Experimental Landings in a Spoiler-Equipped Light Aircraft

Edward Seckel,* David R. Ellis,† and John W. Olcott‡
Aeronautical Research Associates of Princeton Inc., Princeton, N. J.

This report presents the results of a flight test program to determine the effects on landings of wide variations in approach path angle and approach airspeed for different kinds of piloting technique. Over 400 landings were made at approach speeds from 60 to 120 mph and approach path angles from 3° to 18°. Several variations of pilot technique involving different operations of the throttle /spoiler control were investigated. It is shown that very large ranges of airspeed and approach path angle can be accommodated with rather moderate penalties in landing distance and difficulty. With the spoiler-equipped aircraft, the best approach speeds are considerably higher than would be usable without spoilers, and approach path angles can be used which are far beyond those normally possible without spoilers. Discussion, explanation, and analysis of these results are presented in complete detail. Although the context of the experiment (and the airplane used for it) is the general aviation light aircraft, it is felt that in substance the results may be qualitatively applicable as well to light wing-loading STOL aircraft having the capability for steep approach and rapid deceleration.

Nomenclature

$\bar{a}_n$ = normal acceleration, g
CR = Cooper-Harper rating
g = acceleration of gravity, 32.2 ft/sec^2
h = height, ft
R/D = rate of descent, ft/min
S_r = roll-out distance, ft
V = velocity, mph or ft/sec
V_s = stall speed, mph
γ = approach path angle
δ_f = flap deflection, deg
δ_s = spoiler deflection, deg
μ_e = effective braking coefficient

Subscripts

ACC = acceleration-type landing
DEC = deceleration-type landing
WO = wheel-only-type landing

Introduction

THE whole problem of the understanding and analysis of landings is very complicated—the number of factors and parameters being very large. But the introduction of spoilers on the aircraft raises some especially interesting and important questions—for example: What determines the best approach speed? Is stall margin meaningful? What is the best pilot technique and how should he use the spoilers through the landing?

In this report we have singled out for comprehensive experimental investigation the matter of how landing distance and piloting difficulty are affected by approach velocity, path angle, and pilot technique. It will be seen that even these compromise parameters and measured variables present complicated separate effects and interactions.

The primary objective of the project was to explore the possible use of spoilers in landings by general aviation pilots in light aircraft. It is felt, however, that the flight mechanics and piloting problems of the landings are similar to those for light wing-loading STOL aircraft in general, if they have the capability for steep approach and rapid deceleration. Therefore, the results should be qualitatively applicable to that case. For that kind of aircraft in commercial service, there would be great interest in steep approaches for noise abatement and obstacle clearance, and the trade-off against piloting difficulty and landing distance is of considerable importance.

Some 400 landings have been performed in a spoiler-equipped evaluation aircraft which has been extensively tested in other experiments reported previously. The aerodynamic characteristics are those of the Musketeer with partial flap deflection (15°) and full flap (35°), and with spoilers open as required for approach path angle and by pilot technique. The spoiler control was the semi-integrated one described in Ref. 1. Briefly, the spoilers were controlled by a lever situated next to the throttle lever. The two levers were normally operated simultaneously in integrated fashion, as described in the reference. Although there are numerous details that are of some significance, they are a bit outside the scope of this paper. Suffice it to say that the arrangement was essentially optimum. Control over flight path angle, touchdown point, and roll-out with the spoiler-throttle system was very favorable, if not ideal, as previously reported.

All the landings were VFR with approach path guidance in the form of a simple light system. The approach paths defined by the light system were followed quite accurately, down to the flare, in all the approaches. Flares were made with variations of technique, but in all cases slow and soft touchdowns were desired and attempted by the pilot.

The pilot was highly qualified—an expert test pilot with extensive experience in the spoiler-equipped evaluation aircraft in previous phases of the flight test program. His ratings of the difficulty of landings on the Cooper-Harper scale represent his judgment. They are supplemented by extensive commentary for explanation of particular effects and their interactions.

The operating conditions for the landings were constant. All the landings were made in early morning calm air on the same dry runway. The runway had landing zone marks typical of current practice for STOL (Fig. 1); the pilot's task was to land as short as possible in the zone, consistent with the requirement for slow and soft touchdown. Touchdown points were noted by the safety pilot, with reference to distance markers at the sides of the runway. Velocity at touchdown was obtained from a time-his-

Received December 13, 1972; revision received January 17, 1973. This research was sponsored by NASA Ames Research Labs., Moffett Field, Calif., under Contract NAS2-5589. The authors wish to express their thanks to A. E. Faye, contract monitor, for his assistance.

Index category: Aircraft Testing (Including Component Wind Tunnel Testing).

*Consultant; also Professor of Aerospace Sciences, Princeton University. Associate Fellow AIAA.

†Consultant; also Senior Technical Staff Member, Princeton University.

‡Consultant. Member AIAA.

tory oscillograph record of airspeed. This was used to compute a hypothetical roll-out distance and a stopping point. As shown in Fig. 7, the distance from the beginning of the landing zone to the stopping point is what we arbitrarily call the "landing distance."

Calculation of the hypothetical roll-out distance has been made according to a very simple, but reasonable, formula:

$$S_r = (1/\mu_e) \cdot (V^2/2g) \tag{1}$$

representing a constant deceleration at an effective braking coefficient, μ_e. Several effects are admittedly omitted, but we have determined μ_e from sample experimental roll-outs, and so the formula may be considered an empirical fit to experimental data. The data are shown in Fig. 2 for 15° and 35° flap deflections and spoilers open and closed. The μ_e coefficient is noted next to each data point.

Most of these runs involved what the pilots called "moderate" braking. A few attempts at "heavy" braking produced a small improvement; but for calculation of stopping distances, μ_e coefficients are based on the "moderate" technique. Values adopted for the calculations are

μ_e = 0.15 for 35° flap, spoilers closed
0.18 for 15° flap, spoilers closed
0.25 for 35° flap, spoilers open
0.25 for 15° flap, spoilers open

The larger μ_e's for spoilers open, of course, correspond to larger tire normal loads and higher aerodynamic drag. The values represent relatively effective braking, but they resulted from the brakes being applied in a normal manner which was consistent with the spoilers-closed cases. They are believed to be a reasonable basis for showing the effects of spoilers on stopping distance.

Data Presentation and Discussion

Consider some of the data for the landings shown in Fig. 3a, for $\gamma = 6°$, $\delta = 35°$.

Wheel-Only Technique

For reference and orientation in the pilot technique-approach airspeed picture, consider first a flare and touchdown done with pure longitudinal control, "wheel-only," (WO) so to speak. This technique, discussed more fully in Ref. 2, produces hard touchdowns and very abrupt flares for low approach airspeeds and long awkward flares with floating for high approach speeds. At an intermediate approach speed, however, a pleasantly gradual flare

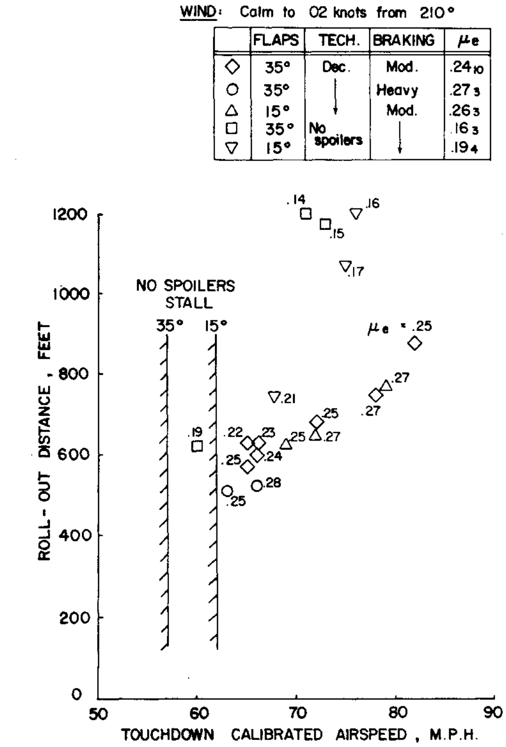

Fig. 2 Measured landing distance with and without spoilers.

produces a nice soft touchdown at minimum speed without floating. We call this particular approach speed V_{WO}. This speed is quite sharply defined. As little as 2 mph greater than the WO speed results in a noticeable float; 2 mph too slow produces a hard touchdown. In Fig. 3a in the center, we show data for landings done in this way for various approach airspeeds. At the top of the figure, the data for float distance are faired to the speed for zero float which is taken to be V_{WO}; 71 mph in this case. At the bottom of the figure, the touchdown speeds are seen to be quite constant at about 64 mph, slightly above a stalling speed for the condition of 62 mph. At wheel-only approach speed, the flare time, taken from control angle time histories, is of the order of 3–4 sec, corresponding to an average normal acceleration of about 0.09 g. The flare time lengthens rapidly with increase of approach speed, excessively extending the flare and causing floating beyond the desired touchdown point.

The situation at approach speed of 71 mph is fine; and this would be a good way to land the airplane, except that speed is critical and perfect airspeed control is crucial. A little slow results in a hard landing; a little fast results in a long float.

Decelerating Technique

At the left side of Fig. 3a, data are shown for a different kind of pilot technique. Here, at approach speeds above V_{WO}, the pilot retards throttle during the flare and, with the integrated controller, opens spoilers. This decelerates the airplane rapidly in the flare, shortens the flare time, and prevents excessive floating as clearly shown by the data. The "decelerate" (DEC) action of the throttle-spoiler control is initiated earlier as the approach airspeed is increased.

The data also show for these landings somewhat higher touchdown speeds. This is presumably caused by a combination of lift "dumping" due to spoiler opening and an increase in stalling speed. It has the effect of somewhat increasing the hypothetical roll-out distance computed according to the formula, Eq. 1.

These landings are considered by the pilot to be quite

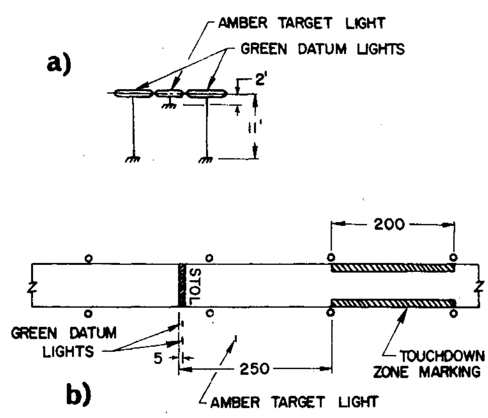

Fig. 1 a) Visual indicator for appraoch path; b) planform of STOL runway and apparatus.

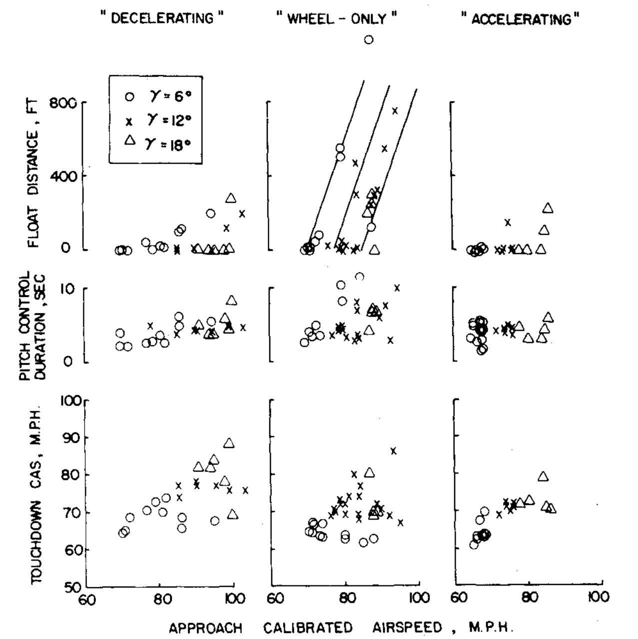

Fig. 3a Experimental landings data for spoiler aircraft: various γ, $\delta_f = 35°$.

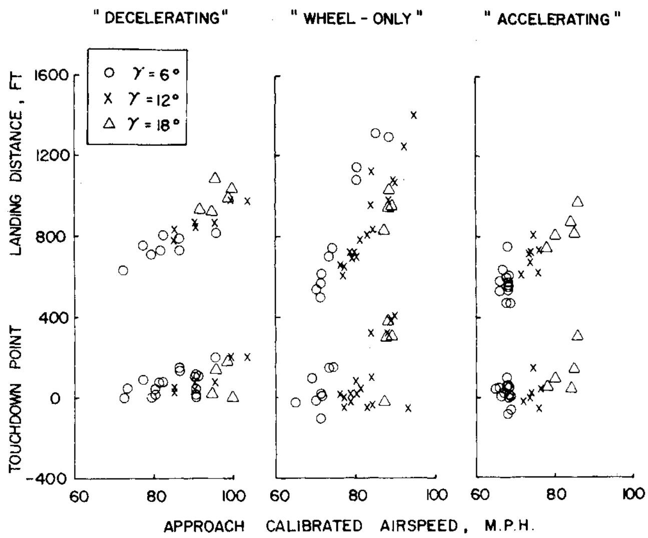

Fig. 3b Landing distances for spoiler aircraft: various γ, $\delta_f = 35°$.

easy. At the higher approach speeds, the handling qualities of the airplane are better and the stall margin is greater. But, most important, the approach airspeed is not critical and, by slight modifications in the decelerate action, the pilot can compensate for approach speed and timing errors and for disturbances due to wind and turbulence. For the $\gamma = 6°$, $\delta_f = 35°$ conditions, the pilot has selected approximately $V_{DEC} = 81$ mph as the best approach speed. In this case, his decelerate throttle action and the flare are initiated at the same time (about $3\frac{1}{2}$ sec) and he touches down about 6 mph faster than with the wheel-only technique.

Accelerating Technique

The opposite pilot technique is to advance the throttle-spoiler control in the flare, tending (relatively speaking) to accelerate the airplane, or at least to reduce the deceleration. This action makes good landings possible from approach speeds below V_{WO}. They tend to be slow touchdowns and short landings, but they are quite critical and demanding. At speeds below V_{WO}, the stall margin is so small that airspeed control is critical, and the timing and amount of the "accelerate" (ACC) action on the throttle-spoiler control must be very precise. One can see in the data on the right-hand side of Fig. 3a how steep the curve of accelerate time is for speeds below V_{WO}. Hard touchdowns are likely to be encountered as a result of small errors or disturbances.

If no restrictions are imposed on the use of accelerating throttle-spoiler control, then, in principle, soft landings can be made from any approach speed down to stalling speed. However, for the reasons cited, the difficulty increases rapidly as approach speed is reduced. This will be discussed more fully under the section on Pilot Ratings.

Combinations

One can visualize a combined technique in which the pilot first opens the throttle and then closes it in the flare. For approach speeds near V_{WO}, this works quite well. The initial accelerating action provides an energy margin that takes the sting out of errors of speed and timing, and disturbances. Then the extra energy, if any, can be removed by the reverse, decelerating action, later. A few trials of this, especially at the steeper approach path angles, have demonstrated that it works. It produces somewhat higher touchdown speeds and slightly extended flares with slightly longer landing distances, just like the decelerating technique used at the higher approach speed, V_{DEC}. The control action and coordination, however, are more complex, and this seems to make it a bit more difficult. The expert pilots agree that the whole maneuver is easier and more natural with the pure decelerating action, starting from a slightly elevated approach speed.

Landing distances for all these cases are shown in Fig. 3b. The accelerate technique produces the shortest consistent landing distances, but it is relatively difficult and occasionally produces hard touchdowns. The wheel-only technique gives a short landing of about 550 ft at the wheel-only speed V_{WO}, but excessive floats and long landings result from any excess speed. The "decelerate" technique produces slightly longer landing distance (about 700 ft), but it is relatively insensitive to approach speed and it is quite easy. In the set of decelerate landings, there were no hard touchdowns and no cases of excessive floating.

Detail of $\gamma = 12°$, $\delta_f = 35°$ Landings

Data for landings on the steep ($\gamma = 12°$) approach path are also shown in Fig. 3a. Again, flaps are full down (35°) and data are given over a range of approach speeds and for the various pilot techniques.

Wheel-Only

The wheel-only speed V_{WO}, determined by fairing the float data at the center, top, is about 78 mph. This pro-

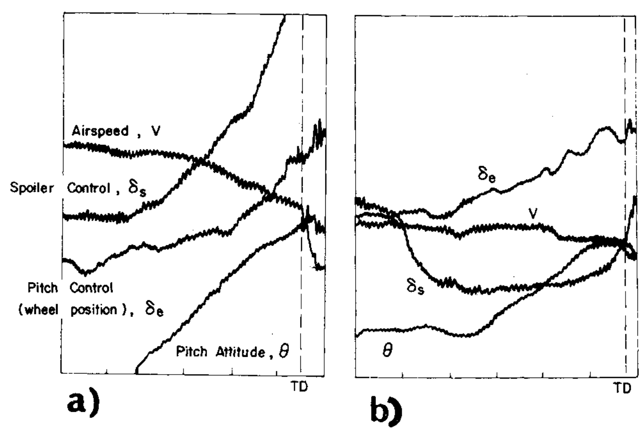

Fig. 4 a) "Deceleration" technique time history; b) "acceleration" technique time history.

duces a short, good landing, but it is relatively difficult with approach speed being critical. The duration of the flare is about 4 sec from the longitudinal control traces, corresponding to an average normal acceleration of about 0.16 g. The flare in this wheel-only landing is thus more abrupt than for the more shallow approach angle, and the whole maneuver is somewhat more difficult and critical.

Decelerate Technique

The decelerate method produces slightly higher touchdown speeds, but the pilot considers it easy and forgiving of errors and disturbances, and it eliminates excessive floating which otherwise results from excess approach speed. The best approach speed V_{DEC} selected by the pilot is 90 mph. It is again the speed for which the data show the decelerate action on the throttle-spoiler control to coincide with the initiation of the flare, at about 4 sec before touchdown. This confirms the very perceptive comment by the pilot that he finds it easy to operate the two controls (the wheel and the throttle-spoiler) when their actions are monotonic and simply correlated. The character and coordination of the control actions are apparently ideal in this case; they consist of simultaneous steady rearward movement of wheel and throttle-spoiler levers. There are normally no reversals and there is no conflict. The coordination is so direct that there is effectively only one dimension of control. Modulation to correct for errors or disturbances can be applied easily by varying the rate of control motion and the timing.

These features are nicely illustrated by the time history of Fig. 4a for one of the V_{DEC} landings. The character of control motions is easily seen to be as described.

Accelerate Technique

The accelerate landings again produce slow touchdowns and short landings, but the pilot again reports that they are difficult; the data show some hard touchdowns. The stall margins at the slower approach speeds are very small but, perhaps most important, the control actions required are more complicated and difficult. Both wheel and throttle-spoiler actions now contain reversals, they are now of opposite directions, and their shapes and timing are not similar. The whole control task clearly, in this case, has two dimensions.

These features are shown in the time history of Fig. 4b. The wheel action is first pull to initiate the flare, and then reverse to touchdown; whereas the throttle-spoiler action is first advance to accelerate and then retard to avoid floating. These are complicated and opposite actions, and the coordination is difficult.

The various landing distances are shown in Fig. 3b. Again the accelerate technique produces the shortest landings (about 700 ft), but they are tricky and prone to hard touchdowns. The wheel-only technique at the correct approach speed (78 mph) produces a short landing, but excessive floating is the penalty of extra speed. Again the decelerate technique allows for a wide range of approach speeds with only a small penalty in landing distance. The best approach speed, V_{DEC} = 90 mph, gives a landing distance of about 850 ft.

Detail of $\gamma = 18°$, $\delta_f = 35°$ Landings

A few landings were done at the extreme approach path angle of $\gamma = 18°$. They are represented by the data of Fig. 3a for different approach speeds and pilot technique. The effects of approach speed and control technique are similar to the effects presented for the shallower paths. The corresponding approach speeds are a bit higher and the landing distances are a bit longer. The flare time is about 5 or 6 sec and more abrupt, with average normal acceleration of 0.21 g.

The decelerate technique is again the preferred one, allowing a wide range of approach speeds with very small penalty in landing distance. The best approach speed is V_{DEC} = 100 mph for a landing distance of about 1000 ft. This is again the approach speed for which the decelerate action on the throttle-spoiler lever coincides with the initiation of flare with the wheel; and, of course, again the two actions are in the same direction and individually monotonic, without reversals.

Pilot comments reveal small but consistent increase in the difficulty of good landings as the approach path angle is increased. This is discussed in detail in the next section.

Effects of Approach Path Angle

In Fig. 5c the various approach speeds for different pilot technique are shown as functions of path angle γ. The V_{WO}, V_{DEC} derived from Fig. 3, as discussed in the previous sections, show consistent increases as γ goes from 3° to 18°. Stalling speeds are also represented. V_{DEC} represents the pilot's preference based upon throttle and elevator control coordination within a broad range of acceptable airspeeds, whereas V_{WO} is quite sharply defined by

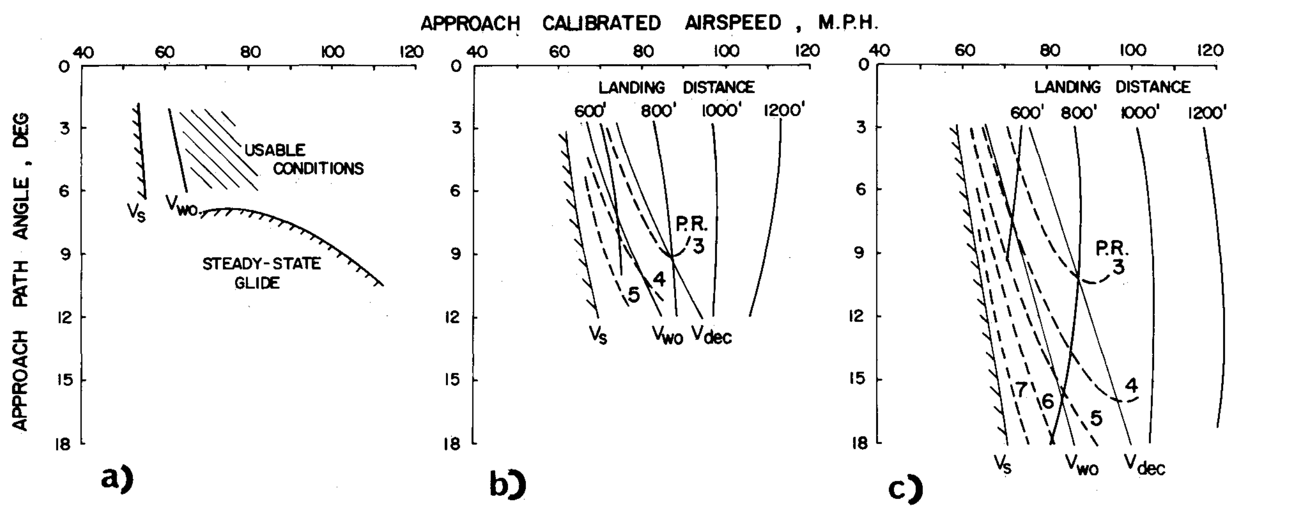

Fig. 5 a) Basic musketeer, usable approach conditions without spoilers, flap position = 35°; b) spoiler musketeer, effects of approach path angle and airspeed on landing distance and pilot rating, flap position = 15°; c) spoiler musketeer, effects of approach path angle and airspeed on landing distance and pilot rating, flap position = 35°.

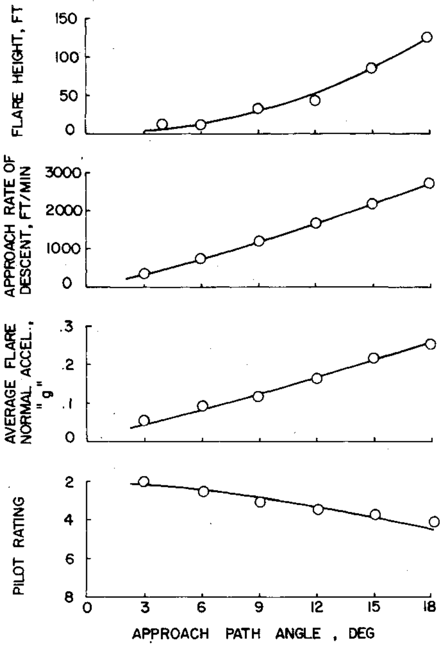

Fig. 6 Effects of γ on landing characteristics. $\delta_f = 35°$, V_{DEC}.

the tendency to float or touch down hard with as little as ±2 mph speed variation. For V_{WO} the stall margin varies from 7 mph (12%) to 16 mph (22%) over the range of γ from 3° to 18°. For V_{DEC} and the decelerating technique, they were the much more adequate 17 mph (29%) to 29 mph (41%). These margins in themselves would normally be enough basis to select the decelerating technique.

Also shown in Fig. 5c are contours of constant landing distance determined from Figs. 3a and b, as previously explained. In the area to the left of V_{WO}, the data correspond to accelerating landings. Along the V_{WO} line, the technique is wheel-only. To the right of V_{WO}, at higher approach speeds, the landings are decelerating. The V_{DEC} line traverses the middle of that area. The shape and spacing of the contours are important. They show that, for a given approach speed, the landing distance is about constant, independent of approach angle, and in the area of decelerating technique, there are only moderate increases in landing distance for significant increases of approach speed. From $\gamma = 3°$ to $\gamma = 18°$, along the line of preferred approach speed, the landing distance increases from about 600 ft to about 1000 ft as V_{DEC} increases from 76 mph to 100 mph.

Superimposed on Fig. 5c are contours of constant pilot opinion rating. These are based on a Cooper-Harper scale. The contours are drawn from numerical ratings and commentary by the pilot immediately following a series of landings for a given set of parameters and pilot technique.

Pilot opinion about the difficulty of landings has been extensively discussed in previous sections. Here we attempt to quantify his judgment and to show in detail how it is affected by the parameters and techniques of the experiment. We should note that the ratings are the judgments of an expert pilot, and they have quite explicit meanings.

In general, a rating system is simply a shorthand method of expressing the relative ease or difficulty of achieving acceptable performance in a given piloting situation. The one used here is the Cooper-Harper system[3] which, as a matter of review, calls for a rating in the 1–6 category if the workload is judged to be tolerable and 7–10 if intolerable. Further, the airplane is to be rated 1–3 if it is satisfactory without improvement and in the 4–6 category if it possesses deficiencies which warrant improvement. The 7–9 category implies major deficiencies, inability to achieve adequate performance, and possible questions of controllability. The 10 rating is given if control is actually lost during some part of the required operation. Evaluation pilots are normally asked to augment the numerical rating with comments highlighting the factors and problems which led to a particular decision.

The workload evaluated here is a total one, made up not only of physical movements of the controls and other discrete actions but also mental factors such as concentration and anticipation. The quality of task performance enters the picture only insofar as ratings in the 1–6 category imply acceptable performance judged against some standard, while 7–10 ratings signify unacceptable performance. In other words, a perfect performance could very well be given a 6 rating because of the difficulty of attaining it. Consistency of performance usually influences the rating, however, in the sense that the evaluator must decide whether or not a given level of effort will produce acceptable results on every attempt. This aspect of the evaluation is simplified if many trials can be flown; otherwise it must be a matter of judgment based on the available evidence and past experience.

For this experiment, the flight segment to be rated was the flare and touchdown. The task was, simply speaking, to land the airplane out of a precisely defined final approach path, touching down as closely as practicable to the approach reference lights (Fig. 1). Acceptable performance was defined as a touchdown which could be described as soft or, at worst, firm, but not hard.

The landings generally required coordination of elevator control and the throttle/spoiler control and, in rating a given landing, separate consideration was given to each. In particular, the evaluator was asked to rate and comment upon the relative ease of anticipating when each of the controls should be used and, once control action was initiated, the ease of obtaining the desired airplane response.

A satisfactory situation might be described as one in which it was easy and natural to judge the starting points of both control inputs, the ensuing actions were neither delicate nor complex, and the whole process could be repeated with consistent acceptable results. This would be rated in the 1–3 category, depending on the judgment of workload. Conversely, for landings in which the point of control initiation was difficult to judge, where delicate control actions or reversals in the direction of input were required, and where such problems led to some inconsistency in touchdown points and hardness, the rating would be in the 4–6 category. The 7 or worse category would be reserved for situations where the correct control action was so difficult to produce, or so limited in authority, that unacceptably hard landings were likely.

The shape and spacing of pilot opinion contours are important. They show at a glance the reported difficulty of landings out of approaches at V_{WO} and slower approach speeds. They also show the reported broad range of favorable approach speeds in the area of decelerating technique. Perhaps the most interesting thing they show is the magnitude of the penalty in difficulty and landing distance that must be paid for the steep approach.

Starting at $\gamma = 3°$, the landing from the ideal approach speed V_{DEC} gets a rating of a little better than 3 (Fig. 6).

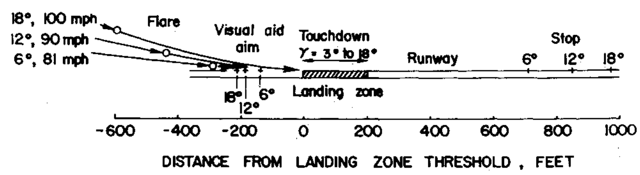

Fig. 7 Approximate dimensions and trajectories of landings. Spoiler musketeer, decelerate technique, VFR conditions moderate braking, no wind. $\delta_f = 35°$.

This corresponds to "a comfortable speed, elevator and throttle use nicely blended, both starting back at the same time . . . no control reversals . . . whole process easy to judge and repeat." A similar comment was obtained for the $\gamma = 6°$ landings started at V_{DEC}.

At $\gamma = 9°$, the rating is still about a 3. As the approach path angle steepens, the rate of descent on approach increases, the altitude of the flare initiation point increases, and the normal acceleration in the flare increases. These changes all make for increasing difficulty. The increased rate of descent requires more attention to predicting the proper flare initiation time; the increased altitude is more difficult to gage, since the altitude cues are less precise; and the increased normal acceleration requires more control action and is more disconcerting. But at $\gamma = 9°$, these effects are clearly very mild since the rating is still very favorable.

As the approach path angle increases from 9° to 18°, the pilot ratings increase gradually from 3 to about 4½. The problems are the three increases of descent rate, flare height, and flare acceleration which, at these higher γ's, are beginning to produce more noticeable difficulties. The variations of these quantities with approach angle are shown in Fig. 6 along with the pilot ratings. Even the landing at $\gamma = 18°$, with a rating of 4½, is a reasonable, operationally viable maneuver under the VFR conditions of the experiment.

We have not experimented with steep approaches in IFR conditions, and so we are unable to discuss them in detail or with much authority. We have to assume that the pilot cannot begin his landing flare until he breaks out into visual contact underneath the ceiling. The increased flare height needed for the steep approach would probably limit the minimum ceiling. The increased rate of descent would clearly be a factor also. Of course, these are the considerations that have aroused interest in segmented approaches and in sophisticated approach guidance systems.

Landing Trajectories

The landings with optimum pilot technique (decelerating) at the best approach speed V_{DEC} are displayed in another way in Fig. 7. For the range of approach path angles, the pertinent dimensions and trajectories are shown. All the conditions, of course, correspond to the calculations and the experiment as previously described.

The aim points set by the visual approach aid in the various cases are indicated. They range from a little more than 100 ft to a little more than 200 ft in front of the threshold of the landing zone. In the landing data previously presented, the touchdown points were within the 200 ft of the landing zone, and the average stopping points were calculated to be as indicated.

The advantages of the steep approach paths for obstacle clearance and noise abatement can be appreciated at a glance. The penalty in terms of runway requirements is seen to be rather slight, the order of a few hundred feet. The elevation of flare point as the path angle is increased accounts for some increase of piloting difficulty and would certainly present problems in IFR conditions with low ceilings.

Landing with Partial Flap, $\delta_f = 15°$

Numerous landings have also been done with partial flap deflection. Our findings in substance are identical. All the considerations and the interplay of the various factors entirely duplicate the previous case for full flap deflection, $\delta_f = 35°$.

The final summary of results is shown in Fig. 5b. Again the advantages of the decelerating technique are obvious. The penalties in difficulty and landing distance for either elevated approach speed or steep approach path angles are seen to be very small. Over most of the range of parameters, the pilot ratings are the same as for full flap deflection, and the landing distances are very slightly longer.

Landings in the Basic Airplane without Spoilers

We have not, in the context of this experiment, explored the landing characteristics of the basic airplane in the detail we have used for the spoiler-equipped airplane investigation. However, a few landings at $\delta_f = 15°$ and 35° and $\gamma = 3°$ and 6° have been made and data taken.

Without the use of spoilers, stalling speeds are somewhat lower so that touchdown speeds are lower and roll-out distances could be shorter. But the braking is poorer. The net result is that landing distances are somewhat longer. It has been reported[1,2] that glide path and touchdown control are not as good with the basic airplane, and these differences make for greater difficulty in landing it. The data reported in Ref. 2 show that various classes of pilots, from students to experts, produce better landing performance in the spoiler-equipped airplane in the range of normal, shallow approaches. The improved touchdown accuracy with spoilers may further reduce the required total runway requirements, in spite of the lower touchdown speeds of the basic aircraft.

As in the case of the spoiler-equipped airplane, a wheel-only approach speed can be defined which leads to short, soft landings with action on only the one control. However, these are difficult and critical with respect to airspeed control, and slight excess speed produces excessive floating. It is possible, of course, to apply the decelerate technique by pulling off throttle during the flare, but without spoilers the available deceleration is small so that the range of useable approach speed is very limited.

The major difference for the basic airplane is that it simply is not capable of steady, steep descent and rapid decelerations. In Fig. 5a we show the steady-state angle of descent vs airspeed for the basic airplane at idle power. A steady approach condition must lie above this line, with a margin for modulating the flight path. At the same time, because of lower deceleration capability, the best approach speed V_{DEC} for the decelerating technique will be lower than for the spoiler-equipped airplane. The ranges of favorable approach conditions, both speed and angle, are thus severely restricted. In Fig. 5a they shrink into the small area at the upper left of the diagram.

Conclusions

On the basis of extensive landings with a spoiler-equipped evaluation aircraft with semi-integrated throttle-spoiler control, using VFR-guided approaches at various speeds and path angles and different pilot techniques, the following conclusions are drawn: 1) At a given approach path angle, an approach speed V_{WO} can be defined which leads to a short, soft landing without throttle-spoiler action; that is, wheel only. In the spoiler-equipped aircraft with full flap deflection, V_{WO} varies from 66 mph at $\gamma = 3°$ to 87 mph at $\gamma = 18°$. 2) Wheel-only landings at V_{WO} are relatively difficult and critical, especially with respect to airspeed control. Stall margins are from 12% to 22% over the range of approach path angle. 3) By using the throttle-spoiler control to decelerate through the flare, higher approach speeds are usable and easier control technique results. The best such approach speed V_{DEC} varies from 76 mph at $\gamma = 3°$ to 100 mph at $\gamma = 18°$ for full flap. 4) The easiest coordination of wheel and throttle-spoiler control actions occurs when both are monotonic and positively correlated; that is, when both actions are steady, nonreversing, backward hand motions initiated at the same time. This is the case with the decelerating technique at V_{DEC} approach speed. 5) With the decelerating technique, the penalties in difficulty of control and landing distance caused by either excess speed or steep angles are very slight. In the experiment, typical landing distances varied from a little over 600 ft at $\gamma = 3°$ to a little under 1000 ft at $\gamma = 18°$. 6) In VFR conditions, as the approach path angle is steepened, the difficulty of the landing gradually increases. Larger rates of descent, higher flare point and increased flare normal acceleration are the contributing factors. Under IFR conditions, these factors would probably severely limit the minimum ceilings that would be operational.

References

[1]Olcott, J. W., Ellis, D. R., and Seckel, E., "Preliminary Flight Evaluation of a Small, Fixed Wing, General Aviation Aircraft Equipped with Spoilers/Dive Brakes," NASA Ames Research Center, NAS2-5589, Sept. 1970, Aeronautical Research Associates of Princeton, Inc., Princeton, N.J.

[2]Olcott, J. W., Seckel, E., and Ellis, D. R., "Additional Flight Evaluations of a Small, Fixed Wing, General Aviation Aircraft Equipped with Spoilers/Dive Brakes," Rept. 174, Jan. 1972, Aeronautical Research Associates of Princeton, Inc., Princeton, N.J.

[3]Cooper, G. E. and Harper, R. P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," TND-5153, April 1969, NASA.

APRIL 1973 J. AIRCRAFT VOL. 10, NO. 4

Flight Evaluation of Three-Dimensional Area Navigation for Jet Transport Noise Abatement

D. G. Denery,* K. R. Bourquin,* K. C. White,* and F. J. Drinkwater III†
NASA Ames Research Center, Moffett Field, Calif.

NASA, working with American Airlines, has completed the first phase of research to evaluate the operational feasibility of two-segment approaches for noise abatement. For these tests, area navigation was used to establish the upper glide slope and an ILS was used to establish the lower. The flight director was modified to provide command information during the entire approach. Twenty-eight pilots representing the airlines, professional pilot associations, FAA, and NASA participated. With an ILS approach for comparison, the procedure gave a noise reduction of 18 EPNdb at the outer marker and 8 EPNdb 1.1 naut miles from touchdown.

Introduction

THE NASA Ames Research Center, in conjunction with American Airlines, has completed the first phase of research to evaluate the operational feasibility of two-segment approaches for use as a noise abatement procedure. Using this technique, the aircraft approaches on a steeper than normal glide slope and then makes a transition to the standard approach path in time to stabilize prior to the landing. By keeping the aircraft higher above the ground and reducing the engine power during landing, the two-segment approach pattern lessens the community noise near airports.

The effectiveness of the two-segment approach as a noise abatement technique has already been demonstrated by both the FAA and NASA.[1-5] However, these studies have all been conducted using experimental equipment and crew procedures which are not typical of those used in air carrier service. A program was therefore formulated with American Airlines to correct this situation. A principal objective of this study was to evaluate the operational feasibility of using three dimensional area navigation equipment for two-segment approaches. The flight director steering computer was modified to include a two-segment approach mode that used the area navigation system and standard Instrument Landing System (ILS), to provide a continuous flight director signal during the entire approach. Two major aims of the program were 1) to develop crew procedures that make use of this equipment and are representative of those that might be used in air carrier service and 2) to demonstrate the equipment and procedures to a broad sample of pilots representing the airlines, professional pilot associations, and FAA.

In this paper, the equipment and evaluation procedures used by American Airlines are discussed. In addition, the pilot and onboard observer evaluations are summarized and data are presented which indicate the precision with which the aircraft was able to follow the two-segment glide slope, the precision with which the two-segment glide slope was established, and the noise reduction that was achieved as a result of flying the two-segment approach.

Equipment Description

A Boeing 720-023B, equipped with Pratt and Whitney Aircraft JT3D-3/3B fan jet engines, was used for the evaluation. This is a 109-passenger version of the standard Boeing 720 model. The maximum takeoff gross weight is 221,000 lb and maximum landing gross weight is 175,000 lb. The normal American Airlines cockpit configuration was maintained with the exceptions that the existing Collins FD 105 flight director and steering computer on the captain's side was replaced by a Collins FD 108 flight director and steering computer, a Butler National three-dimensional area navigation system and the associated display were installed, and a Lear-Siegler barometric al-

Presented as Paper 72-814 at the AIAA 4th Aircraft Design, Flight Test, and Operations Meeting, Los Angeles, Calif., August 7–9, 1972; submitted October 19, 1972; revision received January 19, 1973.

Index categories: Air Navigation, Communication, and Traffic Control Systems; Aircraft Flight Operations; Aerodynamic and Power Plant Noise (Including Sonic Boom).

*Research scientist.

†Research scientist and test pilot.