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Effects of Wing Leading-Edge Design on the Spin Characteristics of a General Aviation Airplane

Dániel J. DiCarlo,* H. P. Stough III,† and James M. Patton Jr.‡
NASA Langley Research Center, Hampton, Va.

Wind-tunnel and flight tests were conducted to determine the effects of several discontinuous drooped wing leading-edge configurations on the spinning characteristics of a light, single-engine, low-wing research airplane. Particular emphasis was placed on the identification of modifications which would improve the spinning characteristics. The spanwise length of a discontinuous outboard droop was varied and several additional inboard segments were added to determine the influence of such leading-edge configurations on the spin behavior. Results of the study indicated that the use of only the discontinuous outboard droop, over a specific spanwise area, was most effective toward improving spin and spin recovery characteristics, whereas the segmented configurations having both inboard and outboard droop exhibited a tendency to enter a flat spin.

Nomenclature

a_n	= normal acceleration, g
b	= wing span, m (ft)
$\bar{c}$	= mean aerodynamic chord, m (ft)
C_L	= lift coefficient, $(F_L/q_\infty S)$
C_ℓ	= rolling moment coefficient, $(M_x/q_\infty Sb)$
F_L	= lift force, N (lb)
M_x	= rolling moment, positive for right wing down, m-N (ft-lb)
q_∞	= freestream dynamic pressure, M/m^2 (lb/ft^2)
r	= yawing velocity, rad/s (deg/s)
S	= wing area, m^2 (ft^2)
V	= velocity, m/s (ft/s)
α	= angle of attack, rad (deg)
δ_a	= average aileron control-surface deflection, positive for right aileron trailing edge down, rad (deg)
δ_e	= elevator control-surface deflection, positive for trailing edge down, rad (deg)
δ_r	= rudder control-surface deflection, positive for trailing edge left, rad (deg)
θ	= pitch attitude, positive for nose up, rad (deg)
ϕ	= roll attitude, positive for right wing down, rad (deg)
ψ	= yaw attitude, positive for nose right, rad (deg)
Ω	= total angular velocity, rad/s (deg/s)

Introduction

THE NASA Langley Research Center is presently conducting a comprehensive research program to develop the technology required to improve the stall/spin characteristics of light general aviation airplanes. Stall/spin accidents have been cited as a major causal factor in fatal general aviation accidents. This research effort includes the following: static and dynamic wind-tunnel tests of models; wind-tunnel tests of full-scale airplanes; radio-controlled model tests; and airplane flight tests. Highlights of the results obtained thus far in the program are discussed in Refs. 1-6.

As part of this research, attention has been focused on the influence of wing geometry on the stall/spin behavior of several representative airplanes since it has been recognized that the wing (particularly the leading-edge airfoil design) can strongly influence lateral-directional stability and autorotative characteristics of this class of airplanes near stall. Recently, these studies identified an extremely effective wing leading-edge modification which significantly improved the spin and spin-recovery characteristics of a low-wing research airplane. The development and results obtained with this modification, which consisted of the addition of a discontinuous drooped leading edge on the outboard wing panels, are summarized in Ref. 5.

This paper discusses the results of additional wind-tunnel and flight tests which have recently been conducted to determine the sensitivity of the spin characteristics of this particular airplane to the geometry of the discontinuous drooped leading edge. Changes in the length of the previous outboard segment and the influence of adding additional inboard segments were examined. Some of the more pertinent results of the study are presented in terms of aerodynamic data, selected flight time histories, and pilot commentary. Correlation of model results with airplane flight results are also made where possible.

Test Configurations

The basic airplane configuration used for the wind-tunnel and flight tests is shown in Fig. 1. Overall characteristics of the test airplane are given in Table 1. The wing airfoil of the basic airplane was a modified NACA 64_2-415 section characterized by a near-symmetric leading edge with a relatively small nose radius.

The leading-edge modification applied to this airfoil consisted of a "drooped" nose section having increased leading-edge radius and camber as shown in Fig. 2. This leading-edge droop was added to the basic wing over various spanwise locations. Selected configurations discussed in this paper are shown in Fig. 3.

The addition of droop to the outboard wing leading edge with a discontinuous inboard juncture, as shown in Fig. 3b, was previously found to improve the stall/spin characteristics of the basic airplane, as discussed in Ref. 5. The "long" and "short" versions of the discontinuous outboard leading-edge configuration were used to determine the geometric sensitivity of the effects of this outboard modification. In combination with the outboard droop, different lengths of leading-edge droop were added to the inboard wing sections to investigate the effect of several discontinuous "gap" sizes, (Figs. 3e and 3f). Such configurations have been studied in Ref. 7. Limited tests of slight variations to these leading-edge configurations have been included in the discussion of results, with comparisons made to both the basic and full-span continuous droop leading-edge configurations.

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*Research Engineer, Low-Speed Aerodynamics Division.
†Research Engineer, Low-Speed Aerodynamics Division.
‡Head, Aircraft Operations Branch, Low-Speed Aerodynamics Division. Member AIAA.

Table 1 Test airplane characteristics

Gross weight, N (lb) at test altitude	6863 (1543)
Moments of inertia, kg-m^2 (slug-ft^2)	
About pitch axis	826 (609)
About roll axis	1010 (745)
About yaw axis	1741 (1284)
Center of gravity, mean aerodynamic chord, %	26
Wing	
Span, m (ft)	7.46 (24.46)
Area, m^2(ft^2)	
Basic wing	9.11 (98.11)
With drooped outboard leading edge	9.21 (99.13)
Root chord, m (ft)	1.22 (4.0)
Tip chord, m (ft)	1.22 (4.0)
Mean aerodynamic chord, m (ft)	
Basic wing	1.22 (4.0)
With drooped outboard leading edge	1.23 (4.03)
Aspect ratio	
Basic wing	6.10
With drooped outboard leading edge	6.04
Dihedral, deg	5.0
Incidence:	
At root, deg	3.5
At tip, deg	3.5
Airfoil section	NACA 64_2-415 (modified)

Fig. 1 Test airplane with baseline outboard leading-edge droop.

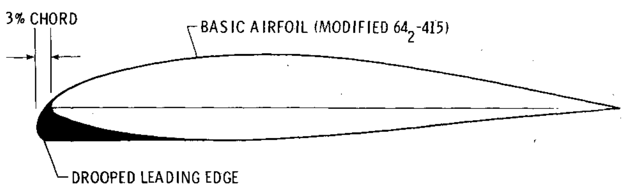

Fig. 2 Airfoil modification.

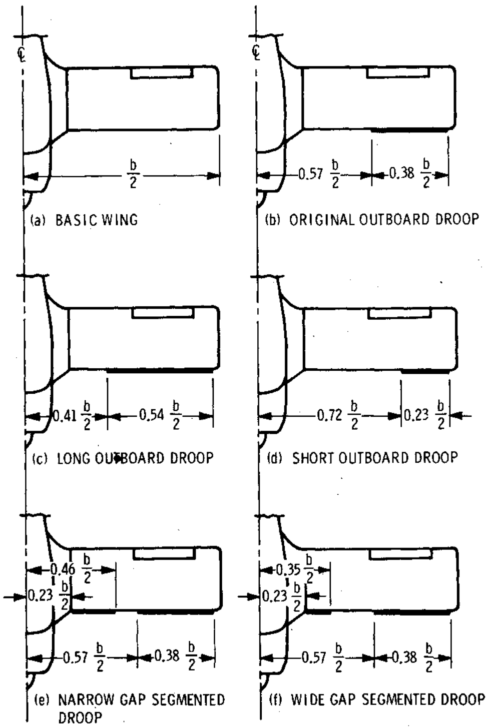

Fig. 3 Wing leading-edge configurations tested.

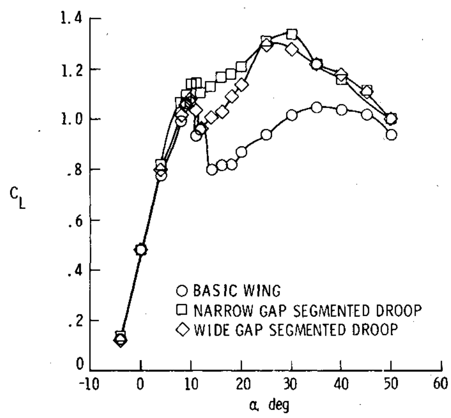

Fig. 4 Static longitudinal data from low-speed tunnel tests.

Wind-Tunnel Tests

Static Force Tests

Exploratory wind-tunnel tests were conducted in the Langley 3.6 m (12 ft) low-speed tunnel to identify promising wing modifications prior to radio-controlled model and airplane flight tests. Aerodynamic data were measured for a Reynolds number of 300,000, based on the wing mean aerodynamic chord of a 1/5-scale model, and over an angle-of-attack range of −10 to 50 deg.

An example of longitudinal data from the static tests is shown in Fig. 4. The data show the variation of lift coefficient C_L with angle of attack α for the narrow gap and wide gap segmented leading-edge droop configurations (Figs. 3e and 3f) as compared with the basic wing having no leading-edge treatment (Fig. 3a). Long and short outboard droop configurations were not tested. For the basic wing, a classical lift-curve shape is indicated with a stall α of about 10 deg characterized by a rather abrupt change to a negative lift-curve slope. The negative slope persists out to an α of about 15 deg with a correspondingly large reduction in lift coefficient. Such a pronounced negative slope is indicative of unstable damping in roll and a prime cause of autorotation. Though not shown in the data, use of a full-span droop produced a higher lift coefficient at stall followed by the same negative slope.[5] The segmented leading-edge configurations altered the character of the lift curve, as noted in Fig. 4, resulting in a secondary peak at a higher lift coefficient and angle of attack. This "double peaked" lift curve is apparently caused and strongly influenced by the gap in leading edge. In particular, the primary or first stall appeared to be related to the stall of the inboard wing section; the secondary stall is attributable to stall of the outer wing panel. With such a configuration, the initial stall buffet can provide a stall warning and allow a more stable penetration to higher angles of attack if sufficient control is available.

Rotary-Balance Tests

Special testing techniques are required to obtain a valid representation of the autorotative moments acting on an airplane during spin entry because of the poststall nonlinear variations of forces and moments with angular rates. To obtain such data for the configurations of interest, rotary-

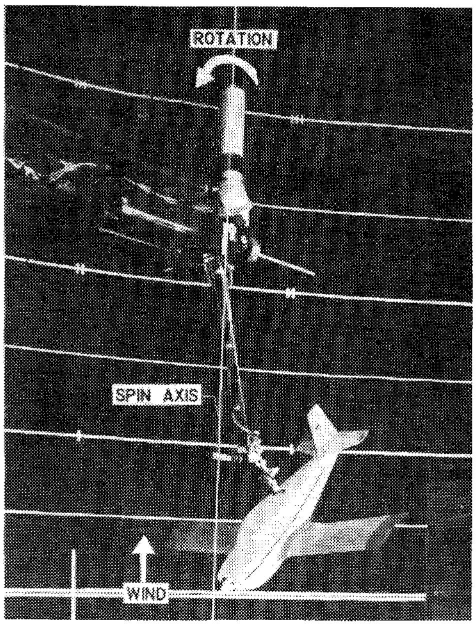

Fig. 5 1/5-scale model installed on rotary balance apparatus.

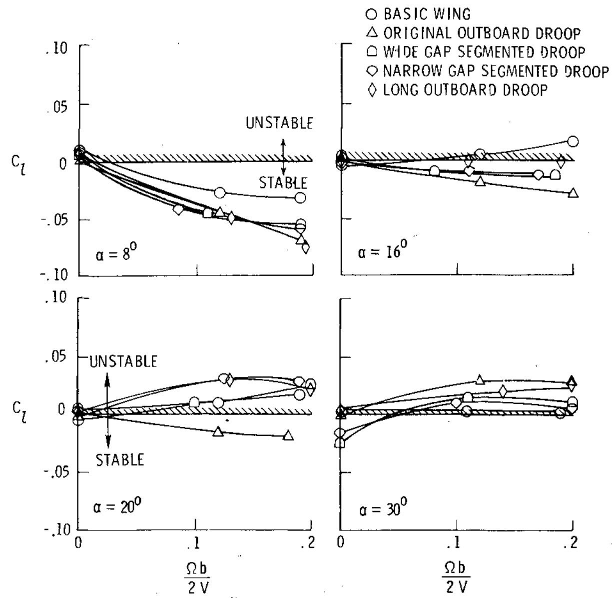

Fig. 6 Effect of wing leading-edge modifications on rolling moments for various rates of rotation (sideslip = 0 deg).

Table 2 Summary of radio-controlled model results

Configurations	Stalls	Spins
Basic wing	Wing rock with abrupt roll-off tendency (either direction) before full-up elevator	Moderately flat, recoverable
		Flat spin,[a] unrecoverable, required chute
Outboard leading-edge droop	No roll-off tendency even with full-up elevator; more stable	Very steep, slow turn rate, with immediate recovery
Long outboard leading-edge droop	Slight wing rock and roll-off tendency	Occasionally entered moderately flat spin, quick recovery
Short outboard leading-edge droop	Increased wing rock roll-off tendency before full-up elevator	Moderately flat spin, recoverable (more like basic airplane)
Narrow gap segmented leading-edge droop	Wing rock at primary stall, no roll-off, entered large radius turn	Ranged from steep and recoverable, to flat and unrecoverable which required chute
Wide gap segmented leading-edge droop	Same as stalls with narrow segmented leading-edge droop	Steep, with slow turn rate and prompt recovery

[a] Model driven into flat spin by cycling elevator.

balance tests were conducted using the method described in Ref. 8. For these tests, a 1/5-scale model was mounted as shown in Fig. 5 on a rotating sting in the vertically rising airstream of the Langley spin tunnel. The model's attitude and rotation rate were varied to permit an evaluation of the autorotative or damping tendencies of the aerodynamic moments for angles of attack from 8 to 35 deg at a Reynolds number of 130,000 based on the mean aerodynamic chord of the wing.

Results of these tests for the leading-edge configurations studied are shown in Fig. 6 in terms of the variation in rolling-moment C_ℓ, with nondimensional rates of rotation $(\Omega b/2V)$. Positive values of C_ℓ, produced by positive values of $(\Omega b/2V)$ are propelling moments, hence, unstable, while negative values of C_ℓ are stable. The data show that at $\alpha = 8$ deg all wing configurations produced a stable variation in rolling moment with rate of rotation. For $\alpha = 16$ deg, the basic wing configuration stalled and autorotative moments are produced. For a slightly higher angle of attack, $\alpha = 30$ deg, all of the configurations, except for the discontinuous outboard leading-edge droop, produced a propelling or unstable rolling moment as a function of spin rate. Finally, at the much higher α of 30 deg, all of the configurations exhibit an autorotative tendency. It should be noted that all of the discontinuous leading-edge configurations exhibit stronger autorotative characteristics than the basic wing at $\alpha = 30$ deg and higher angles of attack. These modifications do not eliminate but rather delay the onset of autorotative moments. These results suggest that the discontinuous outboard leading-edge droop would be the most beneficial leading-edge modification in terms of delaying onset of autorotation, with the segmented leading-edge configurations offering some promise.

Radio-Controlled Model Test

A 1/5-scale powered radio-controlled model of the research airplane was used to investigate the stalling and spinning characteristics of the test configurations. This model was geometrically similar to the static force-test model and dynamically similar to a full-scale airplane weighing 6672 N (1500 lb) flying at an altitude of 1980 m (6500 ft). The model was powered by a conventional model-airplane engine which developed about 1.1 kW (1.5 hp), and equipped with an emergency spin recovery parachute and a seven-channel proportional control system.

The flight maneuvers used to assess the stall and spin characteristics of the model included: 1*g* stalls with idle and full power; accelerated stalls with full power; and attempted spins with neutral and deflected ailerons.

The model was not instrumented. Information regarding the stall characteristics, spin susceptibility, spin mode, rate of rotation, and turns for recovery was obtained from pilot comments, ground crew observations, and photographic records. More detailed information on radio-controlled model testing techniques is given in Ref. 9.

Results of stalls and spins of the radio-controlled model with the different leading-edge configurations are summarized in Table 2. Briefly, the basic configuration stall was characterized by a wing rock and an abrupt roll off into a steep spin. The most improved stall behavior was realized with the addition of outboard leading-edge droop, as noted by a laterally stable stall penetration—no wing rock—and no tendency to roll off.

During spin attempts, the basic configuration exhibited two spin modes. One was moderately flat, having a slow turn rate with satisfactory recovery characteristics. The second was fast, moderately flat, with poor or no recovery characteristics. The model was very reluctant to enter this second mode, and did so only through cycling the elevator to develop higher rotation rates. With the addition of the outboard leading-edge droop, the spin characteristics were very much improved, resulting in a very steep spin mode regardless of entry control conditions or power and acceleration levels. Also, the model was quick to recover from this steep mode by simply relaxing either rudder or elevator. This relatively steep spin mode was also noted for the wide-gap segmented droop configuration, but at times required up to one turn for recovery. All remaining configurations (Fig. 3) exhibited a moderately flat spin mode occasionally requiring use of the spin recovery parachute. These configurations cited produced significant changes in the stall/spin characteristics as determined from tests of these and intermediate configurations.

Based on these radio-controlled model tests, the length of outboard leading-edge droop necessary to be of benefit for this wing geometry is summarized in Fig. 7. The use of various spanwise segmented leading-edge modifications seem to suggest that the addition of any amount of inboard leading-edge droop does not provide significant improvements over that of the original modified outboard leading-edge droop configuration (Fig. 3b). In fact, adding the inboard section appeared to be detrimental from the point of view of stall/spin behavior.

Airplane Flight Tests

Flight tests were conducted at the NASA Wallops Flight Center using the research airplane shown in Fig. 1. The tests included powered and unpowered stalls and spins. Spins were entered by slowly decelerating at idle power to a 1*g* wings-level stall at which time prospin controls were abruptly applied. A variety of prospin and recovery control inputs were investigated for 1-, 3-, and 6-turn spins, both to the right and to the left. Flaps were retracted for all tests.

The airplane was fully instrumented with 30 parameters recorded onboard and telemetered to a ground station. Telemetered data, a picture from a ground tracking TV camera, and pilot commentary were monitored real time in a ground station. These data were supplemented by motion picture film from ground tracking, wing-tip, and onboard cameras.

Stalls

As discussed in Ref. 5, with the baseline outboard leading-edge droop, the airplane's stall characteristics were much improved over those of the basic airplane. At the stall, the pilot noted a reduced roll-off tendency with the outboard leading-edge droop resulting in an overall behavior that was more predictable and better controlled than with the unmodified wing. At times, slight wing rock developed at stall, but bank angle never exceeded 25 deg.

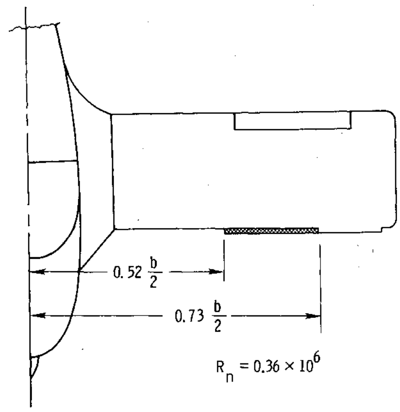

Fig. 7 Range of beneficial length of outboard leading-edge droop determined from radio-controlled model tests.

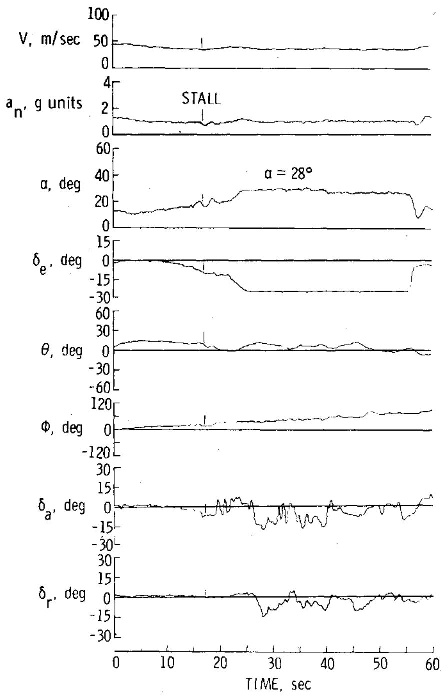

Fig. 8 Stall characteristics with long outboard leading-edge droop (to 41% semispan).

For the long outboard droop configuration (Fig. 3c), the stall characteristics were basically unaltered. The stall break occurred at about 63 knots (73 mph) and resulted in a descent rate of approximately 10 m/s (33 ft/s). These stall characteristics are illustrated in Fig. 8 which shows time histories of selected flight parameters for this configuration. As with the baseline outboard leading-edge modification, the stall was penetrable to an angle of attack of 28 deg; however, the airplane was not as docile as evidenced by the aileron and rudder activity shown and the pilot's comments that moderate amounts of control inputs were required to prevent roll off.

For the other configurations, stall behavior was similar, and compared to the basic airplane, all exhibited some degree of improvement. The stall could be penetrated and controlled with the use of only ailerons or rudder. Generally speaking, although the configurations tested improved the stall characteristics of the basic airplane, none equalled the level of improvement realized with the original outboard leading-edge modification (Fig. 3b).

Table 3 Summary of spin characteristics from airplane flight tests

Configuration	Spin	α, deg	Ω, deg/s	Recovery[b] turns	Remarks
Basic wing	(Two modes)				
	Steady	52	152	1½	—
	Steady	68	209	Parachute	Driven into flat mode by cycling elevator
Outboard leading-edge droop	Steady[a]	28	100	Immediate	—
Long outboard leading-edge droop	Steady[a]	27	70	1/8	—
Short outboard leading-edge droop	Not steady[a]	68	210	2-7/8	Terminated, going flat
Narrow gap segmented leading-edge droop	Steady[a]	76	225	Parachute	—
Wide gap segmented leading-edge droop	Steady[a]	74	235	Parachute	—

[a]Prospin control included ailerons deflected against spin. [b]Normal recovery controls (full opposite rudder followed by down elevator) used in all cases.

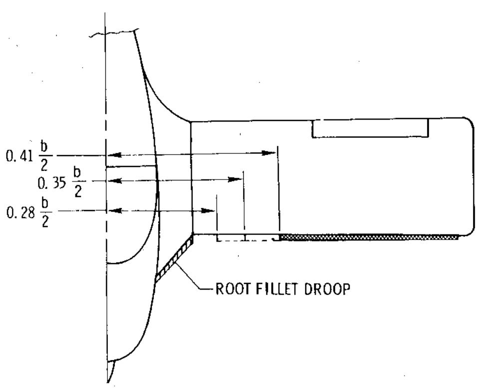

Fig. 9 Extended outboard leading-edge droop configurations and root fillet locations.

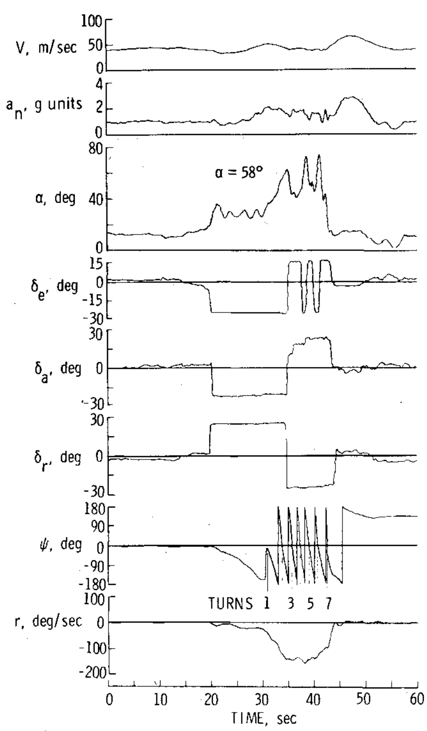

Fig. 10 Spin time histories with outboard leading-edge droop to the 28% semispan point.

Spins

A summary of the spin characteristics for the test configurations of Fig. 3 is given in Table 3. The airplane with the basic unmodified wing had two spin modes: one steep and recoverable; the second flat and unrecoverable. The airplane with the baseline outboard leading-edge droop modification spun very steep at an angle of attack of 28 deg, a turn rate of about 100 deg/s (3.5 s per turn) and a high rate of descent. The spin was the same regardless of the entry conditions and required about 2 or 3 turns to achieve steady state. The pilot noted that in this configuration the airplane was somewhat reluctant to enter a spin and recovered quickly regardless of the recovery control technique employed.

When the leading-edge modification was lengthened spanwise to make the long outboard droop (Fig. 3c) and even a longer configuration (inboard discontinuity located at the 35% semispan point) as shown in Fig. 9, spin characteristics were essentially unchanged. However, when the outboard droop was extended inboard to the 28% semispan location, the spin behavior worsened. A spin-time history for this configuration is presented in Fig. 10. For the first 10 s following application of prospin controls, the airplane rotated very slowly, at an α of 28 deg. The airplane then rapidly began to wind up into a flat spin causing the pilot to terminate the spin at the 2-turn point. The boundary between a good and poor spin configuration obviously had been crossed; therefore, the outboard droop should not extend inboard any further than about the 35% semispan location for this particular leading-edge modification.

These detrimental spin characteristics were eliminated by the addition of a drooped wing-root fillet. This fillet treatment resulted in a very narrow segmented leading-edge gap adjacent to the wing fillet juncture (see Fig. 9).

Shortening the modified outboard leading-edge droop to the configuration of Fig. 3d degraded the spin characteristics.

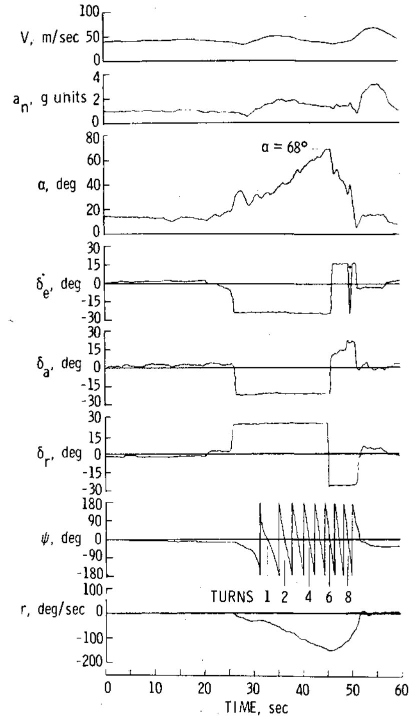

Fig. 11 Spin time histories with short outboard leading-edge droop (to 72% semispan).

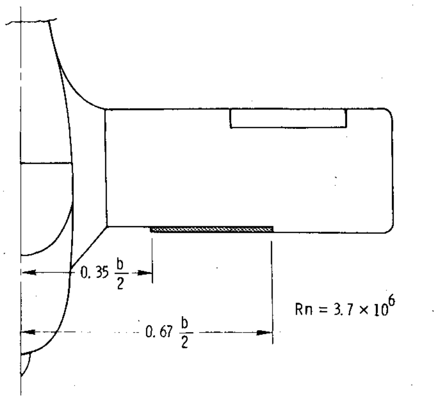

Fig. 12 Range of beneficial length of outboard leading-edge droop determined from full-scale airplane tests.

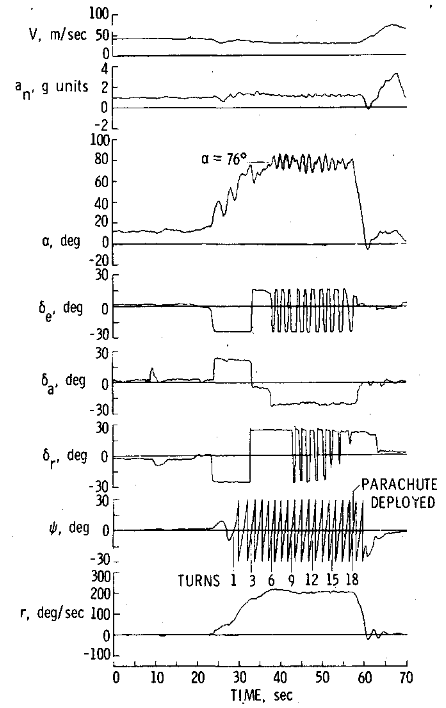

Fig. 13 Spin time histories with narrow gap segmented leading-edge droop.

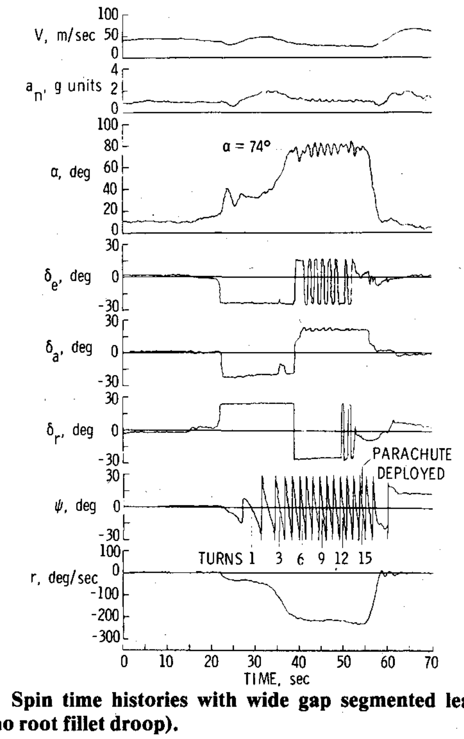

Fig. 14 Spin time histories with wide gap segmented leading-edge droop (no root fillet droop).

As seen from the spin-time history of Fig. 11, this configuration was spinning up into a flat spin when recovery controls were initiated at the 6-turn point. In fact, this configuration was worse than the original unmodified wing. The minimum beneficial length of outboard leading-edge droop must, therefore, have its inboard edge, or discontinuity, between the mid- and three-quarter semispan point. Based on these results of shortening and lengthening the outboard droop segment, Fig. 12 summarizes the range within which the length of modified outboard leading edge appears to provide improved spin behavior.

Time histories of the spin characteristics for the narrow and the wide gap segmented leading-edge droop configurations (Figs. 3e and 3f) are presented in Figs. 13 and 14, respectively. In both cases flat spins resulted when prospin control inputs included deflecting ailerons against the desired spin direction. These spins were quite similar, with angles of attack near 75 deg, and turn rates on the order of 225 deg/s (1.6 s per turn). With the wide-gap segmented configuration, the airplane transitioned quite readily to a flat spin mode, despite the somewhat docile behavior exhibited by the radio-controlled model. Recovery attempts included cycling both elevator and rudder, but were unsuccessful, necessitating the use of the spin recovery parachute.

Since the use of a drooped leading-edge root fillet was shown to be of benefit when used with a lengthened outboard droop, as noted earlier, root fillet droop was added to the wide-gap segmented configuration to assess its influence. The resulting time histories, shown in Fig. 15, definitely indicate an improvement in spin characteristics; yaw rate and angle of attack did not build up as was the case without root fillets (Fig. 14). To investigate the influence of the drooped fillet, it was flight tested with the basic wing having either a sharp discontinuity or faired juncture with the wing leading edge, as shown in Fig. 16. The fillet alone did not affect either the spin entry or the spin mode of the basic airplane; however, when the sharp corner was smoothed, the airplane would not spin

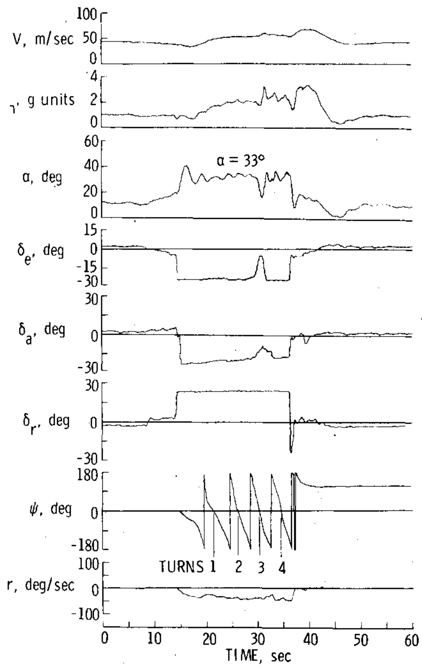

Fig. 15 Spin time histories with wide gap segmented leading-edge droop with root fillet droop.

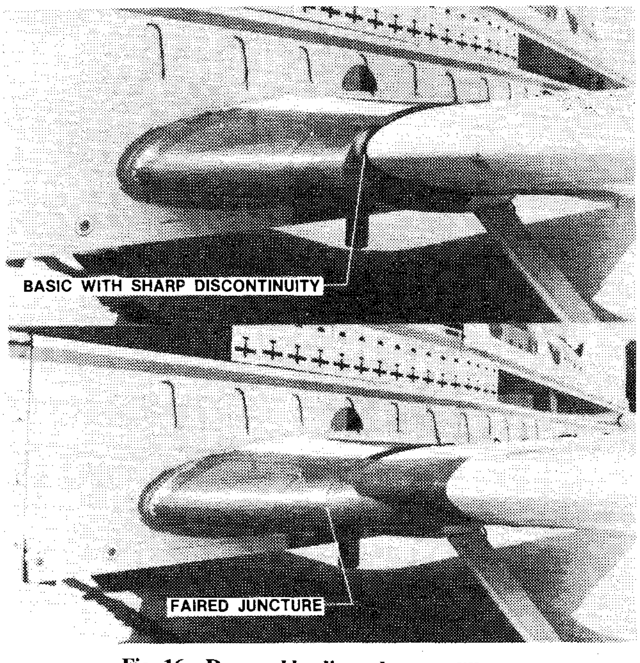

Fig. 16 Drooped leading-edge root fillet.

with power off. Spin entry was achieved only when power was added, and the resultant spin was that of the basic airplane. The use of such a root fillet appears favorable with selected configurations; however, sufficient information is not available to warrant any conclusions.

Correlation with Model Results

Because of the influence of Reynolds number on values of maximum lift coefficient, a special area of interest is the comparison of flight results with those obtained using wind-tunnel and radio-controlled models. In general, the variations in stall and spin behavior realized during the airplane tests agreed well with the model results. The static and rotary-balance data trends used to identify regions of instability for the configurations tested were substantiated by the full-scale tests. Also, the flight characteristics predicted by the radio-controlled model tests were practically identical to those of the airplane, except for the wide gap segmented leading-edge droop configuration. In this case, the radio-controlled model showed no tendency toward flat spin, whereas the airplane did spin flat. Nonetheless, it is significant that such a correlation was realized, and that the full-scale airplane tests were based on analyses of low Reynolds number data.

Concluding Remarks

Several discontinuous droop wing leading-edge configurations were examined to determine their influence on the stalling and spinning characteristics of a representative low-wing general aviation research airplane. An effective range over which an outboard leading-edge droop can be employed to provide acceptable stall and spin behavior for the wing geometry used was identified. The best configuration was that with the drooped leading edge applied from the 57 to the 95% semispan locations on each wing panel. Although adding an inboard segment along with the outboard segment to provide a leading-edge spanwise gap retained the good stall characteristics, the spin and spin recovery behavior degraded. Use of a drooped leading-edge root fillet appeared to improve the spin characteristics associated with several of the configurations; however, insufficient data prevented a thorough analysis of this influence. Flight results were in good agreement with the model data and substantiated flight characteristics predicted by the radio-controlled model tests.

References

[1] Bowman, J. S. Jr., Burk, S. M. Jr., Stough, H. P., and Patton, J. M. Jr., "Correlation of Model and Airplane Spin Characteristics for a Low-Wing General Aviation Research Airplane," AIAA Paper 78-1477, 1978.

[2] Stough, H. P. III and Patton, J. M. Jr., "The Effect of Configuration Changes on Spin and Recovery Characteristics of a Low-Wing Spin Research Airplane," AIAA Paper 79-1786, 1979.

[3] Bradshaw, C. F. and Stough, H. P. III, "Design and Development of a Spin-Recovery Parachute System for Light General Aviation Aircraft," *Proceedings of the 17th Annual Symposium, Safety and Flight Equipment Association,* 1979.

[4] Bihrle, W. Jr. and Bowman, J. S. Jr., "The Influence of Wing, Fuselage, and Tail Design on Rotational Flow Aerodynamics Data Obtained Beyond Maximum Lift with General Aviation Configurations," AIAA Paper 80-0455, 1980.

[5] Staff of Langley Research Center, "Exploratory Study of the Effects of Wing Leading-Edge Modifications on the Stall/Spin Behavior of a Light General Aviation Airplane," NASA TP-1589, 1979.

[6] Johnson, J. L. Jr., Newsom, W. A., and Satran, D. R., "Full-Scale Wind Tunnel Investigation of the Effects of Wing Leading-Edge Modifications on the High-Angle-of-Attack Aerodynamic Characteristics of a Low-Wing General Aviation Airplane," AIAA Paper 80-1844, 1980.

[7] Kroeger, R. A. and Feistel, T. W., "Reduction of Stall-Spin Entry Tendencies Through Wing Aerodynamic Design," SAE Paper 760481, 1976.

[8] Bihrle, W. Jr. and Mulcay, W., "Rotary Balance Data for a Typical Single-Engine General Aviation Design for an Angle-of-Attack Range of 8° to 35°, III-Effect of Wing Leading Edge Modifications Model A," NASA CR 3102, 1979.

[9] Burk, S. M. Jr. and Wilson, C. F. Jr., "Radio-Controlled Model Design and Testing Techniques for Stall/Spin Evaluation of General Aviation Aircraft," NASA TM 80510, 1975.