ARTICLE NO. 78-1551

Historical Overview of Stall/Spin Characteristics of General Aviation Aircraft

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This paper reviews the primary factors which have affected stall/spin behavior of general aviation aircraft over the history of flight in order to obtain a better understanding of the tradeoffs invloved in avoidance of stall/spin. Several basic factors related to the stall/spin problem are 1) aerodynamic effects governing aircraft behavior in terms of the deterioration of several important stability and control parameters at low speeds, 2) stall warning, and 3) methods used for stall limiting. The importance of primary aerodynamic parameters that govern stall/spin behavior, which include roll damping, dihedral effect, lateral/directional cross coupling, and directional stability, are discussed and related to the behavior of the low-speed flight characteristics of several aircraft from the Wright Brothers Flyer to current designs. Prospects for aerodynamic improvements in stall/spin would appear to hinge on 1) more positive control of stall progression on the wing to promote greater post-stall roll damping. 2) development of an acceptable means to limit pitch control power to prevent complete stalling of the wing, and 3) minimization of adverse cross-coupling effects by automatic means.

I. Introduction

FROM man's earliest attempts at flight, stall/spin accidents have plagued the development of virtually all types of aircraft. Even today, stall/spin accidents invloving general aviation aircraft account for more fatal and serious injuries than any other other kind of accident. The classic stall/spin accident is one in which the pilot stalls the aircraft at too low an altitude to effect recovery. This situation usually arises insidiously; the pilot does not expect to stall and is out of practice when he does.

Two examples of stall/spin are the following: First, after experiencing an engine failure on takeoff, the pilot attempts to turn back to the runway quickly before he runs out of altitude. Although most pilots know that a steeper bank angle results in less altitude loss in 180 deg turn, many do not appreciate the need for a much higher airspeed to avoid reaching the angle of attack for flow breakaway on the wing. Further, the actual loss of altitude in a power-off 180 deg turn is not known to most pilots. Altitude loss can range from 125–275 ft (depending on the tightness of the turn) for a Piper 18A aircraft to 400–800 ft for a Cessna 185 aircraft. The second example of a classic stall/spin accident is the one that can occur when turning into the final approach leg in a crosswind. The pilot perceives that for his normal bank angle the turn rate is such that the aircraft will not be lined up with the runway. As a consequence, the aircraft is banked more steeply, using some bottom rudder to help bring the nose around faster; simultaneously, increased back pressure is applied to the elevator control to avoid dropping below the intended glide path. Suddenly, the low wing drops sharply and, given an unaccustomed closeup of the ground from a steep banked nosedown attitude, the pilot instinctively pulls back harder on the elevator control which, of course, is in the wrong direction for stall/spin recovery.

Presented as Paper 78-1551 at the AIAA Conference on Air Transportation: Technical Perspectives and Forecasts, Los Angeles, Calif., Aug. 21-24, 1978; submitted Oct. 13, 1978; revision received Feb. 22, 1979.

Index categories: Aerodynamics; General Aviation; Configuration Design.

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Good stall/spin characteristics have probably been design goals for virtually all aircraft, but they have been difficult to attain. Some light may be shed on the subject by examining the history of a variety of general aviation aircraft, with a view to obtaining a clearer understanding of the trade-offs involved in stall/spin avoidance. Of the many factors related to the stall/spin problem, primary attention is given in this paper to aerodynamic considerations, although it is recognized that human factors and pilot training are also very important aspects of the total problem.

II. Discussion

In designing a normal category, general aviation aircraft, the Federal Air Regulations (FAR Part 23) require the aircraft to exhibit clear and distinctive stall warning and to respond to normal use of the controls in such a way that neither excessive altitude losses nor dangerous attitudes are encountered during stalls and recoveries; spin recovery must always be possible with normal techniques. Since the FAR requirements would appear to be easily achievable with today's technology, let us set the stage for a historical review by examining several aerodynamic considerations which govern the aircraft behavior at and near the stall.

Attention will be directed to the parameters affecting the stall/spin entry and not spin recovery, since spin recovery is a complex problem in itself and beyond the scope of this paper. Even the stall/spin entry is complex; however, it is hoped that the following discussion will help focus attention on possible solutions to the problem.

Aerodynamic Considerations

One may ask why it has not been possible to design general aviation aircraft with built-in aerodynamics which provide such good low-speed handling qualities that even the novice pilot could not get into a stall/spin problem. In particular, from the manufacturer's viewpoint, could the aircraft be made inherently spin-resistant without special gadgetry and without undue compromises in overall performance, appearance, and cost? This is a difficult question to answer because of the interrelated effects of many parameters which affect stall/spin behavior. In the early days not enough was known about the desirable aerodynamic characteristics. Today we not only are developing a good understanding of the factors involved, but also have analytical prediction techniques and high-Reynolds-number wind tunnels to aid the aircraft designer.

Identification of Parameters

Stall/spin behavior of an aircraft is related primarily to the following aerodynamic parameters:

Slope of lift curve top, C_L vs α
Rolling moment, C_l
Roll damping, C_{lp}
Roll control power, $C_{l_{\delta_a}}$
Aileron adverse yaw, $C_{n_{\delta_a}}$
Directional stability, C_{n_β}
Yaw damping, C_{n_r}
Dihedral effect, C_{l_β}
Side force, C_Y
Yawing moment, C_n
Yawing moment due to rolling, C_{n_p}
Pitching moment, C_m
Pitching control power, $C_{m_{\delta_e}}$

Obviously, this is a formidable list and it will be possible to discuss only a few of the more important parameters: the ones that relate to the historical development of aircraft. A more complete discussion of the effects of these parameters is given in Ref. 1.

The variation of lift coefficient with angle of attack near maximum lift (shape of the lift curve top) is one of the most important design considerations for low-speed flight because it directly reflects the potential seriousness of the stall/spin problem. A sharp lift curve top, that is, one where lift decreases rapidly with increasing angle of attack due to large areas of airflow separation, usually results in a large bank angle (roll-off) at the stall. This is illustrated by the data of Fig. 1, which show lift- and rolling-moment variations measured in the NASA Ames full-scale wind tunnel for an aircraft with two wing leading-edge configurations. Note the relatively large roll-off for the cambered leading edge, which in this case was designed for high-speed considerations. Note also that the large rolling moment occurs over a very small angle-of-attack range, which is due to an asymmetric breakdown (stalling) of the airflow, intially over one wing panel. If the flow separation occurs outboard on the wing, lateral controllability deteriorates, roll damping is reduced, and large excursions from level flight occur. The obvious solution is to design for a stall with initial airflow breakdown disposed symmetrically at the wing center section. This action lessens the tendency to roll off at the stall. Because of the reduction of downwash at the tail, the aircraft will tend to pitch down out of the stall region. In addition, natural stall warning is obtained by buffeting of the aircraft and controls. This good stall pattern depends on judicious selection of airfoil sections, proper combinations of wing thickness, twist, taper ratio, etc. To provide the gentle, straight-ahead stall for all combinations of flap, gear, engine power, and c.g. travel, without unduly degrading high-speed performance, is admittedly not an easy task. Although a gentle stall is certainly a most desirable feature, it in itself has not completely solved the stall/spin accident problem. As noted later, the Piper J-3 Cub has a gentle stall, but a poor stall/spin accident record. Let us next examine other aerodynamic factors which promote adverse stall/spin behavior.

Shown in Fig. 2 are typical variations with angle of attack of several aerodynamic rotary derivatives that have a pronounced effect on the spin tendency. Note that these parameters can change sign at the stall and remain unstable at high angles of attack, which tends to promote spinning. An unstable break in pitching moment will cause the aircraft to inadvertently enter the stall region in an uncontrolled manner. Of the various parameters shown, one of the more important is directional stability C_{n_β}, since a reduction in its stabilizing function at high values of α allows yaw excursions to build up to a rate high enough that autorotative forces can predominate. This is true also for roll damping since a resisting force is needed to reduce the roll rate. The change in dihedral effect C_{l_β} is also significant, since at the high α's the self-righting tendency to raise the low wing by sideslipping may be nonexistent. The consideration of directional stability about the stability axes or flight path is called "C_{n_β} dynamic." With the proper (stable) variation of C_{n_β} and C_{l_β} with angle of attack, it may be virtually impossible to promote a spin, in normal control usage. Providing positive directional stability out to angles of attack beyond the stall is difficult, particularly when it is desirable to locate the tail in the stalled wing wake for good stall warning.

The need for stall warning has been recognized as an essential element in providing the safe operation at low speeds. Buffeting and shaking of the aircraft and controls as the stall is approached is the most desirable form of stall warning, since it is relatively difficult to ignore and can indicate to the pilot if he is progressing into or away from the stall.

Finally, and equally important, are the aileron control characteristics. In the event that roll-off occurs at the stall, adequate roll control power is needed to quickly level the wings to minimize altitude loss. In addition, roll/yaw cross coupling should be minimized because large amounts of ad-

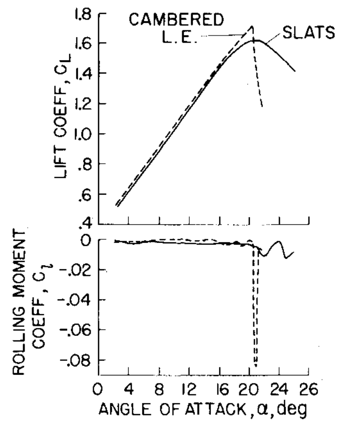

Fig. 1 Lift and rolling moment characteristics.

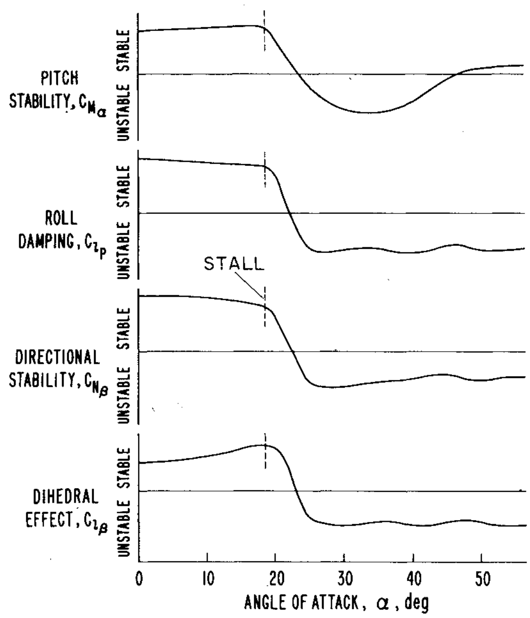

Fig. 2 Typical variations of aerodynamic parameters through stall.

verse yaw due to aileron deflection $C_{n_{\delta}}$ tend to promote spin entry when the ailerons are used to prevent roll-off at the stall. In spite of the continued emphasis given in pilot training to the use of only the rudder to raise the low wing at the stall, most pilots will instinctively use aileron in a stress situation.

In summary, the design philosophy to alleviate the stall/spin problem is threefold: 1) provide good handling qualities up to and beyond maximum lift, 2) make the aircraft spin-resistant, and 3) provide stable static and dynamic stability characteristics with good control about the pitch, roll and yaw axes. The second item requires the designer to know how to achieve stable contributions of several aerodynamic rotary derivatives out to large angles of attack. The third factor requires proper location of flow separation on the wing and judicious horizontal tail placement.

Now let us review the development of aircraft and reflect on the factors required to promote stall/spin avoidance.

Historical Overview

In man's earliest attempts at flight, the importance of satisfactory control at low speeds was underrated. Historic aircraft which exemplify the control problem at the stall are shown in Fig. 3. In a summary of the historical development of stability and control technology,[2] it was noted that Otto Lilienthal in Germany in the late 1800's recognized the desirability of having pitch (static) stability in manned gliders, but failed to provide sufficient pitch control power (obtained by movement of the pilot's body) to maneuver at low speed. Lilienthal made many successful glides before he was killed when his glider was upset by a gust and stalled. The Wright brothers, on the other hand, appreciated the need for adequate control but deemphasized pitch static stability requirements. As noted in accounts of their first flights[3] their canard configuration was longitudinally unstable, resulting in overcontrolling pitch attitude during most of the flights. The Wright brothers did very little maneuvering in their early flights; the first 360 deg turn was not made until September 1904. Because of control problems, frequent inadvertent upsets occurred. In one case, Wilbur Wright allowed the aircraft to pitch up to the stall during a moment of confusion when he inadvertently stopped the engine. The stall occurred at low altitude, resulting in a nose-down impact with the ground. Although damage was considerable, Wright was not hurt. As their flights progressed, the Wrights recognized the need for nose-down control to unstall the wing and the need for a more forward c.g. location to reduce the longitudinal instability. This was made possible by reducing the airfoil camber and providing a favorable hinge moment balance on the horizontal tail which, in turn, allowed a forward c.g. shift. The use of wing warping for lateral control produced large values of adverse yaw which contributed to spin tendencies when stalls were encountered. The 1911 modified "B" flyer used trailing-edge ailerons instead of wing warping to improve lateral control.

Lack of longitudinal stability, low lateral control power, and large cross coupling, factors which usually turned out to be fatal as the stall/spin flight mode was encountered, were common among early aircraft in low-speed flight. An excellent account of the low-speed handling qualities of these early aircraft is given by the late Frank Tallman.[4] The 1909 Bleriot, the first of the monoplane series with conventional placement of the control surfaces, was undoubtedly the most copied aircraft prior to 1914. The early models, with wing warp for lateral control, were judged to have only 10% of the aileron control power of modern aircraft. The stall was deceptive, occurring with no warning by dropping a wing and forcing the pilot to turn into the low wing for recovery at about 25 mph. The Curtiss Pusher of 1910 illustrated a common problem of recovery from stalls because of high drag and small power available to accelerate. The stall was almost instantaneous; if speed dropped too low, full power was not enough to keep from mushing into the ground.

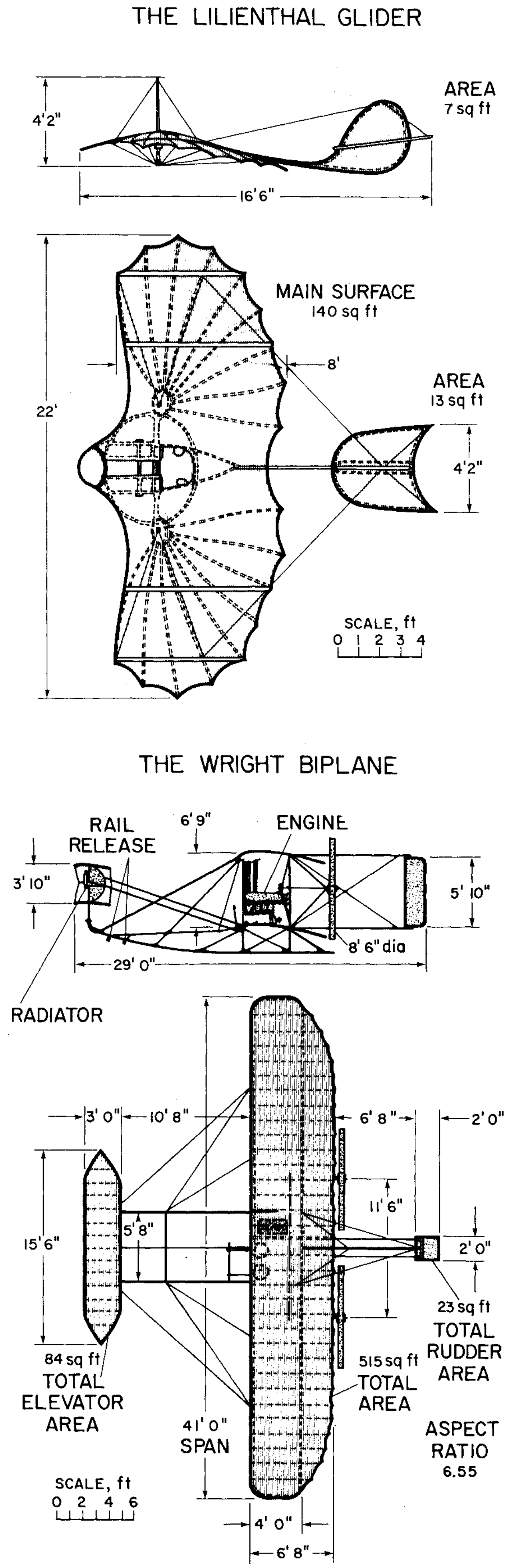

Fig. 3 Early aircraft designs.

It is easy to understand today how the stall/spin problem was such a mystery in the early aircraft. For a decade after Kitty Hawk, stall/spin accidents tended to slow the development of aviation. Because of the frightening aspects of high-altitude flight, it was many years before pilots recognized that some kind of rotation was involved in a spin. Low-altitude operation precluded fully developed spins before ground impact. The nose-dive attitude was evidence in itself to pull back on the stick to attempt spin recovery. It was Orville Wright who discovered that many of the nose-down crashes were due to stalls and not structural failures. He advocated pushing the elevator control forward rather than back for stall recovery, a concept not too popular with pilots who saw the ground from a nose-down attitude.

The World War I aircraft became more maneuverable, higher powered, and structurally capable of being spun without falling apart on recovery. In fact, stall spin maneuvers were often used to escape from an aerial opponent. The spinning aircraft could lose altitude, more rapidly due to its low L/D with separated airflow and more safely with the low airspeeds involved, compared to his pursuer who risked structural failure in high-speed dives. The maneuverability advantage of low-wing loading promoted biplanes and triplanes of compact design such as the Sopwith Camel, Sopwith Triplane, the Spad VII, and Fokker DR1—all with straightforward stall characteristics. The rectangular wing planforms tended to promote flow separation near the wing center with a flat lift curve top, thereby reducing rolling tendencies at the stall. With the multiwing arrangements (triplanes) in particular, the leading wing would stall first, due to increased upwash resulting in a gradual stall. However, low C_{n_β} and C_{l_β} together with large adverse $C_{n_{\delta_a}}$ made it easy to inadvertently spin these aircraft.

The first[a] systematic flight tests to provide a better understanding of the stability and control of aircraft at high lift was conducted by NACA at Langley Field, Va., in the summer of 1919.[5] Tests were conducted on a Curtiss JN4H "Jenny" advanced trainer. This biplane was judged to leave a straightforward stall: however, because of the high drag associated with multiple struts and bracing wires, high rates of sink could develop quite easily, requiring generous application of power to recover. It is interesting to note the commentary on flight behavior near maximum lift: "The airplane can thus be flown level in a very badly stalled condition, the action of the longitudinal control being reversed (i.e., if the machine is losing altitude, it is necessary to decrease the angle of attack by pushing the stick forward in order to ascend). Furthermore, the airplane is very unstable laterally at angles in excess of 12 deg, and it is prone to fall off into sideslips." Most pilots could not fly the aircraft at α's beyond $C_{L_{max}}$ because the ailerons were ineffective and adverse $C_{n_{\delta_a}}$ was large enough to trigger autorotation to a spin.

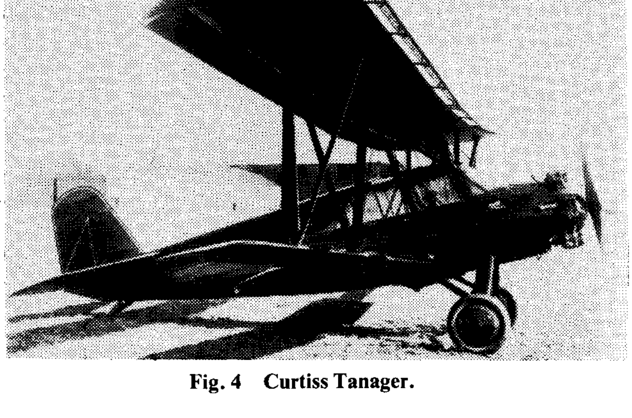

Fig. 4 Curtiss Tanager.

Following World War I, the surplus military aircraft became the first general aviation vehicles, used by barnstorming stunt pilots and in charter operations. Primarily because these aircraft had low wing loading, they could be stalled and spun close to the ground with little airspace needed for recovery. In fact, several of the World War I aircraft were deliberately crashed in spins for World War I movies such as *Lilac Time*, with the pilot walking away unhurt. The technique was to ballast the aircraft to promote a flat spin and provide only enough fuel to get to altitude, thus avoiding a chance of fire. With the low vertical velocity and flat attitude on ground impact, the cockpit area sustained relatively low accelerations.

In the late 1920's the stall/spin problem received formal attention when the Daniel Guggenheim Fund sponsored a contest to promote performance and safety of flight. The Guggenheim Safe Aircraft Competition required that the test aircraft be able to fly from minimum speed of 35 mph or less to 110 mph or more "hands-off controls at any throttle setting." Of the several aircraft entered in the contest, the Curtiss Tanager shown in Fig. 4 was the winner. It featured a floating-tip aileron on the lower wing which was found to be superior in maintaining control at and beyond the stall. Delivery of the aircraft to the Guggenheim Flight Test Section was made on October 29, 1929. The aircraft had superb low-speed handling with full span slats and flaps. The flight tests got off to a bad start when the Curtiss test pilot bent two landing-gear fittings in a demonstration flight when he landed the ship out of a semiwhip stall close to the ground. This aircraft, with a wing loading of 8.5 psf, never became popular. It is ironic that it was severely damaged, when flying in gusty air during a slow flight demonstration, by mushing into the ground.

In the 1930's, increased speed performance resulted from aerodynamic refinements including tapered wings and improved NACA airfoil sections, which, unfortunately, adversely affected stall/spin behavior. In an effort to improve this situation, studies were conducted on means of controlling wing tip stall by use of leading-edge slots and slats. Although these devices were found to improve roll damping at and beyond the stall if they were made large enough, they usually resulted in too large a drag penalty in cruise.

Another approach to stall/spin safety was pioneered by Fred Weick in the mid-1930's.[6] This method consisted of promoting a center-section flow breakdown and limiting elevator travel such that the entire wing could not be stalled. In addition, trim changes due to engine power were minimized, and the use of slot-lip ailerons resulted in less adverse yawing moment. The airplane, designated the W-1A, was purchased by the Bureau of Air Commerce and at their request tested by NACA. This unique concept of two-control operation (no rudders) stemmed from a 1932 NACA test of a Fairchild 22 monoplane.[7] By providing adequate dihedral effect and sufficient directional stability, two-control operation was found to be feasible, thus eliminating the possibility of crossing the controls at the stall. The two-control concept to eliminate stall/spin problems was employed by Weick in the Ercoupe aircraft which has continuously received some degree of popularity in various production versions. It is interesting to note that the Ercoupe has never been in a spin accident. The two-control concept has not come along entirely unscathed, however: NTSB accident records show 13 crashes of the Ercoupe, the large majority due to stall/mush operation into the ground. Because the lateral control remains effective even with fullback longitudinal control, ground impact generally occurred in a flat level attitude that results in relatively minor crew injuries. This backside-of-the-power-curve accident would appear to be corrected by increased engine power.

Prior to World War II, additional technical information pertaining to stall/spin became available. The British at the RAE in a paper by Gates[8] outlined the aerodynamic design features contributing to the wing-dropping problem at the stall. In this country, NACA also reviewed the stalling problems of low-wing airplanes.[9] These reports identified roll instability at the stall as the cause of the problem, pointing out that the trend to increase aircraft performance by high taper ratios lessened the warning of loss of control. Further, the low-wing aircraft inherently had less lateral and longitudinal stability, thus tending to increase the consequence of inadvertent stall. These studies concluded that complete elimination of the roll instability did not seem possible, but that by providing increased stall warning, greater stability at the stall, and a means to limit elevator effectiveness, the severity of the problem could be reduced.

Although aircraft designers knew in general the aerodynamic features that contributed to poor stall/spin characteristics in the 1930's, little quantitative information was available to accurately describe the handling qualities of aircraft near the stall. A first step in defining flying-qualities requirements was started by NACA in the late 1930's.[10] A Stinson SR-8E aircraft was instrumented, and the dynamic behavior at the stall was measured. The aircraft, with its highly tapered wing and large aileron adverse yaw, was noted to have an unstable roll oscillation and autorotative tendencies at and beyond the stall.

In connection with flying qualities, tests of five light airplanes during 1939 and 1940, all of which showed lateral instability at the stall, it was observed that certain stability and control parameters might possibly be modified to increase stall/spin safety. These modifications included increasing wing washout to provide improved roll damping at high α's increasing the area and aspect ratio of horizontal and vertical tails, moving the elevators out of the propeller slipstream, depressing the thrust axis, and limiting rudder travel. The results of these modifications applied to a Piper Cub J3[11] showed the following improvements in stall/spin safety: aircraft dynamic behavior at the stall was improved in that lateral instabilities were essentially eliminated; with the increased directional stability and reduced rudder control power, the aircraft could not be spun; and stalls in turning flight were eliminated by virtue of insufficient elevator control power. These modifications detracted very little from the performance of this particular aircraft, and they could reasonably be made without basically modifying the external appearance. It is not known why they were not incorporated on any follow-on versions of this class of aircraft.

After World War II, the general aviation fleet was again expanded by surplus military aircraft and by improved-performance four-place aircraft such as the Beech Bonanza and North American Navion. Stall/spin accidents continued to take their toll in takeoff and landing, in part because the higher wing loading of these aircraft required more altitude for stall recovery and also because roll instability at stall was aggravated by higher-lift flap systems and effects of increased engine power. Because propeller slipstream rotation causes an increase in sidewash on the vertical tail, large values of left sideslip build up with increase in α when the aircraft is kept at a constant heading during stall approach. Moreover, the left wing receives an upwash due to propeller slipstream, and most aircraft will roll to the left when stalled in the power approach landing configuration. Notorious in this regard were trainer aircraft such as the Vultee BT-13 (shown in Fig. 5) and the North American AT-6. It is of interest to note that when the stall strip was removed from the left wing of the BT-13, the left roll-off at the stall was greatly reduced. Other popularly flown aircraft which have a marked roll-off to the left in a power-on flaps-down stall are the Beech Bonanza and Douglas DC-3, to name just two.

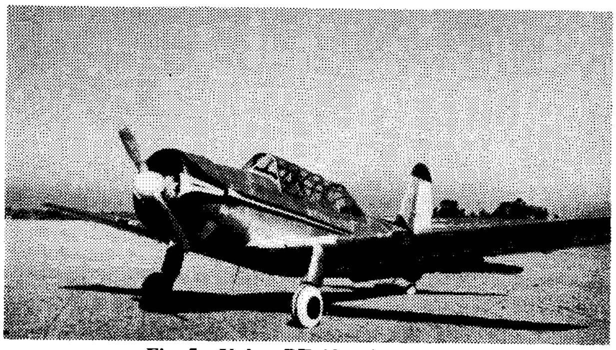

Fig. 5 Vultee BT-13 trainer aircraft.

Interest by NACA in improving the general aviation aircraft safety record picked up again in the 1950's. It was recognized that although some improvement had been made in low-speed handling qualities, only qualitative results were available to guide new aircraft design. Results of flight tests[12] conducted on a Taylorcraft BC-12, which has a NACA 23012 airfoil that promotes a sharp left curve top, indicated that improved lateral characteristics at the stall could be obtained if relatively large wing, washout angles (up to 8 deg) were used or a full-span leading-edge slot were employed. Limiting elevator travel, to have sufficient power to accomplish a three-point landing but insufficient power to exceed the angle of attack for satisfactory lateral control, was achieved only with power-off and a forward c.g. location.

Additional flight tests in this series[13] were conducted on an Interstate S-1A, a Fairchild PT-19, a Piper AG-1, and an Ercoupe with a modified tail. The results confirmed that if the longitudinal control power were limited that the angle of attack obtainable was 2 deg less than that for $C_{l_{max}}$, the aircraft could not be made to spin. It was recognized that limiting elevator travel was not a completely satisfactory solution because $C_{m_{\delta_e}}$ varies too much with changes in configuration, power, and c.g. location.

The British at the RAE[14] were also active in the late 1950's in reviewing stall characteristics for a wide variety of general aviation aircraft. Their conclusions were to employ airfoil sections of known good stall behavior (flat lift curve top) and to avoid high wing taper ratios. Emphasis was also placed on positioning the horizontal tail so as to provide adequate stall warning. Although this work gave an excellent account of the behavior of many popular aircraft at the stall, the quantitative information which would give the designer a useful way of incorporating desirable aerodynamic features was apparently lacking. In defense of these studies, one must admit that it is very difficult to put quantitative values of these aerodynamic parameters in trade-off terms.

The level of research activity devoted to stall/spin problems increased again in early 1970, chiefly as a result of NTSB Report AAS-72.[15] This report emphasized that in spite of improvements made over the postwar years, stall-related accidents still accounted for the largest portion of fatalities and injuries in general aviation flying. Of the 31 general aviation aircraft considered in the study, a wide difference in accident rates was indicated (as much as 20 times greater in some cases). The relative ratings of stall/mush for a wide variety of aircraft are given in Table 1. Most of the aircraft with the poorer ratings are older types, with the exception of the Cessna 177 and Grumman American Yankee. It is surprising to note that the unsophisticated (no flaps, constant chord wing planform, low power) single-engine types like the Aeronca, Cub, Luscombe, and Taylorcraft display the worst records. The aerodynamic features that tend to promote spin entry, i.e., low poststall roll damping, large adverse yaw due to aileron deflection, high elevator power to permit good stall penetration, and large rudder control power to induce sizeable yawing moments, were all inherent in these aircraft. Even though roll instability at the stall increases with larger amounts of engine power, due to the cleanup action of the propeller slipstream over the wing center section, landing approaches with these aircraft were always made power-off because the minimum steady flight L/D was relatively high.

Table 1 Two stall/mush ranking systems for 31 single-engine aircraft (1965-1973)[a]

		Either stall or mush as first or second accident types:				
		Accident rates:[c]		% of total		
Rank 1[b]	Short name	Fatal	All	Fatal	All	Rank 2[d]
1	C-182	0.12 VL[e]	0.60 VL	6.1 VL	3.4 VL	3
2	C-210	0.15 VL	0.43 VL	4.9 L	1.9 VL	2
3	C-175	0.08 VL	1.86 VL	2.8	9.2	1
4	C-185	0.21 L	0.96 VL	10.0	4.6	8
5	C-180	0.19 L	1.47 VL	8.8	5.5	6
6	C-206	0.27	0.68	18.2	4.7 L	19
7	C-172	0.23	1.24	12.8	8.8	15
8	Cher-6	0.25	1.05	9.2	6.2	7
9	Cherokee	0.25	1.32	11.3 L	7.3 VL	11
10	C-150	0.26	1.50	19.4	10.0 H	20
11	Bellanca	0.31	1.23 VL	7.4	3.7 L	4
12	Comanche	0.31	1.34 VL	7.5 L	4.7 VL	5
13	Bonanza	0.40	1.28 H	12.3	7.3 L	12
14	PA-12	0.22	3.38	9.5	10.5	9
15	Tripacer	0.40	1.75	13.8	5.7 VL	16
16	Mooney	0.53	1.61 VL	15.5	7.7	18
17	Ercoupe	0.44	3.13 VH	12.2	8.5	13
18	C-170	0.42	3.71 H	14.1	11.2 H	17
19	C-140	0.52	3.45 VH	21.3	8.7	22
20	B-23	0.59	3.25 VH	23.8	10.5	23
21	Stinson	0.50	4.67 VH	10.4	9.4	10
22	Navion	0.79 H	2.68	12.7	8.9	14
23	C-177	0.94 VH	5.93 VH	29.2 H	18.4 VH	26
24	Citabria	1.24 VH	5.54 VH	27.2 VH	15.2 VH	25
25	Taylorcraft	1.19 VH	7.62 VH	19.6	18.9 VH	21
26	PA-18	1.50 VH	5.17 VH	33.6 VH	18.4 VH	31
27	Luscombe	1.44 VH	6.49 VH	27.1 H	9.8	24
28	Cub	1.52 VH	8.29 VH	30.2 VH	24.9 VH	28
29	Yankee	1.82 VH	5.94 VH	31.4 H	18.6 VH	29
30	Aeron. 11	1.67 VH	8.07 VH	33.3 H	17.9 VH	30
31	Swift	3.05 VH	15.24 VH	30.3 H	19.6 VH	27

[a] From Refs. 15 and 16.
[b] Ranked according to (10 × fatal rate + all rate).
[c] Accident rate per 100,000 flight hours.
[d] Ranked according to (10 × fatal % + all %).
[e] VH, VL, and L indicate that rates are "very high," "very low," or "low" compared to the group mean.

Even aircraft rated better in terms of stall/spin problems (e.g., Cessna 182 and 210) have similar stall and prospin aerodynamic characteristics, but with a notable exception: The pilot has to work a lot harder to stall these aircraft because of the higher stick-free longitudinal stability.

There are, of course, many interrelated factors that contribute to stall/spin problems for the variety of aircraft listed in Table 1. An excellent effort to obtain a better understanding of the circumstances, causes and factors which result in unintentional stalls at low altitude for these representative general aviation aircraft is given in Ref. 16. Summary observations from this study indicate that aerodynamic means to improve the stall/spin accident record include the following:

1) Use of flight path spoilers to permit a higher approach speed (more stall margin) without incurring a landing performance penalty;

2) Use of computer-aided airfoil/wing planform research design information;

3) Renewed attention to improving stall warning systems; and

4) Re-examination of the use of limiting elevator control power.

Prospects for the Future

Looking back at over 70 years of flight with general aviation aircraft, one must realize that the stall/spin problem has not changed significantly. It is still a serious factor in general aviation operations, and it is difficult to obtain a clear understanding of the large differences in stall/spin accident rates for various aircraft. Although the aerodynamic factors for good stall/spin behavior are reasonably well known, incorporating them into current aircraft designs is still difficult. For example, the flight characteristics of one of the latest four-place, high-performance, single-engine aircraft to appear on the general aviation market was evaluated recently with the following comment: "the exciting part of our test was the stalling...though both audio and buffet warning were strong and the aircraft flew impeccably down to the break, it displayed an invariable attraction to autorotation after a stall in virtually any configuration."

It would appear that the best hope for aerodynamic improvement in the stall/spin area is to consider three approaches: 1) control stall progression on the wing to provide greater post-stall roll damping and natural buffet stall warning; 2) limit longitudinal control power in a more practical manner to prevent complete wing stall; and 3) minimize adverse cross-coupling effects by automatic (SAS) means. A short discussion of each of these points follows.

The first point, to promote good tip stall characteristics and thereby minimize wing dropping, is not new, since proper selection of airfoil section, limits on taper, and wing washout have been tried in various forms with only partial success over the years. Another approach to promote positive roll damping at and beyond the stall is to cause the airflow on a high-aspect-ratio wing to behave like that of a low-aspect-ratio planform. This method, discussed in Ref. 17, utilizes a strong vortex flow separation at high α's at the midsemispan through selective airfoil design. The midspan vortex effectively reduces separation both inboard and outboard, and a doublehump lift curve top results, such that greater lift can be made to occur after the initial lift curve peak. Further results of this work are reported in Ref. 20.

The second point, that of limiting longitudinal control power, has also been applied in several ways in the past. Although the method used by Fred Weick in the Ercoupe admittedly has had a certain degree of success, application of this relatively simple scheme has not caught on in larger and more modern aircraft. One reason is the difficulty of handling the c.g. travel aspects. A further improvement in this approach has been studied by Chevalier.[18] This system incorporates a small spoiler on the underside of the stabilizer, deployed by a servo using an angle-of-attack sensor. The spoiler automatically limits pitch control power near the stall and increases the elevator hinge moments, making it more difficult to achieve high-angle-of-attack operation.

Another way to limit stall is to use a canard surface for pitch control as discussed in Ref. 19. By virtue of the fact that the canard operates in the upwash of the wing, it can be designed to stall before the wing. This automatic pitchdown obtained with this arrangement is straightforward; it remains to be seen whether this design scheme has enough merit to attract the attention of the general aviation industry.

Finally, with the advancing digital control system logic appearing on the horizon, the use of SAS or automatic control to improve the rotary derivatives for better poststall behavior is a distant possibility. Military aircraft now employ this technology, and the possibilities of successful application to general aviation aircraft may in the end be the best overall solution.

III. Concluding Remarks

A review of some 70 years of flight has indicated that incorporation of the proper combination of aerodynamic parameters to provide good stall/spin avoidance has persistently remained an elusive goal for designers of general aviation aircraft. Although the primary aerodynamic parameters that influence stall/spin behavior are well known today, the trade-offs involved in incorporating the right combinations of these factors into current aircraft appear to be an insurmountable challenge.

The correct values and combinations of the primary aerodynamic parameters that govern stall/spin behavior, which include roll damping, dihedral effect, lateral/directional cross coupling, and directional stability, are admittedly difficult to obtain by aerodynamic shaping alone. Prospects for aerodynamic improvements in the stall/spin area would appear to hinge on 1) control of stall progression on the wing to provide greater post-stall roll damping, 2) development of an acceptable means to limit pitch control power to prevent complete stalling of the wing, and 3) minimization of adverse cross-coupling effects by automatic means.

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