Evaluation of Spoilers for Light Aircraft Flight Path Control

David L. Kohlman*
University of Kansas, Lawrence, Kan.
and
Carl H. Brainerd†
Northrop Services, Inc., Huntsville, Ala.

The fixed-base flight simulator at the University of Kansas Flight Research Laboratory was used to evaluate wing spoilers for longitudinal flight path control on a modified Cessna 177B aircraft. More than 100 simulated ILS approaches were flown by evaluation pilots using both conventional methods and spoiler controls. Three different spoiler control methods were evaluated. Spoilers provided precise glide path control with constant airspeed and attitude. Control is most effective when the steady-state trimmed airplane C_L remains independent of spoiler position.

Nomenclature

$ASEL$ = airplane, single engine, land
C_L = airplane lift coefficient
C_m = pitching moment coefficient
Δh = altitude perturbation
ILS = instrument landing system
M_{δ_s} = pitch acceleration due to spoiler deflection on one side
n = load factor
rms = root mean square
ΔV = airspeed perturbation
α = angle of attack
$\Delta\alpha$ = angle of attack perturbation
δ_s = symmetrical spoiler deflection
$\Delta\theta$ = pitch angle perturbation

Introduction

THE concept of direct lift control (DLC) has received a considerable amount of attention during the past decade. The purpose of a DLC system is to allow some degree of lift control independent of an aircraft's pitch response by utilizing spoilers, maneuvering flaps, symmetrically deflected ailerons, etc., to generate transient lift increments. The need for such a control has arisen primarily from two unrelated developments: 1) the requirement for more precise flight path control of high performance jet aircraft during carrier approaches to landing and 2) the greatly increased size of military and commercial aircraft, whose decreasing ratio of aerodynamic to inertial moments has produced a more sluggish response to conventional longitudinal control inputs. Reference 1 contains a summary of DLC development work in this country. Reference 2 is an excellent summary of DLC applied to the carrier landing task and Ref. 3 describes an application of DLC to a commercial jet aircraft, the Lockheed 1011, which is now in scheduled service with an operational DLC system.

Although it is well established that DLC is beneficial to large aircraft, it has never been incorporated in production light aircraft. It is of interest to note, however, that spoilers have been used as a landing aid on gliders for many years. The need for improved methods of control during approach and landing seems apparent from the fact that from 1965 through 1969 over 50% of all small, fixed-wing general aviation accidents occurred during approach and landing.[4] The first investigation of the application of spoilers to a light aircraft[5,6] studied the use of symmetrical spoilers on a Beech Musketeer to perform steep VFR approaches and to achieve better control during flare and touchdown.

This paper reports the results of one phase of a project to develop and flight test an entirely new wing for a light airplane incorporating several aerodynamic features, including an integrated spoiler system for both roll control and flight path control. A flight simulator was used, prior to actual wing construction, to accomplish the following specific objectives. 1) Investigate the general suitability of spoilers for longitudinal flight path control compared with conventional throttle-elevator control. 2) Determine the spoiler pitching moment characteristics which produce favorable control and handling qualities. 3) Evaluate several spoiler control schemes and corresponding cockpit spoiler controllers.

To accomplish the objectives several different pilots were assigned a standard ILS approach task. Of particular interest was whether spoiler control resulted in improved pilot performance, or if the task is made easier with the same level of performance. The approach was terminated at the middle marker with no attempt made to evaluate flare and landing characteristics with the tested spoiler systems.

Test Setup

Flight Simulator

The tests were conducted using the fixed-base flight simulator at the Kansas University Flight Research Laboratory. The cockpit is that of a Beechcraft Duke. Control forces and engine noise are simulated for realism, and a full instrument panel is provided. Power control is via a center pedestal-mounted power lever with a bicycle-type handgrip. The simulator is controlled by EAI 580 and TR-48 general-purpose analog computers programed to solve six degree-of-freedom small perturbation rigid airplane equations of motion. The equations and their programing are detailed in Ref. 7.

Turbulence

In an attempt to make the ILS approach task more realistic, a turbulence generator was designed to provide random angle of attack disturbances representing sharp-edged vertical gusts to the equations of motion. Rms gust velocity was 2 fps and peak gust velocity was 4.8 fps. The

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*Professor of Aerospace Engineering, Associate Fellow AIAA.
†Engineer.

Table 1 Modified Cardinal configuration data

Wing span = 31.5 ft	Wing incidence = 3.5° (root) 0.5° (tip)
Wing area = 110 ft²	Spoiler span = 115.9 in. (each)
Mean geometric chord = 43.5 in.	Spoiler chord = 4.0 in.
Taper ratio = 0.5	Total spoiler area = 6.44 ft²
Aspect ratio = 9.0	Spoiler travel = 60° max
Dihedral angle = 3°	Gross weight = 2500 lb

pilots' subjective opinion was that the simulator instrument readings in turbulence were similar to those they had observed in actual flight.

Instrument Landing System

A standard ILS system was programed on the simulator, and the glideslope and localizer needles on the instrument panel indicated with standard sensitivity. The glideslope was 3° with the outer marker and middle marker located 5.4 mile and 0.7 mile from the touchdown point, respectively.

Spoiler Controllers

Three methods of controlling symmetrical spoiler deflection were evaluated during the tests. They were designed to provide spoiler actuation with the right-hand thumb independent of elevator and throttle movement.

1) Bang-Bang Position Control

A standard aircraft pitch trim thumb switch (2-way, center off, spring-loaded) was installed in the top of the throttle handle. With the spoilers positioned at 20° deflection (with a separate on-off switch), pushing the trim switch forward commanded 0° deflection, and pushing the switch rearward commanded 100% DLC deflection (40°). Thus, the sense of the spoiler control was the same as the throttle on which it was mounted. Forward was for airplane "up" and back was for airplane "down." In short, the spoilers could be popped either up or down from a bias position to change the flight path in the desired direction with no throttle change. A first order lag with a time constant of 1 sec simulated the dynamics of a servoactuator. When the switch was released, 50% deflection was again commanded.

2) Thumbwheel Position Command

A small wheel similar to a miniature pitch trim wheel was mounted on the left side of the throttle handle. As the pilot's hand held the throttle, his thumb rested naturally on the wheel. Rotation of the thumbwheel commanded any spoiler position from 0° to 40° proportional to the wheel's angular position. The full range of deflections was covered by approximately 270° of wheel rotation (the wheel was connected to a miniature one-turn potentiometer inside the throttle handle). As with controller (1) above, a first-order lag simulated servo response to position command. Since this controller was, in effect, a sort of longitudinal trim control using spoilers, the sense of the control was made the same as for a conventional elevator trim wheel when used for flight path control. This is, rotating the wheel forward called for more spoiler deflection (airplane down), and rotation aft gave less deflection (airplane up).

Note that the sense of this control was opposite to that of the bang-bang position controller. The bang-bang switch was tried experimentally with both possible senses, but neither seemed natural enough for the pilots to use without consciously thinking about which way to move the switch. The use and sense of the thumbwheel were as natural as possible for several reasons: a) Rotation of the wheel commanded a similar rotation of the spoilers. b) A nose-down rotation of the wheel achieved the same glide path response as a nose-down rotation of the airplane or a nose-down trim change. c) An upward motion of the thumb on the back of the wheel commanded an airplane response which would also tend to move the ILS glide slope needle upward.

3) Bang-Bang Rate Control

This controller utilized the previously described thumbswitch, but instead of commanding spoiler position, the switch commanded a deflection rate. This stimulated spoilers driven by a constant speed electric motor, with the switch merely turning the motor on and off. This controller was analogous to conventional electric pitch trim; pushing forward on the switch caused the spoilers to run up (airplane down), and pushing rearward ran the spoilers down. When the switch was released, the spoiler motion stopped. The deflection rate was about 10°/sec, which was representative of the spoiler actuator on the new wing, a standard Cessna electric flap motor.

Evaluation Airplane

The airplane which was simulated in this investigation was a Cessna Cardinal with new wings designed by the Flight Research Lab. A detailed analysis of this design may be found in Ref. 8 and summarized in Ref. 9. Configuration data are given in Table 1. Important features of the design are: 1) reduced wing area (110 ft^2) compared with the production Cardinal (175 ft^2), 2) high lift system employing Krueger leading and Fowler trailing edge flaps, and 3) spoilers which are used for both roll control and direct lift control.

The flight condition chosen for the evaluation flights was: landing configuration (full flaps); weight = 2500 lb (maximum gross weight); altitude: sea level, standard day; airspeed = 107 fps = 73 mph; and center of gravity @ 3.3% mac.

Complete details of the derivatives and parameters used to simulate the modified Cardinal are contained in Ref. 10 along with more detail on the computer circuitry and the flight simulator results.

Data Recording

An eight-channel strip chart recorder was used to record various flight parameters during the evaluation flights. Of primary interest were: glide slope deviation, localizer deviation, spoiler deflection, throttle position, airspeed, pitch angle, vertical speed, normal acceleration, and altitude.

Flight Path Control

The longitudinal flight path control problem facing the pilot on an ILS approach is illustrated in Fig. 1. The glide path is defined in space by the ILS transmitter and the pilot monitors his position with an instrument panel indicator. If at some point he finds himself displaced from the glide path, he must maneuver the airplane back onto the glide path at the proper rate of descent. Two possible maneuvers are shown by lines 1 and 2. Line 1 shows the maneuver which would be possible with pure direct lift control. i.e., load factor control. The pilot would select a small negative load factor increment which would cause the flight path to curve downward toward the glideslope. About midway at point C, a positive load factor increment would be selected to pull up from the descent and again stabilize at the proper steady-state descent rate. Recovery from the maneuver is initiated before the air-

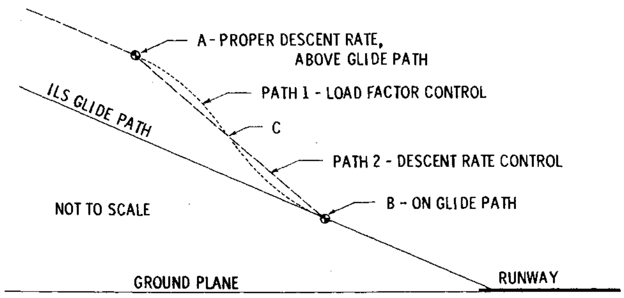

Fig. 1 ILS approach path correction.

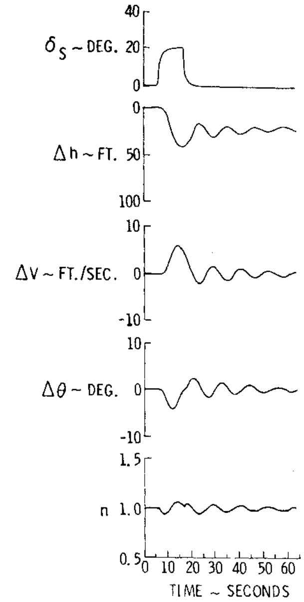

Fig. 3 Airplane response to 10 sec spoiler pulse, "pure" DLC, M_{δ_s} = −0.0979.

craft is on the glideslope, thus there is no definite cue to tell the pilot when he has reached point C and should start pulling out. Of course, this might come naturally with practice. Three control inputs are required: selection of negative "*g*" increment, selection of positive "*g*" increment, and return to unaccelerated flight.

Line 2 of Fig. 1 shows a second possible maneuver to be used by an aircraft provided with direct control of descent rate. In this case, the pilot would select a higher than reference descent rate, maintain it until intercepting the glideslope, and then return to the reference rate of descent. In this case, there is a positive cue to when to recover from the maneuver, and only two control inputs are required. This maneuver actually consists of unaccelerated, steady-state flight connected by brief transition arcs, while maneuver 1 requires accelerated, nonsteady-state flight. Whatever correction is used, it is desirable to minimize excursions in airspeed and airplane attitude, and to avoid excitation of dynamic response modes of the airplane such as the phugoid.

For a visual approach, the situation is simplified because there is no fixed glide path or course to be followed. Thus, the flight path slope can be shallow or steep as long as it leads to the runway threshold. As shown in Fig. 2, if a pilot finds himself displaced from his original intended flight path, the only correcting maneuver required is a change in rate of descent. Thus a direct control of descent rate is more useful for visual approaches than pure direct lift control. Note, however, that visual approaches using glide slope aids such as VASI or aircraft carrier approach light systems should be treated the same as instrument approaches in the context of flight path control.

Airplane Dynamic Response

The stick-fixed dynamic response of the test airplane to various spoiler inputs and throttle inputs was investigated using the flight simulator. The airplane was trimmed for level flight at approach airspeed in smooth air. Spoilers were then deflected as desired using the bang-bang position command controller. No other longitudinal control inputs were made.

Spoiler Pitching Moment

The pitching moment induced by a lift control defines the aerodynamic center location of the control lift increment. Pinsker[11] showed that aircraft response to a given control lift input is largely determined by the aerodynamic center location of that control lift. If the control lift acts far forward, as with a canard, its effect is augmented by the wing-generated lift caused by the rotation to higher angle of attack. On the other hand, if the control lift aerodynamic center is far aft, as with conventional tailplanes, the effect is reversed. The net change in airplane lift is opposite in sign to the applied control lift, and usually much larger. Therefore, it is obvious that the pitching moment associated with a lift control such as spoilers is an important consideration in obtaining the desired response from the aircraft.

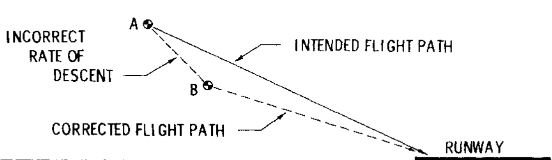

Fig. 2 Visual approach path correction.

Pure Direct Lift Control

Pinsker[11] defines pure direct lift control as a system in which the net change in aircraft lift is the same as the applied control lift. He shows that for this condition to be met the a.c. of the control lift must be as far forward of the aircraft a.c. as the aircraft maneuver point is aft of the center of gravity. This condition implies $M(\delta_s) = -0.0979\ \text{sec}^{-2}$. Theoretically this pitching moment would allow the spoiler system to generate sustained load factors for maneuvering. Figure 3 shows the airplane response to a 10 sec control pulse with this pitching moment. While the initial load factor increment is −0.08, it is quickly washed out by the speed increase caused by the descent. Phugoid excitation caused an initial 6° peak-to-peak pitch angle excursion. To obtain and hold load factors different from 1.0, speed or angle of attack or both must be maintained at something other than the steady-state trim values.

Pure direct lift control is probably useful only for maneuvers such as turns, pullups, and pushovers, where sustained flight at load factors other than 1.0 is desired. During longitudinal glide path control the airplane responds to a change in lift coefficient by seeking a new trim speed rather than maintaining a steady load factor. This leads to undesirably large speed excursions during approach.

Zero Pitching Moment

$M(\delta_s)$ was next set to zero, and airplane response determined. Figure 4 shows the response to a 10 sec spoiler pulse with zero spoiler pitching moment. Although the aircraft descended as much as 38 ft, the actual average altitude loss was approximately 20 ft. Speed and pitch angle changes due to phugoid oscillation were 7 fps and 5.5° peak-to-peak, respectively. This is enough to be ob-

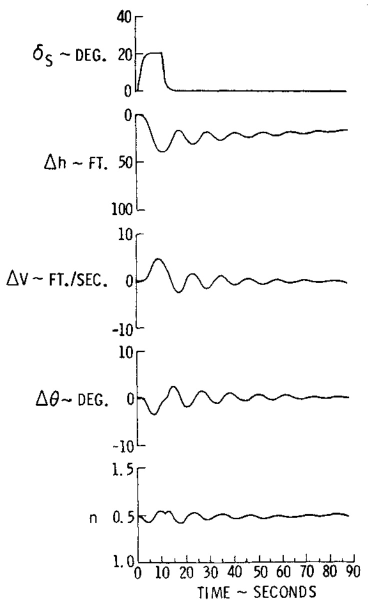

Fig. 4 Airplane response to 10 sec spoiler pulse, $M_{\delta_s} = 0$.

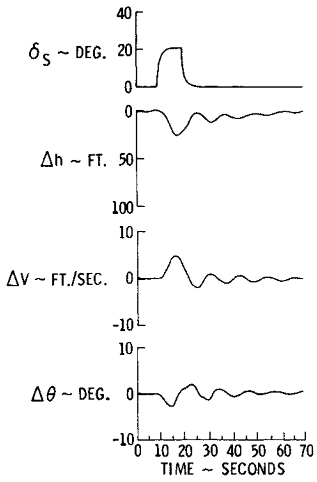

Fig. 6 Airplane response to 10 sec spoiler pulse, zero spoiler drag and pitching moment.

jectionable considering the small altitude change actually involved.

Constant Lift Coefficient

In an attempt to minimize speed variation and phugoid excitation, the spoiler pitching moment was set to maintain a constant aircraft lift coefficient. That is, the spoiler pitching moment caused the airplane to rotate to a higher angle of attack so that the increase in lift due to angle of attack equaled the loss in lift due to spoiler deflection. This condition requires that

$$\partial C_m/\partial \delta_s = (\partial C_L/\partial \delta_s)(\partial C_m/\partial \alpha)/(\partial C_L/\partial \alpha)$$

Substituting the estimated derivatives yielded the dimensional derivative $M(\delta_S) = 0.471$.

The airplane response to a 10 sec spoiler pulse with constant C_L pitching moment is shown in Fig. 5. The plane descended 30 ft and leveled off smoothly when the spoilers retracted with only a 2 ft altitude overshoot. A slight phugoid motion is visible, but speed and pitch angle changes were small (1.2 fps and 1.2° peak-to-peak). This would seem to be a nearly ideal descent rate control. This system rates high from a handling qualities point of view, since altitude and vertical speed are the only variables significantly affected by the spoilers. Pitch attitude and airspeed remain practically constant during the maneuver even though the control input used represents a sudden and relatively large deflection (20°, ½ the available travel).

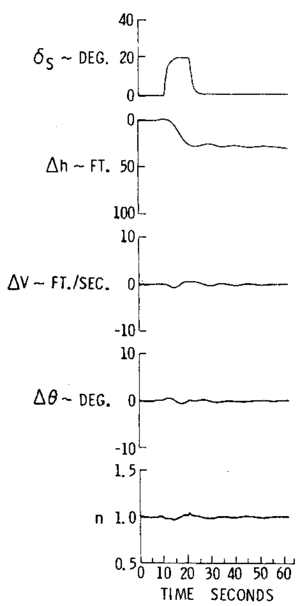

Fig. 5 Airplane response to 10 sec spoiler pulse, constant C_L, $M_{\delta_s} = 0.471$.

Nominal Pitching Moment

The estimated spoiler pitching moment for the modified Cardinal with no elevator interconnect is $M(\delta_S) = +0.433$ sec^{-2}, referred to as the nominal pitching moment. A 10 sec pulse of 20° spoilers showed that the response of the airplane with nominal pitching moment is virtually identical to that in Fig. 5 with pitching moment $M(\delta_S) = +0.471$, the value required for constant trim C_L.

Spoiler Drag and Lift Increments

The effects of spoiler lift and drag were investigated separately. Figure 6 shows airplane response to a 10 sec spoiler pulse with no spoiler drag or pitching moment. In effect, this was a 10 sec decrease in trim lift coefficient. As might be expected, the aircraft at first lost altitude, gaining speed in the descent (trim speed momentarily increased). When the spoilers retracted, most of the altitude loss was gained back, since the maneuver essentially traded potential and kinetic energy off against each other. The response had little in common with the response to the actual spoilers.

When nominal pitching moment was added, keeping spoiler drag zero, a 10 sec pulse had little effect at all on the aircraft flight path, the initial altitude loss being only 7 ft. This would lead to the conclusion that spoiler drag is the major contributor to airplane response. To verify this, the effect of a speedbrake was recorded (Fig. 7). Here $M(\delta_S)$ and $C_L(\delta_S)$ are zero. The aircraft response is similar to that withthe nominal or constant C_L spoilers (Fig. 5)

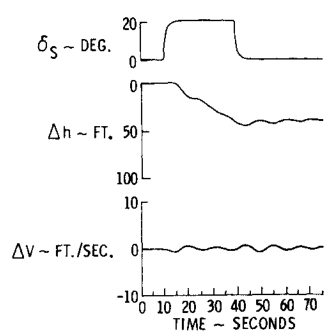

Fig. 7 Airplane response to 10 sec speedbrake pulse.

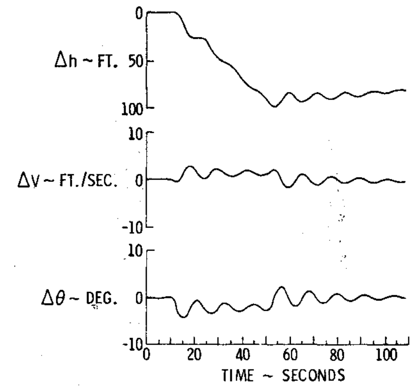

Fig. 8 Airplane response to power change.

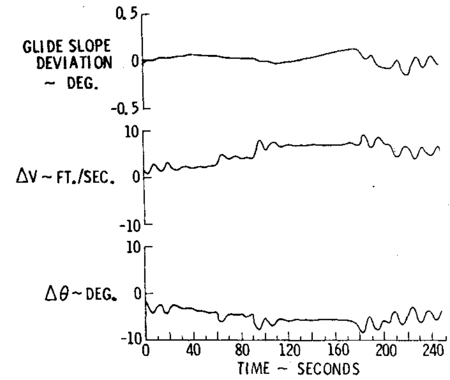

Fig. 9 Conventional ILS approach, pilot A.

except that more time is required to begin the descent because of the absence of a helping negative lift transient, and the pitch angle change is equal to the change in flight path angle.

The real purpose of the constant C_L spoiler system for flight path control, then, is the control of aircraft drag or lift-drag ratio. The ratio determines the equilibrium flight path angle with constant thrust. The advantages of using spoilers rather than speed brakes are that spoilers provide a transient load factor normal to the flight path which results in a faster transition and provides the pilot with a motion cue of the proper sign, and the change in angle of attack required for constant C_L compensates for the change in flight path angle, thus minimizing changes in body attitude.

Airplane Response to Throttle

The airplane response to a change in power setting is shown in Fig. 8. On the test airplane there is a definite trim speed change with power change, estimated to be 10 kt over the complete range of throttle settings. The throttle change used in Fig. 8 was 200 rpm, which gave a descent rate about the same as 20° of spoiler for comparison purposes. The power change excited the phugoid, and this caused the "stairstep" altitude trace. Note that at one point in the descent the aircraft is not descending at all, but holding altitude constant for about 4 sec. The trim speed of the airplane also increases by nearly 2 fps. While the handling qualities seen here (attitude and trim change, phugoid excitation) may not be particularly disturbing to a pilot, they are definitely inferior to those seen with the nominal or constant C_L spoiler systems. The spoiler systems performed the same maneuver with lower airspeed, angle, and vertical speed excursions (less phugoid excitation).

Instrument Landing System Approaches

To evaluate the flight path control with spoilers in a realistic situation, more than 100 simulated ILS approaches were flown using 7 pilots with varied experience and training (see Table 2). Each pilot made several conventional approaches without spoilers as well as a number of approaches using one or more of the spoiler controllers previously described. The starting point of each approach was one mile from the outer marker at 1500 ft altitude, slightly displaced from the localizer centerline. The pilot was instructed to intercept the localizer while holding constant altitude. When the glide slope was intercepted at the outer marker he was to set up a descent and follow the ILS course down to 200 ft altitude (middle marker).

Table 2 Summary of evaluation pilots

Pilot	License	Ratings	Hr
A	Private	ASEL	350
B	Private	ASEL	350
C	Private	ASEL	75
D	Commercial	Instrument multiengine	1000
E	Private	ASEL	150
F	Commercial	Instrument multiengine	1500
G	ATR	Instrument multiengine	7000

Each pilot was allowed to make several practice approaches before data-taking was begun to familiarize him with flying a simulator with no motion cues and to acquaint him with the control and handling characteristics of the test airplane. When a pilot flew a spoiler controller for the first time, he was allowed to make several practice approaches for familiarization. Each nonpractice approach was recorded for analysis, and the rms glide slope deviation was computed for that part of each approach between the outer and middle markers.

Conventional Approaches

Flight path control during conventional approaches was achieved by two methods: throttle modulation and longitudinal trim changes. Pilots A, B, C, E, and G used the throttle, while pilots D and F used the elevator trim. Figure 9, a conventional approach by pilot A, illustrates several characteristics of a nonDLC approach. Although many good approaches were made using throttle modulation only, each throttle change was accompanied by a noticeable change in airspeed and fuselage attitude. Figure 9 represents a good approach (rms glide slope error was 0.055°), but the airspeed varied 8.5 fps and the fuselage attitude varied 6°. Much larger variations were recorded during approaches which were less successful.

Both pilots who used elevator trim normally flew twin engine aircraft. Because they were accustomed to flying approaches at relatively high speed, and frequent power adjustments are more difficult with two throttles, usually resulting in unsynchronizing the propellers, they preferred to leave throttle settings unchanged during the approach. While a number of good approaches were made with this technique, speed and attitude changes were higher than when throttle modulation was used. Furthermore, this technique depended on a proper initial power setting. When trim corrections became large, it was not uncommon for the stall warning horn to sound.

Spoilers with Bang-Bang Position Controller

Pilots A, B, and D made ILS approaches using the bang-bang position spoilers for flight path control. Generally, the procedure used was as follows. Before reaching

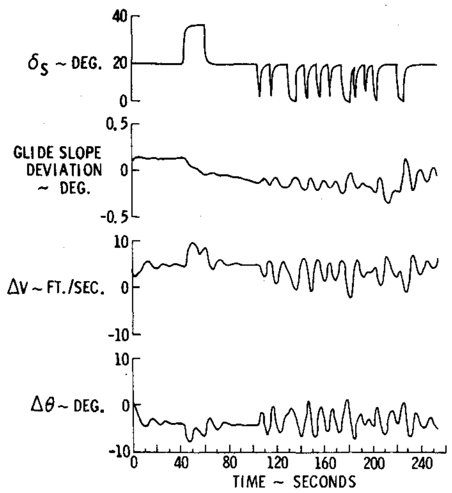

Fig. 10 ILS approach with bang-bang position control spoilers, $M\delta_s = 0$, pilot A.

the outer marker the spoilers were deflected 20°, the 50% bias position. When the glide slope was intercepted, a power reduction was made to achieve the reference descent rate. After that, spoilers were used as required to follow the glide slope, with the throttle remaining fixed.

Pilot A preferred this spoiler controller over conventional methods when $M(\delta_S)$ was either the nominal value or that required for constant C_L. He also flew several approaches with $M(\delta_S) = 0$ and $M(\delta_S)$ of opposite sign and half the absolute nominal value. In both cases, the extreme pitch excitation and oscillations were considered to be very objectionable.

Figure 10 shows an approach by pilot A with $M(\delta_S) = 0$, while Fig. 11 is an approach with nominal pitching moment. The amplitude of phugoid oscillations is considerably decreased with the nominal pitching moment.

Pilot B was considerably more successful making acceptable approaches using spoilers than without them, and felt comfortable with this controller. Pilot D commented that he liked the feeling of precise control offered by spoilers.

The bang-bang position command controller provided sufficient control to follow the glideslope if the power setting was reasonable. However, the smallest control input which could be made with this controller was 20°, 50% of the available authority. These large control inputs tended to excite the aircraft's phugoid mode, with the amplitude increasing as spoiler pitching moment changed in the negative direction. Because of this problem, it would seem better to have a controller which provides for infinite variation of spoiler position, so that small changes in position could be made.

Spoilers with Thumbwheel Controller

The thumbwheel position command controller did provide for infinitely variable spoiler position. At the outer marker, spoilers were deflected about 20° by reference to the spoiler position indicator and a power reduction made to approximately match aircraft descent rate to the glide slope. The spoiler control was then to be used as a descent rate control device to follow the glideslope.

The very first approach made by pilot A using this controller is shown in Fig. 12. The correlation between spoiler position and airplane response can be clearly seen as the pilot used the spoilers to bracket the glide slope. Using about half of the spoiler authority available, the pilot moved up and down through the beam at will. The pilot rated his control capability as "excellent." Note that speed and pitch attitude changes were practically nil even though longitudinal maneuvering was being done. Spoiler pitching moment in this example was nominal. This approach was typical for pilot A, and he was very satisfied with this method of flight path control.

Pilots C, E, and G were also quite satisfied with this controller. They felt they had very precise control over flight path.

During these approaches it was necessary to include the spoiler position indicator in the instrument scan. However, none of the pilots felt that this made an appreciable difference in the work load since less attention could be given to the engine controls and instruments.

In general, the evaluation pilots were quite enthusiastic about the thumbwheel spoiler system. They felt that it was far superior to the bang-bang position system because of the precise control available and the absence of any spoiler-induced pitching motion (when using nominal or constant C_L spoiler pitching moment). All agreed that these spoiler-controlled approaches were less demanding to fly than conventional ILS approaches.

Spoilers with Bang-Bang Rate Controller

The bang-bang rate spoiler controller, like the thumbwheel controller, provided for infinite variation of spoiler position. The six pilots who evaluated this controller were told to think of it as a descent rate trim control, since it was quite similar to a conventional electric pitch trim

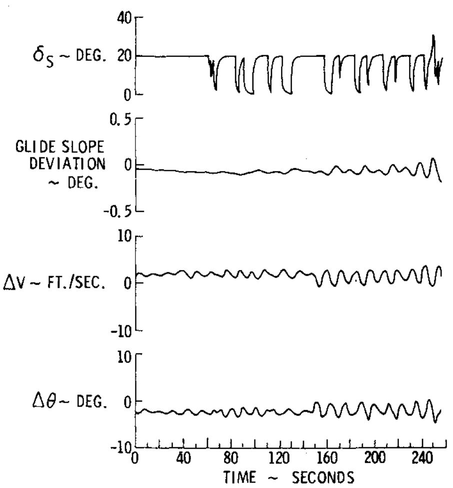

Fig. 11 ILS approach with bang-bang position control spoilers, nominal pitching moment, pilot A.

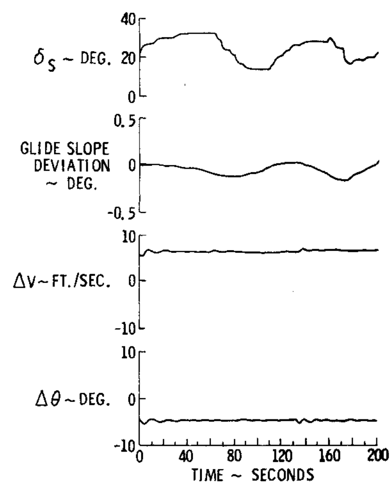

Fig. 12 ILS approach with thumbwheel spoiler controller, nominal pitching moment, pilot A.

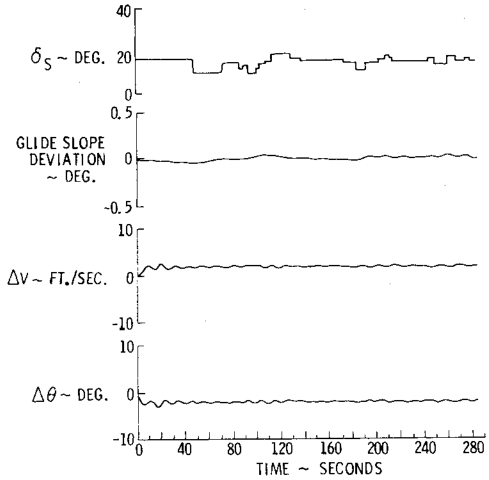

Fig. 13 ILS approach with bang-bang rate controller, nominal pitching moment, pilot C.

control. Approach procedures were the same as for the thumbwheel controller. All of these approaches were flown with the spoiler pitching moment giving constant C_L, since that moment had the best potential for good handling qualities.

Figure 13 is a typical approach by pilot C. Spoiler inputs are more abrupt than with the thumbwheel, but phugoid excitation is still only minimal.

This controller, like the thumbwheel controller, required occasional reference to the spoiler position indicator. With a little practice, most of the evaluation pilots learned to make short "blips" of the control switch like they might use with a trim switch. This gave some feel for the magnitude of the deflection being made without actually watching the position indicator.

All of the pilots had a favorable reaction to this method of flight path control, considering it effective and easy to use. There was no strong preference among them for this controller over the thumbwheel, or vice versa. Several pilots liked one a little better than the other, but couldn't give any solid basis for their preference. Since both controllers actually accomplish the same thing, infinitely variable spoiler position, the choice is primarily a matter of personal preference or practical considerations.

Summary of ILS Performance

The instrument rated pilots (D, F, and G) felt that the simulation of the ILS approach situation was realistic. The judgment of pilot G was especially valued because of his wide flying experience and the fact that he had flown a number of sophisticated airline simulators. He felt that the realism of this simulation was quite adequate for the use intended.

The performance of all pilots using the various methods of control discussed above is shown in Fig. 14. These figures show the rms glide slope error for each approach except those with zero or negative spoiler pitching moment. Table 3 lists the mean rms value for each method of approach. All spoiler methods resulted in a better average accuracy, with the thumbwheel showing the best accuracy, a 47% improvement over conventional approaches.

As a general rule, the approaches with rms error of 0.1° or less would be considered very good, and 0.2° or less would usually be satisfactory. Eight approaches had rms error greater than 0.2°, and five of those were conventional. In all eight approaches, the problem was caused by power mismanagement. While some very accurate approaches were flown conventionally, the pilots generally

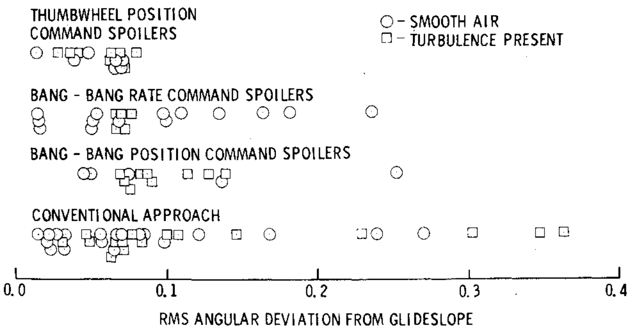

Fig. 14 Summary of ILS approach performance using various methods of glidepath control, all pilots.

agreed that the level of difficulty, and thus pilot workload, was lower with the spoiler flight path control system.

Discussion and Conclusions

At the beginning of this investigation, the spoiler system on the modified Cardinal was known as a "DLC" system. However, this work has demonstrated that a system giving direct control of aircraft lift coefficient, even if possible, is probably not a workable method of flight path control on a light aircraft. Without some kind of automatic speed control the aircraft responds to a change in C_L by seeking a new trim speed; any change in flight path is only incidental. In a landing approach it is desirable to hold constant speed. Thus, a spoiler system rigged to hold aircraft C_L constant has been shown to be a very effective and easy-to-use descent rate control, i.e., flight path angle control. With this system, the aircraft can be maneuvered at essentially constant speed and attitude over a wide range of descent rates using only spoilers for control. At least for light airplane applications, the term "DLC" seems to be a misnomer. A better term might be "DRC" for "Descent Rate Control."

Spoiler pitching moment has a great bearing on the handling qualities of a spoiler control system. If $M(\delta_S)$ is zero or negative the spoiler system is similar to a pure DLC system, and the changes in trim speed and pitch angle caused by spoiler deflection result in an undesirable amount of phugoid activity. When the spoiler pitching moment is large in the positive direction (nose-up), the above comments also apply. Spoilers which give just enough nose-up moment to keep aircraft C_L constant give the best handling qualities in the form of minimum phugoid excitation and effective control of descent rate. The spoilers actually control descent rate by changing the net aircraft drag, or lift-drag ratio while providing a transient lift increment which shortens the transition time between initial and final descent rate.

The ILS approaches flown by the evaluation pilots clearly showed the effectiveness of a good descent rate control system. All the pilots indicated that they liked not having to contend with the throttle on final approach. The throttle is somewhat difficult to use on an ILS approach because it is not a precise control, particularly if

Table 3 Summary of ILS approach performance using different glidepath control methods

Method	Rms glidepath angle deviation, deg
Conventional	0.106
Bang-bang position command spoilers	0.101
Bang-bang rate command spoilers	0.088
Thumbwheel position command spoilers	0.056

there is no throttle vernier. Evaluation pilots were observed tapping the throttle in an effort to get a small correction. In light aircraft, the throttle can induce large trim changes.[12] Throttle friction and the problem of propellor synchronization in multiengine aircraft also tend to make the throttle unsuitable for a precision flying task such as the ILS approach. Therefore, it is not surprising that the pilots liked having very precise control of descent rate literally at their fingertips. They commented that the spoilers were generally easier to use than conventional methods. In addition, the approaches flown by most pilots were more consistent using the spoilers. The reduced pilot workload which is possible using spoilers to control precision instrument approaches has a potential for increasing safety.

The test results showed the advantage of a control system having continuously variable position. The bang-bang position type control could be used to keep the aircraft near the glideslope, but the frequent, large control inputs made the system act like a built-in turbulence generator. The greater precision and smoothness of the thumbwheel and bang-bang rate controllers made them superior. A spoiler position indicator on the instrument panel is required with either spoiler controller.

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