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Analysis and Flight Evaluation of A Small, Fixed-Wing Aircraft Equipped with Hinged-Plate Spoilers

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ANALYSIS AND FLIGHT EVALUATION OF A SMALL, FIXED-WING AIRCRAFT EQUIPPED WITH HINGED-PLATE SPOILERS

John W. Olcott, Edward Seckel, and David R. Ellis

SUMMARY

The results of a four-phase effort to evaluate the application of hinged-plate spoilers/dive brakes to a small general aviation aircraft are presented. The test vehicle was a single engine light aircraft modified with an experimental set of upper surface spoilers and lower surface dive brakes similar to the type used on sailplanes. The lift, drag, stick-free stability, trim, and dynamic response characteristics of four different spoiler/dive brake configurations were determined. Tests also were conducted, under a wide range of flight conditions and with pilots of various experience levels, to determine the most favorable methods of spoiler control and to evaluate how spoilers might best be used during the approach and landing task.

The test results indicated that spoilers offered significant improvements in the vehicle's performance and flying qualities for all elements of the approach and landing task, provided a suitable method of control was available. The most favorable method of control was to integrate spoiler deployment with power changes so that the throttle became an authoritative and effective flight path controller. Touchdown accuracy and touchdown dispersion were noticeably improved for both low experience-level pilots and for advanced pilots. Student pilots with little or no prior experience were able to use the spoilers effectively for approach and landing tasks. Spoilers improved the ability of all grades of pilots to make good landings in difficult conditions of crosswind and turbulence.

The effects of approach path angle, approach airspeed, and pilot technique using throttle/spoiler integrated control were investigated for day, night, VFR, and IFR approaches and landings. Results of over 400 day VFR landings are presented for speed margins ranging from 1.05 to 1.55 and for approach angles from 3° to 18°. Similar results are presented for approach angles of 3°, 6°, 9°, and 12° for night VFR landings and for day IFR landings. The results indicate that large ranges of airspeed and approach angle can be accommodated with only minimal penalties in landing

distance and difficulty. Due to the higher descent rates and higher flare initiation altitudes which characterize steeper approach angles, higher ceiling heights were needed for IFR operations to allow sufficient time to accommodate the transition from IFR to VFR conditions. Night VFR landings at the steeper angles suffered due to improper orientation of the landing light, but shallow approaches at night, where the landing light was properly positioned, were similar in character to day landings.

It was concluded that spoilers properly integrated with the throttle offered significant improvements in the landing task performance and handling qualities of the test aircraft. It is expected that the findings are directly applicable to light aircraft in general, as well as to low wing-loading STOL vehicles.

INTRODUCTION

Landings present a challenging task for general aviation pilots of small fixed-wing aircraft. Not only do many people find landings difficult to master, but the approach and landing phase of operation represents a period of high accident risk. An analysis of National Transportation Safety Board aircraft accident data for the years 1967 through 1971 indicates that approximately 50% of all small fixed-wing general aviation accidents involve landings (refs. 1 through 5) (fig. 1). In 1969, for example, out of a total of 4443 accidents, 308 occurred on final approach, 876 involved flare and touchdown, 722 were related to rollout, and 112 were attributed to the go-around phase of operation (ref. 3).

An obvious need exists to improve the ability of a pilot to successfully land his aircraft under normal and emergency situations. While training and individual judgment will always remain important factors, improved landing-task aircraft performance and flying qualities could provide the pilot with much of the additional capability he requires.

An analysis of problems encountered during landings indicates that in the approach phase the primary cause of accidents involves overshoots, undershoots, or collisions with objects. Groundloops/swerves, hard landings, and overshoots comprise the majority of touchdown accidents. Rollout accidents consist primarily of groundloops/swerves, overshoots, and collisions with objects. Over half of all go-around accidents during the period under examination involved collisions with objects and stall/spins/mushes. Summarizing the analysis of small fixed-wing aircraft landing accidents for the 1967-1971 period, approximately 50% involved groundloops/swerves, overshoots, or hard landings (refs. 1-6).

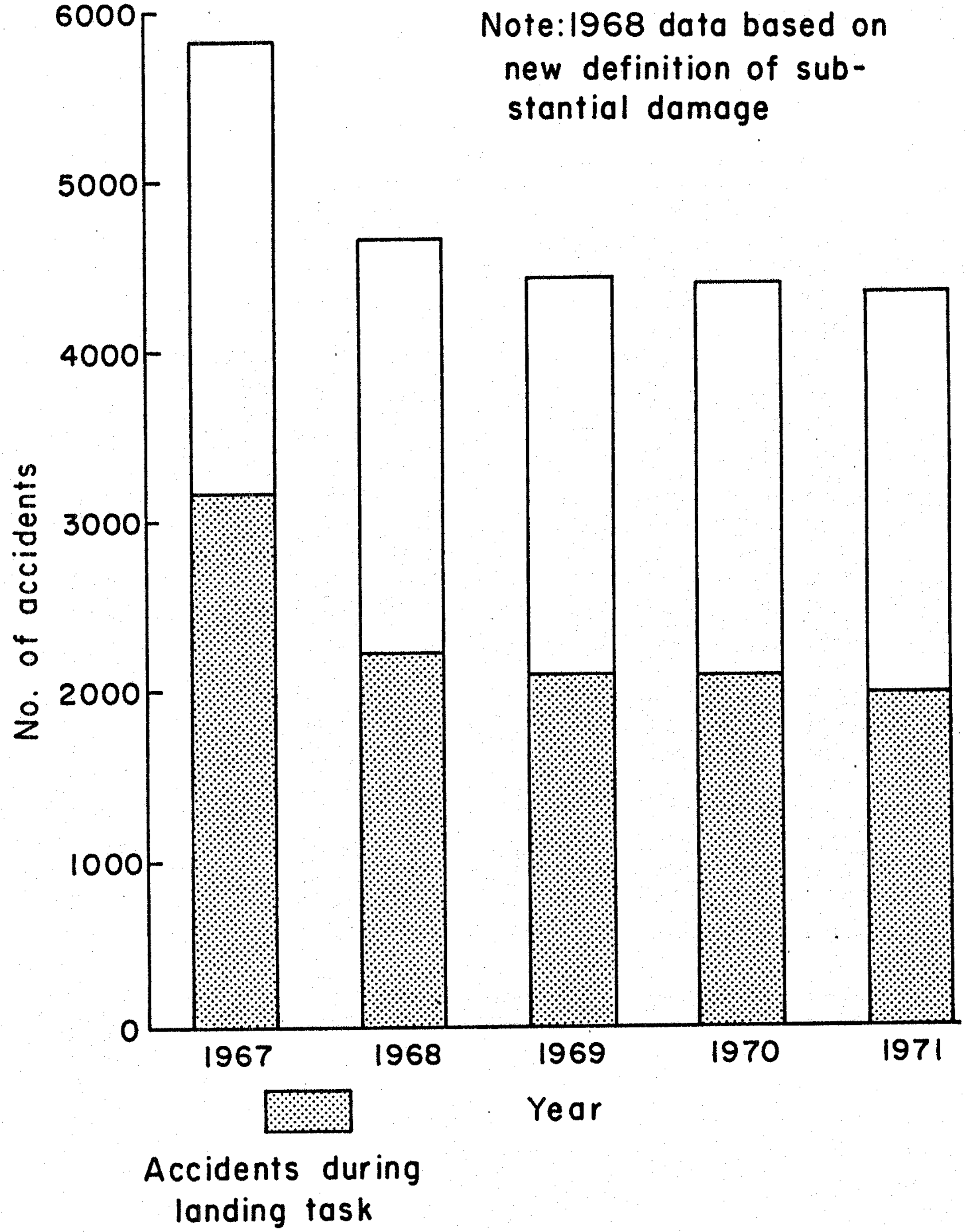

Figure 1.– U.S. General Aviation small fixed-wing aircraft accidents for the period 1967-1971 (Source: NTSB)

Aircraft flying qualities for the approach, flare, touchdown, rollout, and go-around elements of the landing task must be a factor in these landing accidents. Glide path control certainly relates directly to overshooting, undershooting, and colliding with objects. The ability of the pilot to perform the flare and touchdown maneuvers must be a prime factor in many of the hard landing and gear collapse accidents. Failure to maintain rollout control can be considered a critical element in the groundloop/swerve accidents. Stall/spin/mush landing accidents involve airspeed control.

Spoilers and dive brakes offer several characteristics which suggest that their application to a small general aviation aircraft might improve the vehicle's flying qualities for the landing phase of operation. The descent versus airspeed performance of a spoiler-equipped aircraft can be made to exceed the performance possible with typical light aircraft flap systems. The lift transient due to spoiler application produces an initial response in flight path angle which is in a correct or favorable sense for glide path control; that is, an <u>increase</u> of drag (spoilers open) to steepen the glide path, is accompanied by a <u>decrease</u> of lift which produces an initial transient in the consistent (down) direction. By way of contrast, flap deflection of a sense to <u>increase</u> drag and descent angle (flaps down) initially <u>increases</u> lift, thus initiating a transient response in the wrong direction. Because of the correct sense of the lift change and because spoilers can be designed to be activated without producing large longitudinal trim changes, they can be used in a continuous mode to modulate glide path angle with ease and precision.

This study of the application of spoilers/dive brakes* to a small fixed-wing general aviation aircraft was accomplished by Aeronautical Research Associates of Princeton, Inc. (A.R.A.P.) under the sponsorship of the Ames Research Center of the National Aeronautics and Space Administration. The general objective of the study was to identify and evaluate the benefits and risks associated with equipping a typical light aircraft with spoilers. The program developed into multiple phases as further investigations were justified by the results of preceding studies.

Phase I involved the design, installation, and preliminary evaluation of a set of hinged plate spoilers on a four-place, single engine, light aircraft. Preliminary flight studies showed that significant landing task performance and flying qualities improvements were achieved with spoilers and that integrating spoiler deployment with the throttle provided a simple and effective means for controlling the considerable performance spoilers provided.

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*Throughout this report, the word "spoiler" refers to a spoiler/dive brake system similar to the upper and lower hinged plate configuration used on the test vehicle described herein.

The objective of Phase II was to develop a fuller understanding of what spoilers did to improve landing task performance and flying qualities and to consider how the benefits of spoilers might be limited by the real-world constraints of the general aviation community. Several flight tests were conducted to identify, document, and interpret those spoiler characteristics that appeared to be the most beneficial to the pilot during approach, flare, touchdown, rollout, and go-around. In order to determine whether spoilers could be used successfully by low-time general aviation pilots, the Phase II effort included the selection and evaluation of ten student pilots (six with no previous flight time), eight private pilots with limited flight time, and, as a reference, two experienced pilots with no previous exposure to the spoiler program. The landing performance of the group while flying the research aircraft with and without spoilers operative was analyzed to determine what benefits and difficulties might be anticipated if spoilers were used by less experienced members of the general aviation community. Phase II also addressed certain real-world aspects of applying spoilers to small aircraft, such as whether a practical, low cost, mechanical spoiler system could be made to operate in a manner similar to the throttle-controlled, servo-actuated system used on the test aircraft.

Phase III flight tests were to evaluate the effects of approach path angle, approach speed, and pilot technique on landing a spoiler-equipped aircraft. Wide ranges of these variables were evaluated in a series of over 400 day VFR landings using a visual glide slope indicator.

Phase IV studies concentrated on the same type of evaluations for approaches under night VFR and day ILS conditions. In addition to providing valuable information on the use of spoilers to expand acceptable combinations of approach airspeed and flight path angle, insight into the nature of landings in general has resulted from the Phase III and IV efforts.

Before spoilers will be seriously considered by the general aviation community, manufacturers must be convinced that they can properly assess the risk/reward relationship that spoilers will offer. They will consider many factors, including availability of data to design a satisfactory spoiler system, the attitude of customers towards spoilers, and the likelihood that the average pilot will be able to use them safely and effectively. The cost of spoilers in terms of development, certification, hardware, and promotion must be weighed against the possible gains derived from market expansion due to added utility and increased safety. The information presented here may be of use to those who must make such evaluations.

SYMBOLS

A, B, C	constants
ACC	accelerating type technique
AR	aspect ratio
$\bar{a}_n$	normal acceleration, g's
a_w	slope of the lift curve, wing, 1/deg or 1/rad
b	span, m (ft)
CAS	calibrated airspeed
C_D	drag coefficient
C_{D_i}	induced drag coefficient
C_{D_o}	zero-lift drag coefficient
C_{D_p}	parasite drag coefficient
C_{D_s}	spoiler drag coefficient, $C_{D_s} \equiv \Delta C_{D_o}(S/S_s)$
C_L	lift coefficient
$C_{L_{max}}$	maximum lift coefficient
C_{L_α}	slope of the lift curve, 1/deg or 1/rad
C_M	pitching moment coefficient
C_{M_q}	dimensionless damping-in-pitch parameter, $\dfrac{\partial C_m}{\partial q\bar{c}/2V}$, 1/rad
C_{M_δ}	dimensionless pitch control effectiveness parameter, $\partial C_m/\partial\delta$, 1/deg or 1/rad
$\bar{c}$	mean aerodynamic chord, wing, m (ft)
D	drag, N (lbs)
DEC	decelerating type technique
D_V	dimensional drag derivative, $\frac{1}{m}\frac{\partial D}{\partial V}$, 1/sec
D_α	dimensional drag, angle-of-attack derivative, $\frac{1}{m}\frac{\partial D}{\partial \alpha}$, $\dfrac{m/sec^2}{rad}\left(\dfrac{ft/sec^2}{rad}\right)$
D_δ	dimensional control derivative, $\frac{1}{m}\frac{\partial D}{\partial \delta}$, $\dfrac{m/sec^2}{rad}\left(\dfrac{ft/sec^2}{rad}\right)$
e	span efficiency factor for induced drag
G	gearing constant, rad/m (rad/ft)
g	acceleration of gravity, m/sec^2 (ft/sec^2)
h	height, m (ft)
h_c	ceiling height, m (ft)
IFR	instrument flight rules

ILS	instrument landing system
I_y	moment of inertia in pitch, kg m^2 (slugs-ft^2)
j	imaginary unit $\equiv \sqrt{-1}$
K_b	induced drag factor for basic aircraft
K_s	induced drag factor with spoilers
L	lift, N (lb force)
L_V	dimensional lift-velocity derivative, $\frac{1}{m}\frac{\partial L}{\partial V}$, 1/sec
L_α	dimensional lift derivative, $\frac{1}{m}\frac{\partial L}{\partial \alpha}$, $\frac{m/sec^2}{rad}\left(\frac{ft/sec^2}{rad}\right)$
L_δ	dimensional control derivative, $\frac{1}{m}\frac{\partial L}{\partial \delta}$, $\frac{m/sec^2}{rad}\left(\frac{ft/sec^2}{rad}\right)$
LLI	left lower inboard (dive brake)
LLO	left lower outboard (dive brake)
LUI	left upper inboard (spoilers)
LUO	left upper outboard (spoilers)
ℓ_s	spoiler length, m (ft)
ℓ_t	tail length, m (ft)
M	pitching moment, N m (ft lb)
M_V	dimensional moment derivative, $\frac{1}{I_y}\frac{\partial M}{\partial V}$, $\frac{rad/sec^2}{m/sec}$ $\left(\frac{rad/sec^2}{ft/sec}\right)$
M_α	dimensional angle-of-attack static stability derivative, $1/sec^2$
$M_{\dot\alpha}$	dimensional derivative, $\frac{1}{I_y}\frac{\partial M}{\partial \dot\alpha}$, 1/sec
M_δ	dimensional control derivative, $\frac{1}{I_y}\frac{\partial M}{\partial \delta}$, $1/sec^2$
$M_{\dot\theta}$	dimensional damping derivative, $\frac{1}{I_y}\frac{\partial M}{\partial \dot\theta}$, 1/sec
m	mass, kg (slug)
mac	mean aerodynamic chord, m (ft)
N_m	maneuver point, % c.g.
N_o	neutral point, % c.g.
n	load factor
n_{z_α}	normal acceleration derivative, $\frac{\partial n_z}{\partial \alpha}$, g/ rad
P	period, phugoid (sec)
q	dynamic pressure, N/m^2 (lb/ft^2); also pitch rate, deg/sec
R/D	rate of descent, m/min (ft/min)

RLI	right lower inboard (dive brake)
RLO	right lower outboard (dive brake)
RUI	right upper inboard (spoiler)
RUO	right upper outboard (spoiler)
S	wing area, m^2 (ft^2)
S_s	spoiler area, m^2 (ft^2)
s	Laplace operator
T	thrust, N (lb)
T_B	breakout (transition) time, sec
T_V	dimensional aerodynamic derivative, $\frac{1}{m}\frac{\partial T}{\partial V}$, 1/sec
t	time, sec
V	flight velocity, knots (mph, ft/sec)
V_c	calibrated airspeed, knots (mph, ft/sec)
V_i	indicated airspeed, knots (mph, ft/sec)
V_A	approach airspeed, knots (mph, ft/sec)
V_S	stalling speed, knots (mph, ft/sec)
V_{WO}	best V_A for wheel-only landing, knots (mph, ft/sec)
V_{DEC}	best V_A for <u>decelerate</u> technique, knots (mph, ft/sec)
VFR	visual flight regulations
W_{SP}	spoiler aerodynamic loading
X	force along fore and aft axis, N (lb)
$\bar{x}$	fraction of $\bar{c}$ behind leading edge of mac
α	angle of attack, deg or rad
γ	flight path angle, deg or rad
γ_{ss}	steady state γ , deg or rad
Δ	change in the indicated quantity; also determinant
$\bar{\delta}$	size of control input step function, deg or rad
δ_e	deflection of tailplane, deg
δ_f	deflection of flaps, deg
δ_s	deflection of spoilers, deg
ε	downwash angle, deg or rad
ζ	damping ratio (short period mode)
θ	pitch attitude angle, deg or rad
$\dot{\theta}$	pitch rate, deg/sec or rad/sec
μ	relative density factor $\equiv m/\rho S\bar{c}$

μ_e	effective braking coefficient
ρ	air density, Kg/m^3 $(slug/ft^3)$
ϕ	a phase angle, deg
ω_0	undamped natural frequency (short-period mode), rad/sec

DESIGN AND ANALYSIS OF GLIDE PATH SPOILERS

General Considerations

The purpose of installing spoilers on a low wing-loading aircraft, whether it be for research or production purposes, is to provide for large drag changes with favorable lift and moment coupling. Spoiler drag that can be added or diminished at will provides improved glide path performance plus improved speed stability, $\partial\gamma/\partial V$, and increased phugoid damping when the spoilers are deployed. The favorable lift and moment coupling provides the proper initial transient response of the vehicle to spoiler deflection without exciting adverse trim changes.

The favorable characteristics described above appear to enhance the landing performance of light wing-loading aircraft for many reasons. An obvious advantage that has been enjoyed by sailplane pilots for many years is the ability to use spoilers for glide path modulation rapidly and effectively without inducing large trim changes. Because of their large drag, spoilers improve approach flying qualities by also providing a favorably large negative value of speed stability. Good speed stability is considered an important characteristic for approach flying qualities (ref. 7), yet it is interesting to note that, for typical light aircraft, desirable values of $\partial\gamma/\partial V$ can only be achieved at relatively high approach speeds which are considered unacceptable for good flare-task flying qualities (ref. 8). Because spoilers provide sufficient drag to produce large negative values of speed stability at reasonable approach airspeeds and because spoilers do not produce adverse trim changes or undesirable transient responses when activated, it is quite easy for the pilot to apply spoilers in the flare to achieve a rapid deceleration to a desirable touchdown speed.

Other advantages possible with spoilers are positive ground contact and good deceleration during the initial rollout after landing and the ability to rapidly reconfigure the plane to a reduced drag state by retracting spoilers for an aborted landing.

A prime consideration in a spoiler system for light aircraft is sufficient drag to achieve good glide path performance and deceleration capability in the flare. Large drag changes must be favorably coupled with lift and moment changes to achieve the proper transient response. Another consideration is the ease with which the pilot can control the large drag changes possible with spoiler deployment. With so much performance capability contained within a spoiler system, the pilot's actions must be easy to effect and not subject to confusion.

Aerodynamics

Aerodynamic data that can be used to design spoiler systems for small general aviation aircraft are sparse, and those which exist are not particularly relevant. Just prior to and during World War II, the British conducted several experimental studies to evaluate the use of aerodynamic surfaces for fighter-type aircraft (refs. 9, 10). In both the U.S. and the U.K., the primary emphasis appeared to be on the use of spoilers for lateral control (refs. 11 - 16) and many of the data apply to transonic, low aspect ratio swept wings, such as presented in reference 17. A theoretical treatment of the aerodynamic characteristics of spoilers can be found in reference 18, but the information is not readily applicable to design problems.

Drag.- As stated previously, drag is the critical aerodynamic force provided by spoilers. Therefore it is necessary to estimate the spoiler drag contribution accurately. The problem is complicated, however, because total spoiler drag is derived from the combined effects of flat plate drag due to spoiler surface area, induced drag due to redistribution of spanwise lift on the spoiler-equipped wing, and interference drag due to the effect of a pronounced wake which results from the disturbed airflow around the spoiler. Therefore, it is not surprising that the use of a flat plate drag coefficient of 1.0 underestimates the drag contribution of spoilers. According to Hoerner (ref. 19), the effective drag coefficient based upon spoiler area of a fully deflected surface is between 1.2 and 2.0. The drag contribution varies with airfoil section. For a given airfoil, drag depends upon chordwise location, the maximum contribution occurring with the spoilers placed near the point of maximum section thickness (ref. 19). Due to the influence of induced drag, the total drag contribution of spoilers also will be a function of spanwise location, wing aspect ratio, and spoiler-span to wing-span ratio. Venting at the spoiler hinge line influences the formation of the aerodynamic wake behind and around the spoilers, thus also influencing total drag (ref. 10).

The Federal Aviation Administration stipulates that a uniform aerodynamic loading on spoiler surfaces can be estimated for gliders using the formula

$$W_{SP} = .0052V_i^2 \text{ lb/ft}^2 \qquad \text{(ref. 20)}$$

where V_i is in mph. It is common practice within the glider industry to use this formula to estimate the total zero lift drag contribution of upper and lower hinged plate spoilers. As will be demonstrated in a subsequent section on documentation of the spoiler research aircraft, drag estimates based upon the formula agree quite well with flight test data, and it is suggested that for moderate aspect ratio hinged plate spoilers vented at the hinge line and located near the point of maximum section thickness, with spoiler chord approximately equal to maximum section thickness, a zero lift drag coefficient of 2.0* based upon projected frontal spoiler area is satisfactory for preliminary design. The breakdown of the above-noted zero lift drag between flat plate spoiler drag, wing parasite drag due to separation and induced drag due to distributed lift is not known. The formula must be considered empirical, and some variations must be expected.

The induced drag effects of spoilers do not lend themselves to such a convenient representation. Based upon limited experimental data presented in a subsequent section documenting tests with the spoiler research aircraft, an initial estimate that the induced drag is increased by approximately 20% at nominal deflections of 25° appears reasonable (fig. 19). Induced drag due to spoilers, however, will depend upon several geometric factors previously mentioned, so the use of figure 19 to estimate an induced drag factor is, at best, rather crude.

Drag designs the spoiler configuration and using the above formula it is possible to select a spoiler size approximately meeting a design requirement. It is probably structurally convenient to locate the spoilers near the point of maximum section thickness, which falls very near the 50% chord position on most general aviation airfoils such as the 63_2A415 series used on the spoiler research aircraft. Experience with the spoiler research aircraft plus a review of available data (refs. 9, 10) indicate that favorable spoiler drag and hinge moment characteristics are achieved for spoiler deflections of approximately ±15° about a nominal deflection of approximately 25°. The larger deflection range up to 90° can be useful, however, for gross correction on normal approaches, deceleration, and lift dumping after landing. Therefore, the spoiler drag used to modulate glide path angle change should result from the change in projected spoiler area and the integration of thrust that occurs within the deflection parameters stated above.

As an example, consider a design requirement to provide a capability for flying a 9° approach path with a 10 knot tailwind component; this would permit moderately steep normal approaches,

*Multiplying the drag coefficient of 2.0 by the constants relating miles per hour to dynamic pressure results in a constant approximately equal to the .0052 factor used in the reference 20 formula.

6°, with the ability to make sizable corrections. Further, assume the requirement is for a hypothetical aircraft with the following specifications:

Weight	10 450 N (2350 lb)
Wing Area	14.9 m^2 (160 ft^2)
Approach Speed	74 knots (85 mph)
Drag Coefficient at 74 knots	.084
C_{D_O}	.040
C_L	.795

It should be noted that these characteristics were chosen for illustrative purposes only and do not represent the corresponding values for the spoiler research aircraft described in this report.

From the above information, it can be shown that the maximum power-off glide path angle is 6°; therefore, the spoilers must provide additional drag. In terms of rate of descent, the requirement is determined by the approach condition

$$R/D \doteq (74 + 10) \times \frac{(3° + 6°)}{57.3} = 13.2 \text{ knots}$$

Therefore, the drag requirement is

$$C_D \doteq \frac{13.2 \times .795}{74} = .142$$

Hence, the extra drag which must be supplied by the spoilers is

$$\Delta C_D = .142 - .084 = .058$$

Using a spoiler drag coefficient of 2.0 based upon projected spoiler frontal area and assuming a 40% increase in induced drag due to spoiler deflection, the effective spoiler area needed will be

$$\Delta C_D = \frac{2S_s}{S} + .4 \times .044$$

$$\frac{S(.058 - .018)}{2} = S_s = .298\text{m}^2 \quad (3.20\text{ft}^2)$$

Assuming that the maximum spoiler deflection desired for the approach is 40° for the upper spoiler and 20° for the lower, assuming the wing thickness at the desired chord location is .20 m (.67 ft), and assuming the lower spoiler chord is 75% of the upper spoiler chord, the size of the spoilers can be determined as follows:

$$\ell_s \times .20 \times \text{sine } (40°) = \text{projected area, top spoiler}$$

$$\ell_s \times .20 \times .75 \times \text{sine } (20°) = \text{projected area, bottom spoiler}$$

Considering both wings:

$$2\ell_s \times .129 + 2\ell \times .051 = .298$$

$$\ell_s = .83 \text{ m } (2.70 \text{ ft})$$

The additional drag available from extending the spoilers beyond the 40° upper and 20° lower deflections would be used for gross corrections in glide path angle and for lift dumping during rollout.

Lift.- At the nominal approach airspeed of 75 knots, flow visualization using wool tufts located on the wing of the spoiler-equipped aircraft indicated that the loss of circulation in the region of the spoiler is a strong function of spoiler deflection. At small deflections, in the order of 5° to 10°, the flow over and on either side of the spoiler is attached; only the region immediately behind the deflected surface is separated (figs. 2, 3). At larger deflections, between approximately 10° and 40°, the flow over the spoiler and to either side of it is separated. The area of disturbed flow adjacent to the spoiler appears to grow with increasing spoiler deflection (fig. 4). Beyond about 40° or 50°, the flow also becomes separated over the region extending approximately one spoiler chord ahead of the deflected surface (fig. 5). However, flow over the leading edge of the wing immediately ahead of the deflected spoiler remains attached.

As a first order approximation, it might be assumed that a fully deployed upper spoiler with chord equal to the maximum airfoil section thickness destroys local circulation and that the wing must rotate to an increased angle of attack to recover the spoiled lift. However, such a simple approach tends to underestimate the lift loss associated with large spoiler deflections, at least for the spoiler research aircraft used for this program. Considering the results of the flow visualization study described above, it is not too surprising that such is the case. Spoilers cause the largest lift loss when located in front of flaps since that is where, due to the presence of the flaps, the section lift is the highest.

Chordwise spoiler position influences both the lag between spoiler deflection and heave mode response (ref. 11) and the slope of the lift curve of the spoiled wings (refs. 18, 21). Lift and

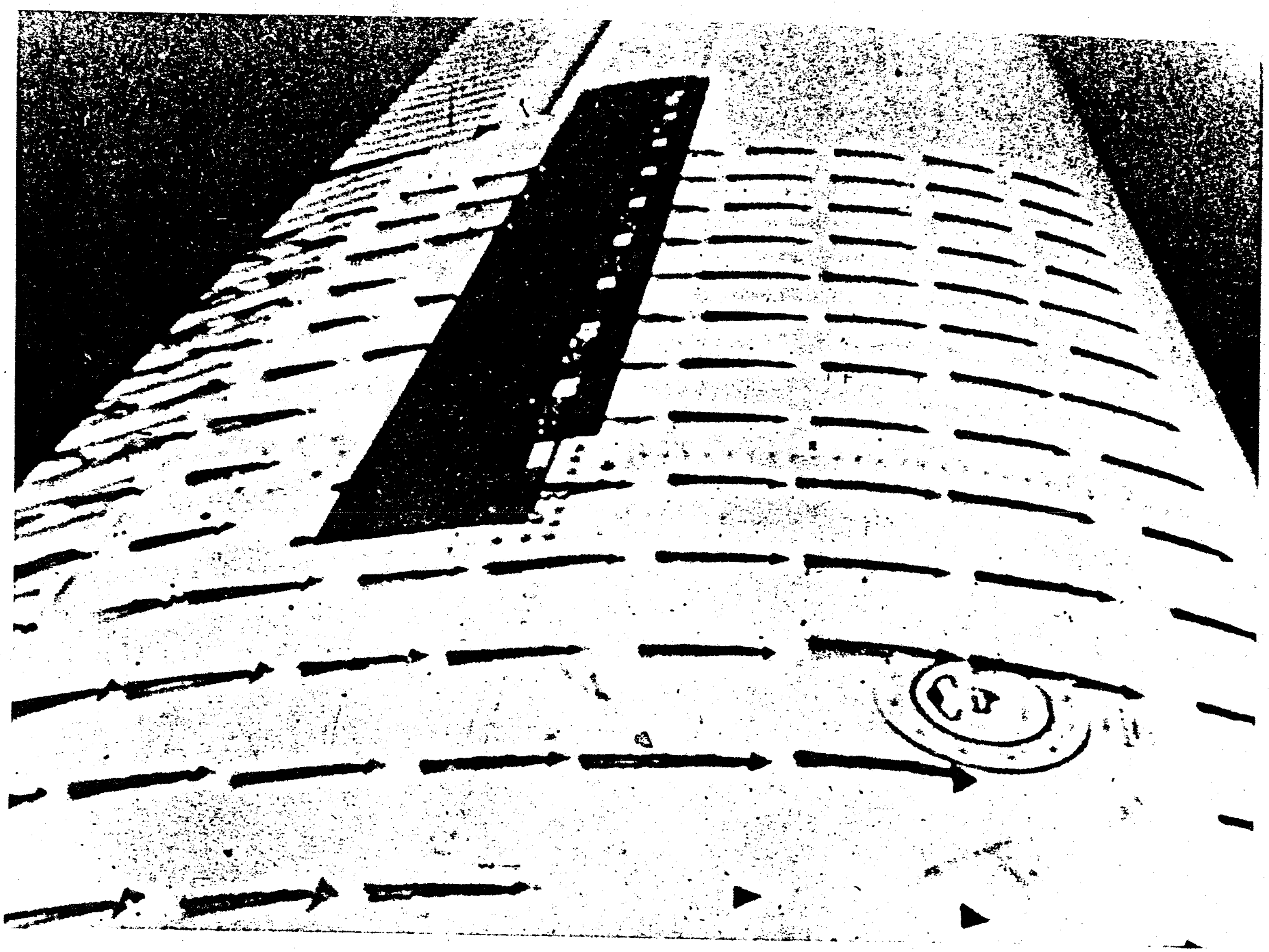


Figure 2.- Flow visualization. Spoilers closed; V_c = 72 knots; flaps = 0°

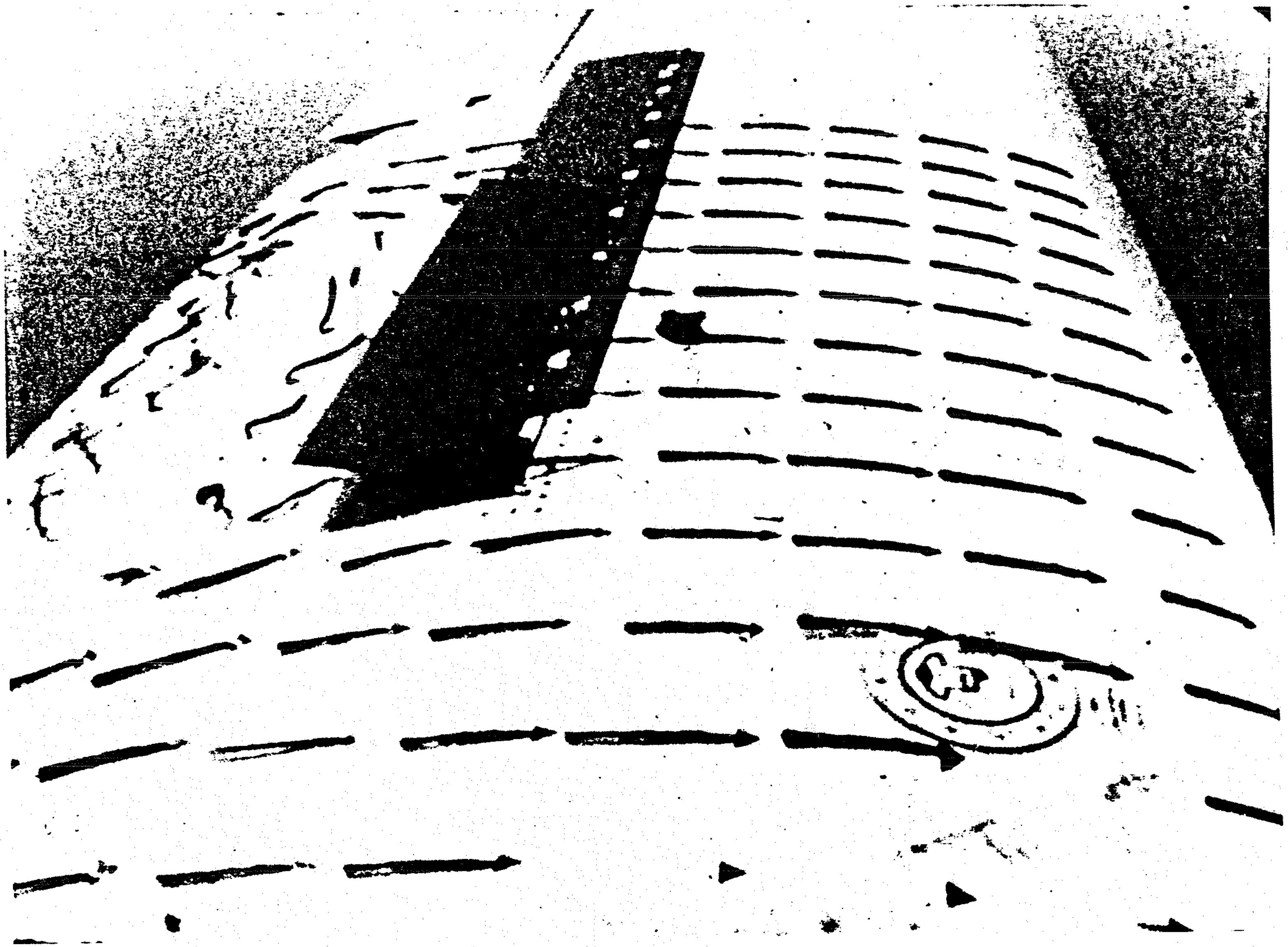


Figure 3.- Flow visualization. Spoiler open ~ 10°; V_c = 72 knots (83 mph); flaps = 15°

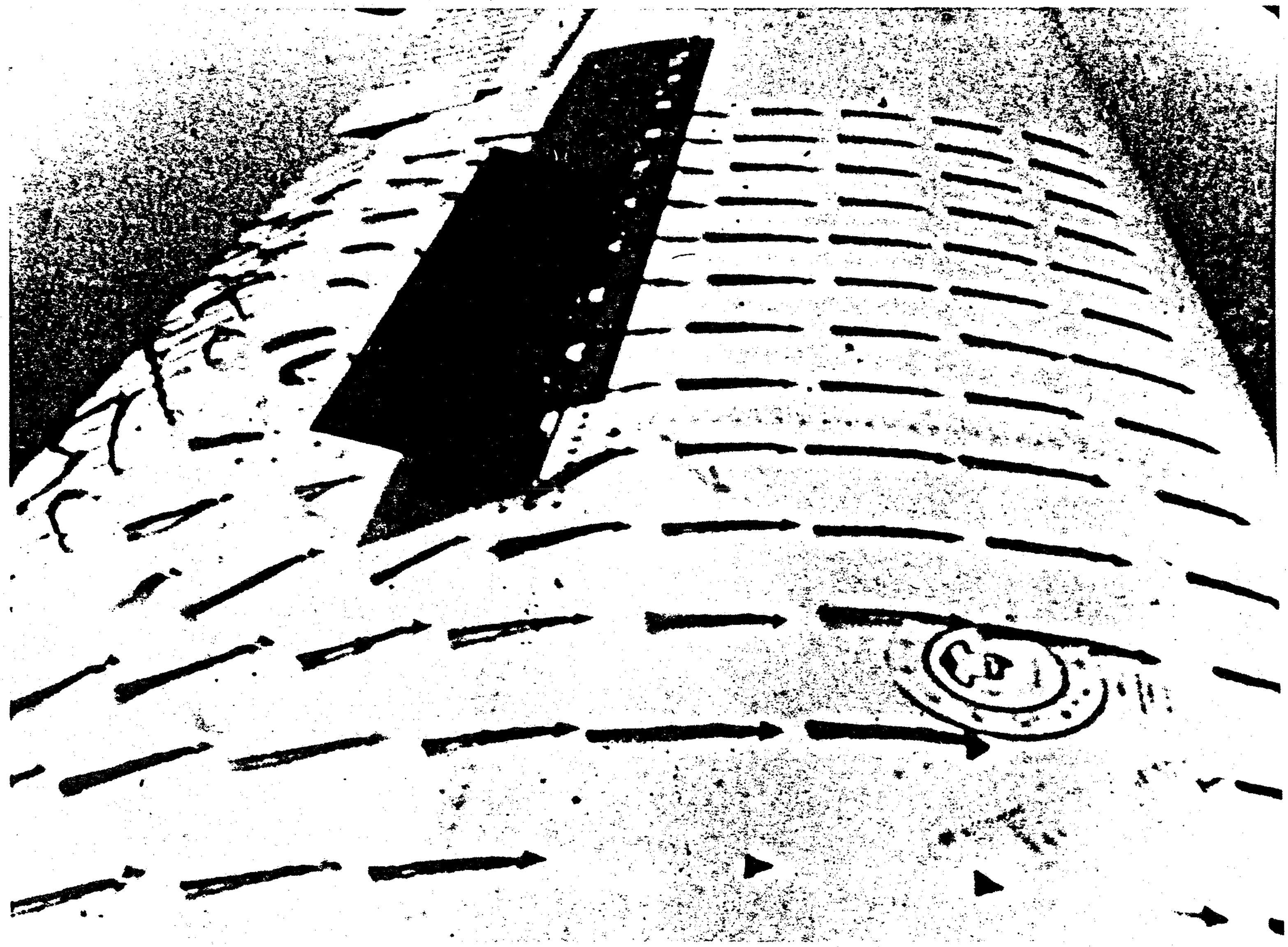


Figure 4.- Flow visualization. Spoiler open ~ 40°; V_c = 72 knots (83 mph); flaps = 15°

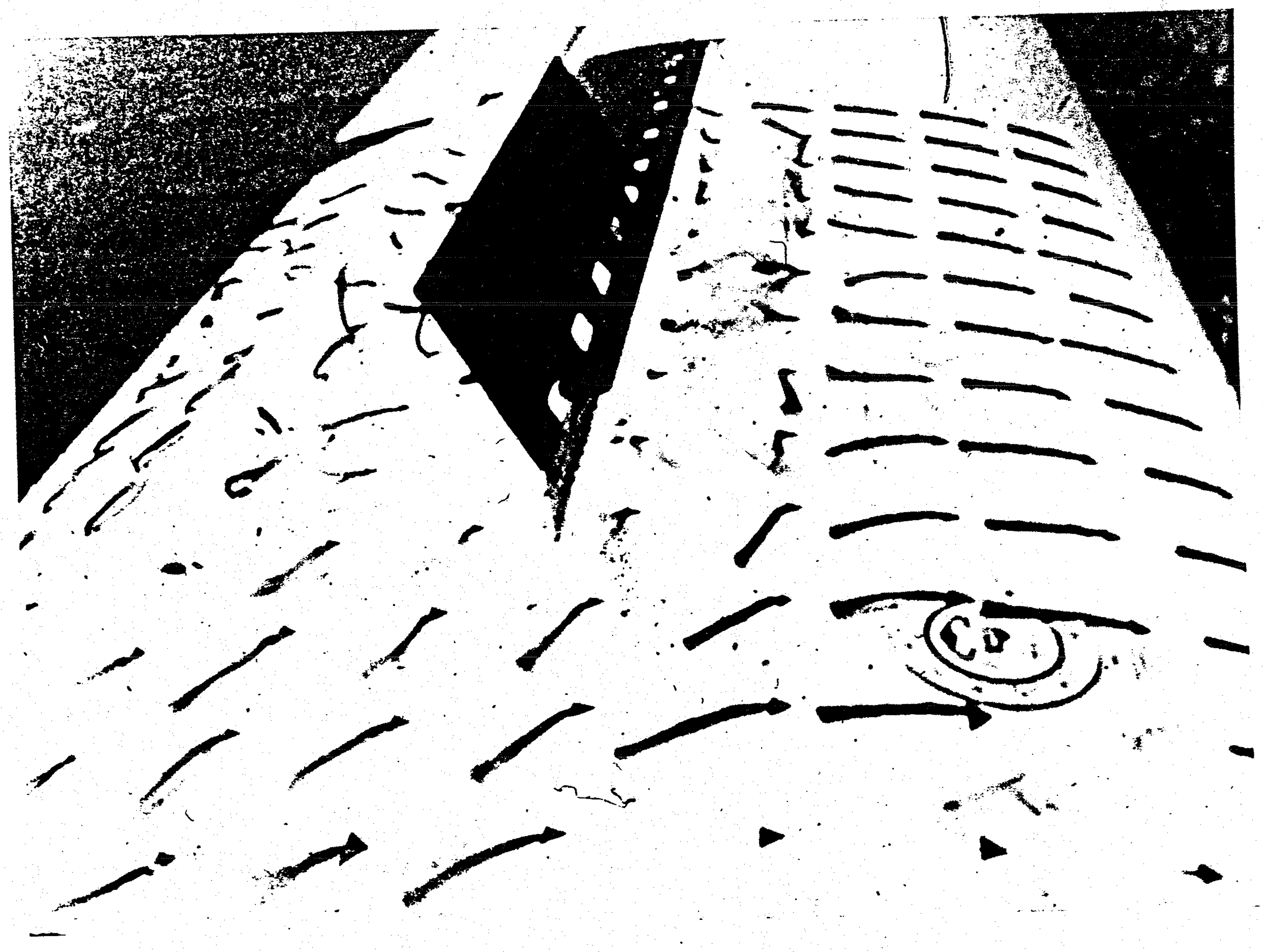


Figure 5.- Flow visualization. Spoiler open ~ 70°; V_c = 72 knots (83 mph); flaps = 15°

drag contributions of spoilers located in the vicinity of 60% chord are relatively independent of angle of attack according to information presented in references 18 and 21. Although the further aft spoiler locations reduce the lag between spoiler deflection and initial response, experience with the test aircraft indicates that midchord positioning on the relatively small-chord wings used in general aviation aircraft produces lags which are without consequence.

Information presented in references 18 and 21 for upper spoilers and data obtained from flight tests suggest that the top spoiler has the principal influence on lift changes. On the spoiler research aircraft, there was no difference in the lift increment due to spoiler deflection between the upper spoiler alone and the upper and lower in combination. It should be noted that the lower spoiler opened with the deflected edge into the wind.

While in theory it might be possible to tailor the top spoiler size to achieve a particular lift response that would be considered favorable for the total drag contributions of a spoiler configuration consisting of both upper and lower wing spoiler surfaces, in practice spoilers probably would be sized and positioned more by drag, structural, and hinge moment requirements than by lift considerations. The spoiler size, shape, and location that meet these other design requirements appear likely to also satisfy the need for a proper lift response, provided the spoiler configuration does not depart radically from the simple upper and lower surface hinged plate arrangement evaluated in this report.

Pitching moment.- Whereas the lift change due to opening spoilers is certainly a decrease, as discussed in the previous section, the pitching moment change seems quite clearly to be nose-up. These are the favorable characteristics tending to cancel and produce a neutral over-all trim change.

The nose-up pitching moment seems to arise from two obvious effects. First, the airfoil section pitching moment due to camber and flap deflection would normally be nose-down. The spoilers tend to "spoil" this, along with lift, producing the opposite, or nose-up, increment. Second, the spoiling of lift at midspan of the wing would distort the spanwise load distribution and produce trailing vortices which increase the downwash at the tail. This also produces nose-up pitching moment.

At this time, rules of thumb or simple procedures for predicting these effects quantitatively are not available. Simple assumptions based on canceling section lift do not adequately predict the lift loss, so they probably would not be accurate enough for the section pitching moment change. Methods for predicting the downwash change have been developed by superposition of downwash fields behind flapped wings (refs. 22 and 23) but some very crude assumptions are necessary, and the accuracy could only be checked in detail by series of wind tunnel tests.

Thus, although there is little doubt that the partial (constant $-\alpha$) pitching moment change would be nose-up for opening spoilers of this configuration, there is no method currently available for predicting it in detail. It may be taken empirically that the spoilers flight-tested in this program exhibited negligible trim changes, with lift and pitching moment increments effectively offsetting each other. It probably is reasonable to assume that this is not particularly configuration-dependent; rather it is inherently characteristic of spoilers of this type. This implication may be drawn from the results presented later, where the trim changes are not much affected by spoiler size, spanwise location, or other geometric variations.

Hinge moments.- Good hinge moment data for the design of an upper and lower surface hinged plate spoiler system are lacking. Furthermore, the net hinge moment on a common drive system, such as a torque tube connected to both the upper and lower spoiler surfaces, would be highly dependent upon geometry. Data presented in reference 9 indicate that the moment about the hinge line of an upper surface spoiler which opens with the deflected edge downstream is characteristically sinusoidal, while the moment about the hinge line of a lower surface dive brake which opens with the deflected surface into the airstream tends to rise in nearly a linear fashion until a dive brake deflection of 10° to 15°, and then tends to be nearly constant independent of deflection.

Due to relatively high friction forces within the system it was not possible to generate good hinge moment data from flight tests with the spoiler aircraft. The limited information that was obtained indicated that the upper spoiler exhibits an opening moment that decreases up to a deflection of approximately 20°. The hinge moment reverses sign and continues to increase with deflection. The relationship between deflection and moment appears to be regular and without discontinuities. With both the upper and lower spoilers operating together, the total hinge moment has a strong opening character at zero deflection. The spoilers tend to pop open to a deflection approaching 35° to 40°, and then exhibit a closing moment that increases with deflection although the gradient is small.

It appears from the observed characteristics of the spoiler system that tailoring the hinge moments would be possible by the use of overcentering springs, varying the size of the upper and lower spoilers, and adjusting the drive geometry to achieve different deflection ratios between the upper and lower spoilers.

Spanwise location.- Although in theory there may be an optimum spanwise location for spoiler contributions to drag, lift, and pitching moment, in practice a principal consideration is the aerodynamic interaction between the spoiler wake and the tail in terms of interference and buffet. Naturally, it is highly desirable to ensure that there is no wake impingement on the horizontal tail, and the best means of achieving that condition is to locate the spoilers outboard on the wing. Spoilers diminish the effectiveness of aerodynamic surfaces such as flaps and ailerons that lie in their wake; thus, care must be exercised in selecting the appropriate spanwise location. Venting the spoilers at the hinge line has the effect of narrowing the wake and diminishing opening transient effects (ref. 10), but there is no evidence that venting can eliminate the adverse effects of direct wake impingement.

Controller Considerations

The drag characteristics of spoilers can enhance an aircraft's performance significantly. Thus, it is imperative to take advantage of the aerodynamic potential of spoilers in a way which does not compromise operational safety. Aside from mechanical integrity and fail-safety, an overwhelmingly important part is played by the operational features of the spoiler control. In particular, the designer must minimize chances for incorrect operation or even momentary confusion on the part of the pilot and strive for a system with straightforward operational procedures requiring little or no special transition training; if lacking in either respect, spoiler systems will probably be as much hazard as help to the pilot.

Controller types.- For manual operation, one can easily conceive of spoiler control schemes which range from a simple additional switch or lever in the cockpit to a system which completely integrates spoiler action with an existing control such as the throttle. In-between variations (here termed semi-integrated) might encourage simultaneous manipulation of spoiler and some other control but would be arranged so as to permit certain types and amounts of independent operation.

Many of these possible controller variations have been considered in this program, and several have been tried in flight, as described in detail in a later section. It is useful at this point, however, to consider some of the important general features associated with certain types of controller.

Separate controller.- A separate spoiler controller is one which permits operation of the system independently of any other cockpit control. Many forms are conceivable: a switch, lever, or push-pull control on the instrument panel; a handle akin to the common manual flap actuation devices; a thumb-operated switch on the pitch control or throttle.

The idea of a separate controller might be appealing on grounds of simplicity, flexibility of placement, or minimum interference with an existing cockpit arrangement, but judged against the design goals just stated, the concept is lacking in several respects. The foremost problem is the requirement for division of attention between the normal pitch and throttle control and the spoiler control; at best, this will introduce the need for new piloting techniques and, at worst, will be the source of delay in control action or even confusion and incorrect action. There will be questions of how to mix throttle and spoiler usage on the approach, how to handle the flare and suppress floating, and what sequence of action to take on rollout or go-around. None of these present insurmountable difficulties, but the overall piloting task becomes more complex, requiring training and practice. Added to this is the possibility of delay or wrong action at a critical moment, leading to a hard touchdown or worse.

To alleviate such problems, one can conceive of interlocks to prevent, for example, the spoilers remaining fully open when the throttle is advanced beyond a certain point. This will complicate the mechanism, however, and do little to reduce the piloting workload. Another scheme would have the spoilers deployed but not modulated during the approach and landing operation, the size or deflection being limited so as to preserve some climb performance at full throttle. Although some of the objectionable features of the separate controller might thus be avoided, it is obviously not the way to obtain maximum utility from a flight path spoiler system.

Elevator-integrated spoilers.- In this case, the system is mechanized to cause spoiler retraction to accompany a nose-up pitch command and vice versa; in order to have two-way modulation, the spoilers must be partially deployed to some nominal operating point. The results are an augmentation of the lift response to angle of attack due to spoiler-caused lift changes and an increase in speed stability ($d\gamma/dV$) due to spoiler-induced drag changes.

If the airplane in the spoiler-retracted configuration is deficient in its flight path response to elevator, then the elevator-integrated spoilers will probably offer some improvement in flare capability and glide path modulation with elevator. While many light aircraft have marginal speed stability at approach airspeed, most have favorable pitch control and very adequate lift response to elevator inputs, so any augmentation of the latter is likely to result in an overly delicate height control situation during the landing flare. Moreover, the drag reduction resulting from spoiler retraction during the flare will most likely lead to an undesirable tendency to float. In fact, it is probable that the approach and landing qualities of the usual lightplane would be improved by the elevator-integrated spoilers only for much lower than normal speeds where lift response and path control tend to be poor.

Other possible operational difficulties are apparent. In addition to providing for partial deployment prior to use, special attention would have to be given to assuring quick spoiler retraction for a go-around, since the change in elevator position for that maneuver might not be in the amount or direction needed. Also, a separate means for obtaining the desirable full spoiler deflection for landing rollout might have to be considered in order to avoid the wheelbarrowing tendencies which would accompany down-elevator (and thus up-spoiler) applications.

Throttle-integrated spoilers.- Here the spoiler system is coupled to the throttle in a sense that has the spoilers opening for throttle retardation, giving the throttle, in effect, a much enhanced authority as a thrust/drag modulator. Flight path control on the approach can be carried out in the normal manner using coordinated elevator and throttle. From a piloting standpoint, the main difference between this and the no-spoiler airplane will be a notable increase in throttle effectiveness. A go-around can be initiated at any point in the approach or landing process simply by opening the throttle; the automatic retraction of the spoilers aids the process with an immediate lift increase and drag reduction.

During the flare and touchdown, the throttle/spoiler control can be used effectively to control deceleration and prevent ballooning and floating tendencies. (Here a pilot transitioning from a nonspoiler airplane should be cautioned against large or brisk throttle reductions to avoid a hard touchdown; however, this is the only aspect of the throttle-integrated controller which warrants any special briefing prior to use.) No action is required during landing roll other than the normal one of holding throttle/spoiler control in the full aft position for simultaneous idle power and full spoiler deployment.

A variation of the throttle-integrated spoiler concept is a semi-integrated arrangement where the throttle and spoiler controls are physically located so that simultaneous operation is easy for the pilot, yet each control can be moved separately within certain range restrictions which prevent undesirable or opposing operations of the two controls. The semi-integrated control scheme accommodates throttle/spoiler integration tailored for the range of deflections that is best for approach and flare conditions, but allows the spoilers to be deflected to larger angles by moving the spoiler control beyond the position corresponding to idle throttle setting.

Aircraft Response to Spoiler Deflection

The response of the airplane to control deflection largely determines how the pilot will use the spoiler control. The response, of course, can be predicted. For a sudden movement of the control lever (a step function), the longitudinal response can be calculated from the following equations, presented in the style of reference 24:

$$[s + (D_V - T_V)]\Delta V + \qquad D_\alpha \Delta\alpha + \qquad g\Delta\gamma = -D_\delta \frac{\bar{\delta}}{s}$$

$$\frac{L_V}{V_0}\Delta V + \qquad \frac{L_\alpha}{V}\Delta\alpha - \qquad s\Delta\gamma = -\frac{L_\delta}{V}\frac{\bar{\delta}}{s}$$

$$-M_V\Delta V + [s^2 - (M_{\dot{\alpha}} + M_{\dot{\theta}})s - M_\alpha]\Delta\alpha + (s - M_{\dot{\theta}})s\Delta\gamma = M_\delta \frac{\bar{\delta}}{s}$$

In these equations, the size of the step function control input is $\bar{\delta}$ and the three derivatives, D_δ, L_δ/V, and M_δ, on the right-hand side represent the drag, lift, and moment changes applied to the airplane by the deflection of the control surface.

The initial part of the response of the airplane, corresponding to the "short period mode" can be found simply by neglecting, in the short term, any V change. Hence, $\Delta V \equiv 0$, and

$$\frac{L_\alpha}{V_0}\Delta\alpha - \qquad s\Delta\gamma = -\frac{L_\delta}{V}\frac{\bar{\delta}}{s}$$

$$[s^2 - (M_{\dot{\alpha}} + M_{\dot{\theta}})s - M_\alpha]\Delta\alpha + (s - M_{\dot{\theta}})s\Delta\gamma = M_\delta \frac{\bar{\delta}}{s}$$

The Laplace solution for $\Delta\gamma$ can be given as

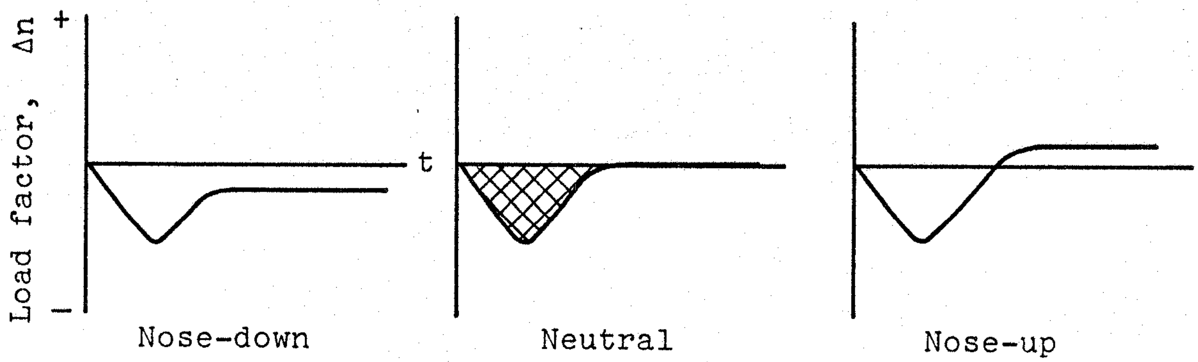
$$\frac{\Delta\gamma(s)}{\bar{\delta}} = \frac{\begin{vmatrix} \frac{L_\alpha}{V} & -\frac{L_\delta}{V} \\ [s^2 - (M_{\dot{\alpha}} + M_{\dot{\theta}})s - M_\alpha] & M_\delta \end{vmatrix}}{s^2[s^2 + 2\zeta\omega_0 s + \omega_0^2]}$$

It is instructive first to consider the rate of change of γ. The function of time can be found from the above. It is proportional at constant speed to load factor Δn.

$$\frac{\Delta\dot{\gamma}}{\bar{\delta}} = \frac{g}{V}\frac{\Delta n}{\bar{\delta}} = \frac{\frac{L_\alpha}{V}M_\delta - \frac{L_\delta}{V}M_\alpha}{\omega_0^2} + Ae^{-\zeta\omega_0 t}\cos[\omega t + \phi]$$

The first term represents the short-period, steady-state load factor resulting from the spoiler deflection. It is a measure of the control position trim change, indicating nose-up trim change when positive and nose-down when negative. The two parts are the direct lift change, L_δ , which would be negative for spoilers and would contribute to the trim change in the nose-down sense, and the direct moment change, M_δ , which is positive for spoilers, contributing nose-up trim change. If the two parts are equal and cancel, the trim change is neutral - which is desirable.

The functions of time represented above, for quick opening of the spoilers, typically look like one of the three alternatives sketched below, depending on the direction of the trim change. The middle case, where the lift reduction is just cancelled by the increase in angle of attack that results from the nose-up moment, is the most favorable. The area under the curve, cross-hatched in



Trim changes due to spoiler opening

the sketch, represents a change in the flight path angle $\Delta\gamma$. It is a change in the right direction. For opening spoilers, the drag will be increased and ultimately steepen the flight path, and the negative short-period response in $\Delta\gamma$ shown above is part of that ultimate change. It occurs rapidly and makes the flight path response to spoiler deflection seem immediate - "crisp and precise," as the pilots put it. It can be shown that this short-period response is given by

$$\text{short-period } \Delta\gamma_{ss} = \frac{g}{V}\frac{\Delta C_L}{C_L}\frac{(M_{\dot{\alpha}} + M_{\dot{\theta}})}{\omega_0^2}$$

Because of the ω_0^2 term in the denominator, its size is quite CG position dependent. In fact, it can be shown that if $M_V = 0$ (which is likely for idle power), then

$$\text{short-period } \Delta\gamma_{ss} \doteq \frac{\Delta C_L}{C_{L_\alpha}}\left(1 + \frac{d\varepsilon}{d\alpha}\right)\frac{N_m - N_0}{N_m - \bar{x}_{cg}}$$

The simple expression is quite informative. The $(N_m - N_0)/(N_m - \bar{x}_{cg})$ term increases as the CG is moved aft. Its maximum permitted value, however, is unity, since at that point the static margin $N_0 - \bar{x}_{cg}$ is zero. At CG positions forward of the neutral point, the magnitude is correspondingly less than unity.

Now the ultimate γ change due to opening spoilers can be evaluated quickly from the constant terms in the complete equations. If speed is maintained constant by use of the wheel (stabilator), then $\Delta V = 0$ and

$$\text{final } \Delta\gamma_{ss} = -\frac{\bar{\delta}}{g}\left[D_\delta - L_\delta \frac{D_\alpha}{L_\alpha}\right] = -\frac{\Delta C_L\big|_\alpha}{C_L}\left[\frac{\Delta C_D}{\Delta C_L}\bigg|_\alpha - \frac{D_\alpha}{L_\alpha}\right]$$

$$\doteq -\frac{\Delta C_D\big|_\alpha}{C_L} + \frac{2\Delta C_L\big|_\alpha}{\pi e A}$$

In these forms, the ΔC_D and ΔC_L are the partial effects at constant α , as indicated. A more convenient form may be for constant C_L where

$$\text{final } \Delta\gamma_{ss} = -\frac{\Delta C_D}{C_L} = -\left[\frac{\Delta C_{D_P}}{C_L} + C_L(K_s - K_b)\right]$$

If the short-period and final steady-state γ changes were equal, there would be no phugoid excitation and no airspeed oscillations in the response to spoiler deployment. As the airplane came out of the short-period mode, having changed γ the correct amount, it would be in drag equilibrium and no airspeed transient would be excited.

Now to recapitulate, the above analysis has dealt with the response of the airplane to spoiler deflection. Parameters of the equations have been identified that correspond to familiar features of the response. In particular, control position trim changes are related to the spoiler lift and moment changes; and phugoid excitation and velocity transients are related to spoiler drag and lift changes. It is plausible that particular ratios between spoiler drag, lift, and moment changes might be desirable. For typical spoiler configurations, such as those evaluated in this program, desirable coupling of drag, lift, and moment change appears to be an easily achieved characteristic.

THE EXPERIMENTAL AIRPLANE, WITH AND WITHOUT SPOILERS

Description of Research Aircraft

A small fixed-wing general aviation aircraft was modified with an experimental hinged plate spoiler system consisting of two spoiler surfaces and two dive brake surfaces located on the top and bottom, respectively, of each wing (figs. 6, 7, 8). Before modification, the evaluation aircraft was a typical light (W/S = 768 N/m^2 (16 lb/ft^2)), low wing, fixed trigear aircraft representative of a class of vehicles used for flight training, industrial aid, and pleasure purposes (Table I, fig. 9). The upper or spoiler surfaces were hinged at their upstream edge, 0.724 m (28.5 in.) (53.2% mac) behind the wing leading edge; the lower or dive brake surfaces were hinged at their downstream edge, 0.864 m (34 in.) (63.5% mac) from the wing leading edge. Spanwise location of the inboard edge of the system was 1.194 m (47 in.) from the root chord for the spoilers and 1.353 m (53.25 in.) for the dive brakes. The dimensions of the individual spoiler plates are shown in figure 10. The surfaces could be deflected individually or simultaneously by means of a single torque tube located in the wings (fig. 11). Thus, various system configurations were available for evaluation. Figures 12 and 13 show the upper and lower spoiler system fully deflected.

The aerodynamic surfaces were vented to reduce the size of the wake which resulted when the spoiler system was deployed (ref. 10). A venting path also existed between top and bottom surfaces of the wing (figs. 8, 13). The spoiler configuration was representative of a hinged plate spoiler/dive brake system, commonly referred to simply as "spoilers," used on several popular U.S.-manufactured sailplanes.

In order to develop a fuller understanding of the influence of spoiler area, spanwise location, and upper versus lower surface effects, four different configurations were documented. These were

Upper Inboard	0.331 m^2 (3.56 ft^2)
Upper and Lower Inboard	0.531 m^2 (5.71 ft^2)
Upper Outboard	0.331 m^2 (3.56 ft^2)
Upper and Lower Outboard	0.579 m^2 (6.23 ft^2)

All the configurations were evaluated during the course of the program. The unguided, day VFR landings used either the inboard or outboard systems with a 1:1 deflection ratio between the upper and lower surfaces. The guided, day VFR landings used either the upper and lower inboard or the entire system; the deflection ratio was 1:1. The night and IFR evaluations used the outboard system with a 2:1 ratio between surface deflections.

TABLE I.- GENERAL SPECIFICATIONS
UNMODIFIED EVALUATION AIRCRAFT

Power Plant

Continental IO-346-A engine rated at 165 hp at 2700 rpm. The engine drives a forged aluminum, fixed pitch, 188 cm (74 in.) diameter propeller equipped with spinner.

Performance[a]

Maximum speed at sea level, 2700 rpm	127 kts (146 mph) TAS
Cruising speeds:	
75% at 2134 m (7000 ft)	119 kts (137 mph) TAS
65% at 3048 m (10000 ft)	112 kts (129 mph) TAS
55% at 3048 m (10000 ft)	102 kts (117 mph) TAS
Stall speed, landing (zero thrust, 35° flaps)	51 kts (59 mph) CAS
Rate of climb (gross weight, sea level)	235 m/m (770 fpm)
Service ceiling	3810 m (12550 ft)
Absolute ceiling	4389 m (14400 ft)
Take-off distance (15° flaps)	
Ground run	287 m (940 ft)
Total over 15 m (50 ft) obstacle	424 m (1390 ft)
Landing distance (35° flaps)	
Ground roll	186 m (610 ft)
Total over 15 m (50 ft) obstacle	380 m (1240 ft)

Weight

Gross weight (normal category)	10 450 N (2350 lbs)
Moment of inertia, I_Y	(approx.) 1855 kg m^2 (1370 slug-ft^2)

Airplane Dimensions

Wing span	9.98 m (32.75 ft)
Wing area	13.6 m^2 (146 ft^2)
Airplane length	7.62 m (25.0 ft)
Airplane height	2.44 m (8.0 ft)
Flap positions	0°, 15°, 25°, 35°
Wheel base	1.98 m (6.5 ft)
Wheel tread	3.61 m (11.83 ft)

[a]These performance figures are the results of flight tests of the aircraft type with a gross weight of 10450 N (2350 lbs) conducted by the aircraft manufacturer under factory-controlled conditions.

Figure 6.- Spoiler research aircraft; inboard spoilers deployed 70°

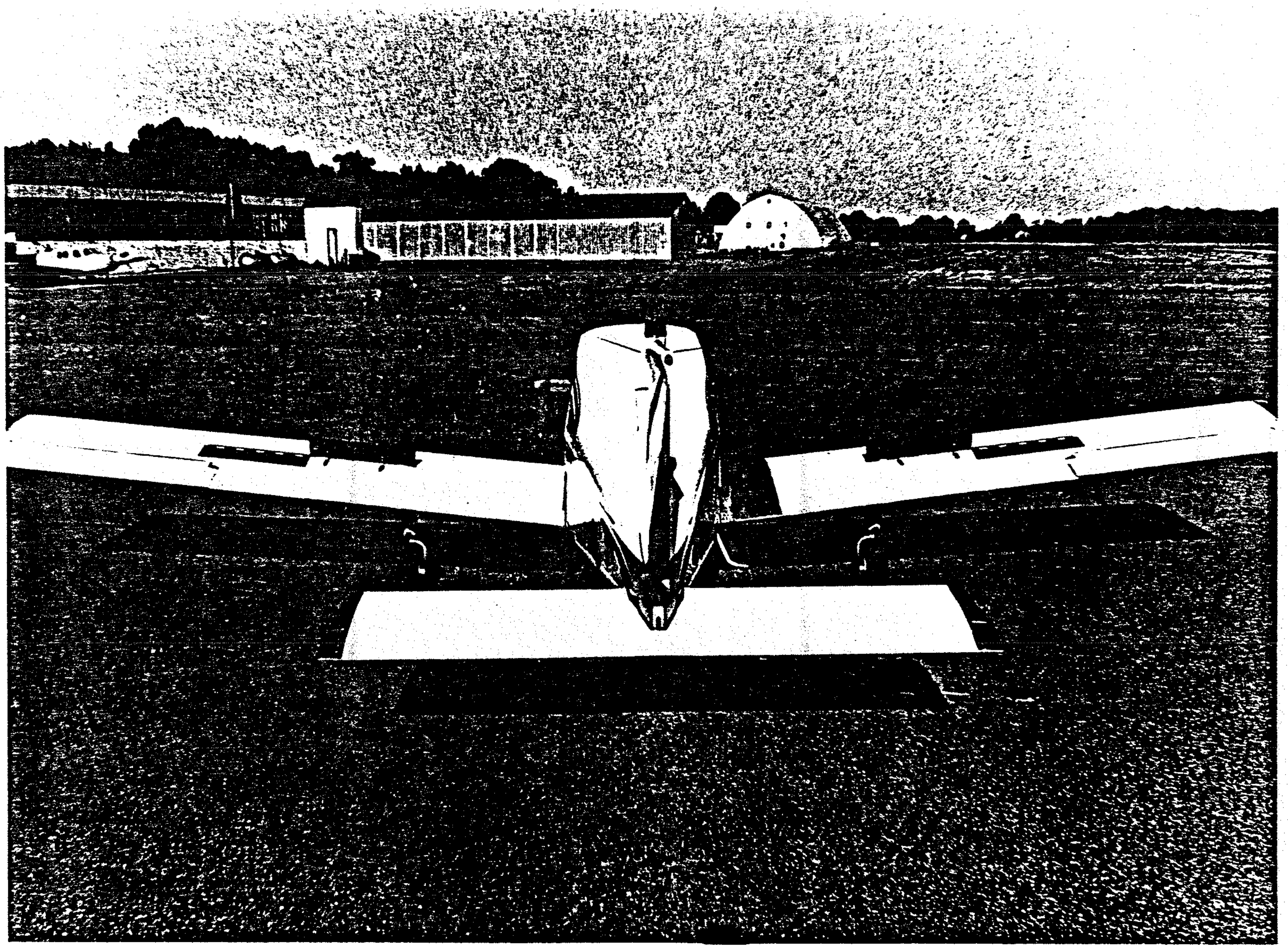


Figure 7.- Spoiler research aircraft; rear view

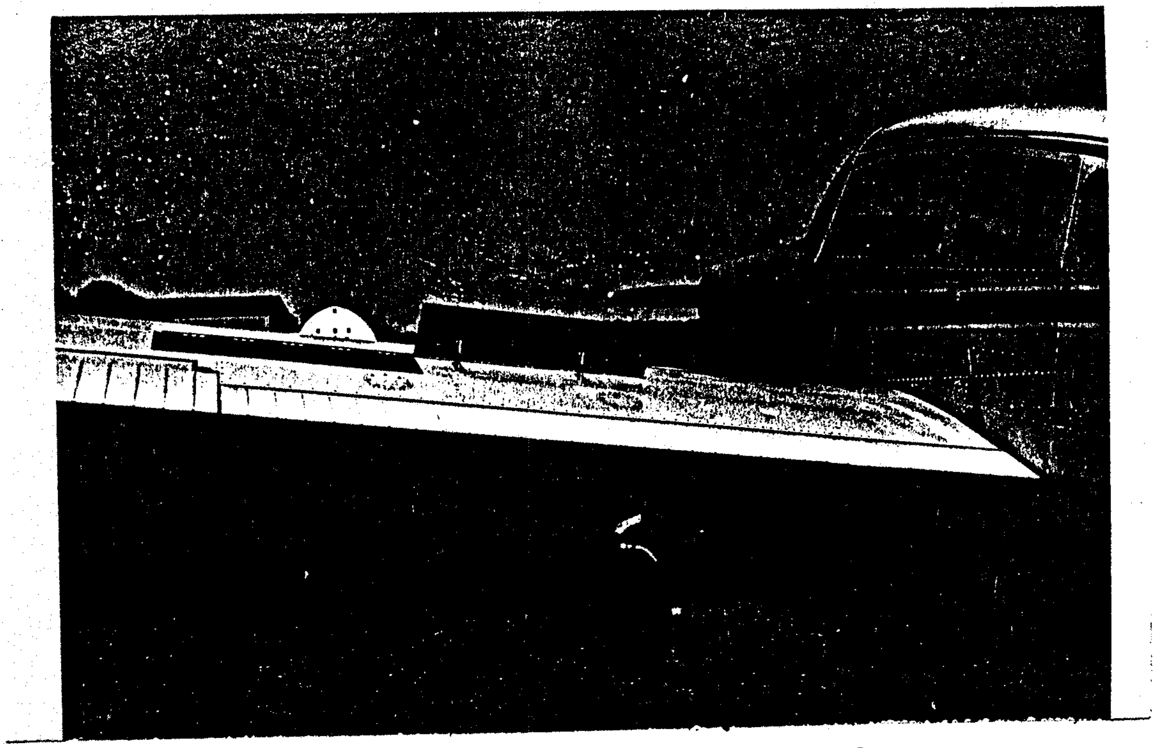


Figure 8a.- Upper inboard spoilers deployed 70°

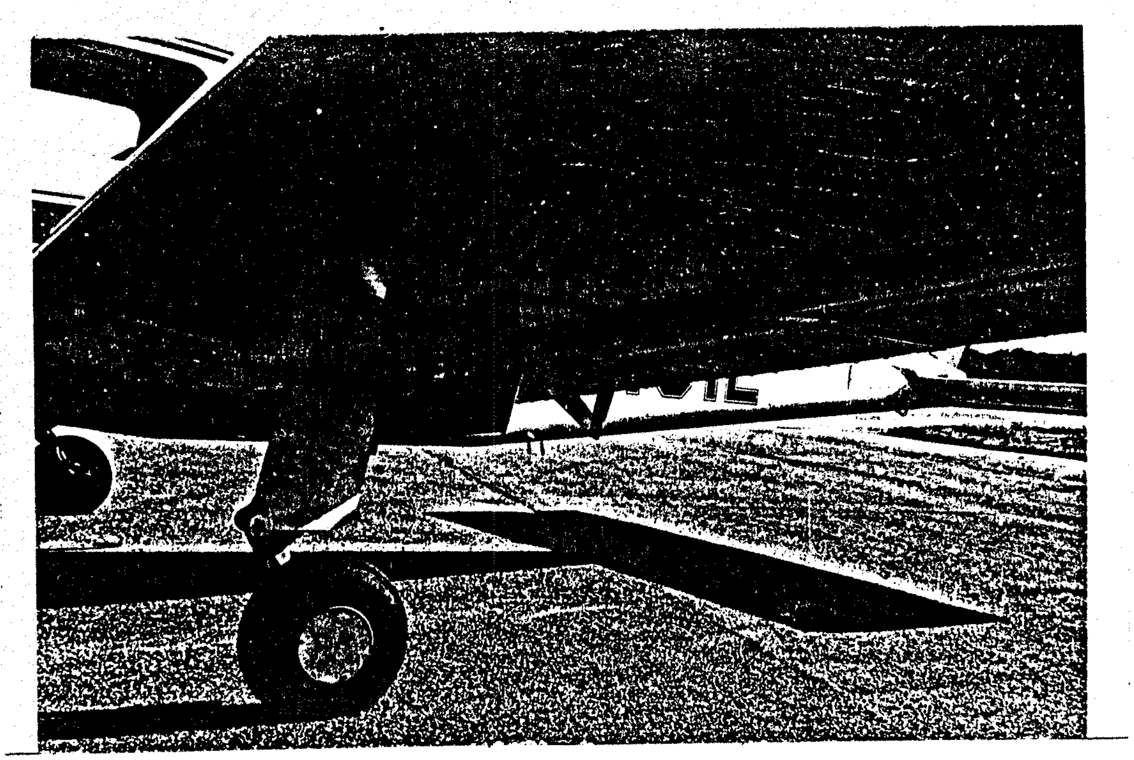


Figure 8b.- Lower inboard spoilers deployed 70°

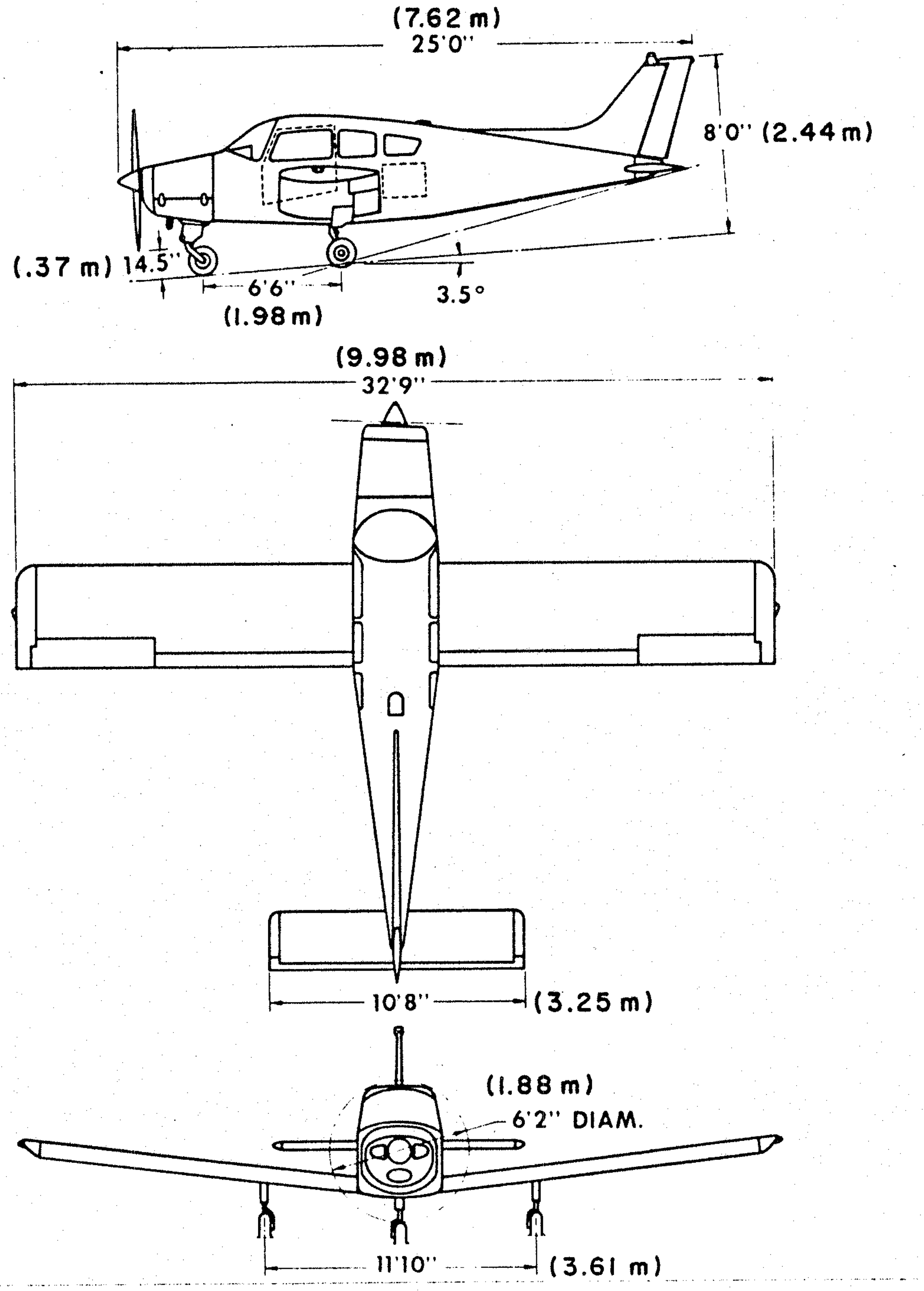


Figure 9.- Evaluation aircraft

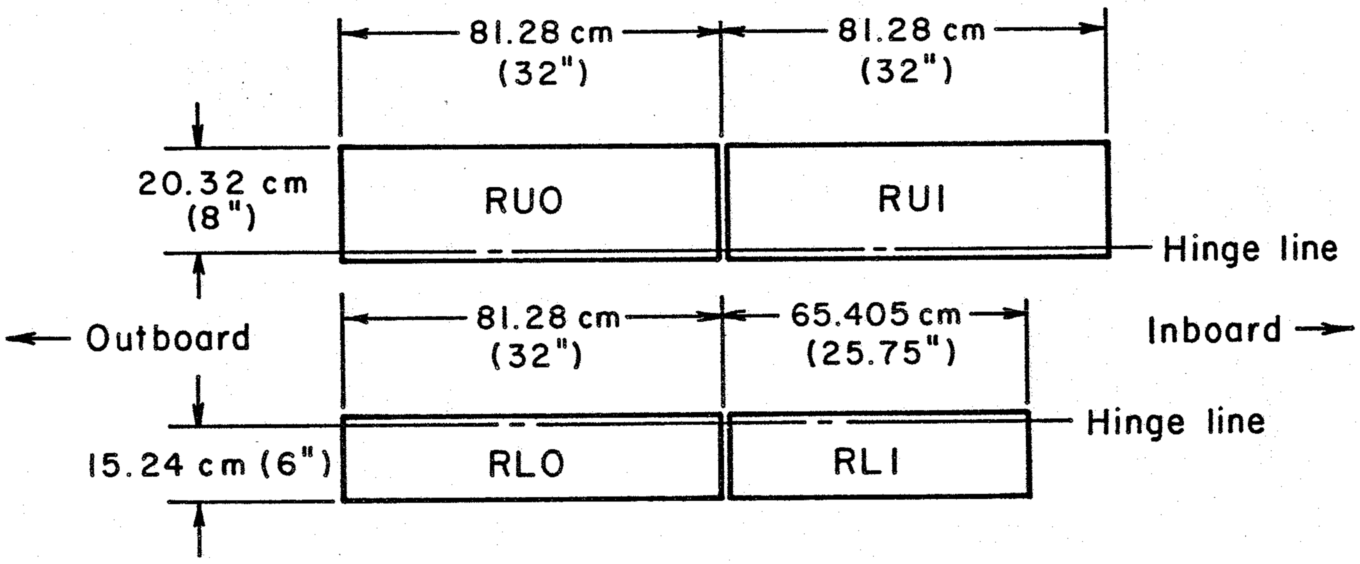


Figure 10.- Schematic of right wing spoiler system (typical)

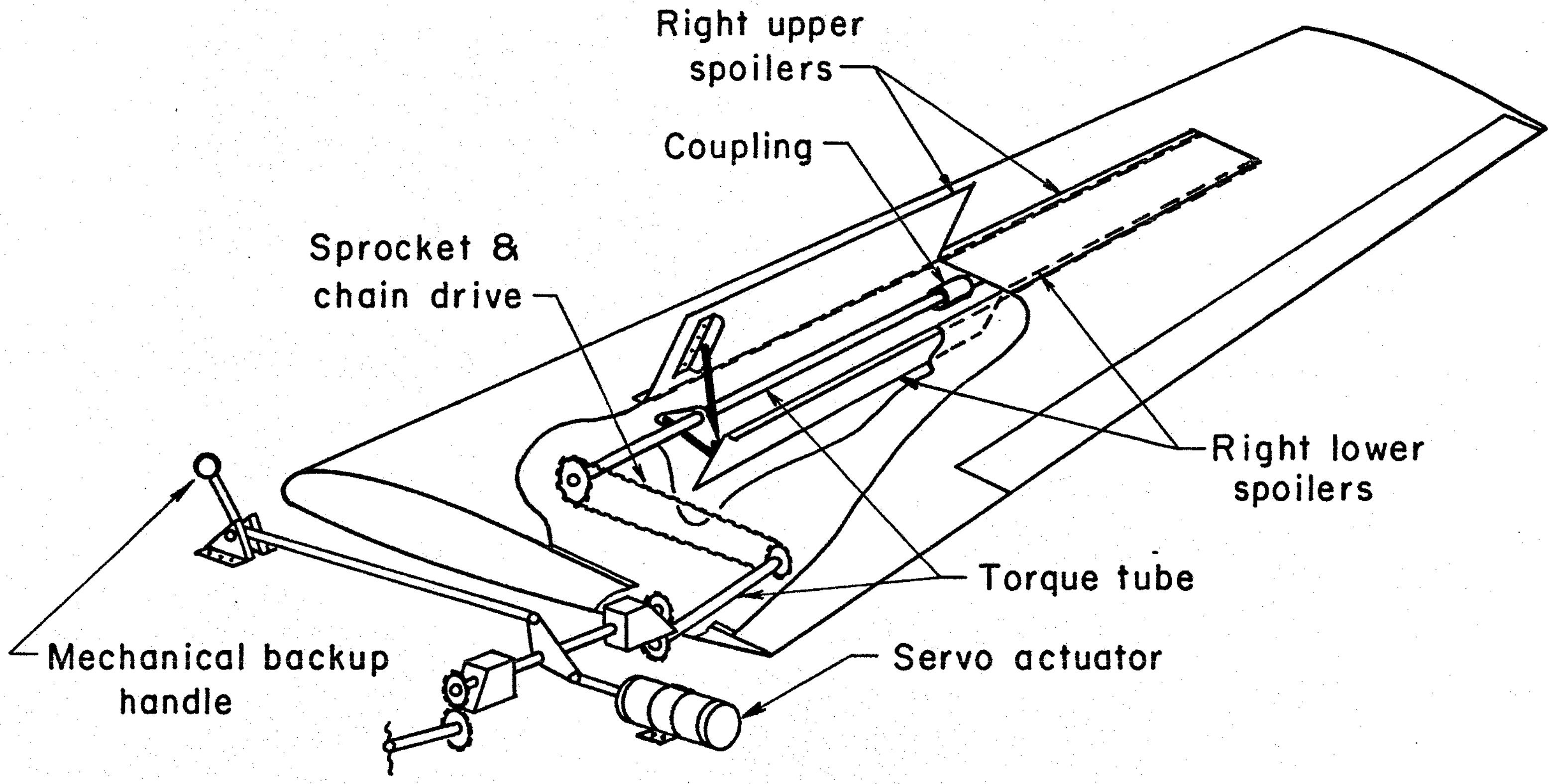


Figure 11.- Schematic of spoiler arrangement and drive system

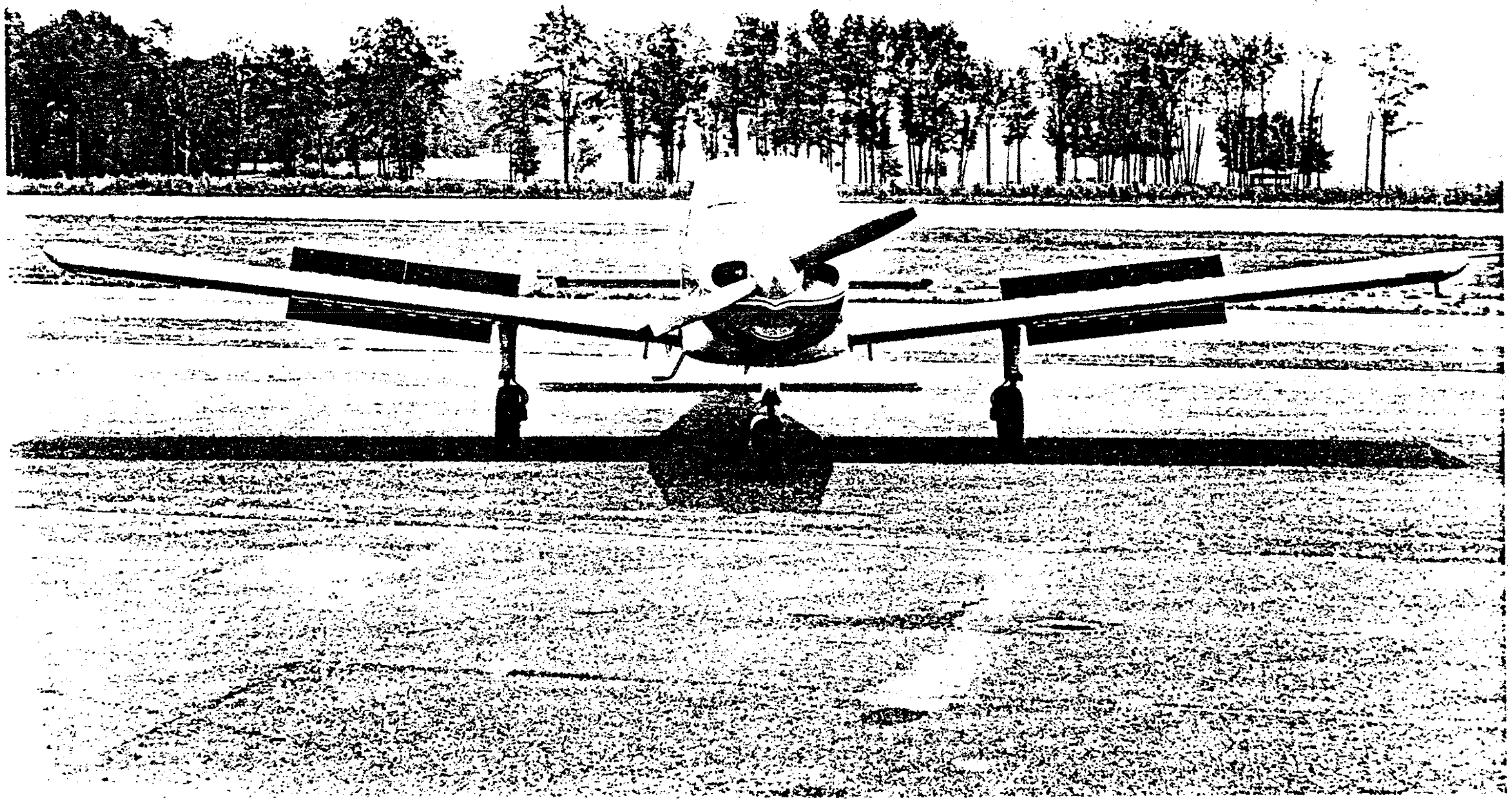


Figure 12.- Spoiler research aircraft; all spoilers deployed 70°

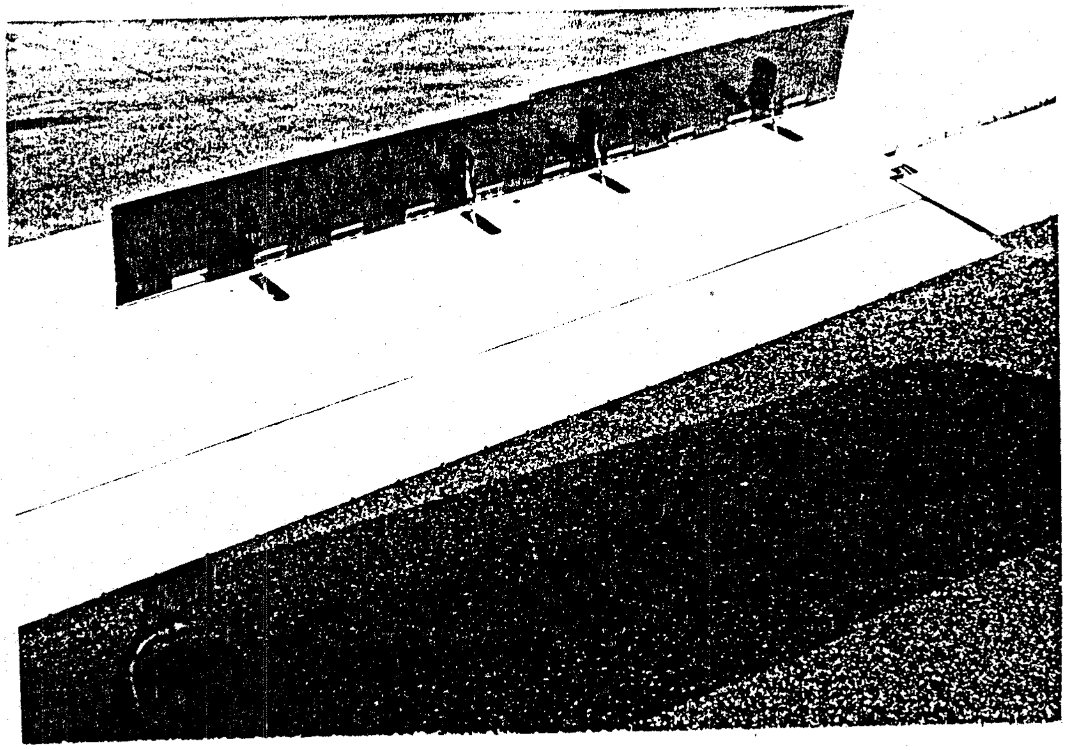


Figure 13a.- All upper spoilers deployed 70°

Figure 13b.- All lower spoilers deployed 70°

The spoiler system could be activated either mechanically by means of a 0.5 meter- (21 in.) long handle mounted between the two front seats or hydraulically by means of an electrically controlled hydraulic servo-actuator. The mechanically operated handle was configured so that the pilot could exert a torque on the spoiler drive mechanism. It was used to establish various fixed spoiler deflections during the documentation portions of the program, and it served as a mechanical backup to the hydraulic spoiler control system. The torque which the pilot could exert using the mechanical system was sufficient to override the action of the hydraulic servo.

The hydraulic system used a conventional position feedback network to control a servo actuator with a piston area of 7.09 cm^2 (1.1 in^2) (fig. 14a). Four potentiometer-type transducers, each with its own gain control (fig. 14a) could be used individually or in combination to sense control positions. A control washout circuit and gain adjust feature, shown as the left remote box in figure 14b, also was available. Although various means of spoiler control, such as coupling spoiler deflection with stabilator position, were explored in a cursory manner, the method of control used for the detailed evaluations was the integration of spoiler deployment with throttle movement.

In order to accommodate the hydraulic servo actuation system, the servo electronics, and the data acquisition system, the vehicle was modified to accommodate a 50 amp, 24 volt electrical system and an engine-driven hydraulic pump capable of supplying a system pressure of 68-75 atm (1000-1100 lb/in^2). The rear seat was removed for installation of the spoiler drive mechanism, the electronic signal conditioning equipment, and a Honeywell Model 206 Visicorder. A manual trim interconnect system which adjusted stabilator trim tab setting as a function of spoiler deflection was installed, but it was found to be unnecessary and was not used. The simple device is visible in the right foreground of figure 14a.

Weight and size of the experimental spoiler system were not design considerations. Strength and flexibility, however, were critical to the success of the entire program. The spoilers, supporting electronic signal conditioning equipment, and data acquisition instrumentation added 1025 N (230.5 lb) to the empty weight of the basic aircraft; 440 N (99 lb) was the weight of the complete spoiler system including the mechanical actuation mechanism. While the system was not intended to be commercially viable, it represents aerodynamically a spoiler arrangement that could be applied to a general aviation aircraft.

Instrumentation

Data acquisition instrumentation consisted of the following components:

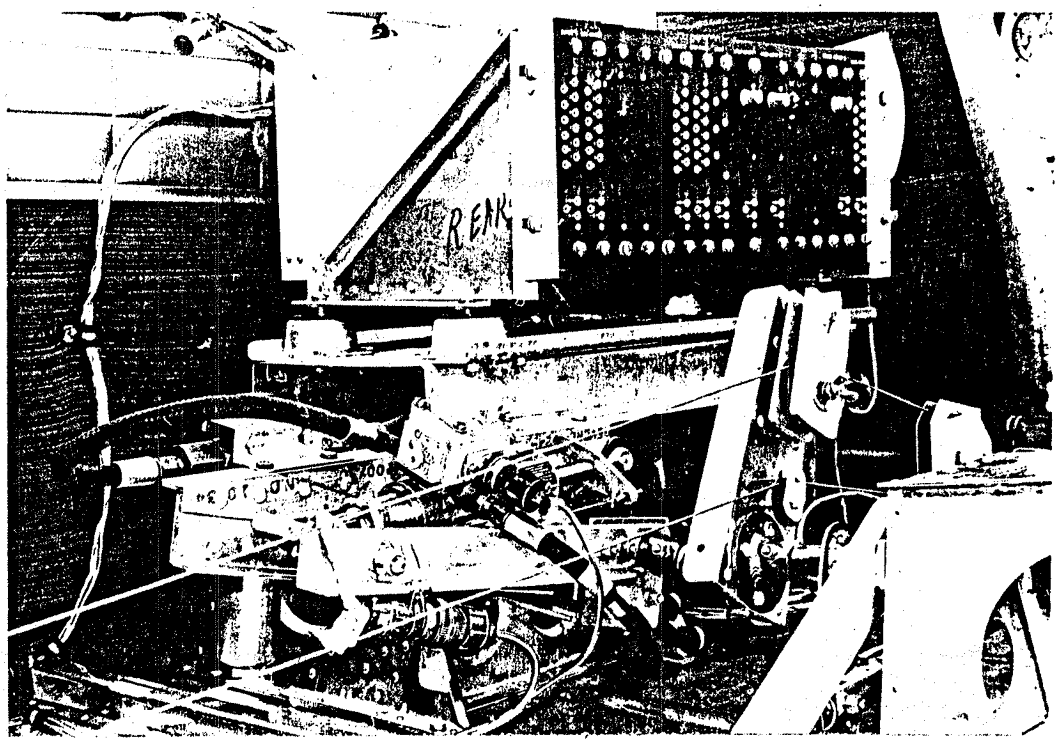


Figure 14a.- Hydraulic actuator and signal conditioning box

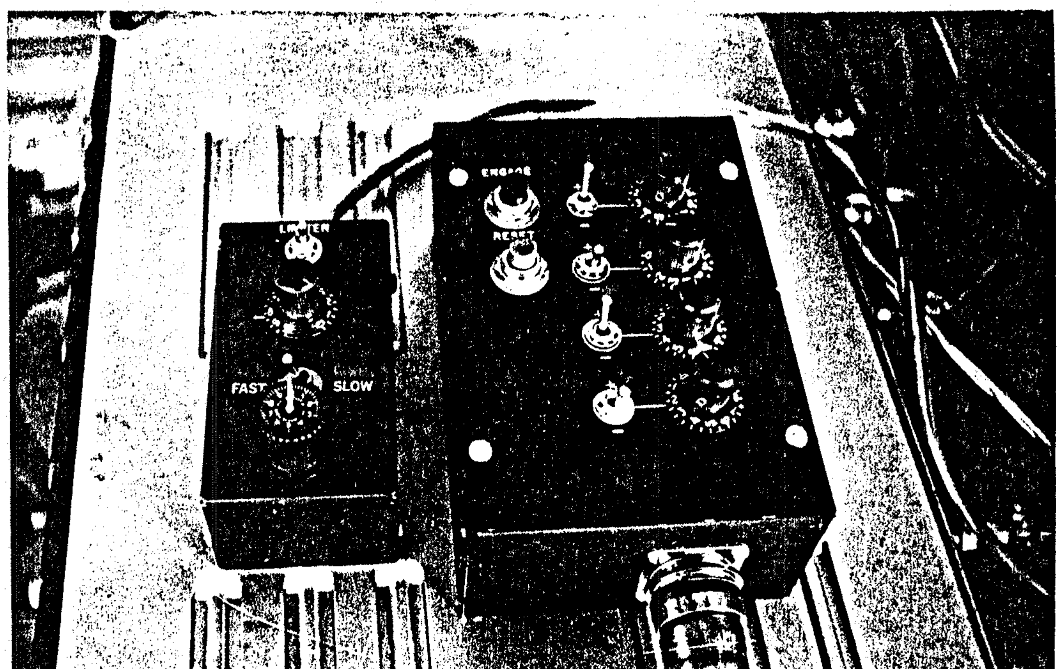


Figure 14b.- Remote gain adjust boxes

Pitch attitude vertical gyro
Pitch rate transducer
Angle-of-attack transducer
Airspeed transducer
Pressure altitude transducer
Servo accelerometer
Control position transducers for elevator, spoiler, and integrated controller
Stick force transducer
Mechanical spoiler control handle force transducer
12-channel Visicorder

In addition to these transducers and recording equipment, the aircraft's flight instruments consisted of a full blind-flying panel and a panel-type recording accelerometer.

Each transducer, as well as the aircraft's airspeed and altimeter, was calibrated at the initiation of the documentation flight tests. Spot calibrations also were made at various stages of the program to assure that no changes had occurred. In addition to bench checks for instrument error prior to installation, both the aircraft's airspeed system and the airspeed transducer were calibrated for total error (instrument plus position error) via the speed course method (ref. 25). Angle of attack also was calibrated in flight for position error.

Test parameters were recorded on a 24 VDC Honeywell Visicorder mounted in the aircraft. Where warranted, certain quantities such as time, pressure altitude, and outside air temperature were observed and recorded by the flight test engineer. Reduction of raw flight test data traces was done manually.

Drag Changes Due to Spoilers

The most basic and important characteristics of the spoiler configurations tested were their ability to change the flight path of the airplane. With idle power, the steady-state glide performance of the airplane, with various sets of spoiler plates fully open, is shown in figure 15 for flaps fully retracted, partly, and then fully extended. These data were obtained from direct observations of airspeed and rate of descent under the various conditions.

The flight path effectiveness of these spoilers is extremely high. Whereas the basic airplane with flaps down at approach speed simply cannot maintain a steady descent steeper than about 7°, the inboard or outboard sets individually increase the available γ_A to about 13°, and together they increase the descent capability to about 18°.

It is also clear from the curves of figure 15 that whereas a normal approach with the basic airplane would have about neutral

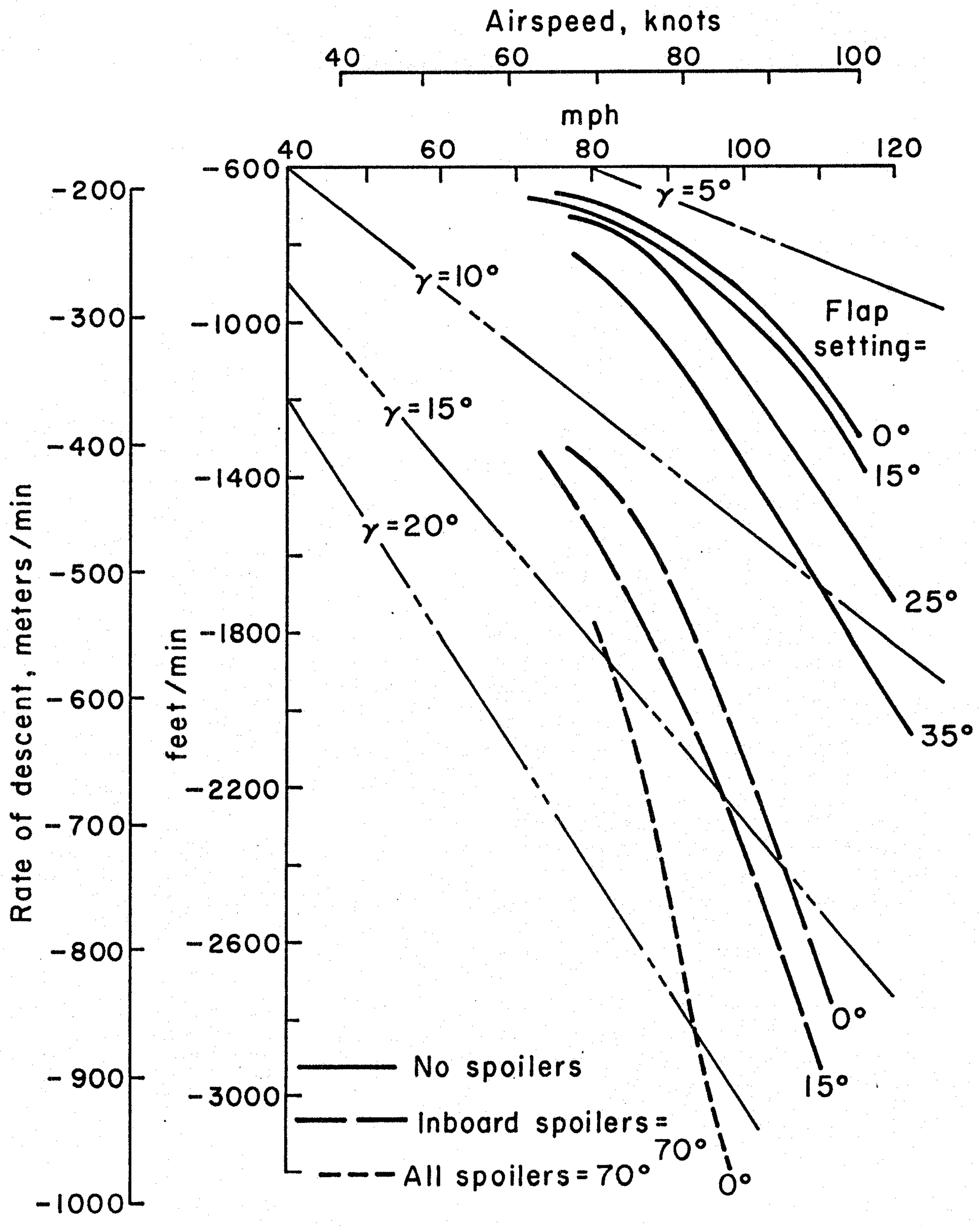


Figure 15.- Steady-state glide path performance; 10450 N (2350 lbs)

speed stability, $d\gamma/dV = 0$; with spoilers deflected, the speed stability is positive, $d\gamma/dV < 0$. This means that with the basic airplane on approach, the pilot cannot control steady-state glide path with wheel (stabilator) whereas he can with spoilers deflected. This, of course, is the matter discussed at some length in the section on experimental results.

The steady-state flight path polars of figure 15 have been reduced to apparent drag and lift coefficients and plotted in the usual way for drag analysis: C_D vs. C_L^2 . These drag polars, for the various cases, are shown in figure 16. No correction for propeller thrust or drag has been attempted. It is assumed that between various spoiler deflections and configurations thrust would be constant and not influence the spoiler characteristics deduced from these curves.

The zero-lift drag coefficient is shown separately in figure 17 for the various cases. These data have been reduced further to a change in drag coefficient based on spoiler projected (normal) area according to

$$\Delta C_{D_0} = C_{D_s} \frac{S_s}{S} \sin \delta_s$$

The results so obtained are shown in figure 18 where it is seen that $C_{D_s} = 2$ fits the points very well. This value agrees favorably with drag data presented in reference 20.

The apparent large drag increment, beyond what would be expected from flat plate drag alone, probably is due to wake, interference and load distribution effects. Tuft studies of the area around the spoilers indicate that the region of separated flow, with spoilers deflected, extends ahead of and to either side of the spoiler hinge line (fig. 5). Part of the observed drag increment would be separation (pressure) drag on the wing surface.

The slopes of C_D vs. C_L^2 curves are shown in figure 19 as a function of spoiler deflection. The scatter is considerable, but the trend is clear: induced drag increases with spoiler deflection. This presumably relates to distortion in the spanwise lift distribution due to spoilers. At any rate, the value $K_b = 0.054$, with spoilers closed, corresponding to a span efficiency factor, $e = 0.78$, is greatly increased by spoiler deflection. The factor e is correspondingly reduced to the order of 0.41.

Lift Changes Due to Spoilers

The action of the spoilers to reduce (spoil) wing lift is shown in figure 20 for the different configurations. The angle of attack is with respect to an arbitrary axis which is consistent for all the

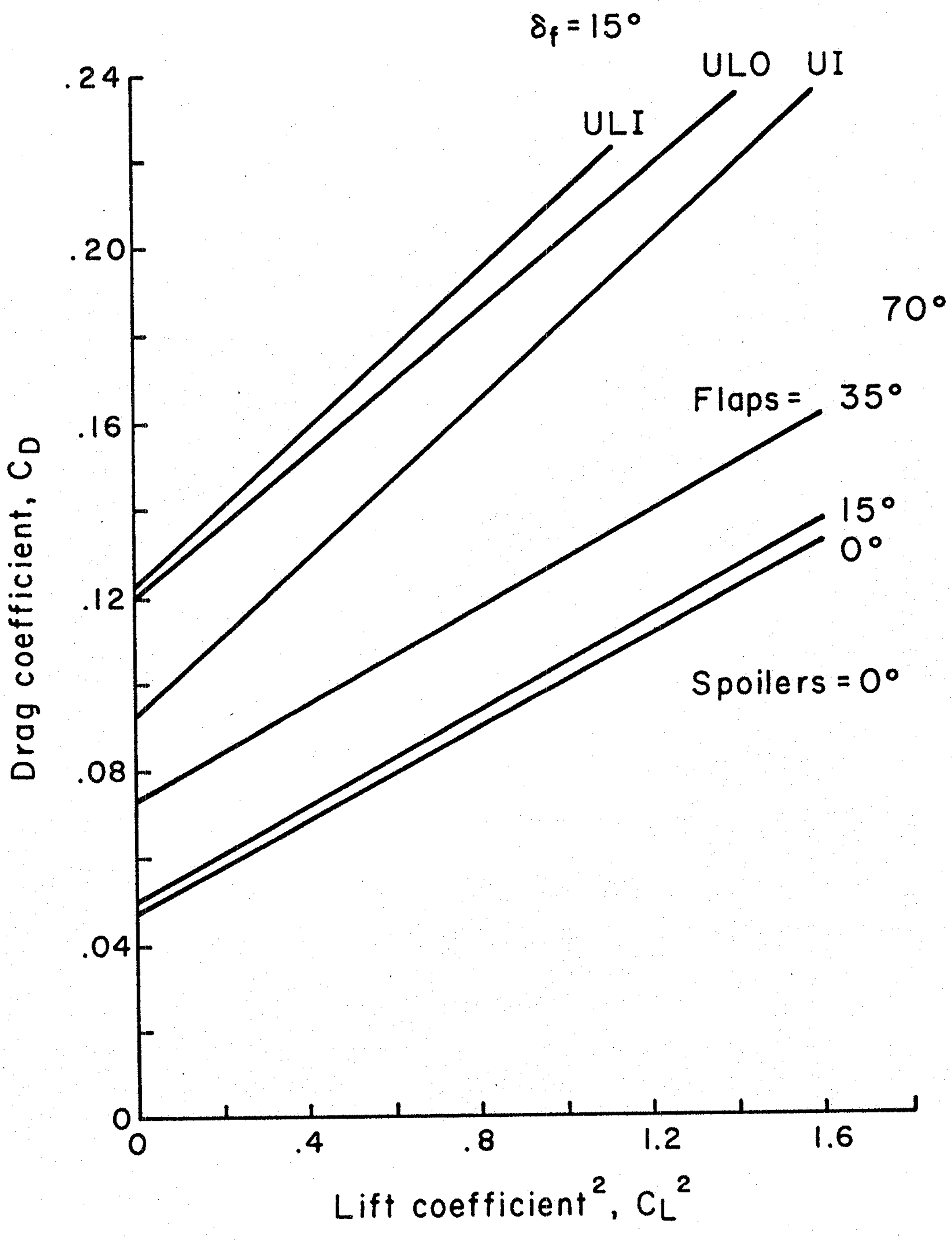


Figure 16.- Drag performance, C_D vs. C_L^2

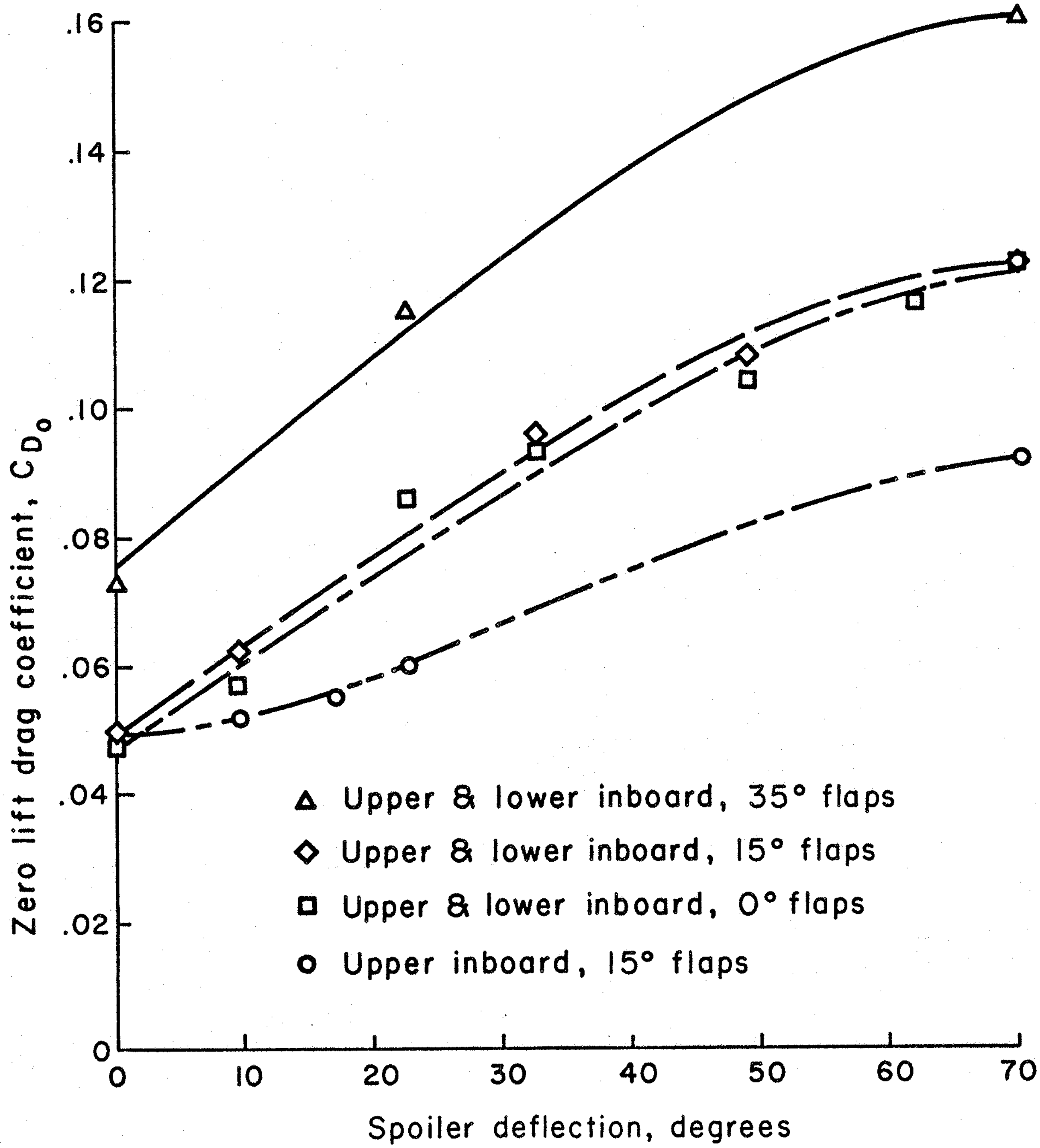


Figure 17.- Change in zero lift drag coefficient with configuration and spoiler deflection

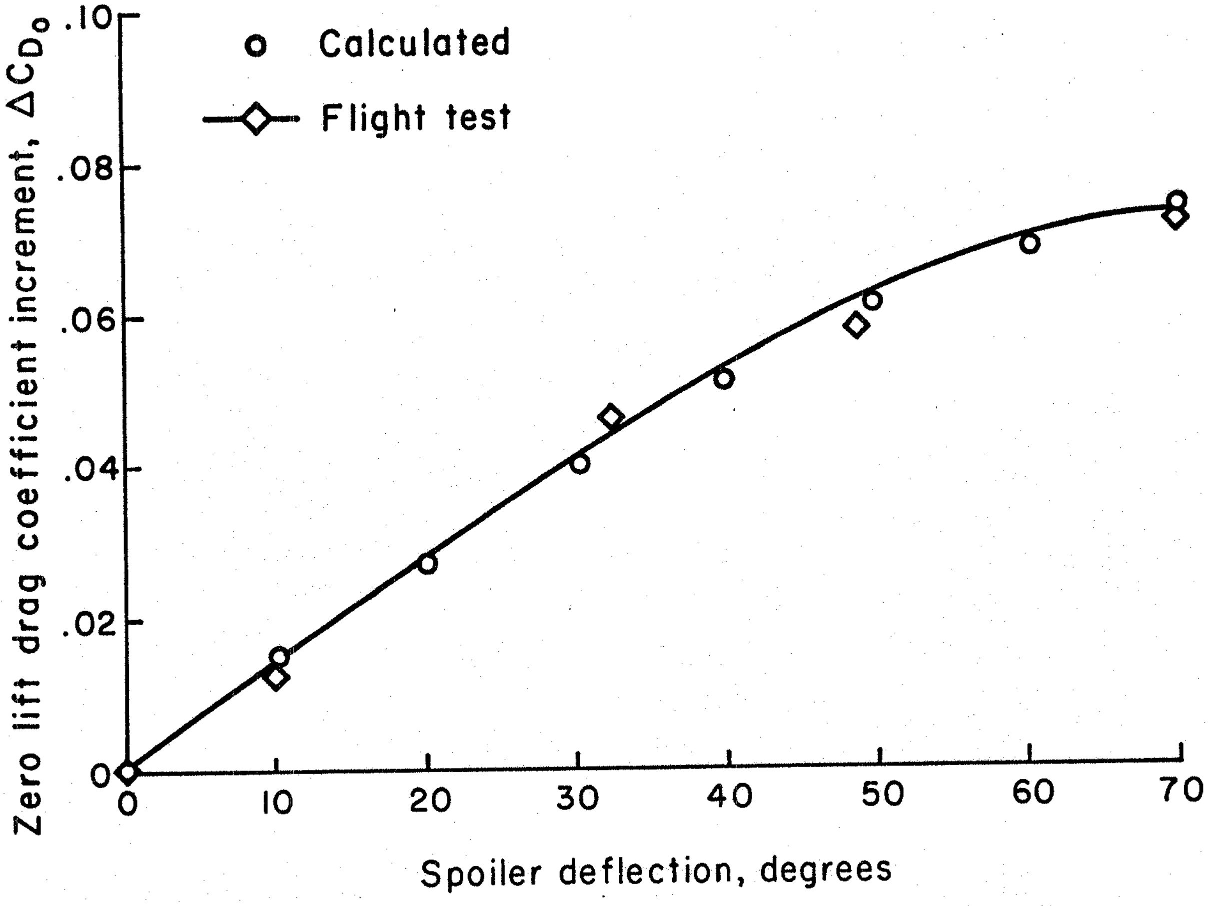


Figure 18.- Change in zero lift drag coefficient assuming $C_{D_S} = 2$

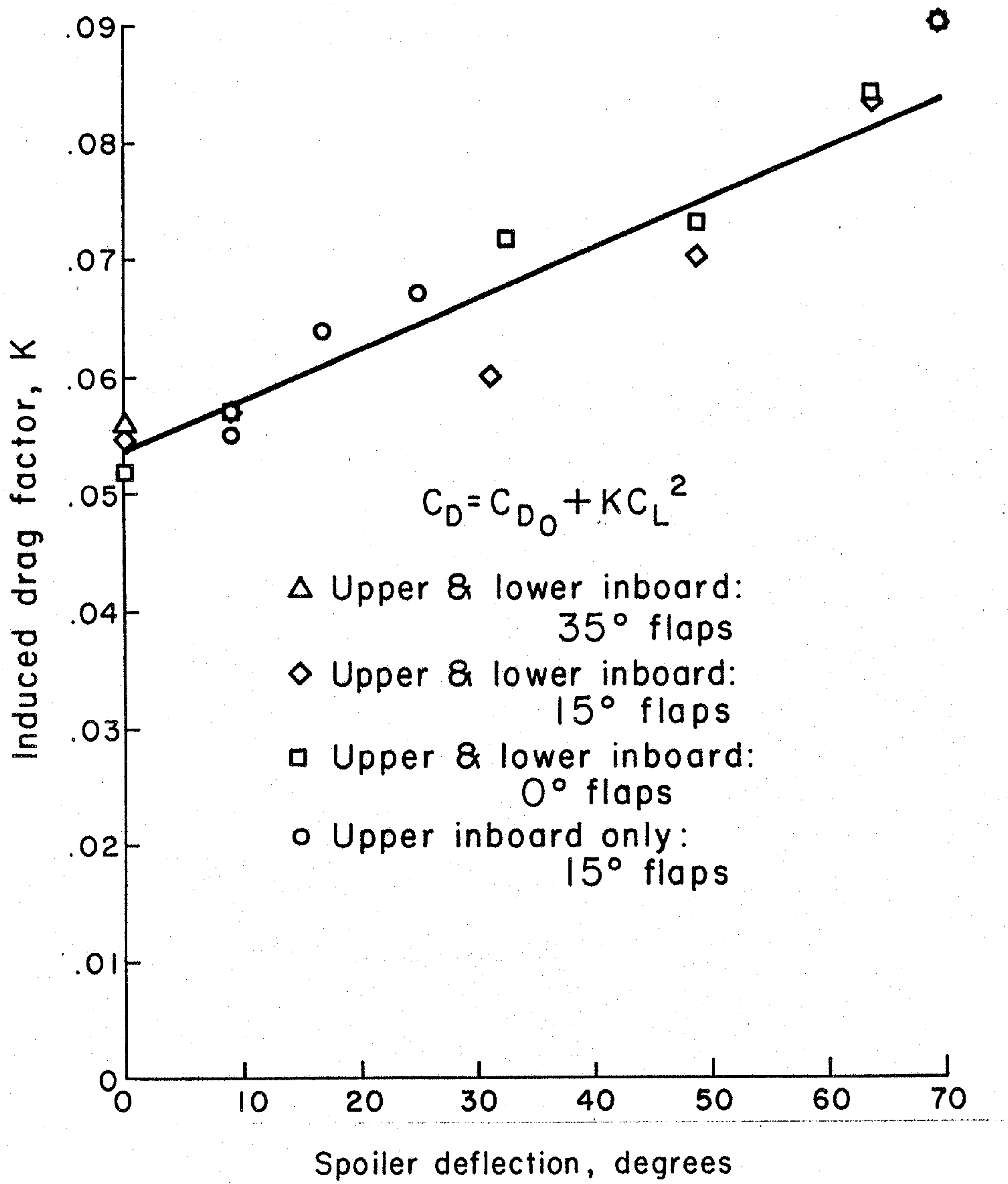


Figure 19.- Slope of C_L^2 vs. C_D curves for various configurations

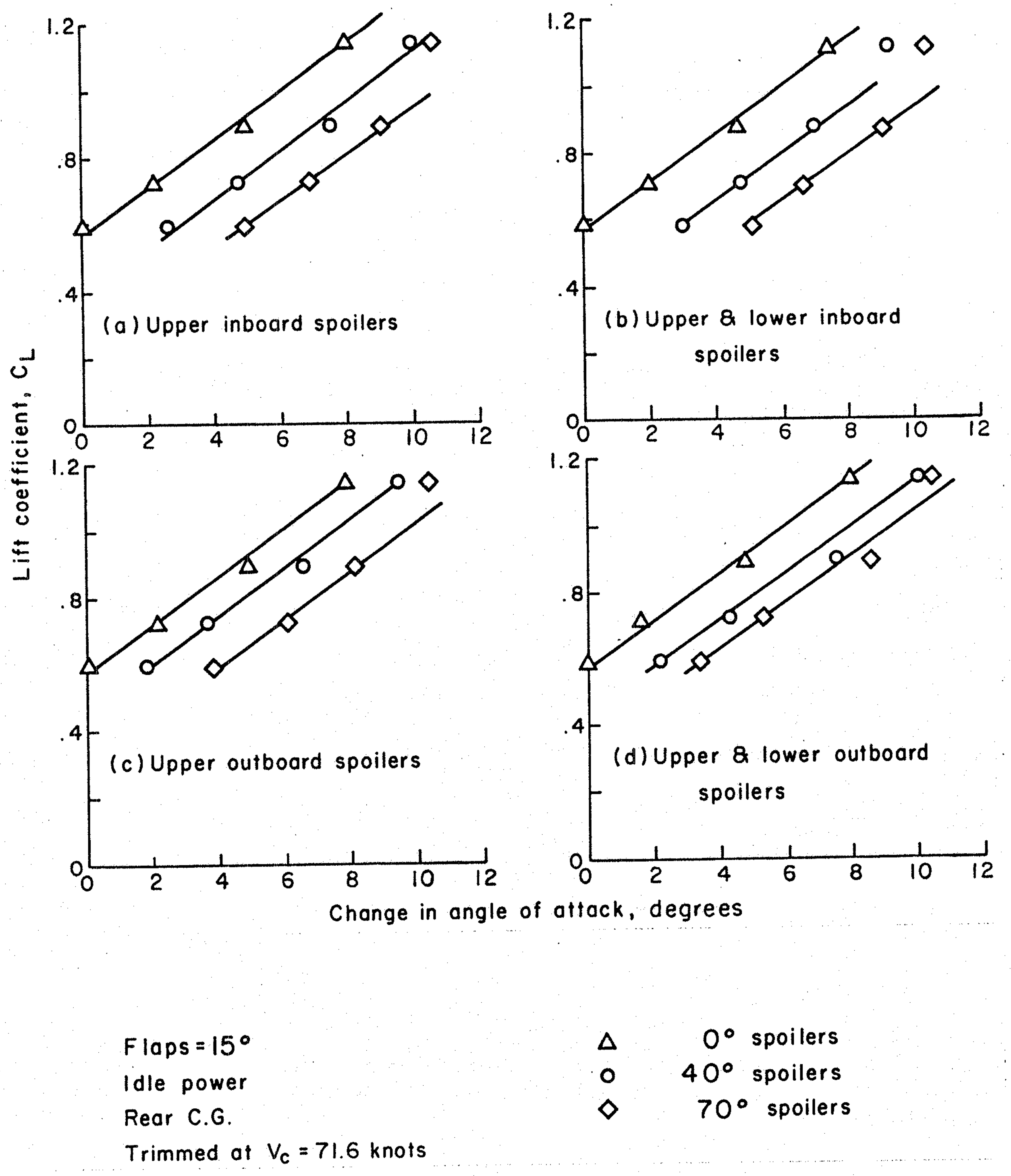


Figure 20.- Lift decrement, C_L vs. α

measurements, so that slopes and increments of C_L or α are meaningful.

The basic airplane appears to have a slope of lift-curve about $a_w = .073/\text{deg}$ (4.18/rad). This seems low compared to the classical

$$a_w = \frac{2\pi AR}{AR + 2}$$

of lifting line theory which would predict $a_w = 4.95/\text{rad}$ for this case. For the thick airfoil with flaps partly deflected, it may be reasonable.

The data appear to indicate that, in the unstalled range, the decrement of C_L due to spoilers is independent of α, and so the slope of lift-curve is independent of spoiler deflection. The decrements are about as presented in Table II.

TABLE II.- DECREMENT IN C_L DUE TO SPOILER DEFLECTION

Configuration	ΔC_{L_s} for $\delta_s = 70°$
Upper inboard	-.33
Upper and lower inboard	-.35
Upper outboard	-.22
Upper and lower outboard	-.22

These results suggest that the lift changes are due to the upper spoiler plates alone, and that the spoiling of lift is more effective in front of the flaps where the section lift coefficient is higher. These spoiler sets are individually 16% of span, and so it seems they spoil more than their local spanwise share of lift at a constant α. The ΔC_L's are larger than would be predicted by any simple rule based on strip theory. This has not been pursued in depth, and no rational explanation is currently available.

Stalling Speeds

Although stall speeds were, of course, increased by spoiler deflection, stall characteristics of the test aircraft were not changed appreciably by spoilers. Data for three spoiler deflections (0°, 40°, 70°), three flap settings (0°, 15°, 35°), and two power settings (idle, full) are presented with pilot comments in Appendix A. Standard techniques for determination of stalling speed were used (refs. 25, 26). The aircraft's center of gravity was at its rearmost position (29% mac) and the results are corrected for weight.

Corresponding to the stalling speeds tabulated in Appendix A, the decrements in $C_{L_{max}}$ due to spoiler deflection, of course, vary widely with flap deflection, power, and spoiler deflection. With idle power, the largest decrement is for full flap deflection and full spoiler deflection and corresponds to a reduction of $C_{L_{max}}$ from 2.23 to about 1.53. At part flap deflection (15°), the $C_{L_{max}}$ decrement is much smaller and is, in fact, comparable to the ΔC_L cited above for the unstalled range of angle of attack.

Longitudinal Control Effectiveness

The pitch control effectiveness C_{M_δ} has been determined from special flight tests. They were accomplished by trimming the airplane for steady flight at one CG position at the desired velocity and power; then, keeping speed and power unchanged, changing CG position and reading the increment of elevator position. In the test aircraft, the CG position change was accomplished by the passenger moving from front to rear position in the cabin. The corresponding change of moment of 1146 N-m (840 ft-lb) was determined by weighings on the ground and, for a gross weight of 10450 N (2350 lb), corresponded to a CG shift of 8.23% mac. The control effectiveness was calculated according to the following equation:

$$C_{M_\delta} = - C_L \frac{.0823}{\Delta\delta_e}$$

Two power settings (idle and full) and three flap positions (0°, 15°, 35°) were tested for 0° spoiler deflection and full (70°) spoiler deflection. The results are tabulated in Table III. With the exception of the full (35°) flap configuration, variations of C_{M_δ} are within ±10% of the basic 0° value and are considered to be insignificant. It may be inferred that at least for the configurations of principal interest the tail is reasonably clear of the spoiler wake. With full flap deflection, a 20% reduction of C_{M_δ} is indicated, but it was not enough to cause any problems of trim or control in the flight conditions investigated.

Static Longitudinal Stability

The basic longitudinal stability has been determined from longitudinal control angle to trim in steady flight at different speeds (lift coefficients). The data are shown graphically in figure 21 for various spoiler configurations and deflections. Since only the slopes are of interest, the abscissa is an increment from the starting value for each configuration. It is seen that the data can be faired consistently by straight lines and the static stability can then be calculated by the formula

TABLE III.- PITCH CONTROL EFFECTIVENESS, C_{M_δ}

	0 FLAPS			
	0 SPOILERS		70° SPOILERS	
	Idle Power	Full Power	Idle Power	Full Power
Upper inboard	-.042	-.049	-.041	-.045
Upper and lower inboard	-.042	-.049	-.042	-.054
Upper outboard	-.042	-.049	-.044	-.047
Upper and lower outboard	-.042	-.049	-.047	-.050
	15° FLAPS			
Upper inboard	-.043	-.050	-.041	-.051
Upper and lower inboard	-.043	-.050	-.043	-.048
Upper outboard	-.043	-.050	-.042	-.050
Upper and lower outboard	-.043	-.050	-.042	-.049
	35° FLAPS			
Upper inboard	-.048	-.053	-.040	-.046
Upper and lower inboard	-.048	-.053	-.041	-.048
Upper outboard	-.048	-.053	-.040	-.052
Upper and lower outboard	-.048	-.053	-.040	-.052

$$\frac{dC_M}{dC_L} = \frac{d\delta_e}{dC_L} \times C_{M_\delta}$$

Results are tabulated in Table IV for the cases tested. Power (idle) and flap setting (15° down) are the same for all conditions tested. The values are for the rear CG position (approx. 29% mac).

The stability levels are essentially unaffected by spoiler deflection, except for the inboard configurations which show a sizeable increase in stability at maximum (70°) spoiler openings. This effect, amounting to almost 10% mac of equivalent CG shift, has not been explored and the explanation for it is not available.

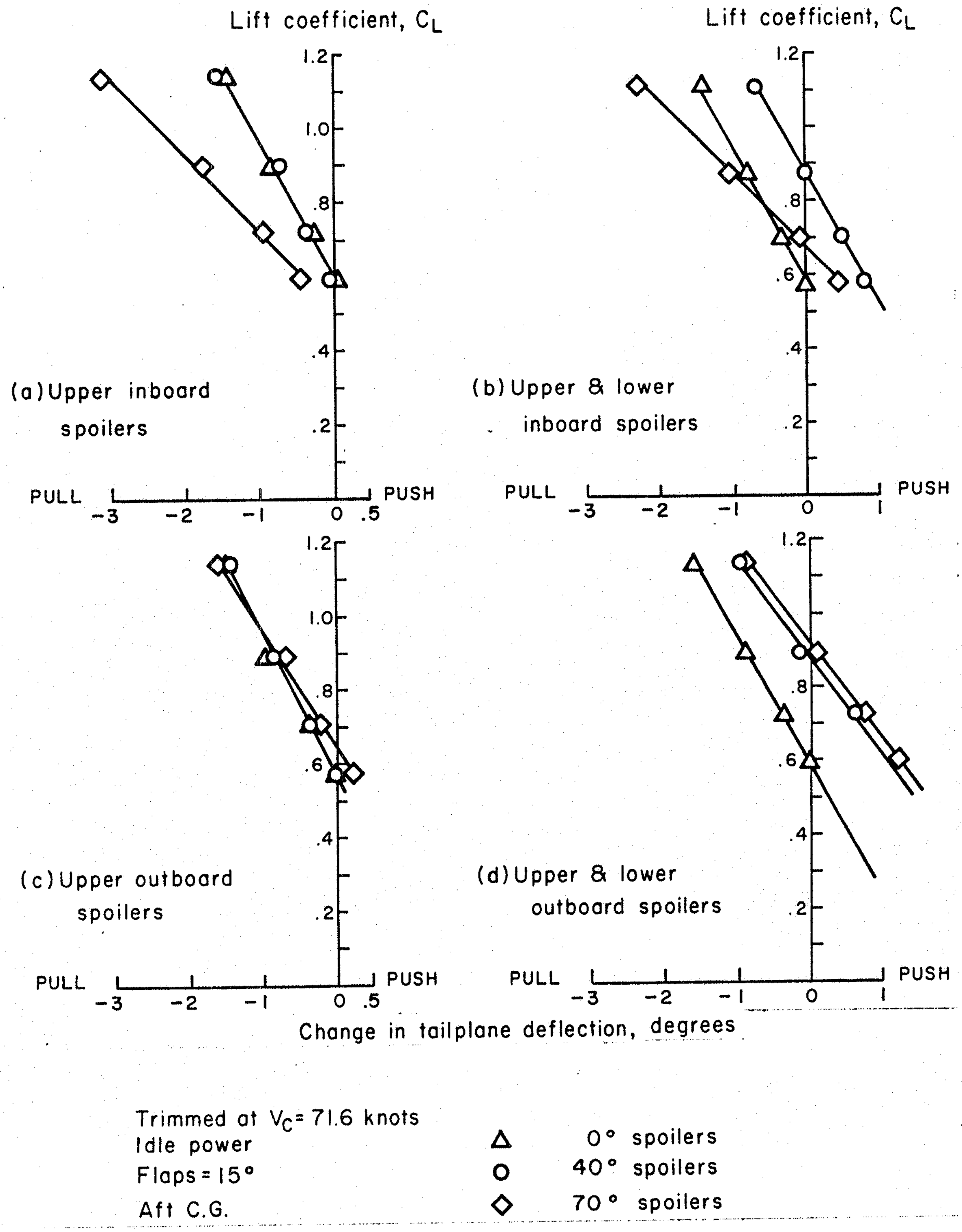


Figure 21.- Static longitudinal stability, C_L vs. $\Delta\delta_e$

The dC_M/dC_L values of Table IV are for straight steady flight at 1g idle power. In these flight conditions, there should be no strong slipstreams or interacting power effects, and it is reasonable to assume $\partial C_M/\partial V = 0$. The dC_M/dC_L is then directly convertible to $\partial C_M/\partial \alpha$; hence, maneuver margin and short-period frequency may be deduced.

TABLE IV.- STATIC STABILITY, dC_M/dC_L

(Idle power, Flap $\delta_f = 15°$, $\bar{x}_{cg} \sim 29\%$ mac)

Spoiler, δ_s →	0°	70°
Upper inboard	-.120	-.203
Upper and lower inboard	-.120	-.213
Upper outboard	-.120	-.130
Upper and lower outboard	-.120	-.155

At constant speed, the increment of static stability due to pitching is

$$\Delta\left(\frac{dC_M}{dC_L}\right) = \frac{C_{M_q}}{4\mu}$$

Although C_{M_q} , the damping-in-pitch, cannot be evaluated directly from the flight data, it can be estimated well enough from C_{M_δ}, according to $C_{M_q} \doteq 2(\ell_t/\bar{c})C_{M_\delta}$. In this, two opposite effects are implicitly assumed to cancel: first, a decrement due to the leading tab which works for C_{M_δ} but not for C_{M_q} ; second, an increment for the fuselage and wing contributions to C_{M_q} which are not accounted for in the formula. Using the basic $\delta_s = 0$ value for C_{M_q} ,

$$C_{M_q} = -17.0/\text{rad}$$

and for $\mu = 46.8$,

$$\Delta\left(\frac{dC_M}{dC_L}\right) = -\frac{17.0}{4 \times 46.8} = -.091$$

The maneuver point may then be estimated by subtracting the total dC_M/dC_L level (the sum of the value from Table IV and -.091 from the CG position, $\bar{x}_{cg} = 29\%$ mac. Its position is about 50% mac, except for the cases of full deflection of the inboard configurations where a rearward (stabilizing) shift is present.

Trim Changes

The trim changes due to spoiler openings are presented in Table V in terms of change in tailplane angle (incidence) to trim in steady, 1g flight at V_i = 74 knots (85 mph). In the second row of each division for a spoiler configuration, increments of control-to-trim are given for changes of flap settings (from $\delta_f = 0$) with spoilers closed and power off. In the other rows and columns, the additional increments for changes of spoiler deflection and power are given. The various interacting effects can be seen readily.

First, all these trim changes are small. In terms of wheel force at V_i = 74 knots (85 mph), one degree of control angle corresponds to only 7.8 N (1.75 lb). The accuracies of the measurements can be judged by comparing entries for the various configurations in the rows "$\Delta\delta$ for δ_f" and "$\delta_s = 0$." They should, of course, be the same for all configurations.

For the inboard spoiler configurations, the pilots preferred an intermediate flap setting, $\delta_f = 15°$, for its overall advantages. These include a favorable nose-down attitude for approach, negligible trim changes due to spoiler deflection and/or power with relatively little flap drag and good $C_{L_{max}}$. This all adds up to an especially favorable wave-off characteristic, discussed later. The full flap setting, $\delta_f = 35°$, which looks good in the table, exhibited the disadvantage of buffeting at full spoiler opening and high flap drag which is difficult to get rid of in wave-off.

In the table, a positive number indicates a positive control increment for trim and a wheel-forward control angle to balance a nose-up pitching moment. The upper inboard configurations therefore exhibit a nose-down tendency with opening spoilers, whereas the upper and lower inboard sets exhibit the opposite for $\delta_f = 0$ and essentially neutral for $\delta_f = 15°, 35°$.

The Phugoid Mode of Dynamic Stability

The phugoid characteristics have been observed in flight records (fig. 22) of transient response to spoiler movements and other disturbances. The period at V_i = 74 knots (85 mph) is quite uniform and independent of configuration and spoiler deflection at about 20 seconds. This compares to the approximate expression (ref. 24)

$$P = .137V = 17 \text{ sec} \quad (V \text{ expressed in ft/sec})$$

TABLE V.- TRIM CHANGE INCREMENTS OF CONTROL ANGLE
(Degree of Stabilator Angle, Positive Wheel Forward)

a) Upper inboard configuration

δ_f =	0		15°		35°	
$\Delta\delta$ for δ_f	0		+.55°		+1.0°	
Power	Idle	Full	Idle	Full	Idle	Full
δ_s = 0	0	+.2	0	+.05	0	+.25
40°	-.1	+.15	0	+.05	-.4	-.45
70°	-1.5	-1.3	-1.05	-.95	-1.35	-1.45

b) Upper and lower inboard configuration

δ_f =	0		15°		35°	
$\Delta\delta$ for δ_f	0		+.50°		+1.0°	
Power	Idle	Full	Idle	Full	Idle	Full
δ_s = 0	0	+.1	0	+.25	0	+.35
40°	+.3	+.5	+.8	+.8	+.5	+.6
70°	+.9	+1.0	-.2	-.1	0	-.1

c) Upper outboard configuration

δ_f =	0		15°		35°	
$\Delta\delta$ for δ_f	0		+.55°		+.90°	
Power	Idle	Full	Idle	Full	Idle	Full
δ_s = 0	0	+.2	0	+.2	0	+.35
40°	+.15	+.3	-.05	+.2	+.15	+.40
70°	-.20	-.1	+.08	+.15	+.35	+.50

d) Upper and lower outboard configuration

δ_f =	0		15°		35°	
$\Delta\delta$ for δ_f	0		+.60°		+.90°	
Power	Idle	Full	Idle	Full	Idle	Full
δ_s = 0	0	+.3	0	+.15	0	+.25
40°	+.75	+.8	+.80	+.80	+1.0	+1.0
70°	+.15	+.6	+.95	+.65	+1.2	+1.2

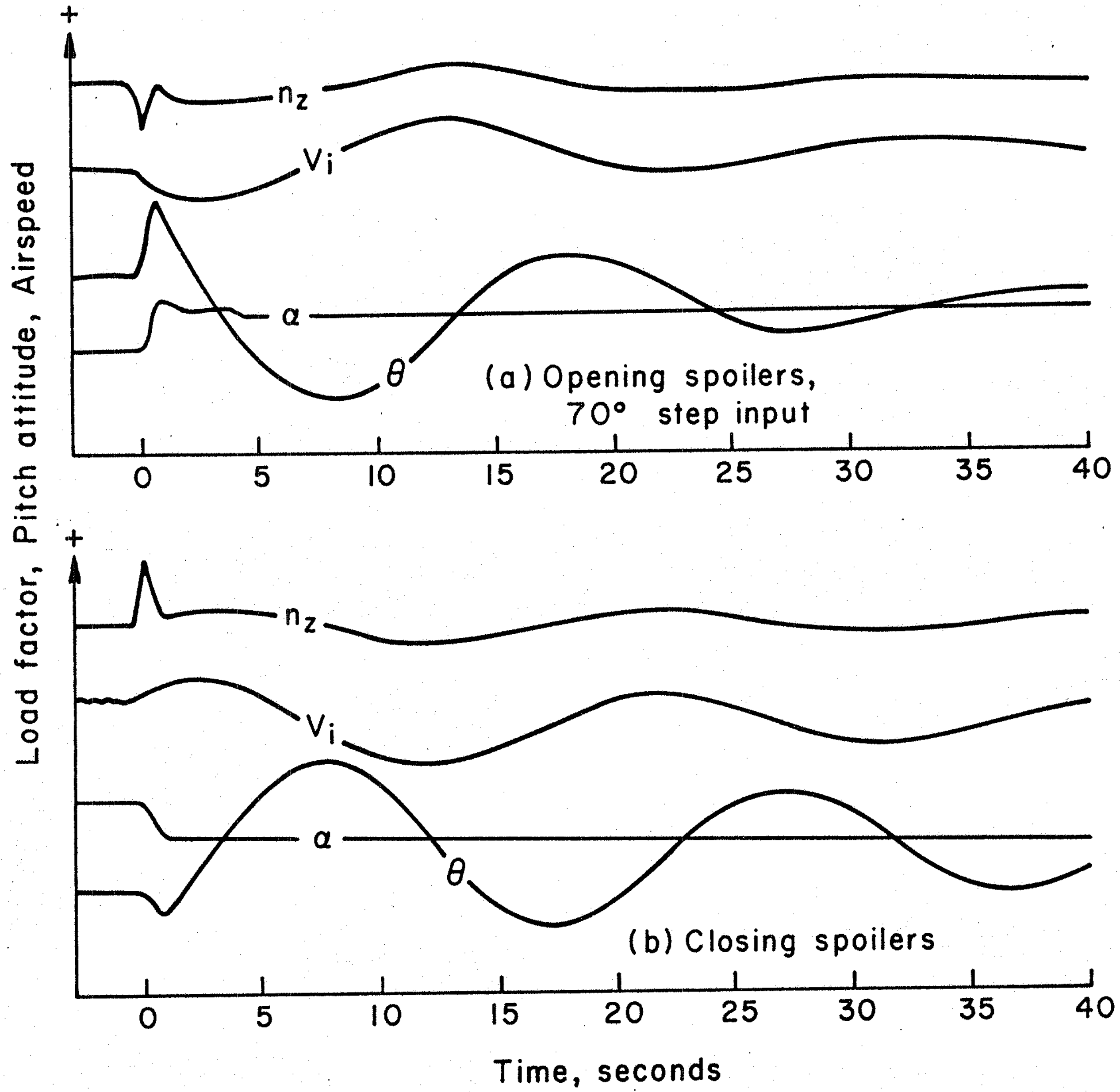


Figure 22.- Dynamic response characteristics

and suggests that the velocity stability derivative $\partial M/\partial V$ is indeed small, as has been previously assumed.

The phugoid damping is, of course, affected by drag coefficient and, hence, by spoiler opening. In the clean configuration (fig. 22), the mode is very lightly damped; with full spoiler deflection, the damping is somewhat heavier.

Short-Period Mode

The short-period mode of longitudinal motion, as in most airplanes of the type, is very heavily damped. This makes it very difficult to observe and to test directly for frequency and damping ratio. The undamped natural frequency is estimated from the "maneuvering" stability discussed in the Static Longitudinal Stability section. Using the typical stability level from Table IV and converting into M_α by using $I_y = 1370$ slug-ft^2 and $C_{L_\alpha} = 4.0$ (from C_L vs. α data, fig. 20),

$$M_\alpha = \frac{qS\bar{c}}{I_y} C_{L_\alpha} \frac{dC_M}{dC_L}$$

$$= -\frac{18.5 \times 146 \times 4.4}{1370} 4.0 \times .123 = -4.3$$

Finally,

$$\omega_0 = \sqrt{-M_\alpha - \frac{L}{V} M_{\dot{\theta}}} = \sqrt{4.3 + 1.25 \times 2.60}$$

$$= 2.7 \text{ rad/sec}$$

This, of course, is for the CG position of Table IV ($\bar{x}_{cg} \sim 29\%$ mac) and for the approach speed of $V_i = 74$ knots (85 mph). For the spoiler configurations showing an increase of stability, the frequency would be somewhat higher.

The damping ratio can be found from the total damping which consists of three parts due to pitch damping, angle-of-attack damping, and vertical damping. The first is (using the previous estimate for C_{M_q})

$$M_{\dot{\theta}} = \frac{\bar{c}}{2VI_y} \times qS\bar{c}C_{M_q}$$

$$= -\frac{18.5 \times 146 \times 4.4^2}{2 \times 125 \times 1370} \times 17.0 = -2.60$$

The second is roughly $d\varepsilon/d\alpha$ times $M_{\dot\theta}$, or

$$M_{\dot\alpha} = -\ .4 \times 2.60 = -\ 1.04$$

The vertical damping is

$$\frac{L_\alpha}{V} = \frac{g}{VC_L}\ a_w = \frac{32.2}{125 \times .82} \times 4.0 = 1.25$$

The total damping is

$$2\zeta\omega_0 = \frac{L_\alpha}{V} - M_{\dot\alpha} - M_{\dot\theta} = 1.25 + 1.04 + 2.60 = 4.95$$

for

$$\zeta = \frac{4.95}{2 \times 2.7} = .92$$

Control Effectiveness Derivative

The longitudinal control effectiveness follows directly from the nondimensional form by

$$M_\delta = \frac{qS\bar{c}}{I_y}\ GC_{M_\delta}$$

$$= -\ \frac{18.5 \times 146 \times 4.4}{1370} \times 2.35 \times .0434$$

$$= -\ .885\ \text{rad/sec}^2\text{/in.}$$

Lift Slope (Vertical Damping) Derivative

The lift slope is based on the previously cited estimate of C_{L_α} . It may be given as

$$\frac{L_\alpha}{V} = 1.25\ \text{sec}$$

or

$$n_{z_\alpha} = \frac{V}{g}\left(\frac{L_\alpha}{V}\right) = \frac{125}{32.2} \quad 1.25 = 4.85\ \text{g/rad}$$

$$= .085\ \text{g/deg}$$

The foregoing parameters of the short-period mode all relate to the pitch attitude loop of the pilot-vehicle system. They are, by any published standards, entirely favorable, as would be expected for an airplane of the type.

Response to Spoiler Deflection

Most of the foregoing parameters and characteristics are visible in the airplane responses to abrupt spoiler deflections. Two responses to step-like spoiler motions are shown in figure 22. In these, the initial responses relate to the trim changes. There is first an abrupt change of lift, followed by a pitch (and angle of attack) adjustment in the short-period mode response to the pitching moment change. These details are evident in the normal acceleration traces where they are seen to be of opposite sign in both cases. The first change is a loss of lift due to the spoiler opening, which is approximately cancelled by the subsequent increase in angle of attack caused by a nose-up pitching moment.

The transient jump of lift (negative) and the following short-period mode response involving an increase in angle of attack and lift to a nearly neutral quasi-steady value corresponds exactly to the nearly neutral overall trim characteristics noted under Trim Changes.

If the net trim change in the initial transient were zero, the airplane would be in moment and lift equilibrium at the end of the short-period response without additional control action. There is, however, the pulse of downward acceleration whose area (cross-hatched in the sketch on page 24) represents a change of flight path angle γ . If this exactly matched the $\Delta\gamma$ for the drag increase due to spoiler opening, then the condition at the end of the short-period transient would present drag equilibrium also, and there would be no tendency for a speed and flight path oscillation to occur. This, of course, is the matter of phugoid excitation.

The formulas of the section on Aircraft Response can be applied here, using parameters of the airplane and the spoilers developed above. All the terms involved in the short-period, steady state γ formula are available and indicate roughly (UI configuration, full deflection at 75 knots (86 mph))

$$\text{short period } \Delta\gamma_{ss} = -\,2.8 \text{ deg}$$

The final steady-state γ changes have been shown graphically (fig. 15) or they can be estimated using the formulas of the Aircraft Response section and the derived parameters. The values are larger (up to about twice) the above, and so some phugoid oscillations and velocity transients should be expected.

It can indeed be seen in the traces of figure 22 that the "pulse" of normal acceleration is not so big as to provide enough γ change. The phugoid is excited and a speed oscillation does occur. However, the resulting oscillations of speed and flight path are apparently easy for the pilot to damp out, and they do not appear to be much of a factor in his evaluations. The phugoid oscillations of the two cases of figure 22 exhibit somewhat different damping, as they should for different spoiler openings and drag levels.

CONTROLLER EVALUATIONS

Several different spoiler control concepts were tried experimentally with a view towards defining acceptable controller characteristics and operating procedures. The candidate schemes were either of the throttle-integrated (or semi-integrated) controller or of the separate controller variety. As discussed in Controller Considerations, it was felt that the integrated controller system, wherein spoiler action is blended with power changes, would offer a straightforward approach to the problem of taking maximum advantage of the spoiler aerodynamics without increasing pilot workload. On the other hand, it was appreciated that the integrated controller would generally be more complex and difficult to mechanize than the separate controller, so several forms of the latter were selected in order to study the problems of handling an additional cockpit function.

Qualitative evaluations of such general factors as ease of operation and potential for confusion or wrong action were of primary concern; in addition, other parameters such as the power setting at which the spoilers were deployed, idle power rate of descent, and controller sensitivity were varied over a considerable range in order to find the most favorable operating points.

The standard push-pull throttle control of the basic airplane was replaced by a quadrant-style unit which could be readily modified to accommodate different styles of spoiler controller. The modified throttle system turned out to have nearly linear rate of descent vs. travel characteristics in the range of approach power settings, with a sensitivity of about 619 m/sec/cm (800 ft/min/in.). The friction force could be varied, but the average value in normal use was about 4.45 N (1 lb).

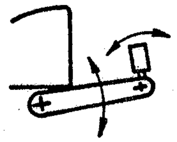
Results of the controller evaluations are discussed below.

Separate Controllers

Three separate controller variations were evaluated during the testing.

Throttle-like controller.- This controller resembled a push-pull-type throttle controller and was located approximately one foot below the modified throttle quadrant. The full-forward position corresponded to zero spoiler deflection; pulling the controller aft extended the devices.

Double-jointed controller.- The double-jointed controller was articulated from the instrument panel and allowed one-hand operation of throttle and spoilers but not in an integrated manner. As indicated in the sketch below, vertical motion of the arm controlled spoilers while a fore-and-aft wrist motion worked the throttle.



Collective-like controller.- A 53.3 cm- (21 in.) long controller resembling a helicopter collective control was evaluated. With the spoilers closed, the handle, which was located between the seats, rested at a 60° upward angle; with spoilers fully deployed, it was nearly horizontal. A spring-loaded latch could be used to hold the spoilers in any one of six different positions.

Operating characteristics.- For all the separate controllers, simultaneous control of the spoilers and the engine presented special problems. Coordinating power changes with spoiler deflection had to be accomplished manually and, in those cases where the spoiler handle and the throttle handle were physically separated, a lag resulted as the pilot switched his hand from one to the other.

The question of what power setting to use for initial spoiler deployment was evaluated for the separate controllers, and it was concluded that the most favorable condition was idle power. The pilots found that the workload involved in manually coordinating power with spoilers was objectionable, and they opted for a constant-power setting, high approach technique which could be controlled effectively with spoilers alone. Under these circumstances, any engine power at all detracted from the needed "go-down" capability and necessitated an additional action of closing the throttle during the landing rollout.

High and low limits on spoiler control sensitivity were determined. For sensitivity approaching 1394 m/min/cm (1800 ft/min/in.), precision approach control was difficult, and over-controlling during the flare and touchdown was likely. Very low sensitivities, in the neighborhood of 155 to 232 m/min/cm (200 to

300 ft/min/in.), were objectionable due to large controller motions and, if the operating force gradient was high (greater than 5.2 to 7.0 N/cm (3 to 4 lb/in.)), due to large forces.

Controllers Integrated with the Throttle

The important variations of this form of controller may be described briefly as follows.

Single-lever controller.- In this case, the pilot was given a single throttle-like lever which, at some point in its rearward travel from the full power position, blended spoiler deployment with power reduction. In general, the spoilers would not be fully opened at the idle power point, but additional rearward motion of the lever was available to achieve full deployment. In the pre-idle range, only normal throttle friction was felt, but in the post-idle range, a spring provided a force gradient.

Latching semi-integrated controller.- This also was a single lever, throttle-like control which was used more or less in the integrated style of the previously described device, except that a thumb-operated latch was provided which enabled spoiler control to be exercised independently of throttle control (hence the identification as a "semi-integrated" controller). The unlatching action was mandatory for spoiler deployment into the post-idle large deflection range. The friction level remained constant for all handle positions.

Split-handle semi-integrated controller.- In this variation, shown in figure 23, two throttle-like levers were placed closely adjacent, the left side operating the engine and the right side the spoiler system. They were grasped with one hand and normally were moved together, giving combined engine and spoiler operation as in the fully integrated single-lever case. However, when additional spoiler was desired, the right-hand lever could be moved independently. The handle splitting operation took place against a spring-supplied force gradient; the spoiler lever could be moved to the rear of the throttle lever but not ahead of it due to a physical stop on the spoiler lever.

Operating characteristics.- Typical operating characteristics of the spoiler-equipped aircraft with an integrated-style control are shown in the sketch. The blending of spoiler with power begins at a throttle position a little aft of that needed for level flight at the normal approach speed and continues to the idle power point. Moving the controller further aft deploys additional spoiler up to the maximum available.

With favorable values for the indicated parameters, glide path control is effective and natural. Modulation of the spoiler/throttle controller during the flare and touchdown is also effective and easy,

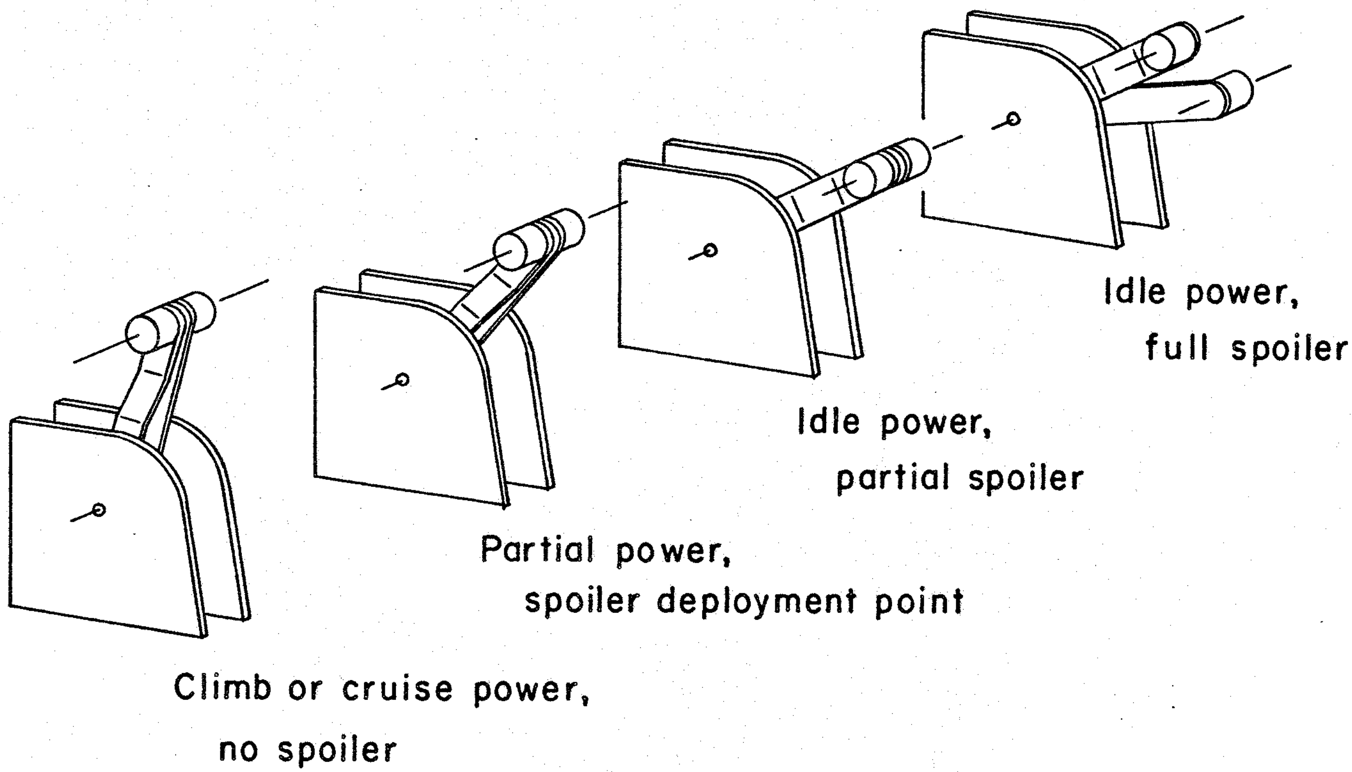
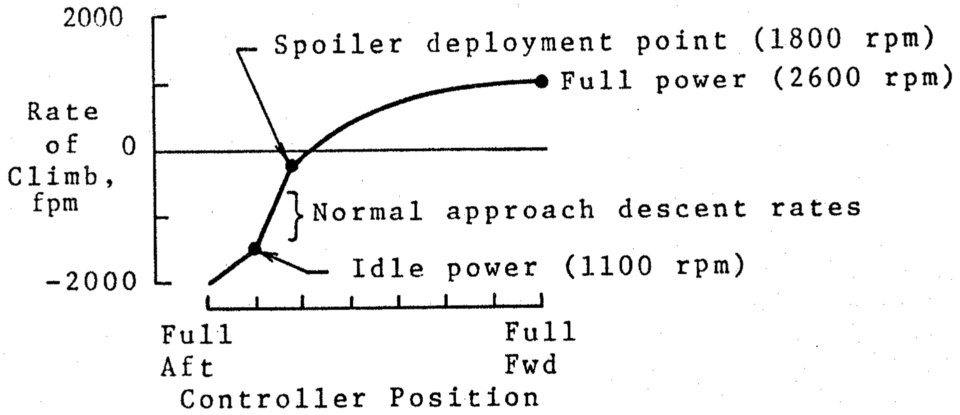


Figure 23.- Split-handle semi-integrated controller



allowing any floating tendencies to be suppressed. Unfavorable values, on the other hand, tend to inhibit effective and full use of the spoilers. The various factors involved were investigated in a series of special evaluations covering spoiler deployment point and controller sensitivity.

The evaluation pilots indicated a preference for smooth, near-linear response to the controller over the 800 to 1400 fpm descent range used for normal approaches and landing flare operations. This was achieved by avoiding continuous operation in the neighborhood of the spoiler deployment point, where there was a small but distracting pitch disturbance associated with small spoiler openings,* or across the idle power plant, where a change in sensitivity occurred due to the additive effects of power and spoiler and where a spring force gradient was encountered.

The most favorable results for the complete landing task were obtained for initial spoiler deployment between 1800 and 2000 rpm, the principal consideration being the aforementioned controller linearity. Near-idle deployment points required continuous coping with both the small opening aerodynamic nonlinearities and the abrupt change in operating force. Higher power deployments resulted in entering the flare with uncomfortably high power which caused pitch control to be abnormally sensitive.

For operation at power settings above idle, the most favorable controller sensitivity was found to be in the range from 852 to 1161 m/min/cm (1100 to 1500 ft/min/in.) of controller motion. Sensitivity in the neighborhood of 1394 m/min/cm (1800 ft/min/in.)

*This is somewhat configuration-dependent; the small opening nonlinearity was found to be much smaller with a later configuration using spoilers located further outboard.

was too high to allow precision control on approach and inhibited spoiler use in the flare due to apprehension about overcontrolling. At values lower than 852 m/min/cm, the pilots found themselves having to operate across the idle power point with its distracting change of sensitivity and force.

At power settings below idle, controller sensitivity in the range 387 to 619 m/min/cm (500 to 800 ft/min/in.) was found to be satisfactory. An important factor on the low sensitivity side was the amount of force required for full spoiler deployment during rollout. The figure of 387 m/min/cm is associated with a force gradient of 6.56 N/cm (3.75 lb/in.); this could probably be reduced for lower force gradients.

Force gradients by themselves were not limiting factors, but the combination of low sensitivity and high force gradient in the post-idle range was unfavorable.

Controller Comparisons

Although all of the controllers tested were in a sense workable, the integrated or semi-integrated types proved to be notably better than the separate types. This is illustrated in Table VI which offers a comparison between the various controllers for approach and landing. In each case, favorable deployment point and sensitivity are implied. The rating system is the familiar Cooper-Harper scale (ref. 27).

TABLE VI.- APPROACH AND LANDING RATINGS

Type of Controller	Approach Rating	Landing Rating
Integrated single lever	1.5	2.0
Semi-integrated:		
Split handle	1.5	2.0
Latch type	2.5	3.5
Separate:		
Double jointed	3.5	3.5
Throttle-like	4.0	4.0
Collective-like	4.5	5.0

For the approach and landing tasks, the integrated or semi-integrated controllers are clearly satisfactory, the latch-type being downrated slightly because of the distraction involved in the unlatching operation if large spoiler deflections were needed. The separate controllers, by comparison, are rated poorer because of the aforementioned difficulty in manual coordination of throttle and spoilers.

Table VII emphasizes a further important distinction between the controllers. Whereas the pilot ratings of Table VI might be said to represent the relative ease of operation once the pilot had accommodated himself to the peculiarities of a particular configuration, Table VII represents the relative concern over possible mishandling of the controls in a stressful situation. The scale here is not the usual pilot rating system but simply a performance scale wherein a low potential for confusion or misapplication was rated 1 and a guaranteed-to-confuse situation warranted a 10.

TABLE VII.- RATINGS OF ERROR OR CONFUSION POTENTIAL

Type of Controller	Rating
Integrated single lever	1.0
Semi-integrated:	
Split handle	1.8
Latch type	2.5
Separate:	
Double jointed	3.0
Throttle-like	5.5
Collective-like	7.0

The fully integrated controller rates highest in this department; the possibility of confusion or wrong action was felt to be no greater than that for normal throttle operation. The split-handle controller presented only a minimal change from this normal operating mode and was also rated as not likely to confuse. The latch-type system was slightly less favorable because of the distracting nature of the unlatching operation which tended to occur at a critical period in the flare.

Serious potential for confusion was felt to exist - and in fact was experienced during the trials - for the two separate controllers which were located at some distance from the throttle. Correcting for an undershoot situation was awkward, and the lag entailed in moving from one control to the other on occasion would result in failure to arrest a high sink rate close to the ground.

With the integrated or semi-integrated controllers, the risk of misapplying the throttle and the spoilers was simply not present; for the cases where separate controls could not be operating simultaneously, the possibility always existed of leaving spoilers open while applying full power. This would be a critical factor in a low altitude missed approach situation.

USE OF DRAG/LIFT CONTROL IN LANDING

As a prelude to the presentation of evaluation data in the next section, certain basic qualities and characteristics of the spoiler research aircraft are discussed. The information contained here has been obtained from specific tests and from numerous landings flown by both experienced evaluation pilots and inexperienced private pilots. The use of various techniques which utilize the capabilities of spoilers is compared with other means of control not involving spoilers.

Approach (Glide Path) Control

There are at least four different ways for the pilot to control his glide path during the landing approach. They are

"Elevator" control.- Adjustment of the glide path by means of the main longitudinal control (the stabilator, or tailplane) is well known to involve the "speed stability" characteristic, the "front-or-back side" parameter, $d\gamma/dV$. On the front side, as a normal approach in the test aircraft would be, $d\gamma/dV$ is negative and control of γ by longitudinal pitch control alone is possible. A change, however, in γ will always be accompanied by a change in V . Although this is possible on the front side, it is generally considered undesirable to change speed in the approach. It is preferable to maintain speed constant, to keep a constant stall margin and constant airplane response. Of course, the speed variation required to make a given change in γ is inversely proportional to $d\gamma/dV$. With a large enough value of $d\gamma/dV$ (far enough on the front side), the required V variation may be small enough to accept. Small values for $d\gamma/dV$ near neutral speed stability require large speed changes for γ control and are, therefore, less desirable. Of course, on the back side with $d\gamma/dV$ positive, normal control of the glide path with stick or wheel alone is not possible.

Various configurations of spoilers on the test aircraft are compared with respect to $d\gamma/dV$ in Table VIII. The speed is the nominal approach value of V_c = 72 knots (83 mph) for all cases, and power is at idle. It is plain that the clean, no-spoiler configuration of the test aircraft is near neutral speed stability and that very little control over γ , by wheel alone, is possible without large speed changes. The effects of spoilers and flaps are clear, due to the drag increments moving the plane "up the front side."

Spoiler control.- The use of spoilers to control flight path consistently received good evaluation from the pilots. Over the complete range of speeds and approach path angles, they find the flight path response "crisp and precise" with the airplane "going

TABLE VIII.- SPEED STABILITY PARAMETER $d\gamma/dV$ FOR VARIOUS SPOILER AND FLAP ANGLES

Upper and Lower Inboard Spoilers
V_i = 74 knots (85 mph), idle power

Spoiler deflection, δ_s →	0	40°	70°
Flap deflection, δ_f ↓	$d\gamma/dV$:		
0	0	-.019	-.043
15°	0	-.090	-.128
35°	-.045	-.108	-.123

where you want it." Little, if any, anticipation or lead compensation is needed.

Clearly, these favorable reports relate to the qualities discussed earlier. The neutral control position trim changes are repeatedly mentioned as contributing to the ease and quality of speed holding, and the short-period component of flight path response is clearly responsible for the "quick and precise" sort of γ control.

It is important to note that these qualities are inherently characteristic of spoilers of the subject type. They characteristically spoil lift and cause nose-up moment which, in combination, tends to produce neutral trim changes; and with drag increase, the short-term γ response is characteristically in the right direction. This is much appreciated by the pilots and is consistently brought out in comparisons with "throttle only" control, as follows.

Power (throttle) control.- The usual drag, or X force, control is simply the throttle. The drag direction force which governs the steady glide angle is usually changed with throttle adjustments, lacking spoilers. It is of interest to compare the quality of this method with that of spoiler control.

First of all, the test aircraft exhibits very small trim changes due to power. The trim data consistently show practically no pitch trim change from idle to full power. The separate moment and lift changes are believed to be individually small, leading to the small net change in trim. This result, which has undoubtedly been achieved by careful design, nevertheless means that for γ control, the short-period "direct lift" response is missing. The comments of experienced pilots are consistent that glide path control is harder and less precise with pure throttle than it is with throttle-like spoiler controls such as the fully or semi-integrated types. With the spoilers operating, they speak of the changes being "crisp and precise" and of the airplane "going where you want it." The throttle-only control is less that way and less desirable.

It might be possible, in principle, to design into the throttle control the same moment and lift trim characteristics as are favorable for spoilers. But this is a very delicate matter and would be extremely difficult to do accurately and consistently, whereas with spoilers it appears to be relatively easy. The fact is that most airplanes of conventional design exhibit nose-up moment changes due to adding power which is of the wrong sign by the above considerations. It appears that the throttle-alone control is likely to be inferior because of unfavorable trim changes and/or lack of direct lift response.

Flap control.- Flap setting, of course, very strongly affects the lift and drag of the aircraft. Flap setting is usually treated as a "configuration parameter" and when extended for landing, flaps increase the approach glide path angles. In this way, flaps partly duplicate one benefit of spoilers - to increase the useable range of steady approach glide path angles. With respect to other important characteristics, however, they are greatly different.

Control over the glide path by modulating the flap setting is, of course, possible in principle. A few trials of it in the test aircraft, which has a manually operated flap handle, have indicated that it is not a good way to do it. The change of lift due to flap deflection is, of course, sizeable - and in the wrong direction. The direct lift control sensitivity is, so to speak, of wrong polarity so that when, for example, the flap is deflected in the direction to steepen γ, the lift change is "up" instead of "down." It is clear in the pilots' comments that this characteristic makes for substantial difficulties, even aside from other problems such as a go-around.

Flare and Touchdown

In the preceding section, the approach part of the landing has been dealt with as a problem in glide path control at constant speed. Here are considered some details of control during the flare and touchdown, involving large changes in flight path and speed. During these stages of a landing, the γ must go from its approach value to nearly zero and speed must decrease from its approach level (with a good stall margin) to touchdown at or near stalling speed.

For the pilot, the flare and touchdown is clearly a job requiring both the longitudinal pitch control and X-force control (throttle, or integrated spoilers). Independent disturbances can perturb the two variables, pitch attitude and flight velocity, and so, in general, two controls would be required. The lift authority of throttle/spoilers is not likely to be enough for the flare, and so the stick or wheel will be used to generate the required normal accelerations. The throttle/spoilers may be used to modify the speed changes that go along with the acceleration history or to counter disturbances to speed from gusts. Consider, below, variations of control technique for this part of a landing.

In order to fix in mind certain basic features of this, consider figure 24. The V,γ chart illustrates, first, a boundary of stalling speed which varies with γ for a given configuration in accordance with the effect of power on $C_{L_{max}}$. The final point of a landing, the touchdown, will be in the small area at the upper left. The approach conditions are points below and to the right like A, B, or C. In a successful flare, the transient variations of V and γ will lie along some path from the approach point towards the area for touchdown.

The shape of the V,γ trajectory is affected by many details of control action and lift/drag variations. Although a complete explanation of all possibilities is not feasible here, certain features can usefully be identified. First, unless drag control is used, constant load-factor trajectories are not straight lines. They are concave downward like the curved lines from A, B, and C into the touchdown. Second, the slope of the trajectory is larger for larger load factor Δn. On these counts it can be appreciated that a successful flare from a flat and fast approach, like A, must be at a low load factor and quite prolonged, whereas from a steep and slow approach, like B, it must be at a high load factor and very abrupt. The former is hard for the pilot to judge consistently and very much subject to disturbances, whereas the latter is extremely critical with respect to timing of initiation and execution. Perhaps in an intermediate area, like C, the trajectory to touchdown would correspond to a pleasantly moderate load factor and a maneuver in which neither timing nor disturbances were too critical.

Now, for the above discussion, the flare maneuver is done entirely with longitudinal control with no action of the throttle (i.e., wheel only). Conceptually, this is certainly possible. It involves back pressure on the wheel throughout and with favorable values of certain parameters and a proper approach point, it is a very workable maneuver.

With the test aircraft, many preliminary trials with a wide range of conditions suggested to the test pilots that for wheel-only flares the favorable approach airspeeds are in the shaded area of figure 25. From that area, the flare and touchdown with longitudinal control alone are found to be easy and natural. A gradual

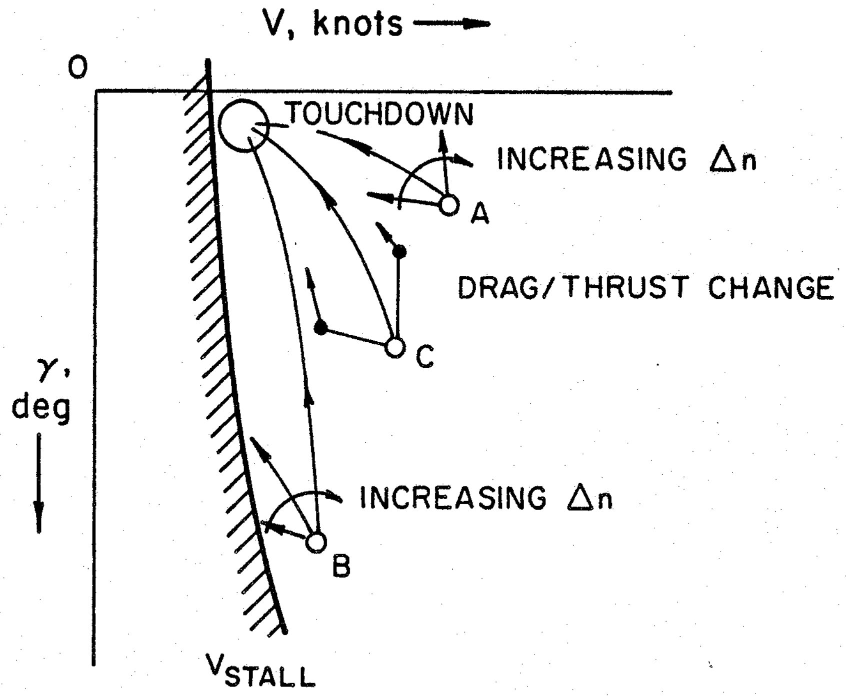


Figure 24.- V,γ trajectory considerations for flare and touchdown

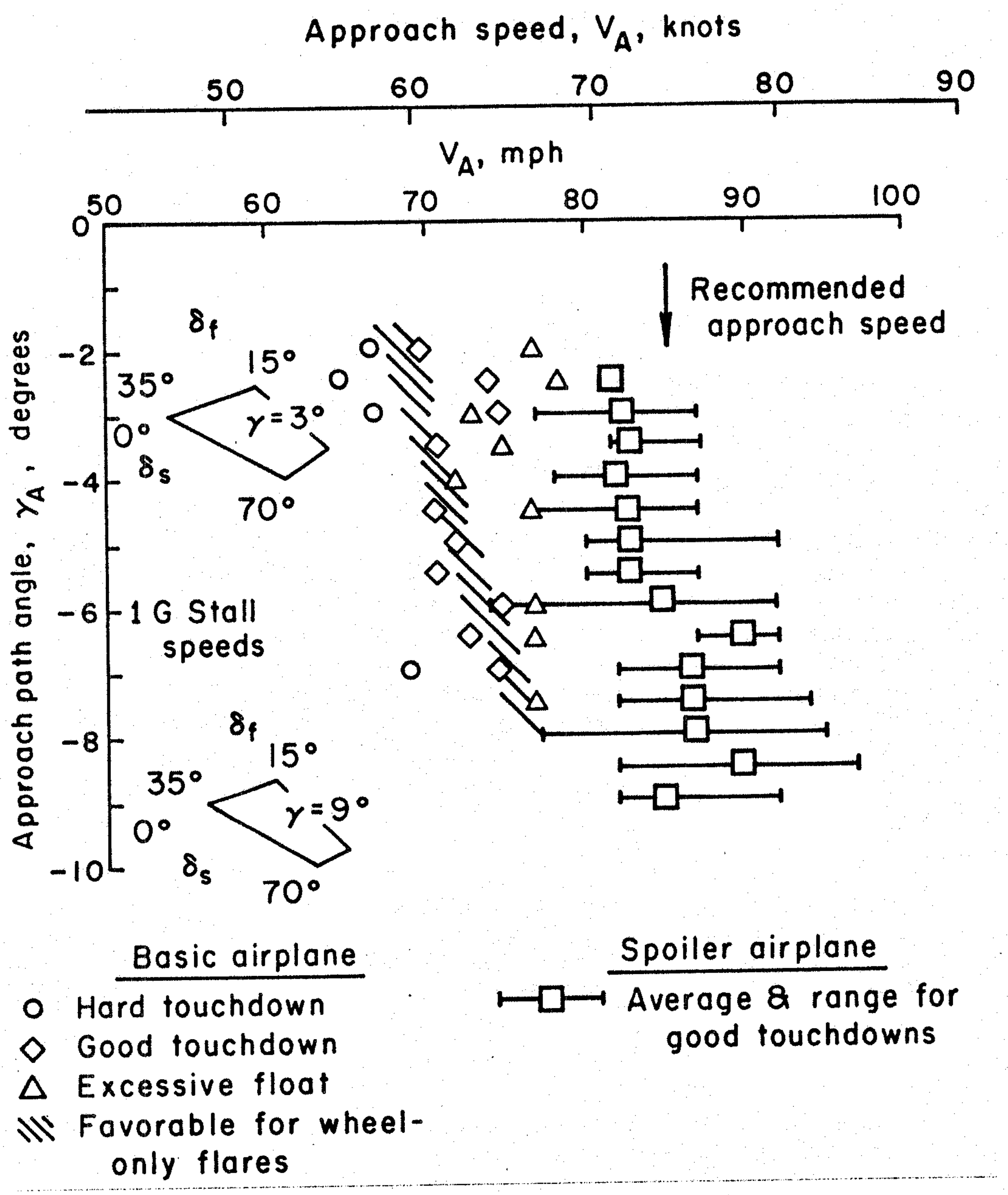


Figure 25.- Approach conditions for the test airplane

flare characteristically produces a speed slightly above stall at the end, with a short but not excessive "float" to touchdown. Above, or to the right, excessive floating and high touchdown dispersions are frequent and sometimes there are problems of wheelbarrowing, ballooning, or lateral drift in crosswinds. Below or to the left of the area, the airplane decelerates very rapidly and must be flared abruptly with perfect timing and very precise control action. The approach conditions for wheel-only flares, which are favorable from the point of view of the speed transients and dynamics of the flare, appear to be relatively little affected by configuration. The governing factor seems to be the approach angle which, after all, governs the total change through the maneuver of the flight path component of the gravity force.

A number of data points are also shown in figure 25 corresponding to actual landings from the licensed pilot evaluation phase of the flight program discussed in the next section. They were done with the basic airplane (no spoilers) with 25° or 35° flap and the wheel-only technique described above. There are four points ○ to the left of the shaded area, each representing the average airspeed for hard touchdowns at the indicated value of γ . For these conditions, there was insufficient energy (speed) in the approach for the low-experience pilots to manage the flare successfully. There are numerous points △ to the right where excess speed in the approach was not dissipated through the flare and floating occurred beyond the touchdown target. There are numerous data points ◇ roughly defining the hatched area where good touchdowns were made. It is clear from the hatched area and the data points that for this kind of flare the range of favorable approach airspeeds is quite narrow, and precise airspeed control is required. This is difficult for any pilot under adverse conditions but especially so for the student pilot or novice.

Stalling speeds are indicated in figure 25 by the little carpets to the left of the shaded area. They show the effects of spoiler and flap deflection on V_S for two different approach path angles. The effect of power is quite small on this aircraft, so the speeds are almost independent of γ . It can be seen, especially for flat approaches ($\gamma = 3°$) that, depending on flap setting, the favorable approach condition exhibits a relatively small stalling speed margin. This could be dangerous especially for inexperienced pilots who are unskilled at airspeed control. While the speed margins are somewhat better at the steeper approach angles, the need for good airspeed control still exists. Experienced pilots can make comfortable and consistent landings of this type. They mostly agree, however, that for beginners or learners the steeper γ's are not desirable.

Now, although this discussion has so far only considered wheel-only control, of course the pilot must be ready and able with throttle to handle exigencies of one sort or another as might arise from gusts or other deviations. The discussion simply started with consideration of nominal flares which come out well without throttle coordination and the conditions for them in this particular aircraft have been presented.

If, in the flare, the pilot so desires, he can control the V,γ trajectory by throttle or spoiler action. This is suggested in figure 24 by the trajectories from approach point C exhibiting sharp bends. On the left one, the corner would correspond to opening throttle or closing spoilers. On the right one, it would be closing throttle or opening spoilers. It is clear that by coordinating X-force control, the pilot should be able to steer the V,γ trajectory to the touchdown point from an extended region of approach points. In figure 24, the steep slow approach on the left would be unacceptable anyway for amateur pilots because of insufficient stall margins. However, the area on the right, of shallow and fast approaches, can be opened up by coordination of this kind.

The coordination of X-force control and wheel action would seem to represent a somewhat more complicated procedure needing more practice and training. In any case, trials with the test aircraft with approach speeds in the region of data points □ to the right produce landings that are accurate, comfortable, and safe under a wide range of conditions. In these landings, the pilot takes off throttle and/or opens spoilers in the flare and by proper manipulation steers the V,γ trajectory towards the touchdown point. With spoilers, the authority of the control of deceleration is high; the airplane responds quickly and effectively, and the coordination involved seems to be easy over a wide range of speeds. The pilot has the capability to compensate for differences of conditions, disturbances, and even his own errors. Especially with the shallow approaches ($\gamma \doteq 3°$), the flare with this technique is very mild and gradual, forgiving of variations of timing, wheel action, and airspeed - in fact, requiring very little action on the wheel or stick. The extra speed margins mean safety to the instructor and cushion to the student. These factors, of course, are what led the test pilots of the program to select an indicated airspeed of 74 knots (85 mph) as the nominal approach speed for the spoiler-equipped airplane. The data points □ are actually the average approach speeds for all the landings made by private and advanced pilots in the spoiler airplane during the licensed pilot investigation phase of the flight program. These averages, and the associated ranges of speed, were derived from a data bank for all the landings; 233 landings by 10 subjects are represented. The test pilots' selection of $V_i = 74$ knots for approach speed for the spoiler airplane seems to be well vindicated.

If the X-force control (throttle or integrated spoilers) has the characteristic of spoilers to produce a down-lift for a drag increase, then it may be used at the end of flare to "set" the airplane quickly and decisively on the ground. This absolutely eliminates floating and, at the same time, produces firm ground contact and rapid deceleration during rollout. The extra technique involved is something the novice should learn anyway to cope with variations in conditions and disturbances.

It is intuitively clear that to use the X-force control this way, easily and smoothly, the trim changes must be small, and it is very desirable to have the direct lift response due to ΔL that was discussed under Approach Control. This would clearly be impossible with a flap since ΔL is large and of the wrong sign. It is difficult to achieve with power alone, especially an appropriate ΔL response, but all these features are inherently characteristic of the spoilers. Where the spoiler control is suitably integrated with the throttle, then very favorable - if not optimum - approach, flare, and touchdown characteristics are achieved.

The series of landings with the test aircraft under various conditions of wind and turbulence have consistently shown the advantages of the integrated throttle/spoiler control used in the coordinated way. The discussion and the data seem to identify the minimal trim changes and favorable lift decrements as the principal features of the arrangement.

Go-Around

It should, of course, be possible for a pilot to abort a landing, or go-around, without undue effort or delicacy. The essential action is a large rapid change of X-force, from decelerating to propulsive, as by advancing the throttle/spoiler control. Accompanying this, it is important to have no more than small pitch trim changes, and it is desirable to have a lift increase along with the throttle opening. These are inherently the characteristics of the integrated throttle/spoiler system, and go-arounds in that case are absolutely easy, safe, and effective - even for novice pilots.

A good go-around characteristic can sometimes be provided with a throttle-alone (no spoilers) airplane, but it is difficult if a very effective flap is used for landing. With large flaps, the moment trim change with power tends to be large and nose-up, requiring large forward wheel forces to be applied. At the same time, it is necessary for the pilot to reduce drag by retracting the flaps, but this changes lift in the wrong way and increases the stalling speed. It is possible to be trapped at slow speed and flap down with too much drag to accelerate rapidly. Under these circumstances, the flaps must be "nursed up" slowly and carefully as the airplane accelerates slowly. It is a delicate and dangerous situation even for an expert pilot.

The flaps of the test aircraft are small enough and restricted enough in deflection that these problems are not severe. Go-arounds with throttle alone are reasonably easy and natural with any flap deflection, but they are not as desirable as with the integrated throttle/spoiler control where flaps have been restricted to 15°, more X-force increment is available, and proper moment, trim, and lift increments are inherently characteristic of the arrangement.

Because of the problems of retracting the flap during a go-around, discussed above, it is not feasible to integrate a flap control to the throttle. This would not be desirable anyway because of the inverted direct lift response, but the go-around problem seems absolutely to preclude the arrangement. Flap controls appear to be relegated to "configuration selectors" - not to be used in maneuvers or in continuous closed-loop pilot-vehicle system functions. By contrast, the spoiler system is ideally suited for continuous action throughout a landing, from approach through flare, touchdown, and even go-around.

PERFORMANCE AND EVALUATIONS OF SPOILER LANDINGS BY EXPERT PILOTS

Day, VFR - Approach Angle, Speed, and Pilot Technique

This section presents a comprehensive experimental investigation of how landing distance and piloting difficulty are affected by approach velocity, path angle, and pilot technique. It will be seen that the compromise parameters and measured variables present complicated separate effects and interactions.

Approximately 400 landings were performed in the spoiler research aircraft specifically for the guided day VFR landing study. The aerodynamic characteristics were those of the test aircraft with partial flap deflection (15°) and full flap (35°) and with spoilers open as required for the approach and landing task. Six different approach angles (3° to 18° in 3° increments) and three pilot techniques for landing were flown. The spoiler control was the semi-integrated one described previously. All the spoiler plates, both inboard and outboard, shown in figure 12, were active. Stalling speeds for a given drag level were a bit higher than for the inboard or outboard sets individually, but control over flight path angle, touchdown point, and rollout was very favorable. Trim changes were nearly neutral, and the aircraft response to throttle/spoiler action was the nearly ideal one discussed previously.

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 (Commercial Pilot license with single and multi-engine ratings plus Certified Flight Instructor

License; total flying time - approximately 6000 hours) as 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 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. 26); 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 history oscillograph record of airspeed. This was used to compute a hypothetical rollout distance and a stopping point. As shown in figure 27, the distance from the beginning of the landing zone to the stopping point is arbitrarily called the "landing distance."

Calculation of the hypothetical rollout distance has been made according to a very simple but reasonable formula:

$$\text{Rollout distance} = \frac{1}{\mu_e} \cdot \frac{V^2}{2g}$$

representing a constant deceleration at an effective braking coefficient μ_e . Several effects are omitted, but μ_e has been determined from sample experimental rollouts, and so the formula may be considered an empirical fit to experimental data. The data are shown in figure 28 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 calculation are

μ_e = .15 for 35° flap, spoilers closed
.18 for 15° flap, spoilers closed
.25 for 35° flap, spoilers open
.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 distances.

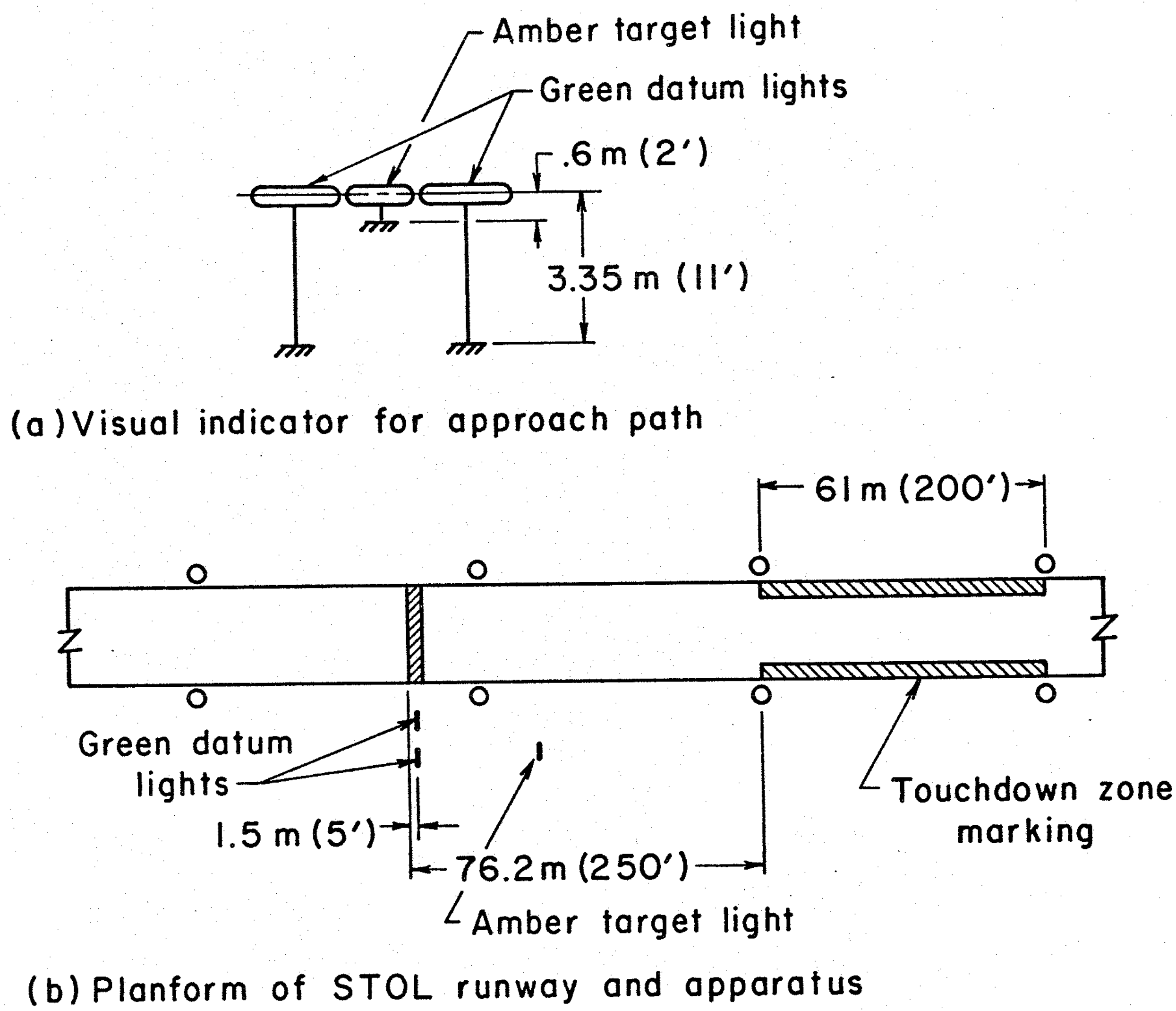


Figure 26.- Approach and landing zone indications

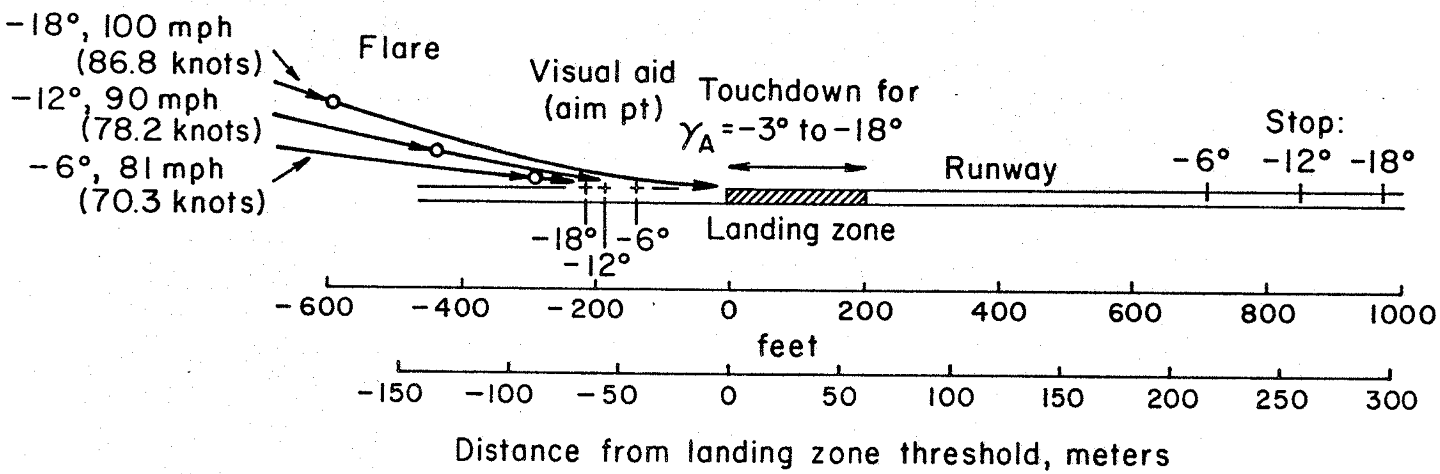


Figure 27.- Summary of landing distance results

	Flaps, Degrees	Technique	Braking	μ_e
◇	35	Decelerate	Moderate	$.24_{10}$
○	35	Decelerate	Heavy	$.27_{3}$
△	15	Decelerate	Moderate	$.26_{3}$
□	35	No spoiler	Moderate	$.16_{3}$
▽	15	No spoiler	Moderate	$.19_{4}$

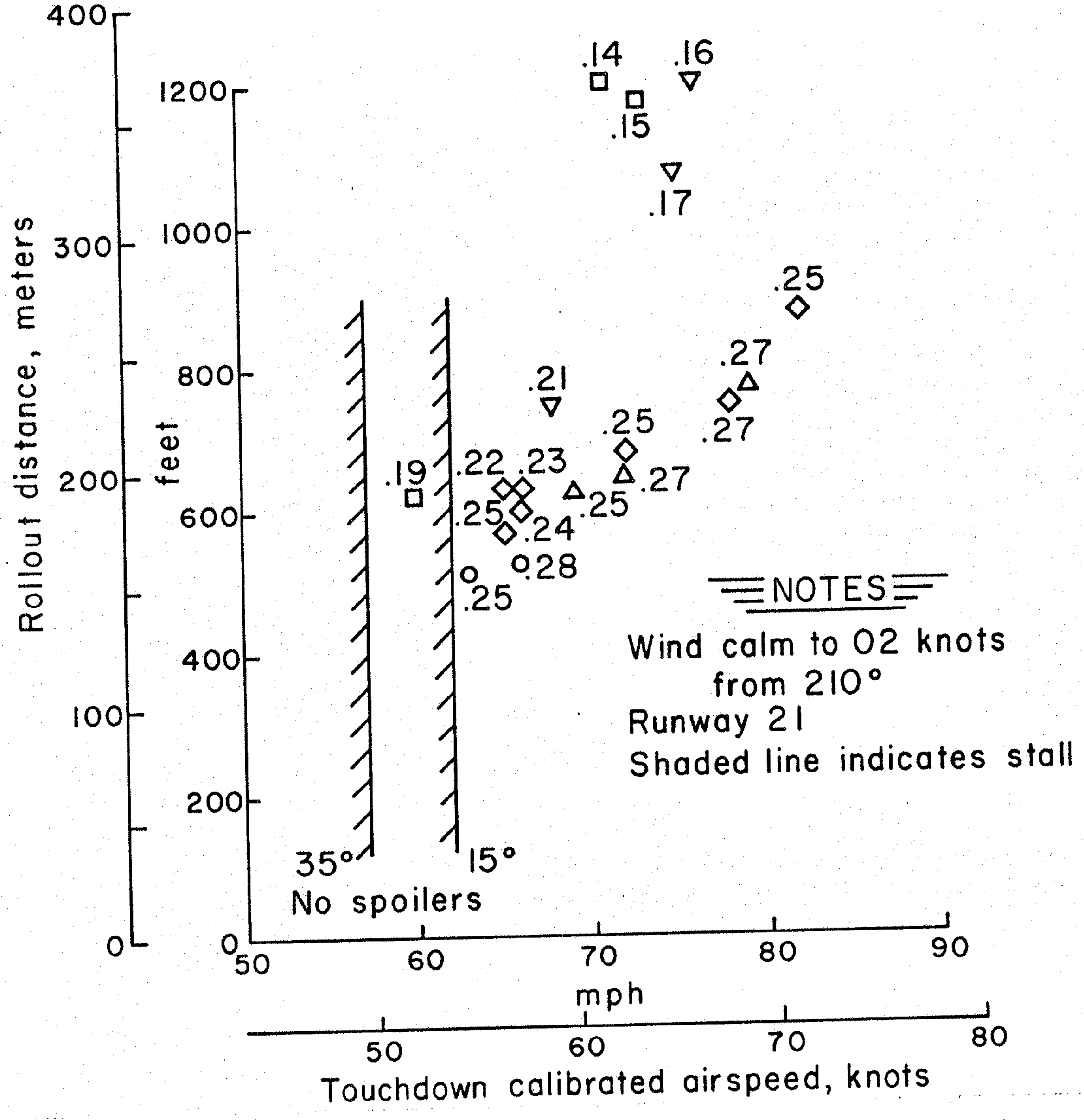


Figure 28 .- Experimental determination of braking coefficient, μ_e

Landings at $\gamma_A = -6°$, $\delta_f = 35°$

Data for the landings are exemplified by figure 29 for $\gamma_A = -6°$, $\delta_f = 35°$. The study evaluated many variations of pilot technique, approach airspeed, flap position, and γ_A; only representative data are presented in the figures.

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 reference 28, 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 produces a nice soft touchdown at minimum speed without floating. We call this particular approach speed V_{WO}. It is quite sharply defined. As little as 2 knots greater than the WO speed results in a noticeable float; 2 knots too slow produces a hard touchdown. In figure 29, data are shown 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}; 62 knots (71 mph) in this case. At the bottom of the figure, the touchdown speeds are seen to be quite constant at about 56 knots (64 mph), slightly above a stalling speed for the condition of 54 knots (62 mph). At "wheel only" approach speed, the flare time, taken from control angle time histories, is of the order of 3 to 4 sec, corresponding to an average normal acceleration of about .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 62 knots (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 figure 29, 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 a somewhat higher touchdown speed. 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 rollout distance computed according to the formula given above.

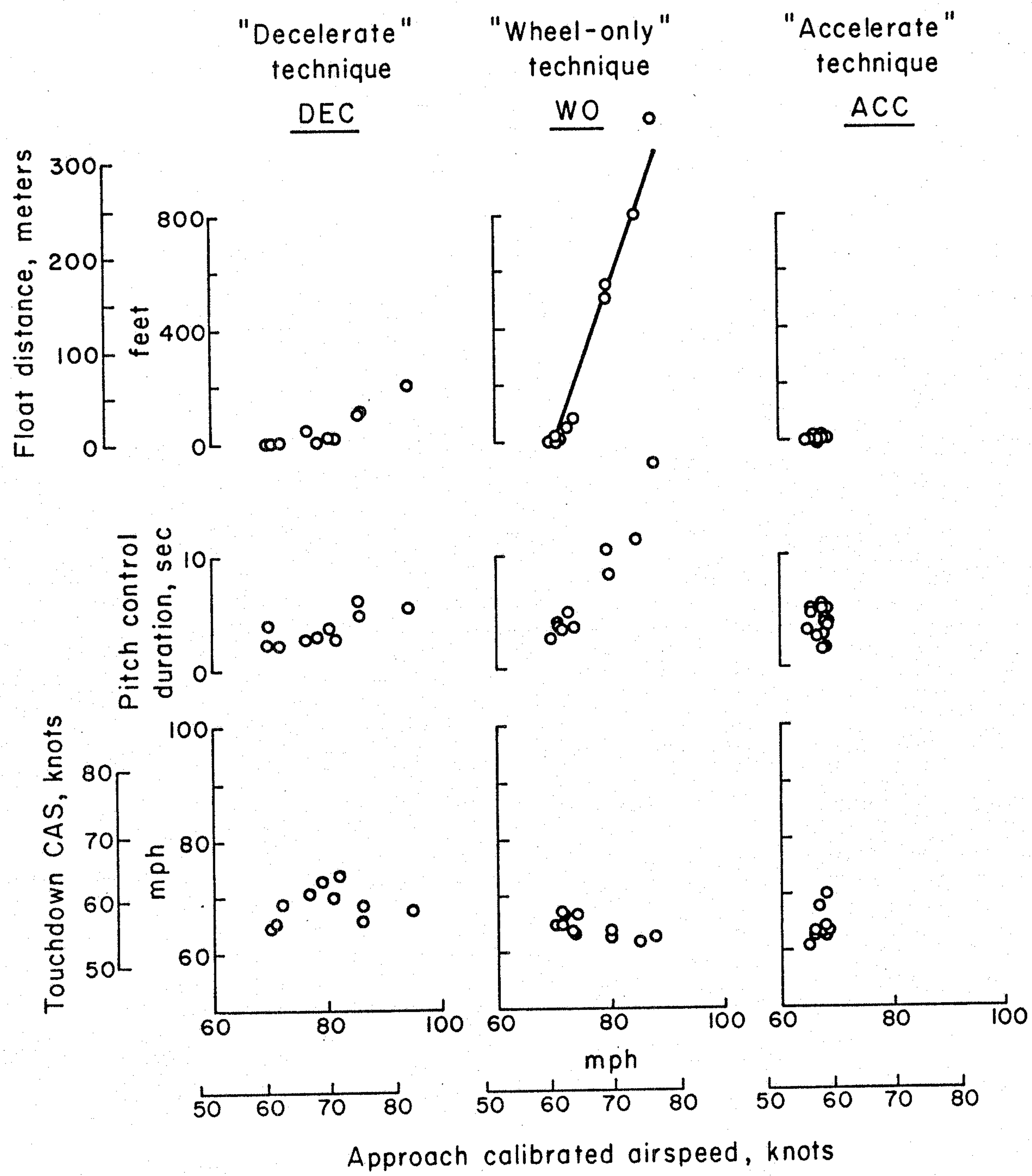


Figure 29.- Data for experimental landings; $\gamma = 6°$, $\delta_f = 35°$

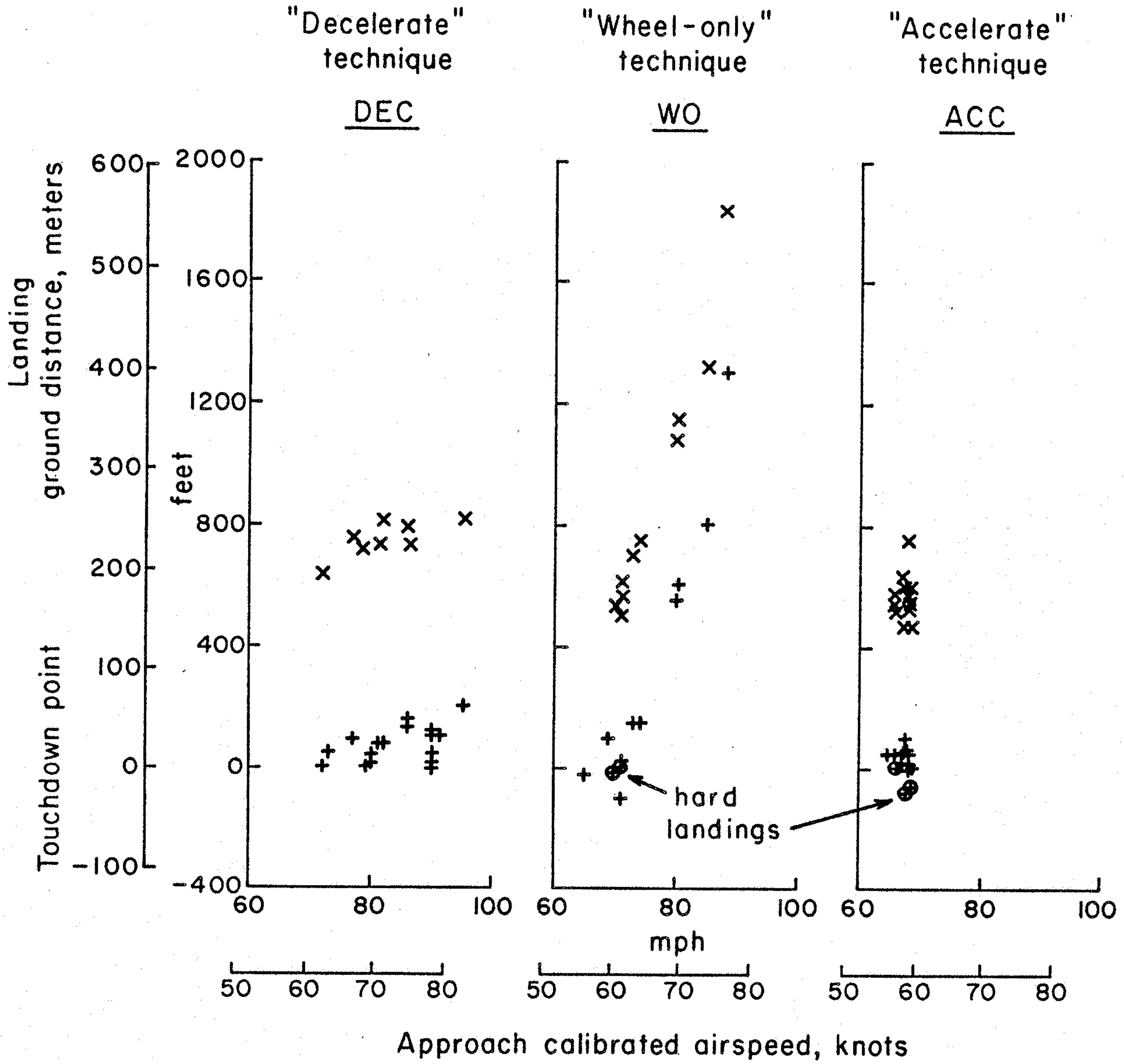


Figure 29.- concluded

These landings are considered by the pilot to be quite 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 $\gamma_A = -6°$, $\delta_f = 35°$ conditions, the pilot has selected approximately $V_{DEC} = 70$ knots (81 mph) as the best approach speed. In this case, his "decelerate" throttle action and the flare are initiated at the same time (about 3-1/2 sec) and he touches down about 5 knots faster than with the "wheel only" technique.

Accelerating technique.- The opposite pilot technique is to advance the throttle/spoiler control in the flare, tending to (relatively speaking) 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. It can be seen in the data on the right-hand side of figure 29 how steep the curve of "accelerate time" is for speeds below V_{WO}. Hard touchdowns are likely 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.

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 also shown in figure 29. 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 168 m (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 distances (about 213 m (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.

Landings at $\gamma_A = -12°$, $\delta_f = 35°$

Data for landings on the steep approach path are shown in figure 30. Again, flaps are full down and data are given over a range of approach speeds and for the various pilot techniques.

Wheel only technique.- The "wheel only" speed V_{WO} determined by fairing the float data (figure 30) is about 68 knots (78 mph). This produces 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 .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 considered it easy and forgiving of errors and disturbances, and it eliminated excessive floating which otherwise results from excess approach speed. The best approach speed V_{DEC} selected by the pilot is 78 knots (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 seconds before touchdown. This confirms the very perceptive comment by the pilot that he finds it easy to operate the two controls (wheel and 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 timing.

These features are nicely illustrated by the time history of figure 31a for one of the V_{DEC} landings. The character of control motions is easily seen to be as described.

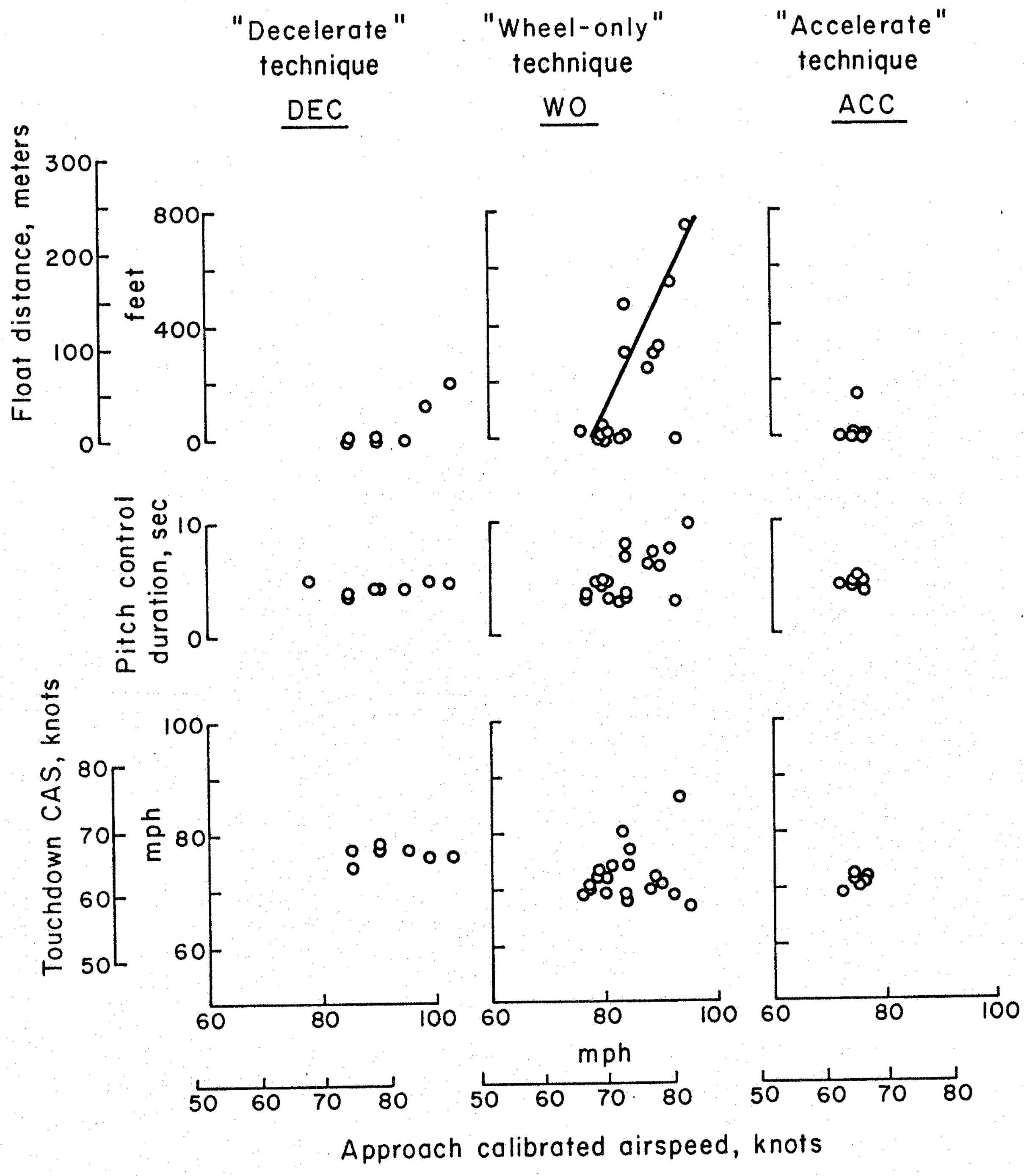


Figure 30.- Data for experimental landings; γ = 12°, δ_f = 35°

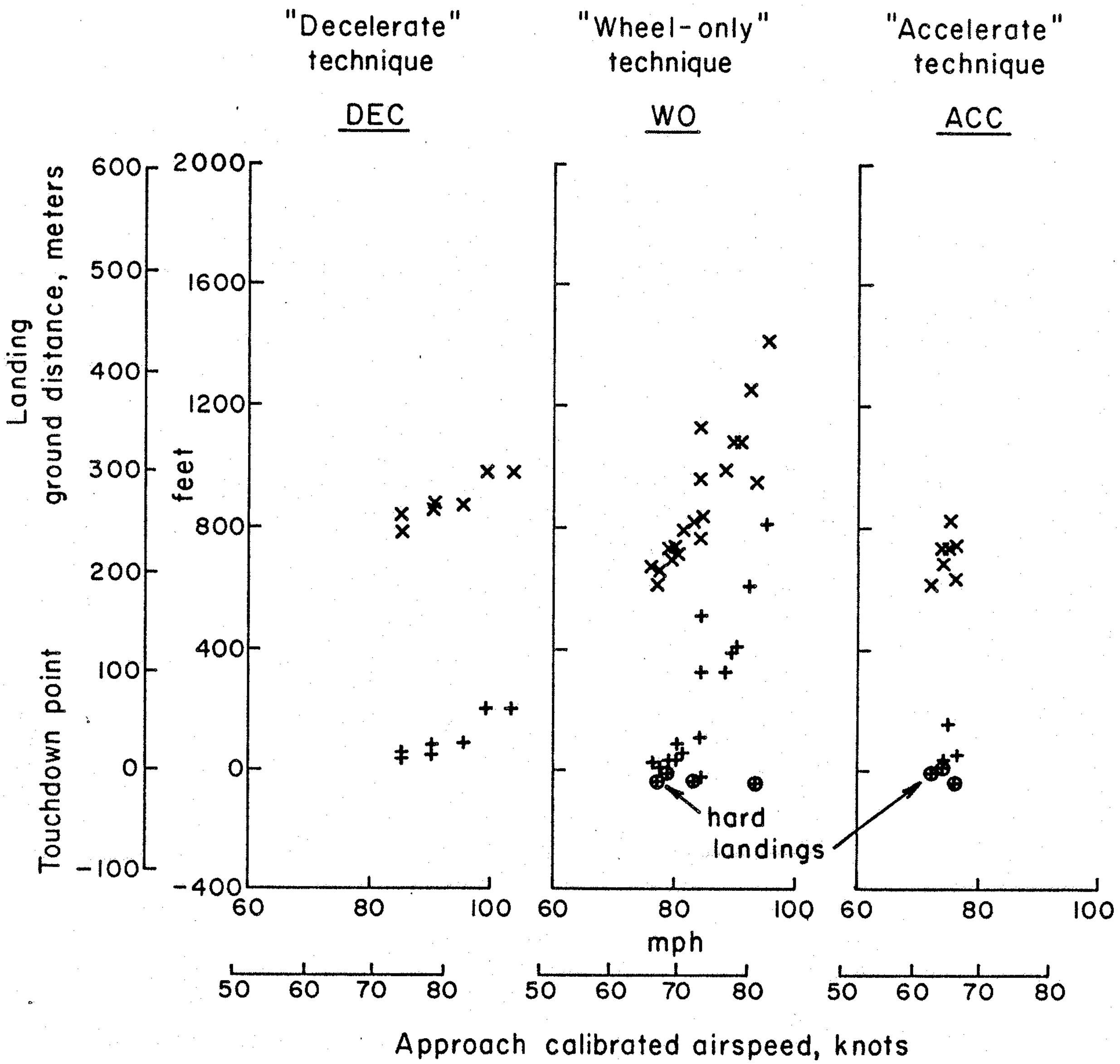


Figure 30.- concluded

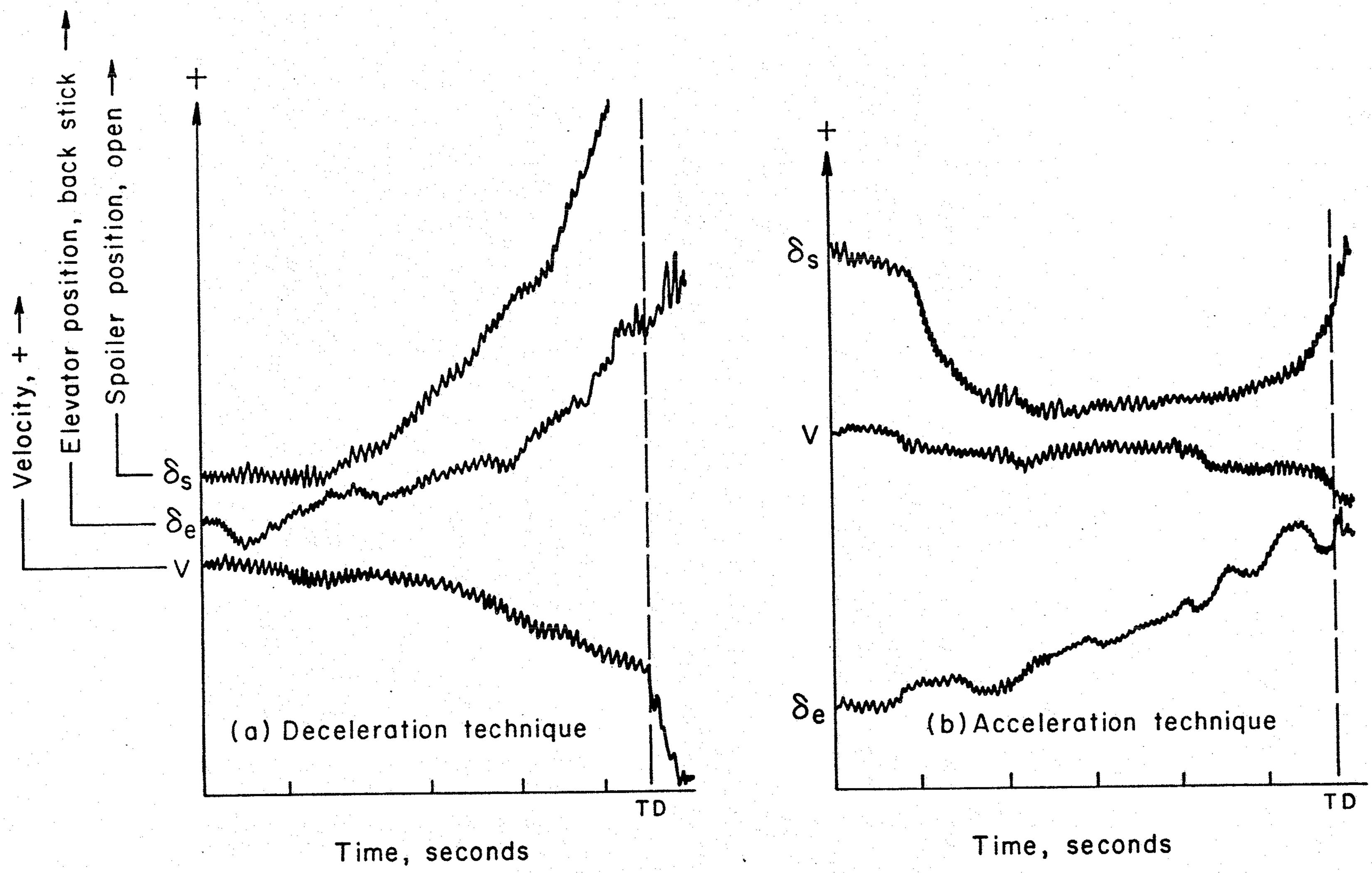


Figure 31.- Deceleration technique time history

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 more 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 dissimilar. The control task, in this case, clearly has "two dimensions."

These features are shown in the time history of figure 31b. The wheel action is first pull to initiate the flare and then reverse to touch down, 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 figure 31. Again, the accelerate technique produces the shortest landings (about 213 m; 700 ft) but they are tricky and prone to hard touchdowns. The wheel-only technique at the correct approach speed (68 knots (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} = 78 knots (90 mph), gives a landing distance of about 259 m (850 ft).

Landings at $\gamma_A = -18°$, $\delta_f = 35°$

A few landings were done at the extreme approach path angle. They are represented by the data of figure 32 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 seconds and more abrupt, with average normal acceleration of .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} = 87 knots (100 mph) for a landing distance of about 305 m (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.

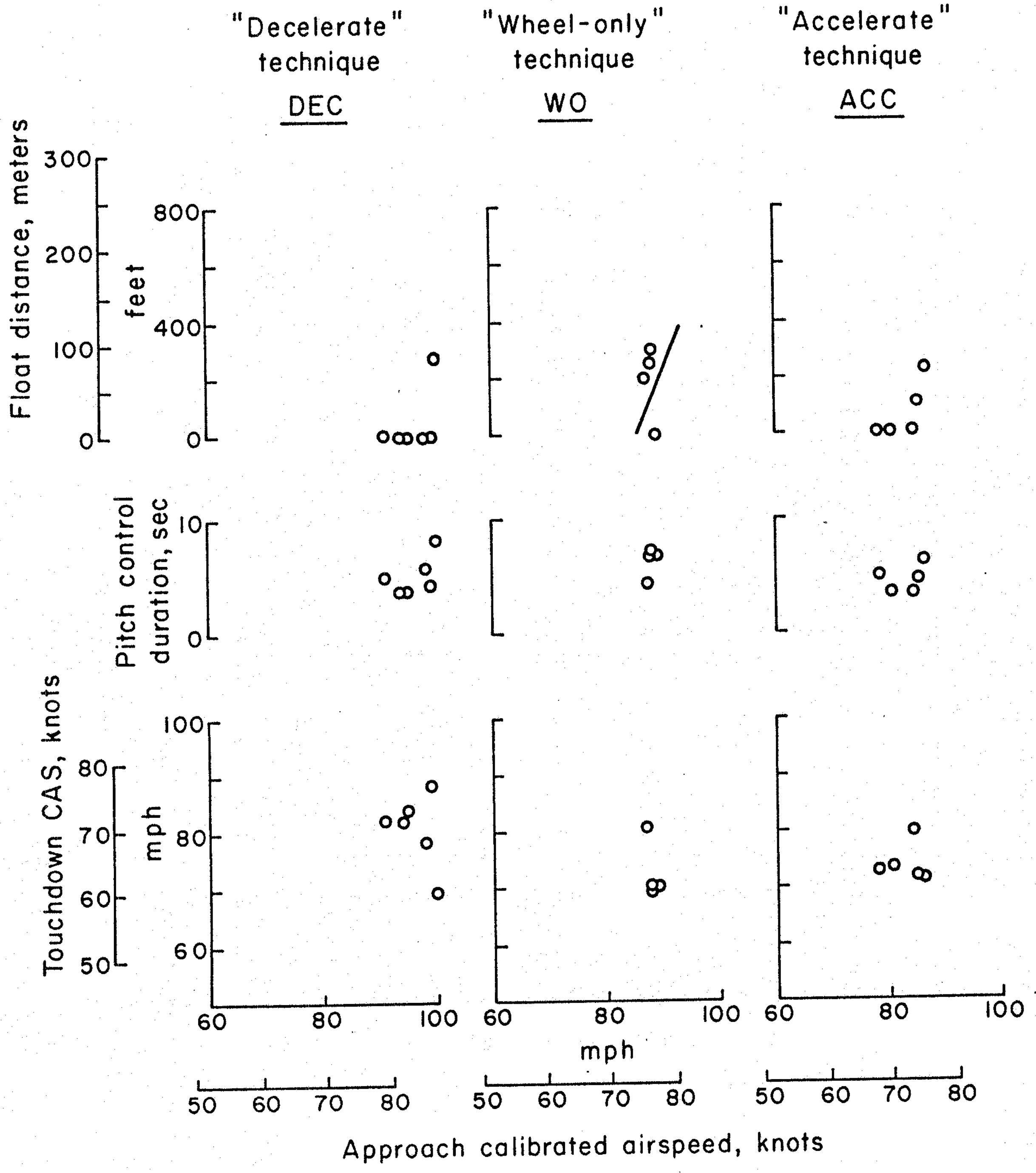


Figure 32.- Data for experimental landings; $\gamma = 18°$, $\delta_f = 35°$

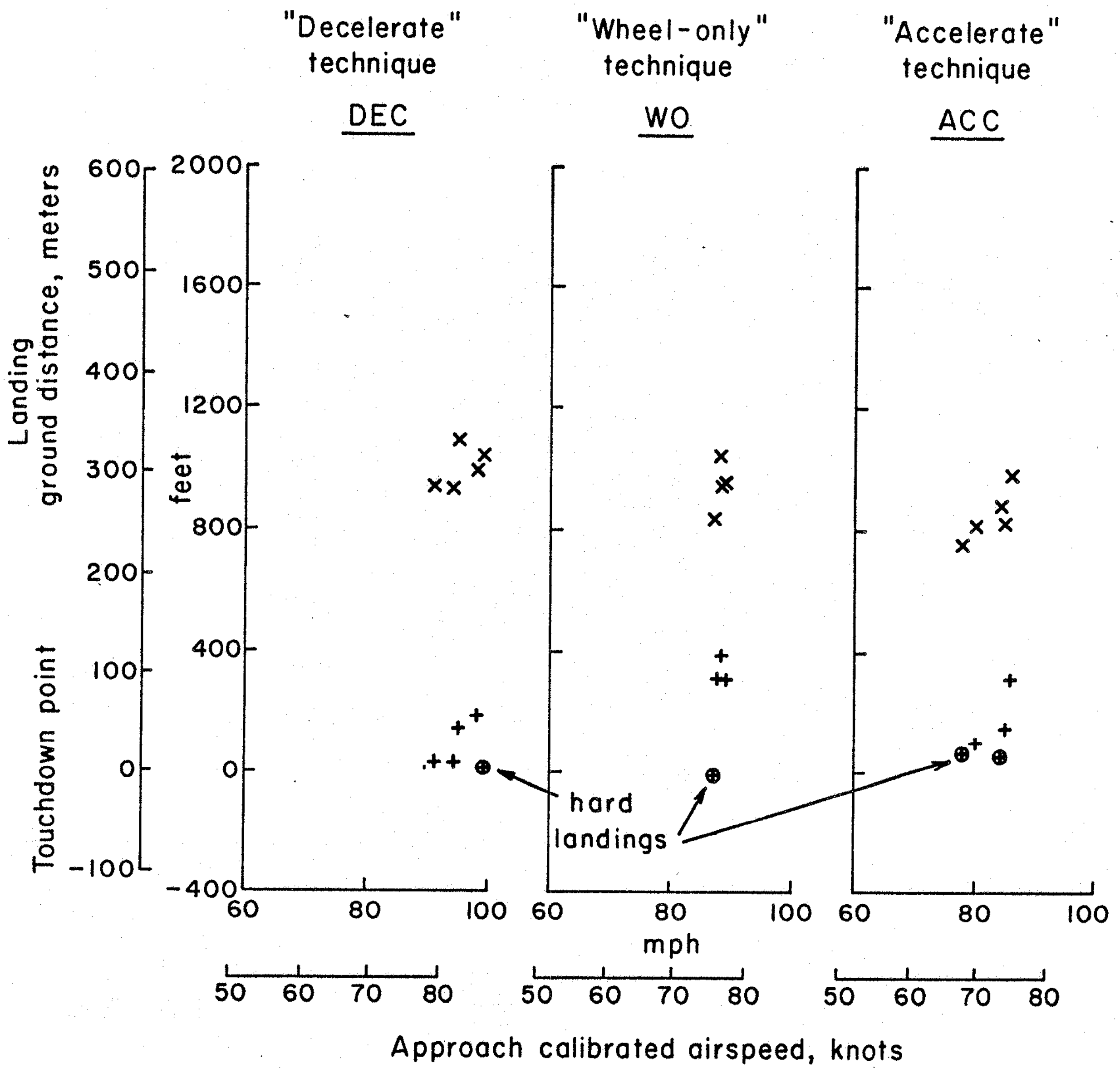


Figure 32.- concluded

Effects of Approach Path Angle

In figure 33, the various approach speeds for different pilot techniques are shown as functions of path angle γ_A. The V_{WO}, V_{DEC} derived from the individual figures discussed in the previous sections show consistent increases as γ_A 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 the tendency to float or touchdown hard with as little as ±2 knots speed variation. For V_{WO} the stall margin varies from 7 knots (8 mph) (12%) to 14 knots (16 mph) (22%) over the range of γ_A from -3° to -18°. For V_{DEC} and the decelerating technique, they were the much more adequate 15 knots (17 mph) (29%) to 25 knots (29 mph) (41%). These margins in themselves would normally be enough basis to select the decelerating technique.

Also shown in figure 33 are contours of constant landing distance determined as previously explained. In the area to the left of V_{WO}, the data correspond to "accelerate" 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 γ_A = -3° to -18°, along the line of preferred approach speed, the landing distance increases from about 183 m (600 ft) to about 305 m (1000 ft) as V_{DEC} increases from 66 to 87 knots (76 to 100 mph).

Superimposed on figure 33 are contours of constant pilot opinion rating. These are based on the Cooper-Harper scale and 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, for convenience, ratings are given to show in detail the effects of the parameters and techniques of the experiments. It should be noted 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, the Cooper-Harper system (ref. 27), calls for a rating from 1 to 6 if the workload is judged to be tolerable and 7 to 10 if intolerable. Further, the airplane is to be rated 1 to 3 if it is satisfactory without improvement and 4 to 6 if it has deficiencies which warrant improvement. The 7 to 9 ratings imply major deficiencies,

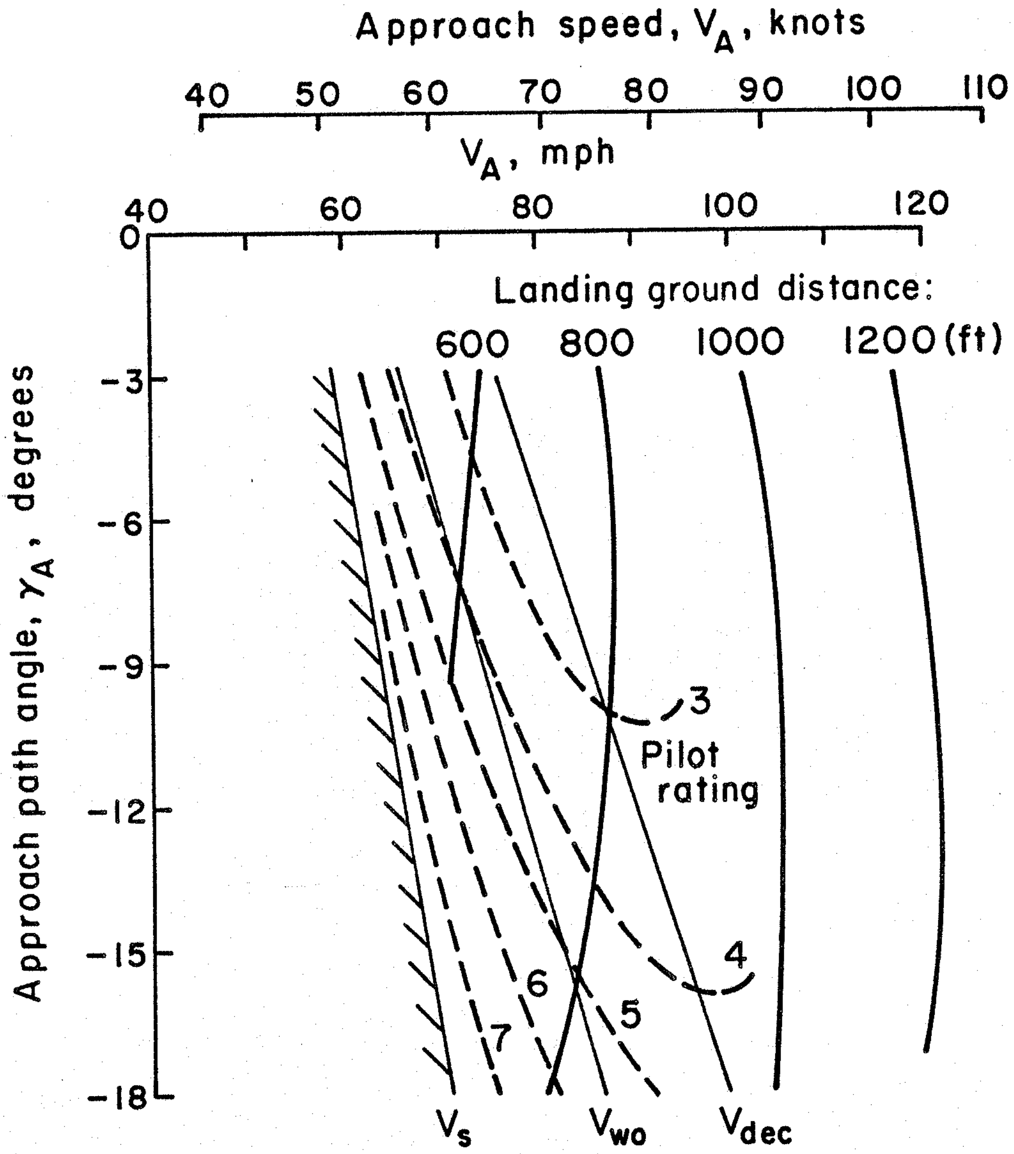


Figure 33.- Effects of approach path and airspeed on landing distance and pilot rating; flap position = 35°

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. Of course, 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. A perfect performance could very well be given a 6 rating because of the difficulty of attaining it. Consistency of performance influences the rating, since the evaluator must decide whether or not a given level of effort will produce acceptable results on every attempt. This judgment is simplified if many trials are flown; otherwise it must be based on 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. 26). Desirable performance was 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 pilot 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 response.

A satisfactory situation was 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 1 to 3, depending on the judgment of workload. 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 from 4 to 6. 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 unacceptable hard landings were likely.

The shape and spacing of pilot opinion contours in figure 33 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 "decelerate" technique. Perhaps the most interesting thing they show is the magnitude of the penalty in difficulty and landing distance for the steep approach.

Starting at $\gamma_A = -3°$, the landing from the ideal approach speed V_{DEC} gets a rating of a little better than 3 (fig. 34). 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 $\gamma_A = -6°$ landings started at V_{DEC} . At $-9°$, 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 increased difficulty. The increased rate of descent required 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 $-9°$, 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 4-1/2. The problems are the three increases of descent rate, flare height, and flare acceleration which, at these higher γ_A's, are beginning to produce more noticeable difficulties. The variations of these quantities with approach angle are shown in figure 33 with the pilot ratings. Even the landing at $-18°$ with a rating of 4-1/2 is a reasonable, operationally usable maneuver under the VFR conditions of the experiment.

Landing Trajectories

The landings with optimum pilot technique ("decelerating") at the best approach speed V_{DEC} are displayed in another way in figure 27 (p. 76). For a 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 30 m (98 ft) to a little more than 61 m (200 ft) in front of the threshold of the landing zone. In the landing data previously presented, the touchdown points were within the 61 m (200 ft) of the landing zone, and the average stopping points were calculated to be as indicated.

The advantage 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 60 to 80 meters (197 to 262 ft). The elevation of flare point as the path angle is increased accounts for some increase in piloting difficulty and would certainly present problems in IFR conditions with low ceilings.

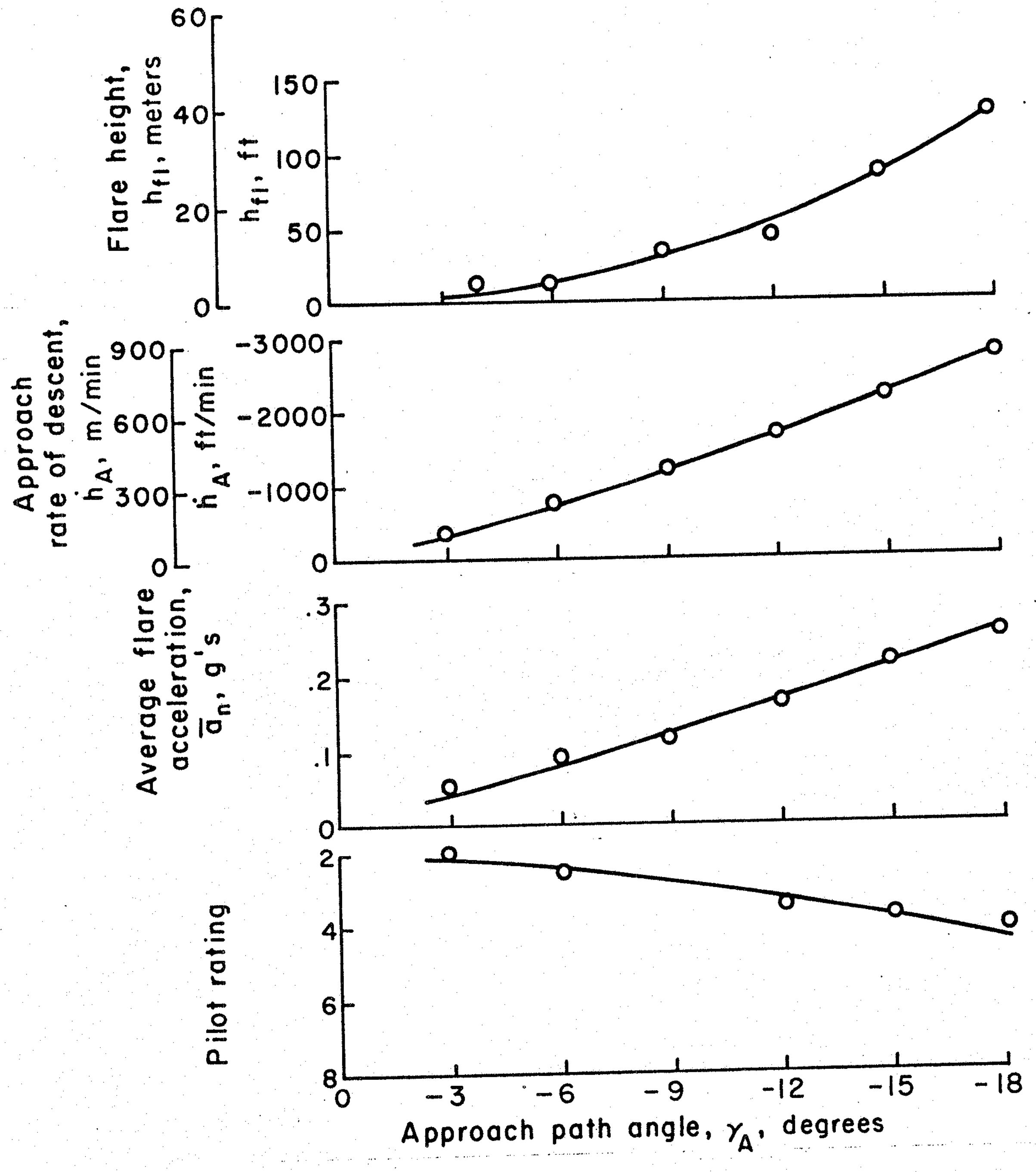


Figure 34.- Effects of γ on landing characteristics

Landings with Partial Flap ($\delta_f = 15°$)

Landings with partial flap deflection involve all the considerations and interplay of the various factors and, in substance, they entirely duplicate the previous case of full flap deflection.

A summary of results is shown in figure 35. Again, the advantages of the "decelerate" 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 Basic Aircraft, Without Spoilers

The basic airplane has not, in this program, been investigated in the detail of the spoiler-equipped airplane. However, a few landings at $\delta_f = 15°$ and $35°$ and $\gamma_A = -3°$ and $-6°$ were made for comparison.

Without the use of spoilers, stalling speeds are somewhat lower so that touchdown speeds are lower and rollout distances could be shorter. But the braking is poorer. The net result is that landing distances are somewhat longer. It has been reported in a previous section 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 earlier show that various classes of pilots, from students to experts, produce better landing performance in the spoiler-equipped airplane in the range of normal 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, particularly for inexperienced pilots with marginal abilities to control glide path and airspeed precisely.

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 usable 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 figure 36 we show the steady-state angle of descent versus airspeed for the basic airplane at idle power. A steady approach condition must lie above this line, with a margin for modulating

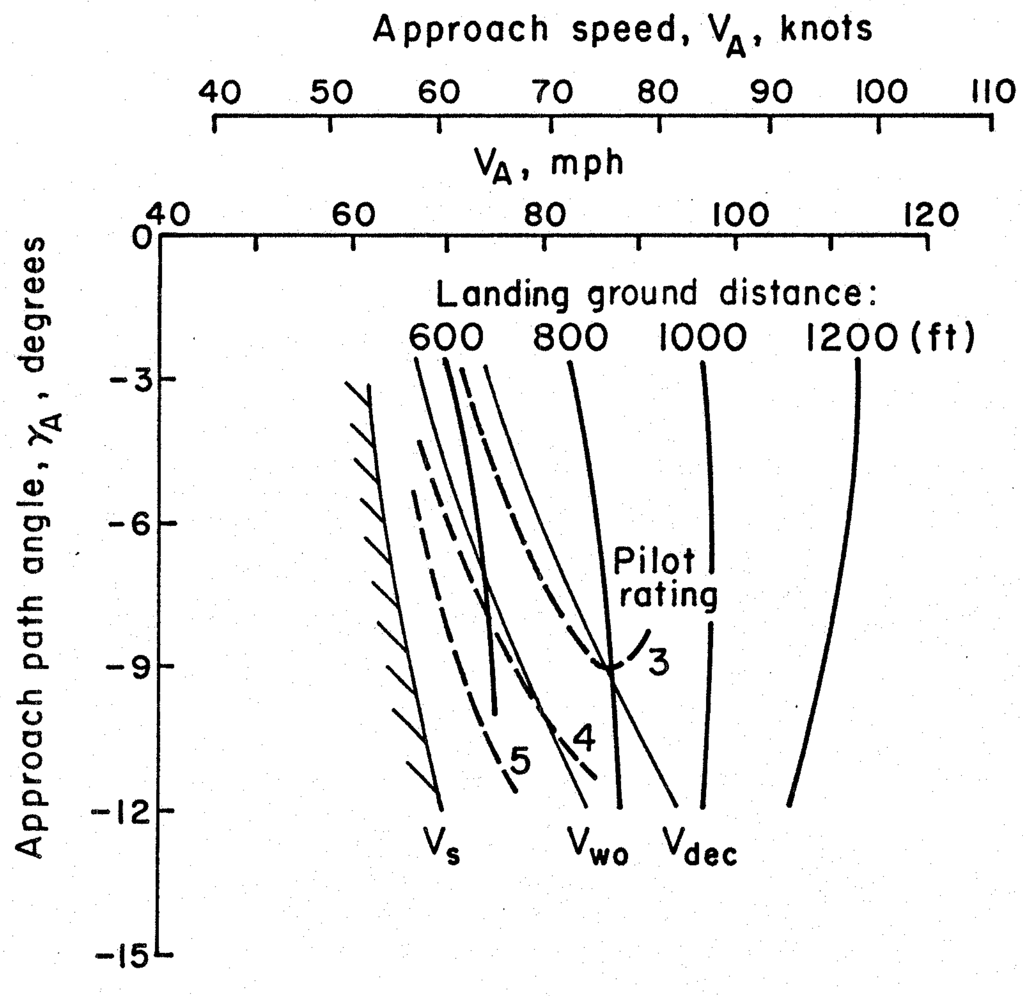


Figure 35.- Effects of approach path angle and airspeed on landing distance and pilot rating; flap position = 15°

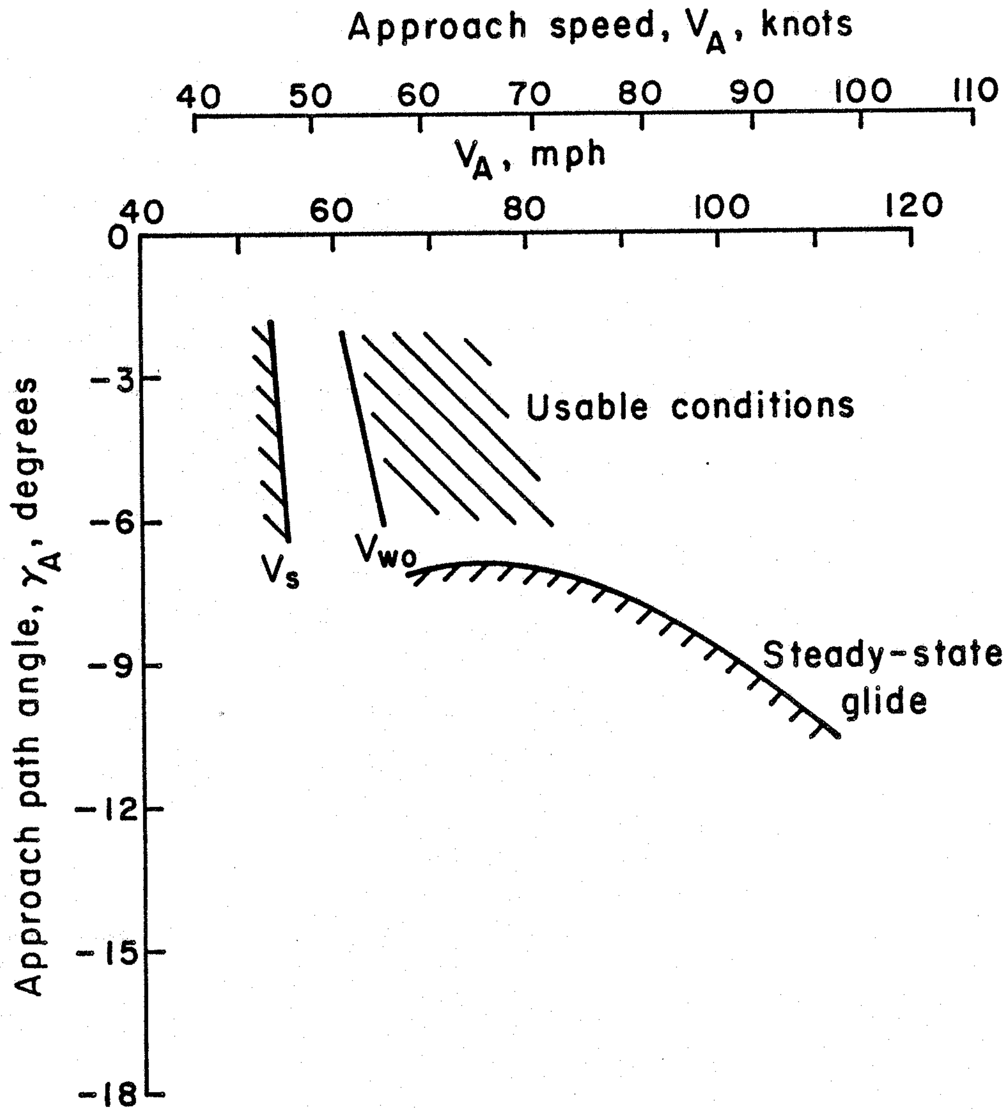


Figure 36.- Test aircraft usable approach conditions without spoilers; flap position = 35°

the flight path. At the same time, because of lower deceleration capabilities, the best approach speed for the "decelerate" 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 figure 36, they shrink into the small area at the upper left of the drawing.

Night VFR Conditions

A relatively short series of landings was made in the spoiler-equipped airplane with full flap deflection in night VFR conditions. The runway, with visual approach guidance, was the same as was used in the day VFR landing experiments. All of the night landings were made in conditions of clear visibility and no more than light turbulence, wind less than 10 knots (11.5 mph). They were all piloted by the same expert test pilot who evaluated sets of runs on a Cooper-Harper scale. Oscillographic recordings of airspeed, acceleration, and control positions, and notes on touchdown quality and accuracy, were made by the observer.

The spoiler controller was the semi-integrated type that had been judged so favorable for the day VFR conditions. The spoiler configuration was the upper and lower outboard set as previously described, except that the gearing and deflection of the lower plates were reduced. The ratio of upper to lower deflection, after these modifications, was approximately 2:1, with maximum deflections of 90° and 45°, respectively. With this configuration it is estimated that the drag authority of the spoilers was reduced perhaps 15% from the upper/lower outboard set of the day VFR landings. The lift change due to spoilers was essentially unaltered, and the trim changes were essentially neutral. The overall characteristics and response were judged by the pilot to be very favorable. The detailed performance and response characteristics were not documented separately as they had been for the inboard and outboard, upper and lower, original sets.

About 80 landings were done over a rather complete range of approach path angles (-3° to -12°) and airspeeds (54 to 87 knots; 62 to 100 mph). At the lowest approach speeds, the pilot used the "accelerate" technique; at V_{WO} he used "wheel only;" at V_{DEC} and above, he used the "decelerate" technique. These techniques were the most favorable ones for their respective conditions, and they all produced successful landings but, of course, with varying degrees of difficulty.

Landing performance.- The landing performance was almost indistinguishable from the day VFR case. The slow approach speeds, with "accelerate" technique, produced short landings with occasional hard touchdowns and occasional undershoots. Approaches at V_{DEC} speeds produced soft landings that were consistently in the landing

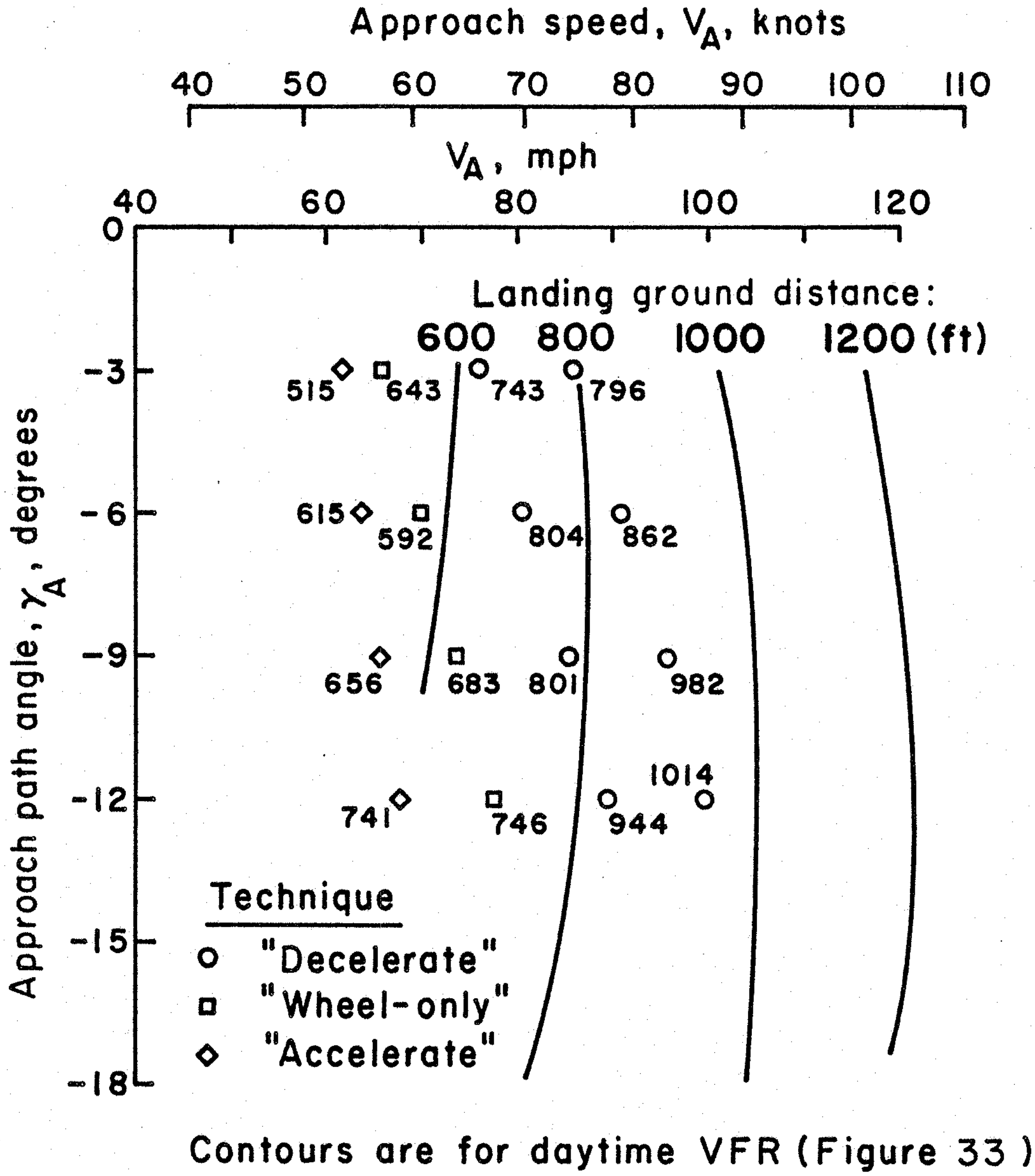


Figure 37.- Average landing distance for night VFR landings superimposed on contours for day VFR conditions; flap position = 35°

zone. There were no cases of excessive floating and no go-arounds.

For practical purposes, the landing distances previously discussed for day VFR conditions were duplicated in the night VFR case. Average landing distances for the various approach conditions are shown in figure 37 superposed on the contours of figure 33 for day VFR conditions. There is no significant consistent difference. Each number noted is an average of five landings. Dispersions within groups were about the same as for the day VFR case.

Pilot evaluations.- The pilot ratings and descriptive evaluations were very similar to the day VFR case. They were best at V_{DEC} approach speed and at shallow approach paths. They degraded at both slower and faster approach speeds and they deteriorated quickly with steepening approach angle. The Cooper-Harper ratings are shown in figure 38 superposed on the contours of figure 33.

At $\gamma_A = -3°$ the best rating at V_{DEC} is the same as for day VFR. The approach guidance lights are the same ones used for the day VFR landings and, with the runway edge lights, all the visual cues for the approach task are there. The approach tracking has the same quality and difficulty as under day VFR conditions. At this low approach angle, the landing light illuminates the landing zone and furnishes the proper visual cues needed for the flare. The whole task is equivalent to the day VFR situation. At speeds slower than V_{DEC}, the flare is more critical, airspeed control is crucial, and the pilot workload and rating go up. There is somewhat more stall margin for this spoiler configuration than for the one used in the day VFR experiment.

The day VFR runs were made with both inboard and outboard spoiler sets operative. At a given drag increment for a certain approach path, the reduction of $C_{L_{max}}$ is larger than for the spoiler sets of smaller span. As a result, the very slow "accelerate" runs in the night condition show less degradation than in the day VFR runs. At speeds higher than V_{DEC}, the higher rate of descent makes for slightly more difficulty and a slightly poorer rating. But the pilot emphasizes that the task is essentially identical to that for day VFR.

As the approach path angle is increased, the pilot ratings degrade rapidly. They are still best along the V_{DEC} line, but the piloting difficulty increases much more rapidly with increasing γ_A under night conditions than in daylight. The difference lies in the quality of the visual cues available to the pilot. If the visual scene (runway outline and landing zone) could be illuminated without restriction, then the night landing task would be equivalent to the day task, and the pilot ratings would be essentially the same. This is apparently the case for the low approach angle

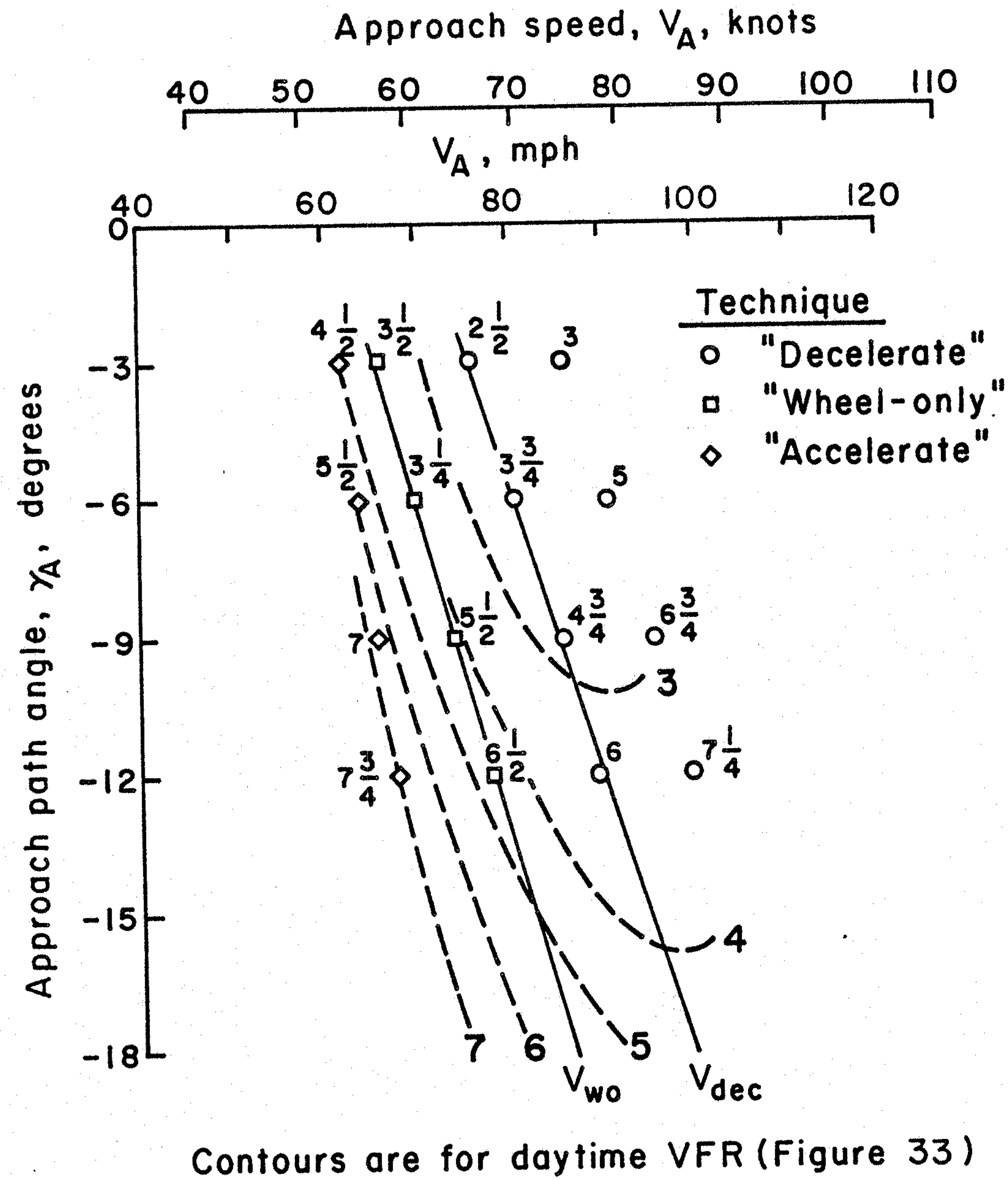


Figure 38.- Pilot ratings for night VFR landings superimposed on contours for day VFR conditions; flap position = 35°

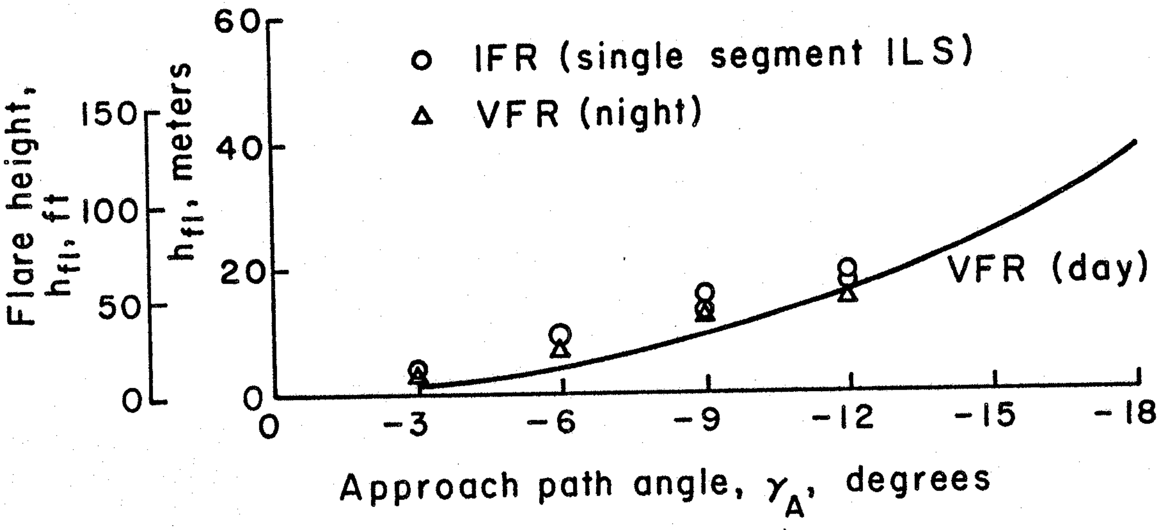
where the flare point is low and near the landing zone. The landing light is oriented correctly on the airplane and, with the landing zone within its range, the pilot has all the visual cues he needs to initiate the flare at the proper time.

As the approach angle increases, the flare point rises and moves away from the landing zone (for example, fig. 27, p. 76). At the same time, the aim of the landing light is increasingly short of the landing zone. As γ_A goes up, both the intensity and direction of the light become inadequate. Without proper visual cues for the flare, the piloting difficulty quickly builds to where adequate performance cannot be achieved and even safety is in doubt.

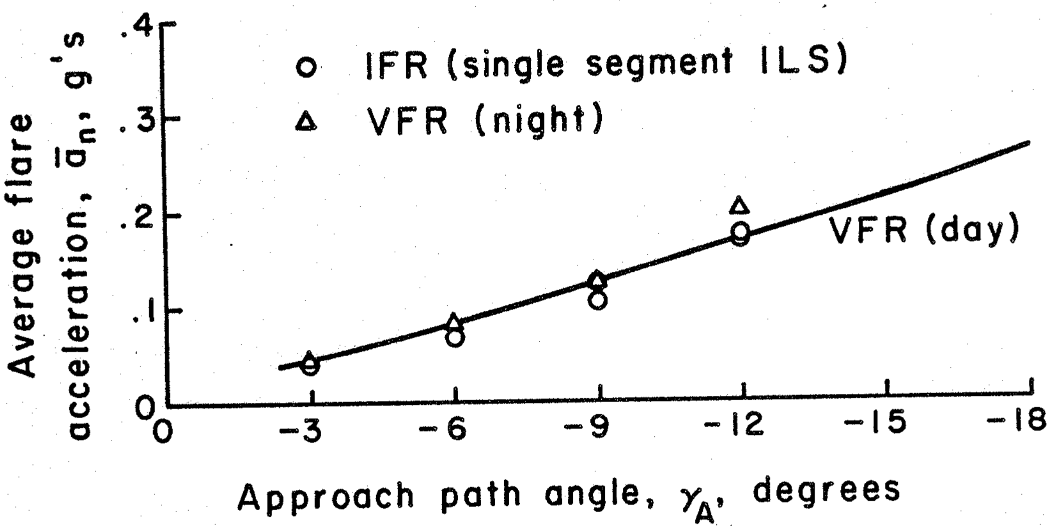
It must be emphasized that this problem is strictly a matter of lighting and, hence, relates to the particular lighting conditions of the experiment - which were about as bad as possible for the steep approach case. In the $\gamma_A = -12°$ case, the landing light is almost useless. The only visual cues for the flare are those of the runway edge lights, and these are inadequate for the task. Thus, the results shown here are not to be taken as characteristic of night operations. They simply illustrate the penalties of inadequate lighting.

The difficulties of these landings out of steep approaches with inadequate lighting may tend to suggest that spoilers are of little use to the pilot where some flaw like lighting has an overriding effect. Actually, quite the opposite is true. A few night landings were made with the test aircraft without using spoilers, under a no-landing-light condition. Of course, only the shallow approaches were possible. There was no comfortable compromise on approach speed or technique. Ratings based on workload would be in the moderately high compensation region, which might be expected under the circumstances. With compromised lighting conditions, however, the pilot using spoilers has good glide path control and has the ability to decelerate rapidly. Therefore he can select a safe approach angle and a comfortable airspeed without paying the penalty of excessive floating and he can "feel" for the ground, using the spoilers to maintain ground contact when it is made. Errors of timing and energy management can easily be corrected. Although the night landing with marginal lighting is a difficult affair even with spoilers, the improvement due to spoilers is judged by the pilot to be at least as significant as under day VFR conditions.

The characteristics of the night VFR landing flares are compared with the other cases in figure 39. In the middle range of approach angles, the flare height is somewhat increased and average deceleration somewhat decreased from the day case. This may reflect the poor visual situation and represent the pilot's attempt to compensate with an earlier, more cautious flare. This trend does not, however, extend to the higher approach angles.



(a) Flare height



(b) Average acceleration

Figure 39.- Flare data compared - night versus day (VFR) and IFR versus VFR (day); deceleration technique at V_{DEC}

The best pilot ratings at V_{DEC} are compared with other cases in figure 40. The rapid degradation and heavy penalty for inadequate landing lights are quite obvious. With better lighting, the -12° case could probably be improved from the marginally acceptable 6 rating to between 3 and 4, approaching the day VFR results.

IFR (Single-Segment ILS) Conditions

About 60 landings were done in simulated IFR conditions with various combinations of approach speed and path angle. The airplane and spoiler controller configurations were the same as for the night VFR landings just discussed. The real conditions were daytime, clear visibility, except that before the simulated breakout, the pilot was hooded in the manner typically used for IFR training exercises. At the simulated ceiling height, the pilot lifted his hood and transitioned to the real day VFR conditions.

The approach path guidance was an ILS raw data cross-pointer display operating from a microwave landing system. The transmitter was portable and could be tilted to produce any desired approach path (glide slope) angle. Runs were made with glide slope angles varying from -3° to -12°. ILS guidance was provided by a variable angle glide slope transmitter. Beam width sensitivity gave a full-scale glide slope deflection for 1° variations in approach angle and a full-scale localizer deflection for ±2.5° changes in azimuth. Cockpit readout of ILS position was presented on a standard cross-pointer-type flight path deviation indicator. There was no flight director or command information available; i.e., only raw ILS data were used.

The evaluation pilot for the IFR runs had been the observer in the day and night VFR experiment, and he had extensive piloting experience in the spoiler-equipped airplane under various conditions. His qualification for the IFR conditions were complete, with extensive flight experience in real instrument flight conditions and light aircraft.

In this part of the experiment, separate ratings and commentary were assigned to the various parts of the whole landings. There were approach, breakout transition, and flare.

Approach tracking.- Without spoilers, the task of tracking the approach path under IFR, using only the localizer and glide slope needles of the ILS display, was judged to be noticeably more difficult than the corresponding task in day VFR. The rather sluggish response of flight path to throttle calls for considerable lead compensation in the glide slope loop. This produces a workload situation leading typically to pilot ratings in the 4 to 5 range (ref. 29). With the integrated spoiler/throttle controller, the response to control is much more direct and immediate. This was

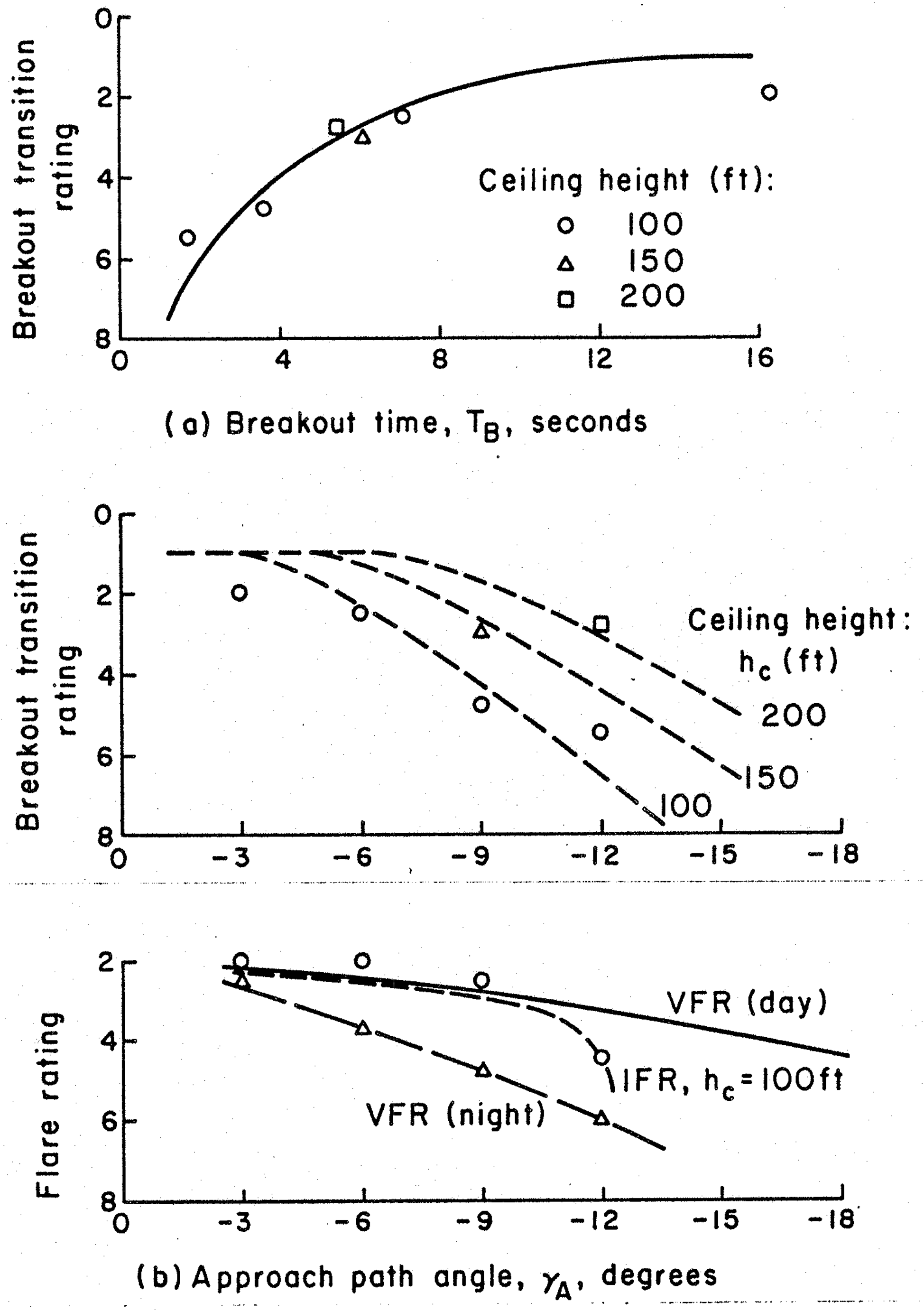


Figure 40.- Pilot evaluation of flare under various conditions

discussed extensively in a previous section. The pilot comments that with spoilers the glide slope tracking task requires some lead compensation, but it is minimal. The task is almost as easy as in day VFR. He consistently assigns ratings of 3 or better. As in the night landings, the improvements due to spoilers are again significant.

Breakout transition.- At the simulated ceiling height, the pilot lifted the IFR training hood, looked up and outside, and executed lineup, flare, and touchdown with outside, VFR-type references. The region between the ceiling height and flare initiation is arbitrarily called the breakout transition or, simply, transition. For the workings of the pilot, it has to be a transient change from IFR to VFR mode of control and from one set of cues to another. It is the period within which he must acquire and assimilate the new visual cues, process the information, predict and decide about vertical and lateral path corrections prior to flare initiation. The difficulty depends strongly on the time available. The time available is easily estimated from the rate of descent on the approach path (glide slope) and the altitude difference between ceiling height and the flare point. Pilot ratings of the breakout transition task are shown in figure 40a as a function of the estimated time interval. The data points involve conditions with variations of approach path angle and ceiling height.

The pilot commentary makes it very clear that these ratings reflect his judgment about the time available. As the time approa approaches infinity - increasing ceiling height and/or decreasing approach angle - it is plausible to fair the curve to a rating of 1 for a highly desirable situation. As the time approaches a fraction of a second, with no opportunity for decision or action, it also seems plausible to fair the curve towards a rating of 10. From the intermediate range, it looks as though the pilot needs about 2 seconds to consistently and dependably complete the task with maximum compensation (rating 6.5) or about 5 seconds to do it in a way that is comfortable and satisfactory without improvement (rating 3.5). In terms of approach angle and ceiling height, the pilot rating function is given in figure 44b. The dotted lines are derived from the previous curve and the calculated estimate of time available. They seem to fit the data points without serious conflict. It is indicated that ceiling heights of 61 m (200 ft) are satisfactory (rating 3.5) even at the steep approach angle (-12°). At this approach angle, the minimum acceptable ceiling height (rating 6.5) is of the order of 30 m (100 ft).

Flare and Touchdown.- The landing distances for the IFR runs are shown in figure 41 superposed on the contours of figure 33 for day VFR. There does not appear to be any consistent or meaningful difference between the two cases. At the very slow speeds with "accelerate" technique, there were some hard touchdowns and slight undershoots. With "decelerate" technique, the landings were soft,

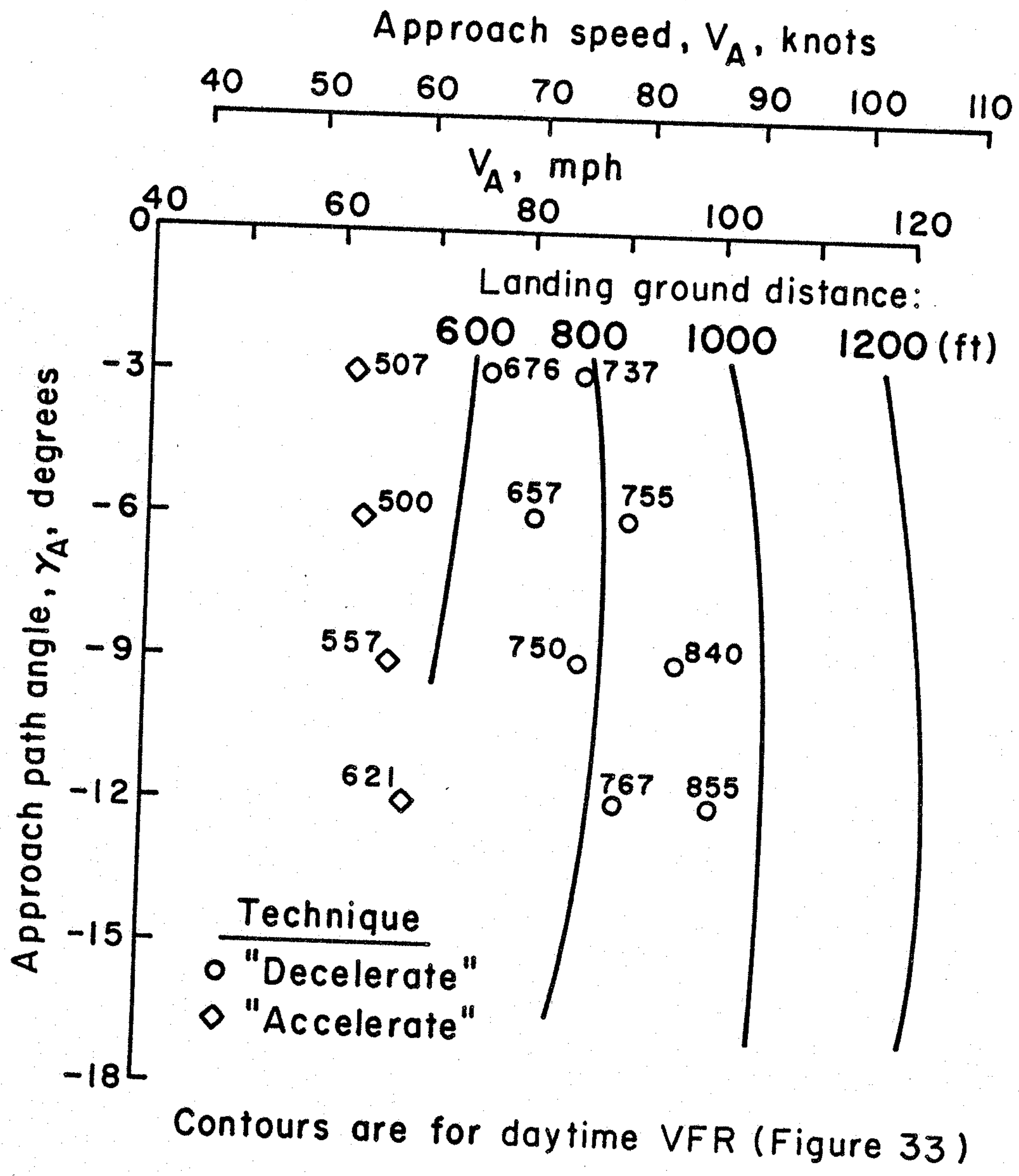


Figure 41.- Average landing distance for day IFR landings superimposed on contours for day VFR conditions; flap position = 35°

within the touchdown zone, and there were no go-arounds. In spite of the difficulties of landing in some of these conditions and their poor ratings, the pilot was able to achieve excellent performance over the entire range of conditions.

Average flare characteristics for the IFR landings are shown in figure 39 along with those for VFR, day and night. The differences appear to indicate a slightly higher, more gradual flare in the intermediate approach angle range (-6° to -9°). This may reflect pilot compensation for poorer cues and shortness of time after breakout. Then at -12°, the flare height seems to level off. Perhaps for this case at the high descent rate and the low ceiling, time after breakout is too short to initiate the flare any sooner!

Pilot ratings for the flare and touchdown for a ceiling height of 30 m (100 ft) are shown in figure 42 superposed on contours of overall ratings from figure 33 for day VFR conditions. The trends indicated are very similar, although certain differences are apparent. It again seems that approach speeds near the previous V_{DEC} are the best at given approach angles. At approach speeds below V_{DEC}, the rating degrades for the same reasons that apply for VFR conditions. The degradation is not quite as severe as in the former case of day VFR - probably because with this spoiler configuration, as in the night VFR case, the stall margins are a little higher. At approach speeds higher than V_{DEC}, however, the ratings degrade a bit more rapidly than under the former conditions. The commentary suggests that under IFR conditions the pilot cannot use the deceleration capability of the spoilers quite as readily as in VFR. Perhaps it is because this spoiler configuration is smaller and less effective than the one for the day VFR evaluations. Possibly it is because at higher speeds and low breakout heights the time available to assimilate the visual cues needed to fully use the spoilers is shorter. At any rate, for this configuration and these conditions, the V,γ envelope is a little less open than for day VFR.

In figure 40 are shown the optimum ratings (along V_{DEC}) as a function of approach path angle. The backdrop, for comparison, has the corresponding overall ratings for day VFR and night VFR cases. Up to an approach angle of -9°, the IFR ratings are essentially the same as for day VFR. The pilot commentary indicates that although there are some problems with the breakout transition that require compensation, in the flare itself conditions are essentially VFR and receive the same rating. This suggests that in those cases the transition to VFR cues is entirely completed by the time the flare point is reached. In the more extreme case of approach angle of -12°, there is a sharp degradation of pilot rating. The commentary suggests that here the shortage of time in the breakout is so severe that the resulting problem carries over into the flare itself. Although pilot ratings were not assigned for several approaches made with increased ceiling heights, the commentary makes clear that they would quickly approach day VFR ratings.

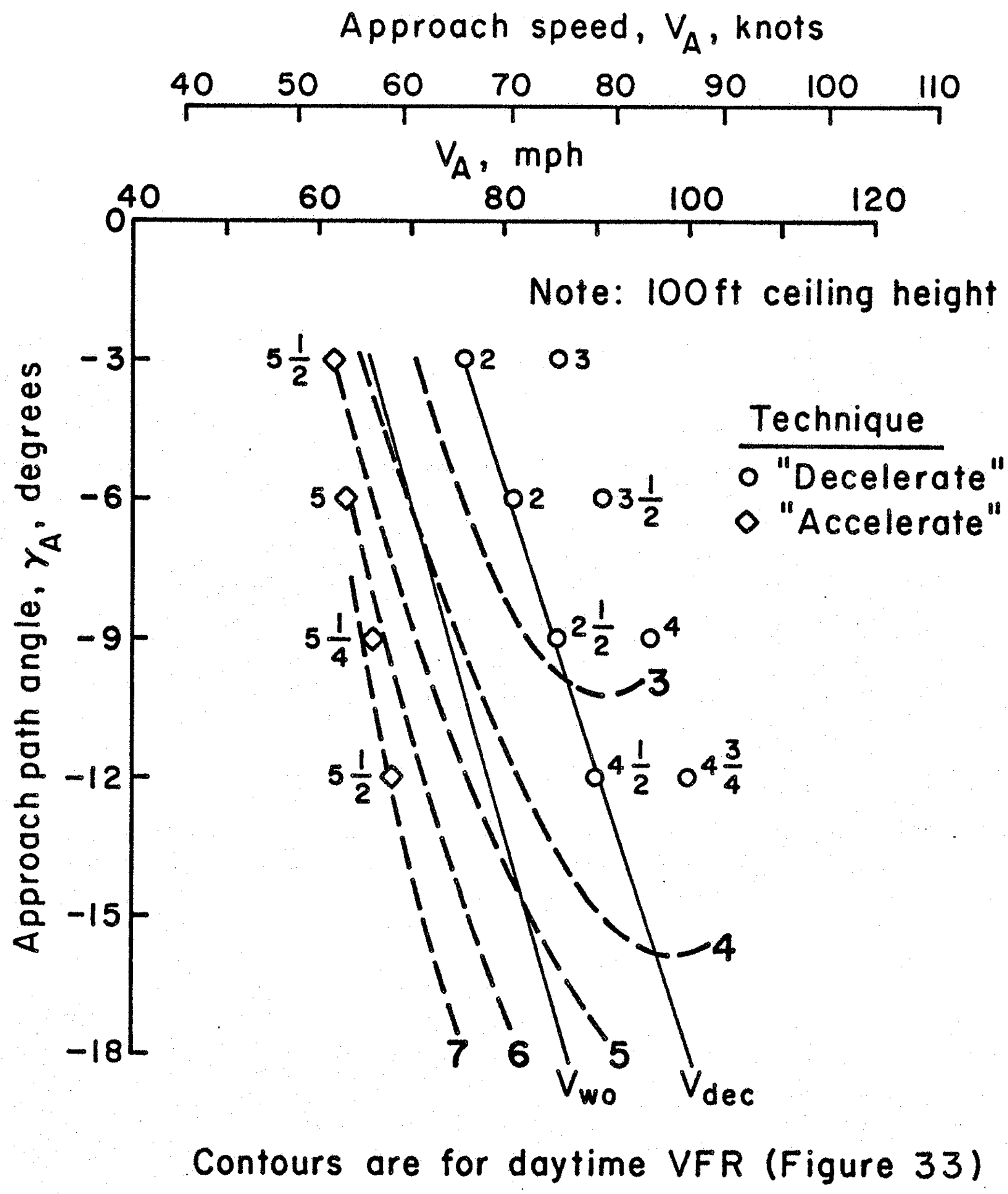


Figure 42.- Pilot ratings of flare under IFR conditions superimposed on contours of day VFR; flap position = 35°

Although the basic nonspoiler airplane was not extensively evaluated in this experiment, enough runs were made at $\gamma_A = -3°$ and -6° to permit some comparison with the spoiler-equippped machine. The commentary cites a "lack of go-down capability" which was especially critical for the -6° approaches, since this is close to the maximum steady-state descent capability at normal approach speeds. It was also noted that precise speed control was more difficult with the nonspoiler configuration. For higher approach speeds (above the no-float speed of V_A = 70 knots (81 mph) but typical of normal IFR operations), the evaluation pilot missed the after-breakout deceleration capability and suppression of floating afforded by the spoilers.

The spoiler/throttle system allows the pilot to approach at the best airspeed with a margin of flare energy and controllability, without floating. It increases the margins of error all around. Its ability under IFR to open the V,γ window is limited only by considerations of breakout transition time. The overall improvement due to spoilers is at least as significant as in day VFR.

DAY VFR LANDINGS BY PILOTS OF VARIOUS EXPERIENCE LEVELS

Background

The initial phase of the program demonstrated that significant landing task performance and flying qualities improvements were possible when spoilers were utilized. Since these preliminary conclusions were based upon flights conducted by two professional evaluation pilots, a Phase II study was conducted to determine whether the favorable initial results also applied to a broader class of pilot experience levels.

Evaluation flight tests were conducted to determine how three groups of general aviation pilots with three fundamentally different levels of flying experience performed when they were exposed to a spoiler-equipped aircraft for a short period of time. While the objective of flying with each group was identical, specific questions to be answered for each differed slightly, as noted below.

1. Would student pilots experience any difficulty following a presolo syllabus in a spoiler aircraft? How would their performance after approximately 10-12 hours compare qualitatively with nonspoiler students?

2. What performance improvements and what potential hazards were likely to be experienced by a group of relatively low-time pilots transitioning to a spoiler-equipped airplane? Could they adapt to spoilers and use them safely and beneficially?

3. What level of precision landing performance would two advanced pilots achieve with the spoiler aircraft? Would they realize a performance increase compared with the basic aircraft?

Twenty subjects, consisting of two advanced pilots, eight relatively low-time private pilots, and ten student pilots (six with no previous flying experience), were selected from 53 respondents to an announcement requesting participants for a flight evaluation program. A copy of the announcement, which was posted at eight airports and several flying clubs within 50 miles of the contractor's home base, is presented in Appendix B. While the three groups consisted of volunteers selected from a small geographical area, the individual subjects appeared to be reasonably representative of typical general aviation pilots, so the results of the evaluation should apply, at least qualitatively, to other pilots with similar experience.

General Spoiler Operating Procedures

When the spoilers were operational, they were controlled by means of an integrated controller, as previously discussed. Three private pilots flew with the single lever controller; the remaining subjects, including all the student pilots, used the split-handle controller. All subjects were advised that the throttle controlled the spoilers and that they could expect the aircraft to descend quite rapidly when power was reduced. Airspeed was controlled by the longitudinal control; the throttle setting determined rate of climb or descent and the glide path angle. No unconventional flying procedures were used. The recommended approach was to plan for a glide path about as steep as a normal power-off landing but to expect to use some power to achieve the desired glide angle. The flaps were set at 15° throughout the entire task, including take-off, climbout, approach, and landing. Therefore, the spoiler approach was similar to a power approach, except that the approach angle was steeper and once the flaps were deflected to 15°, they could be ignored. Power was reduced to idle as the flare was initiated in order to prevent floating and to achieve positive touchdown control. After touchdown, the pilot could use the full spoiler deflection associated with the post-idle or split-handle operation of the integrated controller to achieve firm rollout posture.

The subjects were told that an indicated airspeed of 74 to 78 knots (85 to 90 mph) (V_c = 72 to 77 knots (83 to 89 mph)) was the recommended approach velocity, but that any speed between 74 and 87 knots (85 and 100 mph) was acceptable provided they used a throttle reduction to kill any floating tendency that resulted from fast approaches. The pilots were cautioned not to make their approaches too slow (V_i = 74 knots (85 mph) was considered the minimum approach speed with 15° flaps). The 74 knot IAS provided a speed margin of 1.4 times the 15° flap, zero spoiler, power-off stalling speed, and 1.3 times the 15° flap, 70° spoiler, power-off stalling speed.

If the pilot was extremely high on his initial approach, he could use the post-idle range to lose the excess altitude and locate himself on a more suitable glide path. He would apply full spoilers, by means of the integrated controller, and lower the nose to increase airspeed to approximately 87 to 87 knots (95 to 100 mph). The extra airspeed was recommended for two reasons: 1) it provided for rapid altitude loss due to the large negative value of $\partial\gamma/\partial V$ associated with full spoilers; 2) it assured the pilot of sufficient speed with which to flare if he inadvertently continued the use of full spoiler into the final portion of the landing. Using this "grossly too high" technique, the pilot could easily locate himself on a glide path from which a normal spoiler approach with some power could be made. Subjects were urged to be aware of the possible need for gross corrections and to make them early in the approach, and they were advised not to use the post-idle range below 91 meters (300 ft) unless the aircraft's wheels were on the ground.

Student Pilot Group

Subjects.- Of the 53 respondents, 14 were student pilots whose schedules would allow participation in the program. Of the ten selected, six had no previous flying time, one had 16 hours including 4 hours solo in a conventional gear aircraft eight years earlier, and three were in various post-solo stages of their Private Pilot training. The group appeared to be representative of student pilots one might encounter in the east, particularly in a college town. Two subjects were college students, three were engineers, one was a secretary, one was a labor union executive, one was a draftswoman, one was a securities analyst, and one was an auto mechanic. Eight of the ten subjects were college graduates.

Procedures and Syllabus.- The objective of the student phase of the program was to evaluate, from an instructor's viewpoint, how a novice pilot would react to spoilers. The emphasis was on a qualitative assessment of student performance rather than on obtaining quantitative precision landing data. Flight instruction and student assessment were provided by the A.R.A.P. program manager who holds a current Certified Flight Instructor license and has given over 2500 hours of dual instruction, including approximately 300 hours in aircraft of the same basic type as the test vehicle. Having been involved with the spoiler program since its inception and having served as one of the evaluation pilots in previous phases of the program, he was thoroughly familiar with the characteristics of the spoiler-equipped aircraft.

Student subjects were offered approximately 10 hours of flight instruction which adhered to a syllabus that conformed to the presolo training phase requirements of the Primary Flying School Curriculum contained within FAR Part 141 (refs. 30 and 31). No special provisions were made to accommodate the use of a spoiler-equipped aircraft, and the spoilers were operational throughout the students' entire flight program. Appendix C contains a list of the maneuvers covered by the student subjects. The seven of the ten students who were not currently undergoing flight training elsewhere were given all of the presolo flight maneuvers, from familiarization through takeoffs and landings. The three students in various phases of their post-solo training were given a review of turns, slow flight, and the complete stall series before turning to takeoffs and landings.

The use of flaps per se was not included in the student program. Flaps were regarded solely as a downwind checklist item. They were deflected 15° on downwind and then left in that position for all pattern flying, including takeoffs, touch-and-goes, and go-arounds. Slips were not demonstrated to the student pilots.

In order to obtain an independent third-party assessment of student performance, an experienced flight instructor and professional aviator not associated with either NASA or A.R.A.P. flew with nine of the ten student pilots after they had completed their spoiler evaluation program. (Only nine of the students were available for the third-party review; the tenth had already obtained his private license and was considered to be very proficient in flying the spoiler aircraft.) This outside instructor made his own qualitative assessment of their progress based upon previous experience with student pilots who had flown the same type of aircraft without spoilers.

Approach.- The students appeared to have no unusual difficulty learning to fly fairly precise approaches with the spoiler aircraft. In spite of their limited experience and abilities, each subject was able to modulate the approach trajectory with sufficient accuracy to consistently land within 152 meters (500 feet) of the runway threshold. Since the objective of the student evaluation was to complete a presolo syllabus, specific precision landing tests were not part of their program. At the completion of the evaluation, however, the likelihood of a student's approach resulting in an overshoot or go-around was extremely low.

All of the students were able to use the entire range of the spoilers advantageously during approach. If they were too high, they remedied the situation by reducing throttle setting and they used the split handle feature if needed (i.e., full spoiler deflection). When they were in position for a normal approach, they recognized it and applied enough power to track the appropriate glide path. The better students were more prompt in observing when an approach path correction was needed, and they had smoother glide path modulation skills, but even the least proficient student was able to recognize a problem approach and correct for it safely and with reasonably good results. In fact, those students whose approach judgment was poor probably received the most impressive benefits from using the spoilers.

Students with previous flight training had an initial tendency to allow the approach to become too flat ($\gamma < 3°$) with the result that they were not receiving the full modulation capability of the spoilers. Flat approaches required the student to operate the spoilers in the small opening range with its associated pitch response. Also, correcting for an undershoot from an approach that was already too shallow often meant the spoilers would close as the throttle correction was applied, and the loss of spoiler γ response caused slight over-controlling with subsequent spoilers-closed throttle corrections. Furthermore, a shallow approach meant that a larger throttle reduction was necessary to transition from the approach to the flare and touchdown. The willingness to accept or gravitate into a shallow approach was also noticed with the initial spoiler landings made by the private pilot subjects. Students with no previous flight training flew 5° to 6° glide paths from the start of their pattern work and, as a result, they learned to utilize the spoilers to maximum advantage rather quickly. Because of the tendency of some student and private pilots to make very shallow approaches, and because of the loss of desirable spoiler response characteristics associated with small openings, the spoiler engage point was increased from 1800 to 1900 rpm. Previous spoiler controller evaluations indicated that between 1800 and 2000 rpm spoiler engagement was optimum. The idle spoiler deflection remained at 40° so the spoiler gain was reduced slightly. The increased engage point made the landing task easier for those subjects who occasionally would find themselves in a very shallow approach.

Flare and Touchdown.- The student pilots who had no previous flying time learned to land the spoiler aircraft without unusual difficulty, and the students with previous experience also handled the flare and touchdown tasks easily. The student subjects were able to coordinate the throttle reduction with the flare maneuver with satisfactory results, and they used the post-idle or split handle range very effectively to keep the aircraft firmly on the ground after touchdown.

Good landings with the spoiler aircraft basically required the same depth perception that was needed to land a conventional aircraft. Those students who were able to judge flare height properly and could coordinate the addition of back pressure on the longitudinal control with the nearness of the aircraft to the ground were able to make good tail-low and soft landings repeatedly. They would flare at a normal height, reduce power, and follow through with back pressure on the control wheel in order to land at a minimum speed. Once on the ground, they would split the throttle/spoiler handles and achieve a favorable rollout posture with the aid of full spoiler deflection. Their landings were good and, during the evaluation flights with the independent flight instructor, none of the hardness values for the better student pilots exceeded 1.3 g's. Students with good landing judgment probably would fly a conventional aircraft well also. The student whose height perception was erratic and somewhat typical of the beginner benefitted from the spoilers, however. Ballooning was suppressed with the application of spoilers in the flare, so the student who tended to overreact on the pitch control found the spoilers helpful. The student who touched down flat used the split handle range to prevent a bounce or wheelbarrow problem. Once the wheels were on the ground and the spoilers were fully deflected, the critical aspects of a student's inadequacies in perception and coordination were lessened with spoilers.

Students were taught to use the post-idle or split handle range when the aircraft's wheels were on the ground. They all responded well to that technique, and no accidental split handle operations occurred. The independent flight instructor remarked that all of the student pilots used the spoilers safely in the flare, and that all their touchdowns resulted in positive rollout posture due to the deployment of full spoilers after ground contact was made. Several subjects mentioned, however, that they were concerned they might deploy full spoiler deflections prematurely in the flare. Occasionally they would use small amounts of the split handle range to kill a prolonged float, and the more advanced students probably would be tempted to use post-idle throttle settings in the flare as they developed confidence. Therefore, some form of split handle damper that would prevent gross post-idle operation might be desirable.

Crosswind and Gusty Conditions.- Because of the relatively precise touchdown control that the student pilots could achieve with the spoiler aircraft, it was possible to teach them how to make crab-type crosswind landings. The students would establish a crab angle on approach that compensated for the crosswind. Glide path modulations were made in the normal manner and the effects of gusts and vertical disturbances were countered by appropriate changes in throttle setting. The students would hold the crab angle through the flare and then attempt to decrab when they anticipated the touchdown. Since the touchdown occurred in close harmony with throttle reduction, they could achieve reasonably good results.

Frequently the students were deficient in accomplishing a perfect decrab maneuver and thus would contact the ground with a slight upwind yaw angle. Ground contact, however, was with the rear wheels only and the aircraft's dynamics at touchdown would straighten out the aircraft. Furthermore, since the flare rarely resulted in a prolonged float, there was little opportunity for sideways drift to develop if the crab function was not handled properly. Using the split handle to deploy the spoilers fully after ground contact, the initial rollout was positive and there was no possibility of the crosswind lifting the upwind wing. Even awkward ground contact resulted in a reasonable rollout once the spoilers were fully deployed.

The approach airspeed used with the spoiler aircraft provided ample speed margin to compensate for wind shear effects close to the ground. If the winds were strong or gusty, however, the students were advised to approach about 5 knots faster (i.e., about 78 to 82 knots (90 to 94 mph)) if they felt uncertain about their airspeed or lateral/directional control. Once the subjects had reached a reasonable degree of presolo proficiency with the spoiler landing technique, they were able to maintain their landing proficiency under conditions that on occasion reached crosswinds of 60° to 90° with gusty winds between 10 and 15 knots (12 and 17 mph).

Rollout.- The students experienced no difficulty with the rollout phase of landing. Once the aircraft was on the ground, they would split the throttle/spoiler handle to deploy the spoilers to their full extent and then apply the brakes as necessary. Their rollouts were firm and directional control was no problem. Rollout distance performance was similar to the private pilot results. The subjects commented that the split handle operation presented no confusion.

Go-Around or Balked Landing.- The easy go-around capability of the spoiler aircraft offered the student pilots a means of correcting for gross errors they might make during the approach or flare. Merely by opening the throttle, they could transition from a poorly executed flare into a go-around. Thus they developed confidence that they always had a means for recovering from any mistakes they made. The independent flight instructor commented on the ease with which the students executed effective touch-and go-landings, and he said the one go-around made by a student during his evaluation was handled nicely.

Overall Performance Attained.- While some subjects demonstrated a greater aptitude towards flight than others, all of the ten students in the program had no difficulty in achieving performance consistent with, and in some cases better than, the competence the program manager/flight instructor expected from average student pilots prior to solo. The three students who had soloed a conventional aircraft of a different type and were actively pursuing a private license were thought to be capable of solo flight within 2 to 3 hours of the start of dual flight time in the spoiler aircraft. Five of the remaining students were considered capable of solo after completion of the 10-hour evaluation program. The two remaining subjects required approximately 30% more dual instruction than the others in order to reach the same level of performance. In the opinion of the program manager/flight instructor, the slower subjects demonstrated higher proficiency with the spoiler aircraft than he would have anticipated from them had they been flying a basic aircraft of the same type.

In the judgment of the independent instructor, the subjects flew the spoiler aircraft "as well as or better than" students with equivalent flight time in basic aircraft of the same type. He felt "the spoilers added no additional complexity, and they reduced the level of difficulty normally associated with the approach and landing task." In his evaluation of the student pilots, only one of approximately 50 approaches flown resulted in a go-around and that was attributed to the desire of the student to make a fresh start rather than patch up a potential grossly-too-high situation. All of the other students, however, were able to handle each situation that arose, including various approach problems. Those special tasks or challenges included right-hand approaches (not covered previously in their program), approaches initiated from a much higher than normal altitude, and approaches initiated from a much lower than normal altitude. He felt that a similar group of student pilots flying a basic aircraft under similar conditions would have produced far less precise landing results, and they would have had significantly more go-arounds. He also stated that each subject had good control of the approach at all times, and they were able to handle the spoilers in all flight modes safely and with confidence.

Licensed Pilot Group

Subjects.- For the private pilot group, only pilots who had flown less than 20 hours in the last year or had minimum experience by virtue of recently receiving a private license were considered acceptable for eventual selection. Twenty-eight respondents satisfied those criteria, and a group consisting of seven pilots with an average of 11 hours experience during the previous year and one pilot who had recently received his private license were chosen at random. The average total flight time for the group was 174 hours; three subjects had previous experience in the type of aircraft used for the spoiler evaluation program, but none had previous flight time using spoilers. As a group, they were considered to be representative of private pilots who fly relatively infrequently.

As representative of advanced pilots, two individuals were selected from seven respondents who had over 1000 hours of flying time. One was a professional free-lance aviator who held an Airline Transport Pilot license and was a qualified F-105 pilot for the Air National Guard. His total flying time exceeded 3300 hours. The other subject was an experienced flying qualities research pilot and was carrier-qualified with the U.S. Navy Reserve. His total flight time was approximately 5000 hours and he had recently returned from his two-week summer tour with the Navy. Both men were experienced general aviation pilots, and their ability to handle the light aircraft landing task was considered excellent.

Procedures and Syllabus.- The private and the advanced pilots participated in a precision landing task. Each subject was asked to land on a preselected spot approximately 213 meters (700 ft) from the runway threshold, and any normal technique, such as a combination of throttle, flaps, speed control, slips, etc., could be used to produce the desired result. The program manager accompanied each subject, and he served as a safety pilot and data collector during the flight. He also provided dual instruction as required for safety and understanding.

Performance for landings with and without the spoilers operational was obtained. The task for both configurations (i.e., basic and spoiler aircraft) was identical, and the subjects were not asked to modify or restrict their landing technique just because they were flying a different configuration. Each subject was offered demonstration landings, but in no case did a subject request more than 3 demonstrations per configuration. No particular emphasis was placed on rigid checkout procedures since an objective of the evaluation was to assess how low experience-level pilots with minimal special training would react to a spoiler-equipped aircraft.

The selection of whether a subject started with the basic aircraft or the spoiler aircraft was determined by a toss of a coin. Three private and one advanced pilot started with the basic aircraft; the rest of the subjects started with the spoiler aircraft. The determination of when to transition from the basic to the spoiler aircraft, or vice versa, was made by the program manager based upon the degree of consistency he felt the subject had achieved. When the pilot did not seem to be improving his performance noticeably with additional practice, the switch was made.

Simulated power-shutdown forced landings were included in the landing task program for 6 of the 8 private pilot subjects and for one of the two advanced pilot subjects. These were flown after the subject had completed his basic and spoiler aircraft landings and thus had achieved a level of consistency based upon approximately two hours with each configuration. A 360° overhead approach from 609 m (2000 ft) above the runway was used to achieve a "dead stick" landing to the target. Half the emergency landings were done with the basic aircraft and half were with the spoiler aircraft. The choice of which type would be conducted first was made by the subject. For the basic aircraft configuration, idle power was used to simulate the emergency. For the spoiler case, the engine was shut down with the idle cut off, and the propeller was allowed to continue windmilling. Thus, with the spoiler aircraft, the subject could use the throttle to achieve glide path control, although no power was available to correct for an undershoot.

Data collected consisted of touchdown dispersion, touchdown hardness, qualitative comments on landing task performance, and spot checks of rollout distance. Runway position markers were located at 30 m (100 ft) intervals on both sides of the desired touchdown mark, and the point of touchdown was observed by the program manager from inside the aircraft. The error in touchdown position and rollout distance, using the above method, was estimated to be approximately 25 feet. Touchdown hardness was measured by a recording accelerometer located on the nonshock-mounted portion of the aircraft's instrument panel and noted by the program manager after each landing. Although the location of the recording accelerometer and the precision of the instrument precluded an exact measurement of vertical acceleration experienced by the main landing gear, the accelerometer readings provided a reasonable means of assessing the relative hardness of each landing.

Precision landing performance.- As shown in Table IX and figures 43 and 44, the use of spoilers significantly improved the touchdown accuracy of the private pilots and had a noticeably beneficial effect on the advanced pilot results. It is interesting to note that, using spoilers, the low experience-level pilots achieved touchdown accuracies equal to or slightly better than the results produced by the very experienced pilots flying the basic aircraft.

Comparing the data in figure 43 for the private pilots, it is clear that the character of the touchdown dispersion distributions differs noticeably between the basic and spoiler airplanes, although the task, subjects, and test procedures essentially were identical. While both distributions have the same mode and both are skewed in favor of an overshoot, the number of on-target landings was doubled using spoilers, and the mean overshoot was reduced to 41.4% of the basic aircraft mean. The spoiler airplane landing dispersion range was also reduced to less than half the basic aircraft value - 42.2% to be exact. The spoiler data distribution was more peaked, as indicated by a spoiler standard deviation that was only 45.6% of the basic aircraft results. Equally significant was the lack of any go-arounds with the private pilot spoiler landings, compared with 4 go-arounds due to overshoots with the basic aircraft.

The results presented in Table IX and figures 43 and 44 are based upon all the landings flown by each group with each configuration. No allowances were made for inaccuracies resulting from the subjects' lack of familiarity or training with the basic aircraft or with the spoilers. As can be seen in the representative landing histories for one private pilot and one advanced pilot (fig. 45), the subjects did improve with practice. Most subjects reached a relatively consistent level of performance after about 15 landings with the basic aircraft and about 20 landings with the spoiler configuration.

TABLE IX.- LICENSED PILOT PRECISION LANDING SUMMARY-PERFORMANCE

	Private Pilots		Advanced Pilots	
	Basic	Spoilers	Basic	Spoilers
Touchdown Accuracy:				
Dispersion mode	0	0	0	0
Frequency of mode	11%	22%	22%	43%
Mean dispersion	36.9 m (121 ft)	15.2 m (50 ft)	16.5 m (54 ft)	12.8 m (42 ft)
Dispersion range	541.0 m (1775 ft)	228.6 m (750 ft)	251.5 m (825 ft)	137.2 m 450 ft)
Standard deviation	90.2 m (296 ft)	41.2 m (135 ft)	49.1 m (161 ft)	24.7 m (81 ft)
Number of events	150	209	36	42
Go-arounds[a]	4	0	1	0
Touchdown Hardness:				
Hardness mode	1.2 g	1.2 g	1.2 g	1.2 g
Frequency of mode	30%	23%	28%	29%
Mean hardness	1.41 g	1.44 g	1.31 g	1.36 g
Hardness range	2.1 g	1.9 g	0.8 g	1.1 g
Standard deviation	0.35 g	0.29 g	0.18 g	0.22 g
Number of events	165	233	36	42

[a]Go-arounds not included in measures of location or dispersion

As a group, the advanced pilots doubled the percentage of on-target landings using the spoiler aircraft. Their reductions in dispersion range and standard deviations were 54.6% and 50.3%, respectively, or approximately the same percentage decrease experienced by the private subjects. The mean dispersion decreased to only 77.7% of the basic airplane value, however - a smaller reduction than that achieved by the private pilots.

Approach.- The program manager's assessment of the fundamental approach flying skills of the licensed pilots is shown in Table X. While spoilers had no effect on such important fundamentals as judgment and planning, they did provide the inexperienced pilots with a safe and effective means of correcting for approach errors arising from their low skill levels. Airspeed control for the private pilot was improved with spoilers. Large flap deflections were not used so there were no trim changes due to flaps or power/ flap interactions. Furthermore, the pilot could select a safe

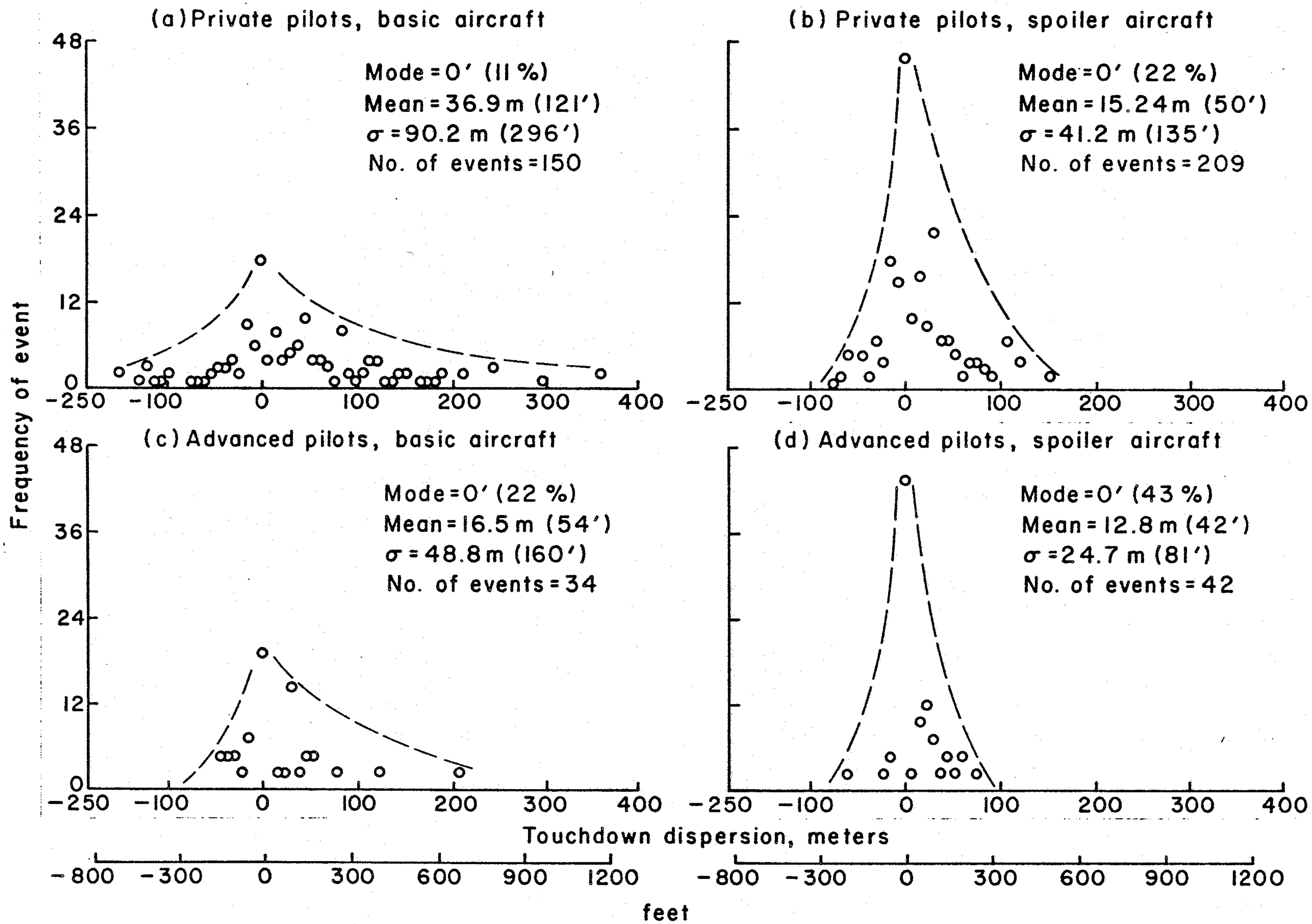


Figure 43.- Licensed pilot landing performance survey; touchdown dispersion

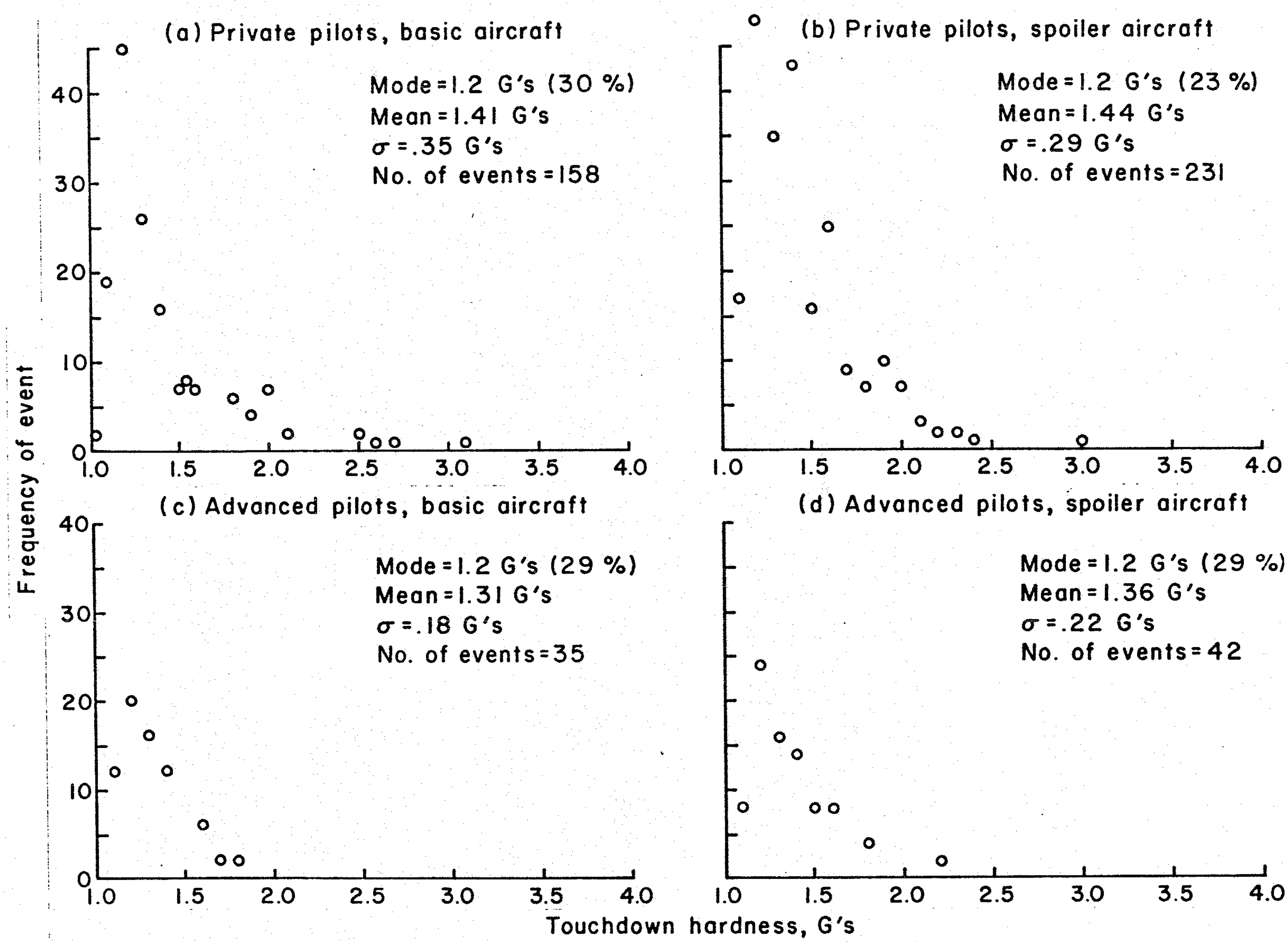


Figure 44.- Licensed pilot landing performance survey; touchdown hardness

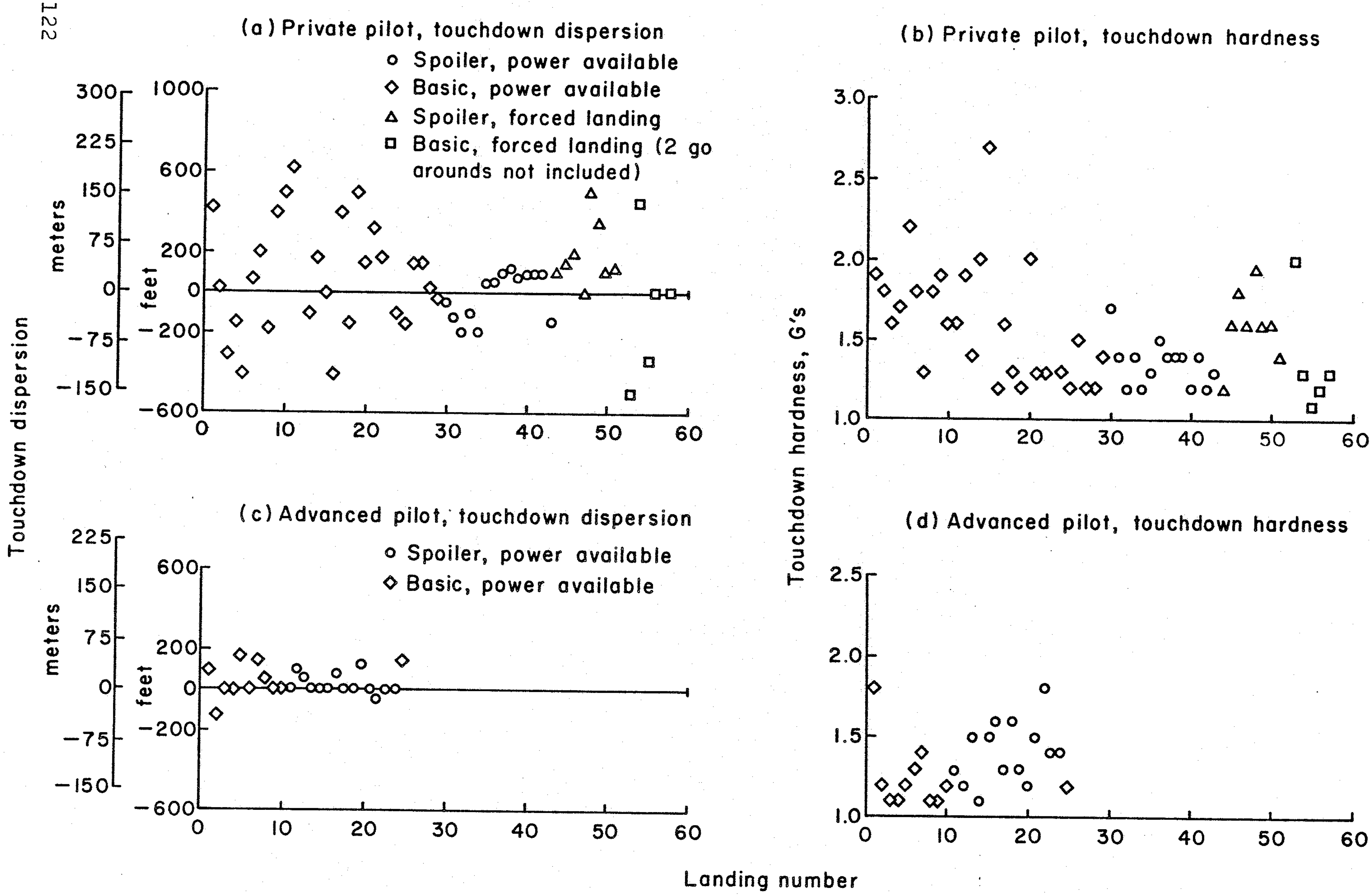


Figure 45.- Licensed pilot landing performance history (typical)

speed margin with good control and then modulate his glide path without concern that he might become too slow.

TABLE X.- LICENSED PILOT PRECISION LANDING SUMMARY - APPROACH

	Private		Advanced	
	Basic	Spoiler	Basic	Spoiler
Judgment	Fair	Fair	Excellent	Excellent
Planning	Fair	Fair	Excellent	Excellent
Airspeed Control	Fair	Good	Excellent	Excellent
Glide Path Control	Poor	Excellent	Good	Excellent
Throttle Usage	Fair	Good	Excellent	Excellent
Confusion	None	None	None	None

Possible comments: excellent, good, fair, poor, unacceptable

The distribution of private pilot basic aircraft dispersion data (fig. 43) is flat, and it is skewed in favor of an overshoot. The flatness, as represented by the large values of range and standard deviation, reflects the imprecise glide path control available with the basic aircraft. All of the private pilot subjects tended to rely on throttle, flaps, slips, and planning to accomplish the basic aircraft precision landing task. While the use of throttle did allow the pilots to make reversible changes in glide path angle with the basic aircraft, their flight path control generally lacked precision. To compensate, they had a tendency to make shallow ($\gamma = 3°$ to $4°$) power approaches with rather prolonged flares and with noticeable floating prior to touchdown.

Most of the private group were reluctant to add power once they had flared and would settle for a short touchdown rather than risk a poor landing or a prolonged float due to throttle overcontrol. They did exhibit a tendency, however, to put the aircraft on the ground with excessive speed if a float appeared to be carrying them beyond the desired landing point. That "hot landing" condition often resulted in poor braking and potential wheelbarrowing. Of the 150 landings made with the basic aircraft, 23 were deemed poor or bad from rollout control and braking considerations.

All of the subjects in this group used the flaps as a configuration control with the basic airplane. They would steepen the glide path with flaps but would never attempt to modulate their approach using the flap control. Since the task allowed the use of power to extend a glide, there was no need to use the flaps in any other way. Raising the flaps after landing would improve the braking action of the basic aircraft, but pilots without previous experience in the test aircraft would sometimes forget that rollout aid.

The private pilots occasionally attempted to slip the basic aircraft to make glide path corrections but, almost without exception, they were unable to achieve effective results. The slips were mild and they often resulted in an increase in airspeed which caused the plane to float after the flare. Furthermore, the pilots seemed to use a slip with reluctance and often delayed the maneuver until too late in the approach.

The advanced pilot basic aircraft touchdown dispersion distribution (fig. 43) is not as spread out as the private pilot data because the advanced pilots were able to compensate for the poor glide path control inherent in the low wing loading test aircraft. They could use $d\gamma/dV$ control and lower speed margins effectively and safely because their airspeed control was significantly better than the private pilots. They were less likely to overcontrol with the throttle and they were more proficient with flap usage and slips. Furthermore, their planning and awareness were better and they could initiate a correction before the approach error exceeded the marginal glide path control capability of the basic aircraft.

With spoilers, the private pilot group found that precise glide path control was easy to achieve. After initial demonstration landings, the subjects operated the spoiler system without physical assistance from the program manager, and they received only limited verbal assistance as required for understanding and safety. After about 4 to 6 approaches, the subjects tended to fly a steeper glide path ($\gamma = 5°$ to $6°$) than was their habit with the basic aircraft. The private pilots felt that judgment of the proper approach trajectory was easier with the steeper spoiler approaches. They also quickly discovered that they had more precise glide path control if they used an approach angle that allowed the spoilers to operate in the linear response range between 10° and 40°. The nominal spoiler deflection of 25° was associated with a glide path of approximately 6° under normal wind conditions. The pilots would make continuous corrections with the throttle in order to modulate the approach, and they would monitor their progress by noting the movement of a suitable reference point associated with the desired touchdown point. No visual approach aids, such as VASI, were used at any time during the evaluation.

Use of the throttle to control rate of descent and, thus, glide path was natural for the private pilots since they all had experience with power approaches. In fact, they were more familiar with power-assisted approaches than with power-off, full flap approaches and landings, and all of the subjects in the private group tended to depend upon a power-on, flat glide for their basic landing pattern procedure. When a subject felt he was descending too rapidly, his natural reaction was to open the throttle and arrest the descent. Although they did utilize the full descent capability of the spoilers to correct for extremely high situations on the approach, at no time during the spoiler landings did a pilot fail to arrest the high rate of descent ($\dot{h}$' ~ 610 m/min; 2000 ft/min) before descending to about 60 m (200 ft). The maximum rate of descent observed prior to the flare was approximately 427 m/min (1400 ft/min) which is the value associated with the idle throttle setting of the integrated controller. Most of the landings, however, were made from power approaches where the nominal glide path prior to the flare was approximately 5° to 6° and the rate of descent was about 230 m/min (750 ft/min).

Comments made by the subjects reflected the degree of confidence they developed in the spoiler system for the precision approach task. All the private pilots said that glide path control was increased noticeably and was easier to achieve compared with the basic aircraft. They indicated that once an error in approach trajectory was recognized, it was very easy and effective to correct the glide path. All the pilots said that use of the spoilers controlled by means of the throttle offered no confusion, and that they were not apprehensive about the steep approach capability of the spoiler aircraft.

For the spoiler landings, neither advanced pilot used airspeed control, flaps, or slips to achieve precision flight path control. Approach path modulation was done entirely by means of the throttle/spoiler integrated control (split handle controller). They remarked that their approach precision and control were enhanced by the use of spoilers and that the need for precise airspeed control was reduced. They appreciated the ability to use a higher approach airspeed in turbulent conditions and still not suffer a float during the landing flare. One pilot expressed his opinion of the glide path modulation capability of the spoiler aircraft with the following statement: "Adverse effects from thermals or vertical gusts can be controlled almost subconsciously with spoilers. On several occasions I did not realize how much heave I was incurring from vertical currents on final until a series of approaches was flown without the spoilers."

With the more precise glide path control provided by the spoilers, the advanced pilots were able to improve their landing performance as a group while they apparently reduced the workload associated with the precision landing task. Both pilots commented that the task seemed easier to accomplish since a higher airspeed could be employed for safety and control purposes and corrections in glide path could be made effectively and naturally by means of the throttle/spoiler controller.

Flare and touchdown.- Table IX and figure 44 summarize the strong similarities in the basic and spoiler touchdown performance data. The touchdown hardness distributions for the basic aircraft and the spoiler aircraft are virtually identical. While the measures of location and dispersion differ slightly, the character of both distributions is similar. For the private pilot group, the mean touchdown hardness with spoilers is only .03 g's higher than the basic configuration (1.41 vs. 1.44 g's), and that small difference is inconsequential under the circumstances of the test program. The ranges of the two distributions are nearly the same - 1.9 for the spoiler aircraft versus 2.1 g's for the basic aircraft. The only interesting difference in the data is the smaller value of the spoiler aircraft touchdown hardness standard deviation (.29 vs. .35 g's) which possibly indicates a greater consistency when the spoilers are used. Both aircraft configurations, however, had the same percentage of landings (96%) with hardness values of 2.0 g's or less. For the advanced pilot group, the mean spoiler hardness was 1.36 g's compared to the basic aircraft value of 1.31 g's. The maximum hardness value was 2.2 g's and that occurred only once when the subject overcontrolled slightly in the post-idle range with the throttle/spoiler controller. The maximum basic aircraft hardness was 1.8 g's. The standard deviations of the distributions were .18 g's and .22 g's for the basic and spoiler aircraft, respectively.

Both spoiler and basic aircraft touchdown hardness distributions are noticeably skewed since the absolute minimum hardness value under any circumstance could not be less than 1.0 g's, but readings in excess of 4.0 g's were possible if the pilot experienced a hard landing. The minimum hardness value of 1.0 g's represents a very soft, almost imperceptible, touchdown vertical deceleration. The maximum observed value of 3.1 g's resulted when a subject "dropped in" the basic aircraft after ballooning.

While it is not apparent from the distributions of touchdown hardness (fig. 44), the manner in which a hard landing is likely to occur differs with the basic and spoiler aircraft configurations. Approximately half of the basic aircraft landings with hardness values greater than 2.0 g's resulted from the approach airspeed being too slow and the pilot having insufficient velocity to flare properly. While a proficient pilot might have been able to manage his limited flare more successfully, in these cases the firm landing resulted from the subject not being able to arrest his descent satisfactorily., The other half of the basic aircraft "firm landings" resulted from an error in judging flare height which caused the pilot either to level off too high, balloon, or stall out at the top of a bounce. Occasionally a pilot would try to achieve ground contact by applying forward control pressure after a bounce, and thus compound the bouncing problem. This type of firm landing, however, represented less than 1% of the basic aircraft landings with touchdown hardness greater than 2.0 g's.

The nature of the spoiler aircraft firm landing differed from the basic aircraft case. Since the spoilers allowed the pilots to approach with ample speed margin, there was no reason for the approach to be made too slowly. At the recommended indicated approach airspeed of 74 to 78 knots (85 to 90 mph), the subject had sufficient airspeed to be 8 to 10 knots slow and still have enough energy to flare. Because of the larger range of acceptable approach airspeeds provided by the spoiler aircraft, no firm landings occurred because of an inability to flare.

The balloon-type firm landings did not occur with proper use of the spoilers. The private pilots who had a tendency to balloon remarked that the spoilers were extremely effective in preventing that type of landing error. Excess airspeed did not cause the aircraft to float excessively; thus there was less chance of a pilot experiencing a ballooning situation during the hold-off phase of landing. Only one balloon-related firm landing occurred during the spoiler portion of the program and that occurred on only the fourth landing made by the subject.

The likelihood of the bounce landing was also very small. Once ground contact was made, normal procedure called for the pilot to extend the spoilers fully via retarding the controller into the post-idle or split handle range. With the spoilers fully deflected, a bounce rarely occurred and, if it did, it was heavily suppressed. Even with slow or delayed use of the post-idle or split handle, the 40° spoiler deflection associated with the idle throttle position tended to suppress a potential bounce and make it easy to handle. None of the firm spoiler landings resulted from a bounce situation.

Approximately half of the firm spoiler landings resulted from a flare which was initiated too high and developed into a drop-in situation because the pilot held the aircraft too far off the ground. As the pilot gained confidence in the spoiler system's effectiveness in reducing a balloon and float situation which might result if he delayed the initiation of his flare, that type of firm landing became less frequent.

The type of spoiler hard landing which is fundamentally different from the basic hard landing related to gross misuse of full 70° spoiler deflection. With either the single lever or split handle integrated controller, full spoiler deflection could be achieved at any time during the flare if the subject failed to follow the recommended operating procedure of using full spoilers only above 90 m (300 ft) or when the aircraft had made ground contact. The aircraft could be landed quite easily with full spoilers being applied in the flare, provided that the throttle/spoiler usage was coordinated smoothly with the flare. Gradual deployment of the spoilers beyond the idle throttle value of 40°, for example, was acceptable for reducing a prolonged float condition, and full spoiler deflection often was used by the contractor's evaluation pilots for precision landings.

A potential firm landing situation exists, however, if a pilot abruptly deploys the spoilers from the idle value of 40° to the full post-idle or full split handle spoiler deflection of 70°. This abrupt throttle overcontrol was the cause of approximately 40% of the spoiler firm landings. Correcting for an overcontrol was accomplished by reversing the throttle action or by adding additional back pressure on the pitch control to arrest the spoiler-induced descent. Additional back pressure generally was effective because the throttle misuse usually occurred before the approach airspeed had dissipated noticeably. However, if airspeed had been lost before initiation of the spoiler overcontrol, increased elevator pressure would not be sufficient to prevent a very firm arrival. Adding power to arrest a drop-in situation was very effective because of the favorable lift and drag transients with spoilers closing. A panic-type throttle application, however, could make it advisable for the pilot to follow through with full throttle and a go-around.

The extra degree of skill needed to coordinate throttle/spoilers and elevator control during the flare and touchdown maneuver appeared to be minor for the private and advanced pilots. For the most part, they felt the timing and coordination required with the spoiler aircraft was no greater than the effort associated with a normal landing. The subjects remarked that the spoilers reduced the tendency to balloon and eliminated floating even when the approach airspeed was excessive. One private pilot felt both timing and coordination were actually simpler after the flare with spoilers since the float was substantially reduced. There appeared to be no confusion or apprehension on the part of the subjects concerning what to do with the throttle during the flare, possibly because the power reduction was similar to the type used with a landing after a power approach.

With the spoiler aircraft, the initiation of the flare and touchdown tend to be opposite ends of a single maneuver since there is usually no prolonged float to separate the end of the flare and the point of touchdown. Consequently, an abrupt use of the throttle in the flare was likely to result in a harder-than-average landing. After one or two firm landings, which generally occurred during the subject's initial introduction to the system, the pilots recognized the need for smooth reduction of throttle setting during the flare. With about thirty minutes' practice, the touchdown hardness with spoilers was similar to the subject's basic aircraft touchdown performance.

<u>Crosswind and gusty conditions</u>.- The private pilots, as well as the advanced pilots, were able to cope with more turbulent wind conditions and more severe crosswinds with the spoiler aircraft. In particular, the performance of the private pilots during less desirable wind conditions was nearly as consistent and apparently just as safe as during calm conditions. The excellent glide path control provided by the spoilers allowed the private pilots to correct for the effects of turbulence and vertical gusts on their approach path. The subjects would fly an airspeed that provided a

comfortable, safe approach in spite of their inabilities to control speed under turbulent conditions. Most of the private group were unaware of or at least unable to compensate for the strong bleed-off which usually occurs as an aircraft enters a strong wind shear near the ground. With the spoiler aircraft, however, they would carry sufficient airspeed on approach to allow for speed bleed-off, and they could make small γ changes to correct for shear effects. If they entered the flare too fast, they easily used the throttle/spoiler to prevent a float. Since there was usually little float after flare with the spoiler aircraft, there was little opportunity for additional sideways drift to develop. Therefore, ground contact was satisfactory. Once on the ground, the private pilots found it very easy to deploy spoilers fully and thus eliminate the possibility of gusts or crosswinds causing any problems during rollout.

With the basic aircraft, however, landing performance and safety were compromised somewhat by strong crosswinds, turbulence, and high wind shear. Glide path control was noticeably harder for the private subjects in turbulent conditions. The relatively poor airspeed control that the low experience-level pilots exhibited in turbulence also caused problems. When the pilots entered the flare too fast, they would drift or balloon under the influence of crosswinds or gusts. If they were too slow on their close-in final approach, they often slowed down in the wind shear and then had insufficient energy to make a successful flare. Occasionally, a pilot would allow his airspeed to build up on approach in order to provide himself with sufficient control; then, in his desire to not let the plane float after flaring, he would put the plane on the ground too fast. This resulted in poor rollout and braking posture which, particularly under crosswind and gusty conditions, was undesirable.

One private pilot remarked that he felt confident flying the spoiler aircraft during rough wind conditions, but he would not fly the basic aircraft under the same crosswind and turbulent conditions. Another private pilot stated that he was able to recognize when the touchdown would occur, regardless of airspeed. The confidence and control provided by the spoilers allowed the private subjects to achieve safe results under wind conditions that were well beyond their capabilities in the basic aircraft.

The advanced pilots also commented on the significant benefits provided by the spoilers during crosswinds and high wind shear conditions. One pilot felt he could achieve precision glide path tracking and touchdown results with the spoiler aircraft even during extremely adverse conditions that would make precision glide path control in the basic aircraft very difficult. The other advanced pilot felt the ability to control the moment of touchdown precisely and to keep the aircraft positively on the ground after touchdown was extremely beneficial for crosswind operations. Both advanced subjects stated that they felt the spoilers reduced their workload and improved their performance during flights in turbulent conditions.

Rollout.- Table XI summarizes the fundamental features of the rollout element of the landing task with and without spoilers.

TABLE XI.- LICENSED PILOT PERFORMANCE AND SKILL SUMMARY - ROLLOUT

	Private		Advanced	
	Basic	Spoiler	Basic	Spoiler
Directional Control	Good[a]	Good	Excellent	Excellent
Braking Posture	Poor	Excellent	Good	Excellent
Wheelbarrowing	Possible	No	Rarely	No
Distance Differential	-	-10% - +15%	-	Under 15%

Possible comments: excellent, good, fair, poor, unacceptable

[a]Good, provided braking posture was acceptable and no wheelbarrowing occurred; otherwise the possibility of gusts or crosswinds affecting poor directional control existed

None of the spoiler landings resulted in poor braking action during rollout, but 23 of the 150 basic aircraft landings flown by the private pilots were considered to be poor or bad based upon braking or wheelbarrowing considerations. All the subjects remarked that the spoiler improved the braking capability of the aircraft. They felt the handle-splitting operation needed to deploy the spoilers fully after landing was easy to achieve and not distracting. One subject commented that use of spoilers after touchdown was less confusing than retracting flaps to improve braking action.

Limited rollout distance measurements were made for the private and advanced subjects. The results for the private group were somewhat inconclusive but, in general, each subject experienced a spoiler rollout distance that was nearly equal to or only about 5% more than his basic aircraft results.

Since rollout distance depends heavily on the manner in which the brakes are applied, on the condition of the brakes, and on the atmospheric conditions at the time of landing, it was difficult to obtain relevant data for each subject. Therefore, extensive collection of rollout distance data was considered of limited value and potentially costly from a brake maintenance point of view. Furthermore, the data that were collected confirmed that rollout distance was not increased noticeably and, for the less proficient, it was reduced.

For three private subjects, however, considerable rollout data were collected. For one subject, the distance observed with spoilers operative was approximately 15% greater than the basic case; for another subject, the average spoiler rollout distance was about equal to the average basic aircraft data; and for the third private pilot, the spoiler rollout distance was approximately 10% less than with the basic aircraft. Spot checks obtained from the remaining five private pilots indicated that rollout distance was not increased more than 5% to 10% and, generally, the better braking action obtained with spoilers caused the rollout distance to be approximately equal to the basic aircraft performance.

Considerable rollout distance data were collected under the same atmospheric conditions for one advanced pilot. Since his piloting techniques were considered good and all the data were collected within a two-hour period, the results are considered representative of relative rollout distances with and without spoilers. His average spoiler rollout distance was 239 m (753 ft) compared to 222 m (729 ft) for the basic aircraft. The increase with spoilers was less than 5% even though the basic landings were made with full flaps at an approach speed of 59 knots CAS (68 mph). From these data, it was concluded that the increase in rollout distance was small and, depending on the piloting technique of the subject, the spoiler rollout distance might differ from the basic distance by approximately -10% to +15%. A pilot who was proficient with the basic aircraft could expect a rollout distance increase of about 5% when he employed the higher approach airspeed recommended with spoilers.

<u>Go-around or balked landing</u>.- Table XII summarizes the principal features of the go-around task with and without spoilers.

TABLE XII.- LICENSED PILOT PERFORMANCE AND SKILL SUMMARY - GO-AROUND

	Private		Advanced	
	Basic	Spoiler	Basic	Spoiler
Airspeed Control	Poor	Good	Good	Excellent
γ Control	Poor	Excellent	Good	Excellent
Confusion	Some	None	None	None
Workload	Moderate	Low	Satis.	Low

Possible comments: excellent, good, fair, poor, unacceptable

The private pilots remarked that flight path and airspeed control were much easier during touch-and-go landings with the spoiler aircraft. One subject commented that he was apprehensive about nonspoiler touch-and-go landings because of trim changes and the need to retract flaps. He felt confident, however, about touch-and-go operations with the spoiler aircraft. Another subject felt his workload was noticeably reduced with a spoiler wave-off.

The advanced pilots also commented favorably about the go-around potential of the spoiler aircraft. They felt that the "instant go up" capability combined with the favorable handling qualities gave them confidence that an effective go-around could be employed at any point during the landing.

Forced landings.- Table XIII summarizes the results of 64 forced landings flown by 6 private pilots and 14 forced landings made by one advanced pilot.

TABLE XIII.- LICENSED PILOT PERFORMANCE AND SKILL SUMMARY - FORCED LANDINGS

	Private		Advanced	
	Basic	Spoiler	Basic	Spoiler
Range	541 m (1775 ft)	221 m (725 ft)	168 m (550 ft)	68.6 m (225 ft)
Standard Deviation	132 m (433 ft)	47.9 m (157 ft)	54.9 m (180 ft)	19.8 m (65 ft)
Successful Results	In Doubt	Highly Probable	Highly Probable	Assured
Safety of Operations	Poor	Good	Good	Excellent
Go-arounds	1	0	0	0
Number of Events	31	33	6	8

Possible comments: Results - assured, highly probable, in doubt, not possible
Operations - excellent, good, fair, poor, unacceptable

All subjects were able to conduct safe and reasonably accurate forced landings with the spoiler aircraft. They came in with sufficient altitude to assure that the plane could glide to the desired touchdown zone, and then they used the throttle/spoiler control to lose unneeded altitude. Once on an acceptable approach trajectory, the subjects found they could use the throttle to make glide path corrections just as they had done during normal landings.

Using spoilers, the private pilots were able to achieve forced landing results comparable with the performance of the advanced pilot flying the basic aircraft. Without spoilers, however, the forced landing safety and accuracy of the private pilots were compromised by their lack of skill with establishing and maintaining a satisfactory glide path. They would plan on a slightly high approach and then use flaps and possibly slips to lose the excess altitude. But a lack of skill and judgment with respect to estimating the touchdown point and rather marginal abilities with respect to slips caused significant scatter in the forced landing touchdown location. Often a subject would not observe the overshoot or undershoot until it was beyond his and the aircraft's capability to remedy the situation.

Airspeed control often was poor during forced landings with the basic aircraft. The private pilots occasionally would attempt to lengthen the glide by raising the nose - naturally with negative results. Frequently they would dive for the desired touchdown location when an overshoot was apparent, only to float excessively. Because of their limited basic skills, the actions of the private pilots during the simulated emergency landings with the basic aircraft suggested that, under less controlled conditions, flight safety might easily be compromised. With the spoiler aircraft, however, the low experience-level pilots exhibited a confidence and control that allowed them to achieve satisfactory results without placing themselves in compromised flight conditions. All the private pilots remarked that the spoilers were of significant help on forced landings. In concluding his comments, one low-time pilot stated, "Even with the engine out, it is possible after very little practice to effectively control both the glide path and airspeed; much simpler than a conventional flap system aircraft, and much less confusing to the occasional or low-time pilot."

APPLICATIONS - BENEFITS AND RISKS

The analysis, documentation, and evaluations presented in the preceding sections present the major features of hinged plate spoilers. It has been demonstrated that the considerable descent performance, the increased speed stability, the improved phugoid damping, the deceleration capability, and the favorable initial glide path angle response characteristics provided by spoilers improve performance and enhance flying qualities for a spectrum of landing tasks. The coupling between drag, lift, and moment that produces these favorable qualities is easily achieved with spoilers but cannot be achieved with simple flap systems.

Whether it is advantageous, in a practical sense, to apply spoilers to various classes of light wing loading aircraft, however, requires an assessment of the benefit/risk relationship. The general aviation community has unique constraints that must be considered if these research results are to be successfully implemented.

The limited R&D facilities and budgets of most light aircraft manufacturers, the conservative nature of the marketplace, and the overwhelming influence of FAA certification represent risks which an aircraft firm will need to balance against the potential benefits of implementing spoilers. Although an analysis of this would be beyond the scope of the program reported herein, a brief discussion of the application of spoilers to general aviation and low wing loading STOL vehicles is considered appropriate.

Easier Learning Benefit

The impressive improvements in landing performance achieved by relatively inexperienced pilots (fig. 43; Table IX) show that spoilers would enhance the landing characteristics of light aircraft. The student pilot study shows that spoilers offer no adverse qualities that would compromise the learning process. Rather, the consistent performance achieved by the low-time and beginning pilots indicates that student pilots would find the landing task less difficult to master. For the student, the prospect of doing better landings, and learning in less time, would be a strong benefit of spoilers.

Approach Conditions Benefit

The benefits of spoilers for improved landing approach flying qualities are documented in a previous section. From the studies, it is clear that spoilers allow a much larger window of acceptable airspeed for entry into the flare and landing without excessive float. In general, a pilot can select his approach airspeed on the basis of good approach flying qualities and safe speed margin. In particular, the inexperienced pilot can select an approach speed high enough to eliminate any danger of stalling or settling in a mushing condition while maneuvering in the traffic pattern. This is particularly important since, in recent years, failure to obtain/maintain proper flying speed was the detailed cause most frequently given for fatal accidents in small general aviation aircraft. With the exception of the initial climb phase of operation, during the 1967-1971 period, more accidents relating to this type of cause occurred during the approach and go-around phases than during any other flight task (refs. 1-6).

Crosswinds and Turbulence Benefit

The ability to select approach airspeed on the basis of the approach task also is beneficial during crosswind and gusty conditions, as indicated by many spoiler flights in adverse winds. Glide path disturbances caused by vertical currents and shear effects could be compensated for easily at any stage of the approach.

Airspeed could be increased to provide good lateral control and to provide an ample speed margin in spite of variations caused by turbulence and wind shear. Extra airspeed could be dissipated easily in the flare without floating which would be troublesome during gusty, crosswind conditions. The ability to effect a touchdown by applying additional spoiler deflection gave the pilot excellent control over the point of touchdown.

Inexperienced pilots and beginners who participated in the evaluation were taught to use the crab/decrab method of crosswind landings with good results, principally because they knew when the touchdown would occur and thus were not likely to encounter a lateral drift after the decrab maneuver. Because of the lift dumping capability of spoilers, the actual touchdown could occur at a higher speed that ensured sufficient lateral/directional control to counter any sudden gusts or unusual conditions. Once on the ground, full spoiler deflection provided good braking posture and reduced the possibility of gusts or crosswinds causing one wing to rise.

Especially for the pilot of little experience, the ability to land with confidence and consistency in adverse conditions would be a strong benefit for the airplane with spoilers.

Flare, Touchdown, and Rollout Benefit

It has been shown that with spoilers allowing a higher approach speed and the "decelerate" pilot technique, the landing flare is easier and the touchdown more accurate. With spoilers open, the rollout is better due to improved braking and better directional control.

Wave-Off Benefit

The favorable trim changes and flight path response of spoilers make for excellent wave-off, or balked landing, characteristics. With the favorable qualities that can be easily achieved with spoilers, this maneuver is safe and easy, even for beginner pilots.

Speed-Limiting Benefit

Although it has not been investigated in detail in this program, it is clear that the spoilers could be used for speed limiting in dives that might result from stall departures or spins, from pilot disorientation, or turbulence upsets.

Hard Landing Risk

Improper use of the throttle/spoiler control, coupled with poor airspeed control, could result in a hard landing. However, the risk of the pilot improperly using the spoilers seems no greater than the risk of improper speed control or elevator action while executing a landing without spoilers. Distributions of touchdown hardness (fig. 44) support the premise that the risk of doing something incorrectly and thus causing a hard touchdown is nearly the same with or without spoilers.

It has been shown in the previous discussion (pp. 125-128) of firm and hard landings that spoilers reduce the likelihood of several types of these. They include the

- flare too high and drop in
- balloon and drop in
- bounce and overcontrol
- too slow and insufficient flare

These hard landing benefits seem to more than offset the theoretical possibility of a hard landing caused by the misuse of full spoiler deflection. This kind of error did not occur frequently and, when it did, it was easily corrected by adding power. The very favorable airplane response to throttle/spoiler advance made it possible to arrest a drop-in very quickly and effectively.

Of course, the misuse of the spoilers must not be ignored in the training and checkout of pilots for spoiler aircraft. On balance, however, the overall hard landing risk may be reduced by spoilers.

Design Risks

Far more significant risks opposing the successful implementation of spoilers for small general aviation aircraft appear to be associated with the lack of good design data and the uncertainties of FAA certification. As previously stated in the section on design considerations, data which can be used to develop a practical general aviation spoiler system are sparce. The lack of good hinge moment information is particularly significant since much of the cost and success of a spoiler system will depend upon the method of control. In order to implement the integrated or semi-integrated spoiler control concept, low actuation forces at the throttle are imperative. That requirement dictates either potentially expensive servo-actuators or reasonably low hinge moments. The latter might be achieved with careful design that balanced the upper and lower surface hinge moments with the action of overcentering springs. With relatively low system forces, it may be possible to obtain the required low throttle/spoiler controller actuation forces with the aid of a simple force-boost system. Vacuum actuators or torque drives used in inexpensive general aviation autopilots might be usable for a light aircraft spoiler system.

Until parametric design data are generated, most likely from wind tunnel tests, a manufacturer would need to rely on the relatively simple nature of spoilers and the ease of modifying a prototype system during flight tests in order to develop an acceptable actuation system. Of course, the time and money risks associated with an experimental approach to spoiler design might be considered reasonable or not, depending upon evaluation of spoiler benefits.

Certification Risks

Although spoilers are commonplace on sailplanes and FAR 25 jet transports, they have not been applied to a modern light aircraft, particularly where the method of control incorporates the integrated throttle/spoiler controller concept. FAA certification is costly under normal circumstances, and in a case such as powerplane spoilers where there is no precedent, it is difficult to assess the time and dollar costs of FAA approval.

It will eventually be necessary to clarify FAR 23 (ref.32) particularly those sections dealing with performance based upon stalling speed and configuration. For example, would the reference stalling speed used for various minimum requirements be based upon spoilers deployed fully, in their failed position, or fully closed? What would be the proper interpretation of spoiler configuration for balked landing climb? What special conditions would the FAA impose on a spoiler system similar to the concept evaluated in this study?

A preliminary assessment of the tasks needed to type-certificate spoilers for powerplanes indicates that the major effort would involve <u>system failure modes</u>, since proper spoiler operation does not compromise the performance of the spoiler-equipped aircraft. Climb is always achieved with the spoilers closed, provided the throttle/spoiler integration scheme functions properly. Stability tests documented in a previous section indicate that handling qualities requirements of FAR 23 could be met without difficulty, assuming, of course, that the basic nonspoiler-equipped airframe met minimum standards.

Low Wing-Loading STOL Applications

Low wing loading is a proven and simple method for achieving STOL performance. By utilizing primarily aerodynamic rather than propulsive lift, this class of aircraft tends to be less expensive and more environmentally acceptable than higher wing loading STOL concepts. The operational viability of low wing-loading aircraft in general is limited, however, by approach and landing problems associated with glide path control, touchdown accuracy, and rollout performance, particularly in crosswinds, high wind shears, and gusty conditions (refs. 33-35). Ride discomfort in turbulence is another unpleasant characteristic of low wing loading (ref. 36).

By virtue of their low wing loadings, the landing task operational problems of small general aviation aircraft and nonpropulsive lift STOL aircraft are similar. The importance of glide path and airspeed control for landing (refs. 37, 38) influences the minimum acceptable airspeed (ref. 39) for professionally flown aircraft — including STOL vehicles to be used in proposed intercity and short haul operations. Thus it appears that the benefits which spoilers offer small general aviation aircraft would be directly transferred to low wing-loading STOL vehicles.

Using spoilers, it should be possible to select STOL approach airspeeds based upon desirable approach handling qualities. The reduced dispersion in touchdown point should compensate for the increased touchdown speed of a spoiler landing. Data collected during an evaluation of simulated ground-level STOL landings (ref. 40) indicate that the long float occasionally experienced with a typical low wing-loading STOL transport resulted in touchdown standard deviations of nearly 30 m (100 ft). If these long floats were eliminated and touchdown accuracy improved, it would be possible to reduce or at least maintain STOL runway lengths while enjoying the benefits of better approach flying qualities, steeper obstacle and noise abatement approaches, and greater speed flexibility in the terminal area just prior to landing.

CONCLUSIONS

The following conclusions have been drawn from extensive analyses and flight evaluations of a small, general aviation aircraft equipped with experimental hinged plate spoilers/dive brakes.

General Benefits of Spoilers

A. Significant improvements of landing task performance and handling qualities are possible when spoilers are applied to a small, low wing-loading aircraft, provided the device for modulating the spoilers offers the pilot an inherently natural control of the considerable performance potential of these aerodynamic surfaces.

B. Effective drag control together with favorable lift and moment coupling are responsible for the landing task improvements observed with the test aircraft. In particular,

1) The short period flight path angle response provided by spoilers resulted in desirable approach handling qualities.

2) Spoilers provided improved approach handling qualities by increasing speed stability and by increasing phugoid damping.

3) The lift and drag authority of spoilers provided favorable velocity and flight path responses for flare and touchdown control.

4) The lift dump and the large drag authority of full spoiler deployment provided favorable vehicle characteristics for rollout.

5) The spoilers produced favorable flight path, attitude, and velocity responses for waveoff.

C. Spoilers expand the window of acceptable approach airspeeds and glide path angles from which a successful flare and touchdown can be made. These characteristics are particularly useful in crosswind and gusty conditions.

D. The landing task performance and handling qualities improvements provided by spoilers can benefit beginning and low experience pilots in achieving significantly greater touchdown accuracy without noticeably increasing the risk of a hard landing. Experienced pilots are able to exploit the spoiler performance to achieve significant improvements in landing precision.

Expanded Approach Conditions and Pilot Technique

Evaluations by expert test pilots of landings in the spoiler aircraft over a wide spectrum of conditions have resulted in the following conclusions.

A. For a given approach path angle, the best approach velocity is one which leads to a gradual flare and touchdown with steadily (monotonic) rearward wheel action. The easiest and most effective throttle/spoiler action is coordinated with wheel action with respect to timing, direction, and shape of hand movements.

B. Over a wide range of approach angles, the best approach speeds with spoilers are well above those usable in the basic airplane. Most important, a wide range of approach speeds can be accommodated without undue difficulty or significant penalties in landing distance.

C. Under day VFR conditions, approach angles up to 18° can be used without excessive piloting difficulty in the spoiler aircraft. With increasing approach angle, rate of descent and flare height increase; flare timing and acceleration become more critical; difficulty gradually increases; and pilot ratings go from 2-1/2 to the order of 4-1/2 on a Cooper-Harper scale. Landing ground distances also gradually increase from about 183 m (600 ft) to the order of 305 m (1000 ft).

D. In night VFR conditions, the usable conditions with spoilers were limited only by the power and orientation of the aircraft landing lights. The advantages of spoilers for flight path control and for flare and deceleration were as fully appreciated as in day landings, and given proper lighting, the full velocity vs. flight path angle envelope probably could be exploited.

E. In IFR conditions in the spoiler aircraft, the only serious limitation encountered is the time between breakout and flare initiation. Flight path control on approach, with the basic ILS cross-pointer display, is easy and natural with spoilers over a wide range of approach angles. All the advantages of spoilers carry over into the IFR regime, except as limited by shortness of breakout time. In particular, raw ILS cross-pointer glide slope tracking was improved due to improved glide path response with spoilers.

Design and Implementation

The following conclusions pertaining to design are based upon documentation flight tests with the spoiler-equipped aircraft.

A. The zero-lift drag contribution of the hinged plate spoiler system used on the test aircraft could be represented with good accuracy by assuming a $C_{D_0} = 2$ based upon spoiler projected frontal area.

B. Lift loss due to spoilers was greater than estimated by a simple strip theory. The lift contribution of the spoiler system evaluated was derived mainly from the top spoiler surface.

C. Each spoiler configuration evaluated on the test aircraft produced favorable lift and moment coupling which resulted in minimal trim change with spoiler deflection.

D. Of the various spoiler controllers evaluated, the most desirable methods involved integrating spoiler function with the normal descent capabilities of the throttle. This integration could be done successfully by blending spoiler control directly into the throttle or by providing a semi-integrated spoiler controller that was co-located with the throttle and could be operated simultaneously with it. With a semi-integrated controller, gates or stops which prevent conflicting spoiler and power applications can and should be provided.

E. A spoiler controller which is physically separated from the throttle can be confusing and can lead to wrong actions in stress situations.

RECOMMENDATIONS

Based upon the findings presented in this report, the following research topics are recommended as being essential to the development of a viable spoiler system for low wing-loading powered aircraft.

A. Wind tunnel tests to develop parametric spoiler design data, particularly in the area of hinge moments, are needed.

B. The risks associated with FAA certification need to be examined in order to expose those areas of concern in FAA certification, expecially where no guidelines exist in FAR Part 23. Further flight studies with participation by the FAA could provide the FAA with certification guidelines that would reduce the certification risks to general aviation manufacturers.

C. An evaluation of spoilers specifically for STOL application seems to be justified based upon the similarity of landing task problems experienced by all low wing-loading aircraft. It is recommended that, if such a study is undertaken, the capability of spoilers to expand the velocity versus flight path envelope be fully exploited to evaluate new and potentially beneficial types of STOL landing operations.

D. Flight research should be continued with spoilers utilized in the post-stall, stall/spin, spin/recovery regimes of flight to assess the advantages or disadvantages of spoilers in these flight regimes.

E. Further research is needed to define the potential benefits of spoilers utilized to recover from inadvertent overspeed flight conditions such as those encountered in pilot disorientation while flying in restricted visibility or upsets due to turbulence.

APPENDIX A.- STALL SPEED FOR VARIOUS CONFIGURATIONS

Flaps, deg	Power *	Spoiler, deg	Calibrated Stalling Speed Corrected to Gross Weight, mph	Comments Upper Inboard Spoilers
0	I	0	66	See upper and lower inboard comments
		40	67	Same as 0° spoiler case
		70	69	Same as 0° spoiler case
	F	0	63	See upper and lower inboard comments
		40	66	Same as 0° spoiler case
		70	68	Tail buffet appeared to be less than 0° spoiler case with full power
15	I	0	60	See upper and lower inboard comments
		40	63	Same as 0° spoiler case
		70	66	Same as 0° spoiler case
	F	0	59	See upper and lower inboard comments
		40	61	Same as 0° spoiler case
		70	64	Same as 0° spoiler case
35	I	0	53	See upper and lower inboard comments
		40	60	Same as 0° spoiler case
		70	64	Somewhat suppressed tail buffet
	F	0	50	See upper and lower inboard comments
			57	Same as 0° spoiler case
			63	Same as 0° spoiler case

*I denotes idle power; F denotes full power

Flaps, deg	Power	Spoiler, deg	Calibrated Stalling Speed Corrected to Gross Weight, mph	Comments Upper and Lower Inboard Spoilers
0	I	0	66	Some tail, elevator buffet; marginal aileron and rudder control in stall, tendency to roll right, typical gentle post-stall dynamics
		40	68	Some tail buffet; otherwise same as 0° spoiler
		70	70	Roll tendency at stall same as 0° spoiler case; high rate of sink post-stall without pitch change or post-stall dynamics
	F	0	63	Tail buffet; post-stall dynamics increased slightly by power
		40	65	Some tail buffet
		70	67	Somewhat subdued post-stall response; otherwise same as 0° spoiler case
15	I	0	60	Lesser aerodynamic warning than 0° flap case; tendency to roll left; sharper post-stall dynamics than 0° flap case
		40	63	Same as 0° case
		70	65	Same as 0° case
	F	0	59	Some tail buffet; noticeable post-stall dynamics; tendency to roll right
		40	61	Same as 0° spoiler case power on; post-stall dynamics not increased - possibly decreased somewhat with spoilers
		70	64	Same as 0° spoiler case power on. Post-stall dynamics about the same or somewhat reduced compared with 0° spoiler case
35	I	0	53	Tail buffet subdued compared with 0° flap case; post-stall dynamics more pronounced; tendency to roll left
		40	59	Tail buffet due to spoilers noticeable prior to stall; post-stall characteristics about the same as 0° spoiler case
		70	62	Tail buffet due to spoilers; other characteristics same as 0° spoiler case
	F	0	50	More tail buffet than idle power, 35° flap case, but not greater than 0° flap case; sharp post-stall dynamics
		40	57	Noticeable tail buffet; other characteristics same as 0° spoiler case
		70	60	Excessive tail buffet; same as 0° spoiler case

APPENDIX A. (cont'd)

Flaps, deg	Power	Spoilers, deg	Calibrated Speed Stalling Corrected to Gross Weight, mph	Comments Upper and Lower Outboard Spoilers
0	I	0	66	See upper and lower inboard comments
		40	67	Same as 0° spoiler case
		70	69	Same as 0° spoiler case
	F	0	63	See upper and lower inboard comments
		40	65	Same as 0° spoiler case
		70	67	Somewhat subdued prestall buffet; somewhat subdued post-stall response
15	I	0	60	See upper and lower inboard comments
		40	62	Slightly less aileron control post-stall
		70	65	Same as 40° spoiler case
	F	0	59	See upper and lower inboard comments
		40	61	Same as 0° spoiler case
		70	64	Slightly less prestall buffet; slightly less post-stall response
35	I	0	53	See upper and lower inboard comments
		40	57	Slightly less noticeable post-stall break; slight tendency for secondary stall during recovery
		70	61	Same as 40° spoiler case
	F	0	50	See upper and lower inboard comments
		40	56	Less noticeable stall break
		70	59	Somewhat subdued post-stall response

APPENDIX A. (concluded)

Flaps, deg	Power	Spoiler, deg	Calibrated Stalling Speed Corrected to Gross Weight, mph	Comments Upper Outboard Spoilers
0	I	0	66	See upper and lower inboard comments
		40	68	Same as 0° spoiler case
		70	70	Slightly less noticeable stall break
	F	0	63	See upper and lower inboard comments
		40	66	Same as 0° spoiler case
		70	68	Slightly less noticeable stall break
15	I	0	60	See upper and lower inboard comments
		40	63	Same as 0° spoiler case
		70	65	Slightly less noticeable stall break
	F	0	59	See upper and lower inboard comments
		40	62	Same as 0° spoiler case
		70	64	Slightly less noticeable stall break
35	I	0	53	See upper and lower inboard comments
		40	57	Slightly higher post-stall settling with a somewhat less pronounced stall break
		70	61	Somewhat less post-stall break and slightly higher settling
	F	0	50	See upper and lower inboard comments
		40	55	Same as idle power case
		70	60	Same as idle power case

APPENDIX B.- ADVERTISEMENT FOR EVALUATION SUBJECTS

Attention: Student and Licensed Pilots

Wanted: Aeronautical Research Associates of Princeton, Inc. desires pilots to participate in a proposed flight evaluation program. Selected participants will be required to fly from 5 to 10 hours in a small fixed-wing General Aviation aircraft during a period from June 15 to September 15. While each subject will control the aircraft, he or she will be under the supervision of a Certified Flight Instructor and will not act as Pilot-in-Command. Participants will provide their services as an independent contractor to A.R.A.P. and will be compensated at the rate of $2.50 per hour.

Requirements:

1. Student, private, commercial, or higher license
2. Current medical certificate
3. Available to fly from Princeton area airports between June 15 and September 15

<u>If interested</u>, please contact by letter or telephone:

Mr. John W. Olcott
A.R.A.P.
50 Washington Road
Princeton, New Jersey 08540
Telephone: 609-452-2950

Include the following information:

1. License presently held
2. Date license was issued
3. Total flying time
4. Breakdown of flying time by type of aircraft
5. Approximate number of flying hours per year
6. Times when you would be available for participation in the flight evaluation program
7. Present address, and location of airport from which you could fly the evaluation aircraft

APPENDIX C.- STUDENT PILOT PRESOLO SYLLABUS

Familiarization

- Introduction to aircraft
- Use of check list
- Use of controls

Fundamental Flight Maneuvers

- Level flight
- Turns
- Climbs
- Descents

Primary Coordination Exercises

- Medium turns
- Shallow turns
- Rolling from turn to turn

Altitude/Airspeed Control

- Slow flight
- Introduction to stalls

Special Flight Conditions

- Stalls - power-off, power-on
- Departure or take-off stalls
- Approach or landing stalls
- Cross-control stalls
- Accelerated stalls
- Spirals

Planning Maneuvers

- Turns to specific headings
- Climbs and descents to specific altitudes
- Airspeed transitions while maintaining altitude

Ground Reference Maneuvers

- Effects of wind on ground track
- Following a road
- Rectangular patterns
- Traffic patterns

Airport Operations

- Take-off and landings

Emergency Procedures (Primary)

- Forced landings

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16. Abstract

The results of a four-phase effort to evaluate the application of hinged-plate spoilers/dive brakes to a small general aviation aircraft are presented. The test vehicle was a single engine light aircraft modified with an experimental set of upper surface spoilers and lower surface dive brakes similar to the type used on sailplanes. The lift, drag, stick-free stability, trim, and dynamic response characteristics of four different spoiler/dive brake configurations were determined. Tests also were conducted, under a wide range of flight conditions and with pilots of various experience levels, to determine the most favorable methods of spoiler control and to evaluate how spoilers might best be used during the approach and landing task. The effects of approach path angle, approach airspeed, and pilot technique using throttle/spoiler integrated control were investigated for day, night, VFR, and IFR approaches and landings.

The test results indicated that spoilers offered significant improvements in the vehicle's performance and flying qualities for all elements of the approach and landing task, provided a suitable method of control was available. The most favorable method of control was to integrate spoiler deployment with power changes so that the throttle became an authoritative and effective flight path controller.

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