the angular velocity about one axis is affected by couples about the other two, there were substantial interactions between them. Earlier work by Glauert had left sideslip out of account, but it could now be seen that this had obscured some significant effects, and it was to be understood that yaw was of the first importance among the factors that determine the spin behaviour. The further calculations had largely confirmed the estimates made by Glauert of typical values of the orientation in a steep spin, but it could be seen that there could also be an angle of yaw, up to around +/- 20°. Though work on autorotation of bare wings had been a vital step in the progress of understanding the spin, it would now be ‘dangerous to assume’ that there was anything more than a loose connection between them.

Work with rotating balances had shown that for complete models, sideslip generated significant contributions to both L and N at higher incidences, and could have been the factor responsible for the continuation of rotation beyond the limits of autorotation found in earlier studies without yaw. The use of tail volume coefficients to represent these moments could provide a way to give numerical expression to requirements for controlling spin behaviour. However, it was clear that these would have to take account of the reduction of effectiveness of the surfaces in the steep descent of the spin if the fin and rudder were enveloped by the wakes from the tailplane and under-surface of the rear fuselage.

These and other pertinent observations made this R&M a very valuable point of reference at this time. Looking to the future, Gates and Bryant foresaw a need to develop a new technique of measurement that would go beyond the current capability of the rotating balance. This had enabled measurements to be made of the moments generated by aircraft models due to their rate of rotation, which had begun to fill a significant gap in knowledge. But at present it could allow measurement of only one variable at a time, and it had become clear that the cross-coupling of moments was of major significance. A new method would have the difficult aim of reproducing the full combination of conditions for the complete aircraft in any orientation. One important objective would be to investigate the effects of aerodynamic moments arising from the empennage and rear fuselage in conditions of deep stall. Further, these effects would need to be fully modelled analytically, as they were now seen to be critically important for further advances in the theory.
From an historical perspective, it is of interest to compare at this point the requirements for pitching and yawing moments given by Gates and Bryant with the conjecture of Barber a decade earlier, before serious investigation had begun. He had attributed the spin to the ‘insufficiency of keel surface behind the vertical axis, or the jamming of the rudder or elevator into a position by which the aeroplane is forced into an increasingly steep and small spiral’. These would have been the ways that he could imagine at the time by which the values of M and N were too small to meet the dynamical requirements unless the incidence became large. For example, the most obvious contributor to a couple about the normal axis would arise from exposure to the airflow of the side area of the fin, rudder and rear fuselage (the ‘keel surface behind the vertical axis’) when the aircraft was yawed.

Barber had also recognised the significance of the dynamical element as now expressed in equations (6) and (9)). His words on this were ‘Owing to the small radius of such a spiral (path), the mass of the aeroplane may gain a rotary momentum greater, in effect, than the air pressure of (on) the keel surface or controlling surfaces opposed to it’.

5 Theory, experiment and practice

There was good support for the judgment of Gates and Bryant as to the direction of future work. The wind tunnel tests of large complete models of the Springbok and Bantam aircraft on the rotating balance at NPL had illuminated the behaviour in which the spin and the rate of rotation had progressively increased until recovery became impossible. It was now confirmed, by tests in which roll and sideslip were applied separately and jointly, that their effects were not additive. To get a representative test condition, both had to occur together and to interact. If that could be achieved there would clearly be a continuing place for this work with models, when tests at full scale could not be undertaken on the grounds of safety.

Tests with the Bantam model on the rotating balance and supporting calculations had been thought to account sufficiently for the dangerous spinning behaviour of this aircraft, but further work was undertaken in 1927 to explore the transition from the slow steep spin to the fast flat one that was so evident with this type. Finding that the pitching moment alone could not account for the increase in incidence, tests were done on the model with the wings in place and removed, in an attempt to measure the characteristics of the empennage in isolation. These revealed an unexpectedly large increase in the rolling moment due to sideslip, which was even sufficient to cause autorotation when only the body and tail were present. Though with local irregularities, the trend was for this rolling moment contribution to increase up to a high value at the greatest incidence of 80°, which could now be reached with the balance. It seemed that the yawed fin was assisting the rotation, rather than opposing it, as expected. The $\Omega^2$ part of the required pitching moment then resulted in the incidence having to increase progressively to enable the tailplane to provide it. Removal of the tailplane in stages confirmed that in rotation, there was substantial interference between the flows over the fin and tailplane and the wake flow from the rear fuselage. But in the complete aircraft there could be further wake effects from the wings also. The likely aerodynamic complexity of these offered little prospect for modelling or calculation of the resultant moments in the near future.
Also in these tests, the drag of the complete aircraft was measured during rotation, with the finding that it was much greater than had previously been estimated by strip theory for the wings alone, leading to a similar conclusion that theoretical predictions for this aspect would also be problematic. Nevertheless, it could be felt that laboratory methods were at last available for reproducing the main characteristics of the flat spin; high incidence, fast rotation, small radius and slow rate of descent.

Some other rolling balance tests were made at the request of the Design Sub-Committee, on a model of another aircraft which had been difficult to recover from spinning. This was described only as ‘a single seater fighter’, but from features shown in a drawing can be identified as one of the Gloster Gamecock series of aircraft, two of which are known to have been used at RAE in experiments in post-stall control and spin recovery at around this time. The model tests included a base-line measurement of moments in yaw without rotation, and went on to confirm that these values were not even a near approximation to those experienced when yaw was combined with rolling. As with the Bantam, the increase in incidence was thought to be due to the requirement for a high pitching moment, resulting from the higher speed of rotation caused by the effects of yaw on the rolling moment.

A possible alternative arrangement for model testing was considered, in which the Whirling Arm at the NPL could be applied to provide a testing environment in which the interactions between the parts were more fully represented. This device had been employed for testing airscrews from earlier times, having an arm of 60ft diameter driven round in a horizontal plane by a 14HP electric motor to give a tip speed of up to 100 ft/s. Reconstructed in 1927, it was robust enough to carry a one-tenth scale model of a large aircraft like the Bristol Fighter, mounted in a frame at the end of the arm, as shown in Figure 16. Facing in the direction of motion, the model could be rotated around a fitting supported by wires to the corners of the frame. Trunnions in the fitting allowed the model to be rotated to the required angles of pitch and yaw up to 30°, while a constant rate of yaw was produced by selecting an appropriate rate of revolution of the arm.

Measurements were made of the yawing and rolling couples, by balances such as that shown for determination of the rolling couple in Figure 16. Wire connections to the balance caused small movements against strong springs, producing tiny changes to the spacing between the faces of iron cores, mounted within a pair of coils. Current was passed through these along radial wires on the revolving arm, to and from rods dipping into troughs of mercury around the axle, effectively providing slip rings to enable the output to be picked up. Differential changes in the inductance of the coils produced changes in the current, allowing the magnitude and sign of the change in core spacing to be determined and thus the couple applied to the balance.

Very careful adjustment was required to minimise the centrifugal effects on the model and the balances during revolution of the arm, requiring much time to be spent in setting-up this facility. Though the magnitudes of the measurements made were found to be of the order expected from other work, it was noted that the rotating arm produced swirl of the ambient air in the test building that had too great an influence on the angles of the relative wind at the model for the method to be satisfactory. Nevertheless, the process was considered to provide enough promise for modifications to be put in hand to reduce the swirl and to allow the measurements to include pitching couples for possible future use.
As work had now confirmed the critical effect of yaw as a factor in spinning, some measurements were made of the consequences of yaw on the pressure distribution over a yawed wing at a range of incidence up to 40°. As these were only on a non-rotating wing, it seems surprising that even basic measurements of this kind had not been made previously. It was found that when the wing was yawed, the flow over the leading half tended to become unstalled, with a pressure distribution having a high suction near the leading edge, as in normal unstalled flight, while that on the trailing half remained fully stalled, with a fairly uniform pressure distribution. As incidence and yaw increased, the maximum suction on the leading wing rose to around five times the stagnation pressure. This difference in the magnitude and the form of the pressure distribution on the two wings produced a large rolling couple, which was validated quite well using strip theory when calculated with the measured pressures. Predicting these 3-dimensional effects, and particularly the further ones when in rotation, was far beyond reach at that time, but their presence raised the possibility that load redistribution might also have implications for stressing that went beyond Glauert’s conclusions, made a decade earlier.

In R&M 1001 there had been a criticism that ‘Full scale work on spinning has never in the past been highly systematic’. Work at RAE to provide the capability for that was now coming to fruition, in the form of a standard pack of equipment that could obtain all the information required to characterise the spin of an aircraft at full scale. One part of this was an arrangement for recording the positions of the control surfaces during movements in flight. This had first been used in the investigations into post-stall control, and later for obtaining base-line measurements of the stability of the Bristol Fighter, which, by allowing an observer to be carried was becoming a kind of standard test vehicle in spinning research. The report on this work gives details of the recording system when fully developed, by which linkages from
the control surfaces operated pens, recording on a paper roll moved between drums across a flat ‘writing table’ by an electric motor and reduction gear drive. The traces were made in different coloured inks by fine-bore glass tubular pens, with another stationary pen to provide a baseline. Flights were made by Capt G T R Hill (later to be Chairman of the Stability & Control Sub-Committee, and originator of the Pterodactyl series of tailless aircraft). They showed that the ordinary Bristol Fighter was only ‘just stable longitudinally over most of its speed range’, confirming at full-scale characteristics that had been indicated by wind tunnel testing.

Some of the main components of the RAE instrument pack were made available to the Cambridge University Air Squadron (CUAS), for proving trials after fitment to one of its Bristol Fighters. Used there in experiments on control in post-stall gliding flight, this consisted of the control position recorders and three recording gyroscopic rate-of-turn indicators, giving the angular velocity of rotation about each of the three principal axes, all synchronised by a clock timer. Tests with this equipment showed the great value of gaining records of the rates of rotation about the individual axes, but otherwise mainly confirmed that the rudder power on the Bristol Fighter could not provide adequate control in stalled flight.

Another outcome of university work might be noted at this point, as part of the historical context. Flt Lt Haslam, also of the UCAS, was participating in Army Cooperation duties in a Bristol Fighter, when he observed the behaviour of strips of bunting that were attached to the trailing edges of the lower wings for identification purposes. In normal flight, these streamed out steadily behind the wings, but when the machine was stalled, they lay forward on the upper surface of the wings, occasionally thrashing about randomly. He conceived the idea of using short lengths of wool, attached at numerous points, to indicate the direction of the local airflow on any surface of an aircraft in flight. In due course, this ‘wool tuft’ technique came to be used regularly, both at full scale and in wind tunnel work, but although justly reported in an R&M it does not seem to have been taken up in spinning investigations in the short term.

A fully comprehensive instrument pack for spinning trials was next installed in the RAE’s modified Bristol Fighter. A hand-operated band-brake was fitted, so that the engine could be stopped with the airscrew held in a given position, to exclude from the assessment the gyroscopic and aerodynamic effects of a rotating engine and airscrew. The instrumentation included developed versions of the movement recorders to give the positions of all controls, the 3-axis gyroscopic rate-of-turn recorders and accelerometers to give the normal and lateral accelerations.

The original ‘spring accelerometer’ of Lindemann’s trials had by now given way to a compact device well-proven by experience. This consisted of a fine quartz glass fibre, bent into a semicircle, at first of about $\frac{1}{2}$ in radius, with the ends of the loop clamped to the body. The fibre provided both the mass to respond to acceleration and the stiffness required to give a suitable resulting deflection perpendicular to the loop. The fundamental period of vibration was about one-twentieth of a second, and the movement was adequately damped by the surrounding air within an enclosed chamber. The deflection could thus faithfully follow the relatively slowly-changing acceleration of a manoeuvring aircraft. Measurements were taken from a recording on film of the motion of an illuminated spot at the apex of the fibre. The sensitivity of the instrument could be arranged to suit the requirements of a given test by using quartz fibres of different diameters and lengths.
In this 2-seat aircraft, the pilot could obtain the time taken to complete five turns, while the observer recorded the vertical velocity with an aneroid and stop-watch, together with the readings from bubble inclinometers in the longitudinal and lateral planes. For the other instruments an ‘automatic observer’ was fitted, as close to the centre of gravity as possible, in which the readings were photographed by a ciné camera, with check marks imposed on the film at half-second intervals from a clock timer. On some of the spins, the rotation of the aircraft was recorded also by a camera on the ground as an additional check on the observations in the air. The improvements given by this more comprehensive instrumentation were soon apparent in the results.

One set of observations is shown in Figure 17, clearly indicating the huge advance in technique for the systematic study of behaviour in the spin at full scale that was now available.

All spins were made with ailerons neutral, the stick fully back and full rudder applied in the direction of the spin. As the instrumentation was running before starting the spin, the records of these tests also showed for the first time details of the unsteady motion at the early stages. In the initial, incipient phase there was a slow rate of roll and yaw in the direction of the spin, accompanied by a small negative rate of pitch as the nose dropped, much as expected. The roll was then observed to increase ‘suddenly’ to the rate experienced in the steady spin, but other quantities, such as the angles of pitch and yaw, continued to change until five or six turns had been completed. Oscillations in pitch were noted in the initial motion, which were usually damped out, though in a few cases persisted to the end of the test. Oscillations in the rate of roll and other anomalies sometimes occurred, but tests with different methods of entry failed to indicate any conclusive origins for these. They were perhaps a reflection of a far-sighted remark made by Earnest Relf of NPL, at the RAeS presentation on R&M 1001 in 1927, that in any periodic occurrence there was not only the steady state to be considered, but also its stability. Oscillations of amplitude about the mean values could be expected to appear, and to continue if they were not sufficiently damped\(^{42}\). In due time, the occurrence of oscillations in the spin would come to be recognised as having a diagnostic character.

The results for the steady phase were analysed by a method suggested by Gates, derived from the basic equations of the prototype spin that were reviewed above. These showed much more variation between tests than had been expected. For example, values of the radius R of the helical path ranged between 3.9 and 8.3ft. The incidence lay in the range 30° - 40° for seven of the 11 spins, but for the others had increased to the highest value of 53°. Glauert’s observation that the resultant aerodynamic force F from the wings lay close to the normal to the chord suggested that the incidence could be obtained approximately from the reading of the accelerometers alone. As was seen in Figure 12, the vertical component of F was equal to the weight, so if \(a_n\) was the normal acceleration (in the direction of F), the incidence would be given by \(\sin \alpha = (g / a_n)\). The mean error in using this was found to be 2.2°. The best estimates, with a mean error of only 1°, were obtained from the component rates of rotation in yaw and roll, which could now be measured independently. Using the values of \(r\) and \(p\), as given in equation (5), indicates that \(\tan \alpha = (r / p)\). It was concluded that with a package of instruments such as this, all the quantities required to define a spin could now be obtained routinely in flight, and more work of this kind with the Bristol Fighter and other aircraft was planned.
Towards the turn of the decade a further example showed how the various methods that had been developed for investigating the spin could now work together. This concerned the case of an unidentified ‘Single-seat Fighter’, with which difficulty in recovering from spins had been reported in trials at A&AE, Martlesham Heath. This was a biplane with forward stagger, in which a thicker aerofoil section had been used, in the expectation that this would result in a more gradual onset of the stall and provide pilots with an earlier warning of its approach. Minor
modifications to the fin and rudder made at A&AEE had failed to make much difference to the recovery, for which up to ten turns had been endured. Tests were then made at the request of the Design Sub-Committee of the ARC, to look at the potential for improvement by more systematic changes to the empennage and rear fuselage, as indicated by the work done with the Bantam and Bristol Fighter. In the first part, baseline values of pitching and rolling moments were measured on a 1/10 scale model at incidences up to \(70^\circ\) and rotation up to \(ps/V\) of about 0.9\(^{(54)}\). The opportunity was taken to make moment measurements in yaw without rotation, which again clearly showed that the behaviour was very different when the model was rotating. Measurements were then made with the normal body and a lengthened one, and with and without wings\(^{(55)}\). Modifications were made in which the body of the model was extended and the rear part deepened, the tailplane raised from the middle to the top of the rear of the body and the fin and rudder areas increased, as shown in Figure 18. Further tests then showed that the yawing moment due to roll (now being referred to as ‘damping’) was significantly increased. The changes to the fuselage and fin and rudder were about equally effective, with both being improved further by the re-positioning of the tailplane.

Figure 18  Modifications to aircraft for model testing and implementation at full scale.  
Left, to the fin/rudder of Bristol Fighter to assist post-stall control, ref 36;  
Right, to the empennage and rear fuselage of ‘single seat fighter’ to assist spin recovery top and centre, for model tests, ref 54; bottom, as applied to test aircraft, ref 55
The final part of the trials reviewed the effects at full scale, in which the aircraft was modified at RAE along the lines indicated\(^{(55)}\). This involved additional deepening of the rear fuselage, moving the tailplane rearward by about half the mean chord, and fitting a larger and taller fin, as shown also in Figure 18. Although a collection of changes such as these might still seem to have an element of empiricism, they do represent a point in the thread of increasing understanding of the spin at which practical measures could now be envisaged for limiting the tendency for progression to the flat spin.

In air tests with the modifications shown it was found that in the early part of the spin the incidence increased gradually to 45\(^{\circ}\), though without any change to the speed of rotation, which was steady and smooth. Recovery had been improved, but with a typical delay of 3 to 4 turns after the start of corrective action, it was felt that a more rapid response was still desirable for an aircraft to go into general service.

6 Advice for designers

There seems now to have been a general recognition of the need to convey the lessons that resulted from research directly to potential users in industry. Evidence for this had already been shown in the issue of R&M 1001, but the ARC Technical Report of 1927/28 gives an outline of specific advice on design aspects of spinning and recovery that had been circulated, which appears to be the first direct action of this kind. This stated that

‘In the light of the evidence available, the following may be regarded as beneficial characteristics from the standpoint of easy recovery from a prolonged spin –

(1) large fin-and-rudder volume;
(2) small inertia coefficient \((C - A)\);
(3) forward stagger;
(4) forward position of the centre of gravity.’

Specifically, it recommended that the fin-and-rudder volume coefficient should be 0.08. This would not be the value as determined by considerations of lateral stability in normal flight but a revised value, allowing for ‘the blanking effect of the tail and for the effect of the body’, at a standard incidence of 45\(^{\circ}\). Some rules for working out the extent of the shielding had been suggested, but these were not yet well established. However, this feature is particularly noteworthy here, as it was to become an essential part of design in the years to come.

The form in which the output of research might best be communicated to industry would continue to be a legitimate concern. For this, the nature of both researchers and the readership would have to be considered.

Excellent fighter aircraft such as the SE 5A had been designed and built at Farnborough in the days of the Royal Aircraft Factory, but since the foundation of the RAE in 1918 there had been no overall design and construction capability there. The better-known designers and other staff had dispersed into the private companies. Researchers whose work has been cited above, like Glauert and Gates, had originally trained as mathematicians, so there would be a question as to
how the conventions of their calling might need to be adapted to ensure effective transfer of the results of their work to engineers in industry.

The firms that became major players in UK aircraft design could generally be recognised as serious professional engineering enterprises from the earliest days of aviation, despite their small scale and low number of employees at first. The country had by then long developed a solid engineering tradition in which they could grow, with men having good training and practical experience in other sectors of engineering becoming available to recruit. The lingering popular impression that their products were primitive and flimsy is not borne out by the facts. An illustration of this can be seen in some very early drawings of aircraft of the British & Colonial Aeroplane Company Limited (later The Bristol Aeroplane Company), now preserved at the National Aerospace Library. These are detailed technical drawings of the components of the Gordon England No. 2 biplane entered for the first War Office military trials at Lark Hill in 1912. They are drawn to the standards of draughtsmanship, dimensioning and lettering that can be immediately recognised as part of well-established practice. And nothing less than full professional competence at all levels could serve the strict constraints of this new field, where to the twin basic requirements in engineering design, of strength and stiffness, was added that of minimum weight, which would call up new techniques, specific to that field.

There had been a huge expansion of the industry by the end of WW1, but that had declined quickly in the absence of orders due to the impoverished state of the nation afterwards, and the 1920s had been a thin time for those aircraft companies that remained in business. Some orders for maintaining the capability of the RAF and RNAS had continued, but at what was seen to be the lowest acceptable level during a time of economic stringency. A few single aircraft in what would later become the experimental (E) category were obtained for testing purposes, though usually after they had first been built and flown at company expense as private ventures. The civil part of the market was however more buoyant, as air travel began to expand, and light aircraft were purchased by wealthy individuals for touring and participation in air racing, which had begun to attract what would become a large popular following.

Efficient use of manpower and other assets was essential. The design team for a new project would be very small. The Chief Designer would be responsible for the basic concept and if there was no Chief Aerodynamicist, or even an assistant, he would be the one who kept up with the required knowledge of aerodynamics and would do the performance calculations. Another key figure would be the Chief Stressman, who had overall responsibility for the structural aspects of the design. This central group, with perhaps only a few others would be an obvious target for the dissemination of information from the research establishments, but there was another potentially receptive group within the works, that was a good deal larger.

Once the general layout of a design had been established, it would be passed on to the Drawing Office, where all of the detailing would be done. Though this was also reduced after the war, as the 20s drew on, replacements for men retiring from this group were often people who had joined firms as young men, perhaps as apprentices, and had subsequently obtained engineering qualifications in the National Certificate range (up to the Diploma), by attendance at local Technical Colleges in the evenings or on day-release. If appointed to the Drawing Office, they would be supervised by a Chief Draughtsman and supported by national organisations such as the Association of Engineering and Shipbuilding Draughtsmen (AESD). As early as 1919 this
had formed a Technical Publications Department, which began to supply for its members design guides and data sheets for the more common detail design tasks. In 1917, The Aeroplane magazine began including a supplementary section called Aeronautical Engineering and Flight magazine followed the same year with one called The Aircraft Engineer. In an introduction to the former series, the Editor C G Gray foresaw ‘a time when the Aircraft Industry, like all other great industries, will need a purely technical paper of its own’ (57). The journal Aircraft Engineering made a bid for that role when it was launched in 1929, presented then as ‘A new Paper for a New Industry’. These and other sources soon became established as an influential element in the dispersal of technical information to those involved in aviation. They were read as avidly in the Drawing Office as in the office of the Chief Designer. Articles on spinning began to appear there, sometimes written by engineers from within the industry rather than by researchers, such as Lt Col J D Blyth of the design staff of the Gloster Aircraft Company (58).

7 Review

Significant advances had been made since the start of systematic scientific study of spinning began in 1917, and this had quickened during the 1920s. Latterly, R&M 1001 had provided straightforward explanations which, if considered carefully and perhaps reworked somewhat, would enable designers and others in the industry to appreciate more clearly what was happening to an aircraft in a spin. This was a major advance in itself. Simplification of the theory allowed the orientation of the aircraft to be readily understood, and the collection of measurements of moments with models in rotating balances had been used to show how they related to quantities like the rate of rotation and descent in the spin. An accelerated phase of flight testing began, in which new instrumentation had enabled the motion of spinning aircraft to be measured completely and reliably at full scale. In this, it was noted that behaviour in the spin was affected by instability in pitch, found in several service aircraft, probably a legacy of designing for high manoeuvrability in combat during the recent war.

Changes in the industry were bringing in a new generation of design staff, who were ready to respond to initiatives to present the latest levels of understanding of the spin, being given in more immediately accessible forms. However, it had not yet been possible to provide them with a set of straightforward rules for design features that would ensure that a new aircraft would have a good chance of being recoverable from a spin.

With the opening of the decade of the 1930s would come more new experimental techniques that would lead to further advances in the understanding of the spin. These provided a basis for the development of empirical criteria that would allow the likelihood of spin recovery of a new or modified aircraft to be forecast. An account of work in that period follows in Part 2 of this paper, to be published later.

Acknowledgement

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<td>Bradfield, F B <em>Lateral control of Bristol Fighter at low speeds. Measurement of rolling and yawing moments of model wings due to rolling</em> ARC R&amp;M 787, Jan 1921</td>
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<td>29</td>
<td>Relf E and Lavender T <em>A continuous rotation balance for the measurement of <em>Lp</em> at small rates of roll</em> ACA R&amp;M 828, Aug 1922</td>
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<td>30</td>
<td>Lavender T. <em>A continuous rotation balance for the measurement of pitching and yawing moments due to angular velocity of roll (Mp and Np)</em> ARC R&amp;M 936, Feb 1925</td>
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<td>31</td>
<td>Bradfield, F B <em>Pitching and yawing moments with sideslip on a model aeroplane with zero stagger</em> ARC R&amp;M 965, Jan 1925</td>
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<td>32</td>
<td>Bradfield, F B and Coombes, L P <em>Autorotation measurements on a model aeroplane with zero stagger</em> ARC R&amp;M 975, April 1925</td>
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<td>34</td>
<td><em>The lateral control of stalled aeroplanes</em> General Report by the Stability and Control Panel, ARC. R&amp;M 1000, Sept 1925</td>
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<td>35</td>
<td>Garner, H M and Gates, S B <em>The full scale determination of the lateral resistance derivatives of a Bristol fighter aeroplane</em> ARC R&amp;M 987, August 1925</td>
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<td>36</td>
<td>Stevens, H L <em>Full scale tests of a Bristol fighter with increased rudder control</em> ARC R&amp;M 972, April, 1925</td>
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<td>37</td>
<td>Stevens, H L <em>Full scale tests of a new slot and aileron lateral control</em> ARC R&amp;M 968, March 1925</td>
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<td>38</td>
<td>Jones, B M and Miss A Trevelyan <em>Step-by-step calculations upon the asymmetric movements of a stalled aeroplane</em> ARC R&amp;M 999, Oct 1925</td>
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<td>39</td>
<td>Stevens, H L <em>The behaviour of certain aeroplanes when the controls are abandoned in stalled flight</em> ARC R&amp;M 1020, Oct 1925</td>
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<td>40</td>
<td>‘WHS’ Concerning spins, <em>The Aeroplane</em>, 18, 4 Feb, 1920, 270</td>
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<td>41</td>
<td>Gates, S B and Bryant, L W <em>The spinning of aeroplanes</em> ARC R&amp;M 1001, Oct 1926</td>
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43 Bradfield, F B and Hartshorn, A S  *Some preliminary tests on the effects of sideslip on the rolling and yawing moments due to roll of a Bristol biplane*  ARC R&M 1439, June 1926

44 Irving, H B and Batson, A S  *Further experiments on a model of the “Bantam” aeroplane. With special reference to the “flat” spin*  ARC R&M 1107, June 1927

45 Irving, H B and Batson, A S  *Experiments on a model of a single seater fighter aeroplane in connection with spinning*  ARC R&M 1184 May 1928

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53 Wright, K V  *Experiments on the spinning of a Bristol Fighter aeroplane*  ARC R&M 1261, May 1929

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Appendix A: The ARC standard definitions and nomenclature of 1927

![System of Axes Diagram](image)

<table>
<thead>
<tr>
<th>Axes</th>
<th>Symbol Designation</th>
<th>(x) longitudinal forward</th>
<th>(y) lateral starboard</th>
<th>(z) normal downward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>Symbol</td>
<td>(X)</td>
<td>(Y)</td>
<td>(Z)</td>
</tr>
<tr>
<td>Moment</td>
<td>Symbol Designation</td>
<td>(L) rolling</td>
<td>(M) pitching</td>
<td>(N) yawing</td>
</tr>
<tr>
<td>Angle of Rotation</td>
<td>Symbol</td>
<td>(\phi)</td>
<td>(\theta)</td>
<td>(\psi)</td>
</tr>
<tr>
<td>Velocity</td>
<td>Linear Angular</td>
<td>(u)</td>
<td>(v)</td>
<td>(w)</td>
</tr>
<tr>
<td></td>
<td>Angular</td>
<td>(p)</td>
<td>(q)</td>
<td>(r)</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td></td>
<td>(A)</td>
<td>(B)</td>
<td>(C)</td>
</tr>
</tbody>
</table>

Components of linear velocity and force are positive in the positive direction of the corresponding axis. Components of angular velocity and moment are positive in the cyclic order \(y\) to \(z\) about the axis of \(x\), \(z\) to \(x\) about the axis of \(y\), and \(x\) to \(y\) about the axis of \(z\).

The angular movement of a control surface (elevator or rudder) is governed by the same convention, the elevator angle being positive downwards and the rudder angle positive to port. The aileron angle is positive when the starboard aileron is down and the port aileron is up. A positive control angle normally gives rise to a negative moment about the corresponding axis. The symbols for the control angles are:

\[
\begin{align*}
\xi & \text{ aileron angle} \\
\eta & \text{ elevator angle} \\
\eta_\tau & \text{ tail setting angle} \\
\zeta & \text{ rudder angle}
\end{align*}
\]
# AERODYNAMIC SYMBOLS

## 1. GENERAL

- \( m \) mass
- \( t \) time
- \( V \) resultant linear velocity
- \( \Omega \) resultant angular velocity
- \( \rho \) density, \( \alpha \) relative density
- \( \nu \) kinematic coefficient of viscosity
- \( R \) Reynolds number, \( R = \frac{lV}{\nu} \) (where \( l \) is a suitable linear dimension), to be expressed as a numerical coefficient \( \times 10^6 \)

Normal temperature and pressure for aeronautical work are 15° C. and 760 mm. For air under these conditions \( \rho = 0.002378 \) slug/cu. ft.

The slug is taken to be 32.2 lb-mass.

- \( \alpha \) angle of incidence
- \( e \) angle of downwash
- \( S \) area
- \( c \) chord
- \( s \) semi-span
- \( A \) aspect ratio. \( A = 4s^2/S \)
- \( L \) lift, with coefficient \( \kappa_L = L/S\rho V^2 \)
- \( D \) drag, with coefficient \( \kappa_D = D/S\rho V^2 \)
- \( \gamma \) gliding angle, \( \tan \gamma = D/L \)
- \( L \) rolling moment, with coefficient \( \kappa_L = L/S\rho V^2 \)
- \( M \) pitching moment, with coefficient \( \kappa_M = M/S\rho V^2 \)
- \( N \) yawing moment, with coefficient \( \kappa_N = N/S\rho V^2 \)

## 2. AIRSCREWS

- \( n \) revolutions per second
- \( D \) diameter
- \( J \) \( V/nD \)
- \( \dot{P} \) power
- \( T \) thrust with coefficient \( \kappa_T = T/nD^4 \)
- \( Q \) torque with coefficient \( \kappa_Q = Q/nD^5 \)
- \( \eta \) efficiency \( \eta = \frac{TV}{\dot{P}} = \frac{Jk_T}{2\pi k_Q} \)