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THE LANDING FLARE: AN ANALYSIS
AND FLIGHT-TEST INVESTIGATION

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16. Abstract The results are given of an extensive investigation of conventional landing flares in general aviation type airplanes. Experimental landings in a variable-stability Navion have simulated a wide range of parameters influencing flare behavior. The most important feature of the flare has turned out to be the airplane's deceleration in the flare, and it has been found to be possible to correlate various effects on this in terms of the average flare load factor. Certain kinds of ground effects are found to be favorable, if they are small and in the right combination. Piloting technique is extensively discussed. Certain implications for design are presented.			
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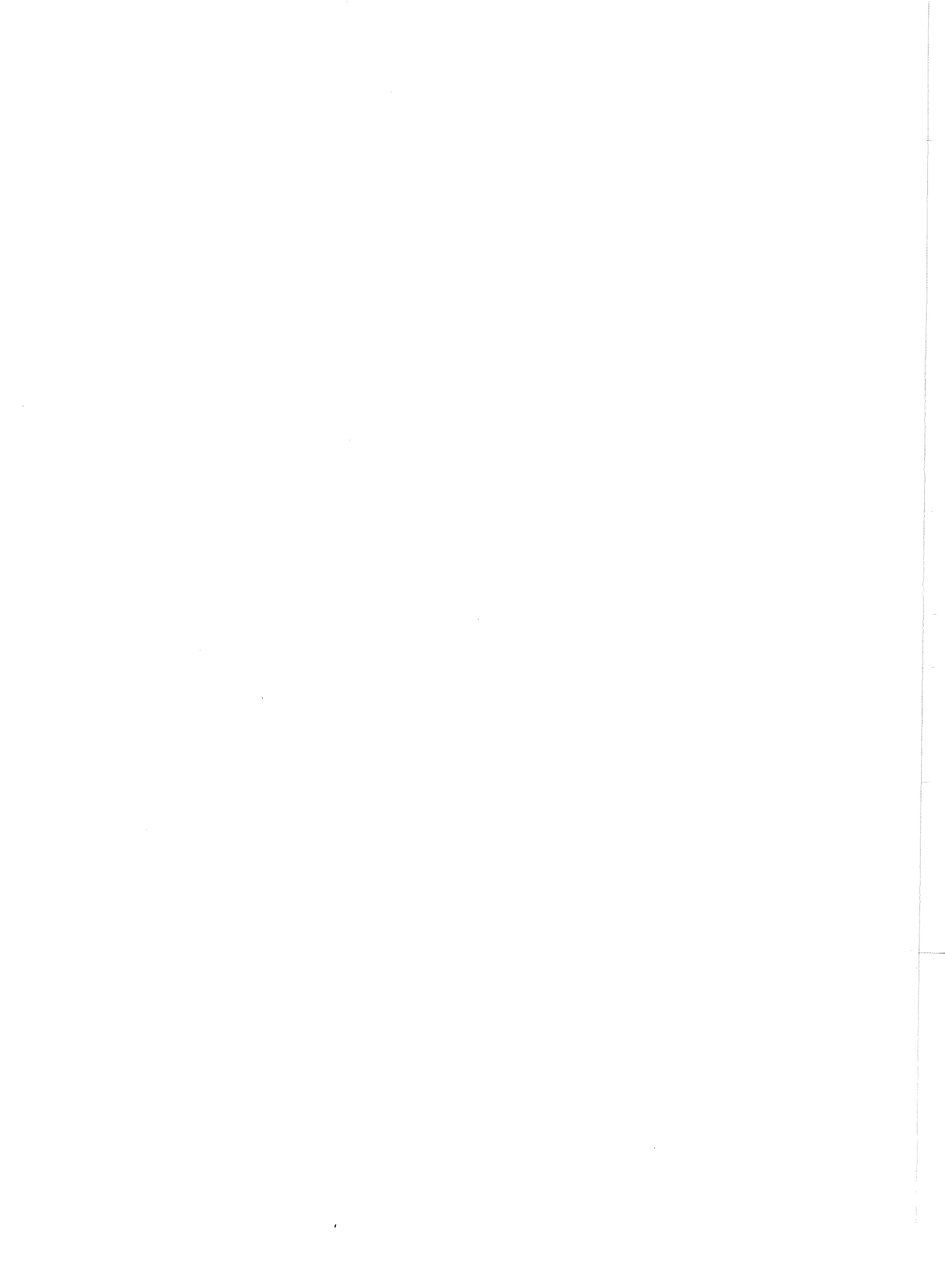


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NOTATION AND SYMBOLS

Measurements and calculations were made in the U.S. Customary Units. They are presented herein in the International System of Units (SI) followed by the U.S. Customary Units in parentheses.

A	wing aspect ratio
C_D	drag coefficient = D/qS
C_{D_p}	parasite drag coefficient = D_p/qS
C_L	lift coefficient = L/qS
C_{L_α}	slope of the lift curve = $\frac{\partial C_L}{\partial \alpha}$
C_m	pitching moment coefficient = $M/qS\bar{c}$
C_{m_δ}	pitching moment coefficient due to control deflection = $\frac{\partial C_m}{\partial \delta}$
D	drag acting on the aircraft, N (lbs)
D_α	longitudinal acceleration due to angle of attack = $\frac{1}{m} \frac{\partial D}{\partial \alpha}$, $m/\text{sec}^2/\text{rad}$ ($\frac{\text{ft}/\text{sec}^2}{\text{rad}}$)
D'_δ	effective drag acceleration due to control, defined in Equation 4b
I^*	speed stability integral, defined in Equation 11, sec^2
I_Y	aircraft pitching moment of inertia, $\text{kg}\cdot\text{m}^2$ ($\text{slug}\cdot\text{ft}^2$)
L	lift acting on the aircraft, N (lbs)
L_α	vertical acceleration due to angle of attack = $\frac{1}{m} \frac{\partial L}{\partial \alpha}$, $m/\text{sec}^2/\text{rad}$ ($\frac{\text{ft}/\text{sec}^2}{\text{rad}}$)
L_δ	vertical acceleration due to control deflection = $\frac{1}{m} \frac{\partial L}{\partial \delta}$, $m/\text{sec}^2/\text{rad}$ ($\frac{\text{ft}/\text{sec}^2}{\text{rad}}$)
L'_δ	effective lift acceleration due to control, defined in Equation 4c
L_v	vertical acceleration due to velocity = $\frac{1}{m} \frac{\partial L}{\partial V}$, $1/\text{sec}$

M	pitching moment acting on the aircraft, N-m (ft-lbs)
M_{α}	pitch acceleration due to angle of attack = $\frac{1}{I_y} \frac{\partial M}{\partial \alpha}$, $\frac{\text{rad/sec}^2}{\text{rad}}$
M_{δ}	pitch acceleration due to control deflection = $\frac{1}{I_y} \frac{\partial M}{\partial \delta}$, $\frac{\text{rad/sec}^2}{\text{rad}}$
M_v	pitch acceleration due to velocity = $\frac{1}{I_y} \frac{\partial M}{\partial V}$, $\frac{\text{rad/sec}^2}{\text{ft/sec}}$
$(N_m - \bar{x}_{CG})$	maneuver margin
$(N_o - \bar{x}_{CG})$	static margin
P.R.	Cooper-Harper pilot opinion rating
S	aircraft wing area, m^2 (ft^2)
T	thrust acting on the aircraft, N (lbs)
$T_{\delta} - D_{\delta}$	net longitudinal acceleration due to control deflection = $\frac{1}{m} \left[\frac{\partial T}{\partial \delta} - \frac{\partial D}{\partial \delta} \right]$, $\text{m/sec}^2 / \text{rad}$ ($\frac{\text{ft/sec}^2}{\text{rad}}$)
$T_v - D_v$	net longitudinal acceleration due to velocity = $\frac{1}{m} \left[\frac{\partial T}{\partial V} - \frac{\partial D}{\partial V} \right]$, $\frac{\text{m/sec}^2}{\text{m/sec}}$ ($\frac{\text{ft/sec}^2}{\text{ft/sec}}$)
V	aircraft velocity, knots (ft/sec)
W	aircraft weight = mg, N (lbs)
\bar{c}	mean aerodynamic chord, m (ft)
e	span efficiency factor
g	acceleration due to gravity, m/sec^2 (ft/sec^2)
h	altitude, m (ft)
k_y	pitching radius of gyration, m (ft)
m	aircraft mass, kg (slugs)
n	load factor

q	dynamic pressure, N/m^2 (psi)
s'	differential operator with respect to $\Delta\gamma$; i.e., $\frac{d}{d(\Delta\gamma)}$
t	time, sec
t_f^*	time required for the flare maneuver, sec
α	angle of attack, rad
γ	flight path angle, rad
Δ	increment from a reference steady-state condition
ΔL_G	incremental lift force due to ground effect
ΔM_G	incremental pitching moment due to ground effect
$\overline{\Delta n}$	time average of load factor variation
$\Delta V'$	nondimensional velocity perturbation = $\Delta V / V_o$
δ_e	elevator deflection, rad
δ_T	throttle deflection
λ	backsidedness parameter = $g \left(\frac{\Delta\gamma}{\Delta V} \right)_{ss} = - \left[D_v - T_v - \frac{D'_\delta}{L'_\delta} L_v \right]$, per sec
λ'	specialized backsidedness parameter = $\frac{V_o}{g} \lambda$, dimensionless
π	3.14159
$()_A$	denotes the approach condition
$()_o, ()_{ss}$	denotes the steady-state condition
$()_{td}$	denotes the touchdown
$\bar{\quad}, ()_{ave}$	denotes an average value

THE LANDING FLARE: AN ANALYSIS
AND FLIGHT-TEST INVESTIGATION

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SUMMARY

A theoretical analysis is presented as a basis for understanding the flight mechanics of conventional landings and to define parameters to be varied in actual flight-test landings in a variable-stability aircraft. The overall objective is to understand the influence of various factors on landings and to see how to improve, for the pilot, their ease and quality. Emphasis is on ranges of parameters typical of conventional, light general-aviation airplanes landed in a conventional manner.

The analysis and the experiment have largely focused on the landing flare. It is a complicated transient maneuver involving many interrelated and interacting effects, and it is clear that it contains some important piloting problems.

The landing flare is dealt with qualitatively by means of linearized equations to demonstrate the influence of various parameters. These include approach speed and flight path angle, touchdown velocity, drag and thrust aerodynamics, control coupling, control technique, and ground effects. All these effects and related parameters have been extensively varied in actual landings, with evaluation and commentary by an expert test pilot.

The most important feature of the flare has turned out to be the airplane's deceleration in the maneuver. If too little, the airplane floats - if too much, it sinks. It has been found to be possible to correlate various effects on this in terms of average flare load factor. An additional parameter of some significance is a certain weighted integral of the speed stability. Certain kinds of ground effects are shown to be favorable, if they

are small and in the correct combination. Piloting technique is extensively discussed. Finally, some rules and procedures for predicting the difficulty of landings are presented.

INTRODUCTION

Landings have always been the most difficult part of ordinary flying. They are the bugaboo of all classes of pilots. At best, they are difficult for beginners to learn. At worst, under poor conditions of wind and turbulence, they are difficult and dangerous even for experts. And they are where the largest numbers of accidents occur.

There are airplanes with good reputation and good record for landings. And there are some known to be hard to land, with poor accident records. But there are a great many interrelated factors that influence these qualities, and their scope and interactions have not been well understood. The objective of the research reported herein was to develop a fuller understanding of the various factors involved, to explore them in flight tests with landings in a variable-stability aircraft, and to draw conclusions that could lead to improvements in the ease and quality of conventional landings in light, general-aviation type aircraft.

The experimental landings were performed in the variable-stability Navion, N5113K (Fig. 1). Actual touchdowns were performed, in touch-and-go style, from variations in approach speed and angle, all under visual flight rules (VFR). Vertical (glideslope) approach guidance was provided, consisting of two rows of lights to indicate, by their alignment, the proper approach path. Variations of lift, drag, moment aerodynamic characteristics were produced by standard variable-stability techniques, using the five-axis system of the Navion. The system, which is described in greater detail in Reference 1, has a computer-controlled Beta propeller for drag simulation, and a computer-controlled double-acting flap for lift

simulation, in addition to the usual aileron, rudder, and elevator computer-commanded controls. Various aerodynamic parameters, including control coupling and ground effects, were simulated by sensing and routing appropriate signals to the control-command computers. For simulation of ground-effect, the sensor of height was a radar altimeter, the electronic output of which was used to command flap and elevator actions. The evaluation pilot operated the airplane fly-by-wire by means of wheel, throttle, and pedal levers of conventional types. A safety pilot was present at all times, and he assisted in observing and reporting results, as well as in setting up simulation conditions.

Concurrently with the program reported here, a flight project involving wing spoilers on a light general-aviation aircraft has been conducted nearby. That project, References 2 through 5, with somewhat similar objectives, has furnished much useful information and understanding to this one, as an important special case. This report deals with generalities and fundamentals of the problem, whereas the other project concentrated on a particular system - spoilers - on a particular airplane. The experimental methods of the two projects have been different, but their objectives have been similar and their findings are entirely consistent.

FLIGHT MECHANICS OF THE FLARE

The landing "flare" is the transition between the steady descending "approach" and the "roll-out" along the runway to a stop. Its beginning and end are the "flare point" and "touchdown," respectively. It is a maneuver caused by control action; the motions are transients; there are accelerations both of flight path and velocity - and so, of course, they are governed by Newton's Law.

For flight paths that are almost horizontal:

$$m \frac{dV}{dt} = T - D - W\gamma \quad (1a)$$

$$mV \frac{d\gamma}{dt} = (n - 1)W \quad (1b)$$

Various approaches to these equations are useful. One, which may not be accurate enough for quantitative estimations, but which is very good for understanding and demonstrating various effects, is a linearization, as follows.

Linearized, Constant-Coefficient, Flare Equations

In the usual textbook jargon, equation (1a) is a general form of the Drag Equation. It is linearized by using truncated Taylor series:

$$T = T_o + \frac{\partial T}{\partial V} \Delta V + \frac{\partial T}{\partial \delta} \Delta \delta \quad (2a)$$

and

$$D = D_o + \frac{\partial D}{\partial V} \Delta V + \frac{\partial D}{\partial \alpha} \Delta \alpha + \frac{\partial D}{\partial \delta} \Delta \delta \quad (2b)$$

Defining, in addition,

$$\gamma = \gamma_o + \Delta \gamma \quad (2c)$$

Taking the expansion point, ()_o, to be a steady-state approach condition, corresponding to the initial condition for the flare

$$\gamma_o = \gamma_A \equiv \frac{T_o - D_o}{W}$$

and

$$m \frac{d(\Delta V)}{dt} = \left(\frac{\partial T}{\partial V} - \frac{\partial D}{\partial V} \right) \Delta V - \frac{\partial D}{\partial \alpha} \Delta \alpha - W \Delta \gamma + \left(\frac{\partial T}{\partial \delta} - \frac{\partial D}{\partial \delta} \right) \Delta \delta \quad (3a)$$

In similar terms, the Lift Equation may be written

$$m V_A \frac{d(\Delta \gamma)}{dt} = \Delta n \cdot W = \frac{\partial L}{\partial V} \Delta V + \frac{\partial L}{\partial \alpha} \Delta \alpha + \frac{\partial L}{\partial \delta} \Delta \delta \quad (3b)$$

In keeping with the linearization of the dynamic equations, we now invoke an approximate moment equilibrium. We assume that adjustments of α , which are governed by pitching moments, take place without dynamic

lag or overshoot. Roughly, this corresponds to suppressing the "short-period mode," and involves the relation*

$$\Delta\alpha \doteq -\frac{M_\delta}{M_\alpha} \Delta\delta \quad (4a)$$

Substituting in (3) and defining

$$D'_\delta \equiv D_\delta - \frac{M_\delta}{M_\alpha} D_\alpha - T_\delta \quad (4b)$$

$$L'_\delta \equiv L_\delta - \frac{M_\delta}{M_\alpha} L_\alpha \quad (4c)$$

we find

$$-\frac{d(\Delta V)}{dt} = (D_v - T_v) \Delta V + D'_\delta \Delta\delta + g \Delta\gamma \quad (5a)$$

$$V_A \frac{d(\Delta\gamma)}{dt} = L_v \Delta V + L'_\delta \Delta\delta = g \Delta n \quad (5b)$$

and finally, these can be combined in the form

$$(s' - \frac{\lambda'}{\Delta n}) \Delta V' = -\frac{D'_\delta}{L'_\delta} \Delta\delta - (\frac{1}{\Delta n}) \Delta\gamma \quad (6)$$

where

$$\lambda' \equiv -\frac{V_0}{g} [D_v - T_v - \frac{D'_\delta}{L'_\delta} L_v] \quad (6a)$$

* This expression implicitly contains the assumption that $M_v = 0$. This probably is reasonable for the conventional, general-aviation, light airplane. In addition, M_α should be based on "Maneuver Margin":

$$\text{effective } M_\alpha = \frac{q S \bar{c}}{I_y} C_{L_\alpha} (N_m - \bar{x}_{cg}) = \frac{L_\alpha}{(k_y / \bar{c})^2} (\frac{N_m - \bar{x}_{cg}}{\bar{c}})$$

In this, s' is the operator for differentiating with respect to $\Delta\gamma$, and the equation could be said to represent an equivalent first-order system with a step and a ramp input. If Δn is considered a constant, (6) is a constant-coefficient equation with $\Delta\gamma$ the independent variable and $\Delta V'$ the unknown dependent variable. It is a useful basis for examining various effects on V, γ trajectories during the flare.

In general, the solution of (6) is

$$\Delta V' = \frac{\Delta n}{(\lambda')^2} \left[1 + \lambda' \frac{D' \delta}{L' \delta} \right] \left[1 - e^{-\frac{\lambda'}{\Delta n} \Delta\gamma} \right] + \frac{1}{\lambda'} \Delta\gamma \quad (7)$$

For the special limiting cases

$$\lambda' = 0, \quad \Delta V' = -\Delta\gamma \left[\frac{D' \delta}{L' \delta} + \frac{1}{2 \Delta n} \Delta\gamma \right] \quad (7a)$$

$$\Delta n = 0, \quad \Delta V' = \frac{1}{\lambda'} \Delta\gamma \quad (7b)$$

$$\Delta n = \infty, \quad \Delta V' = -\frac{D' \delta}{L' \delta} \Delta\gamma \quad (7c)$$

Speed and Flight-Path Trajectories in the Flare

The flare maneuvers can well be viewed on a graph of V and γ , as a trajectory from an approach point to a touchdown point, as shown in Figure 2. The coordinates of the approach point (V_A, γ_A) can be arbitrarily selected, but of course their values will strongly affect what happens in the maneuver. The touchdown point would normally be taken at a knot or two above stalling speed and a foot-per-second or so of sink rate. But some variations would be acceptable, so touchdown conditions translate into a small zone, as shown in the figure.

Effect of Load Factor

From the various equations (7), it can be seen that the V, γ trajectories are concave downward to the left, from an approach point toward the touch-down zone. Although in general the various parameters interact to some extent, it can be seen that the family of V, γ trajectories, for different Δn , is a fan with low (or zero) Δn cases going almost directly left on the diagram, and with very large (or infinity) Δn cases going almost directly upwards. This is very basic and important:

For very low load-factor flares, large velocity changes (for a given $\Delta \gamma$) will occur - the higher the load-factor, the smaller the velocity changes.

This immediately produces some important conclusions

- 1) An airplane which - either because of its inherent characteristics or because of selected approach conditions - tends to "float" in the landing, will have to be flared very gradually, at low load factor.
- 2) An airplane tending to decelerate rapidly and hit hard in touchdown, will have to be flared very abruptly, with relatively high load factor.
- 3) Other factors aside, an increase in approach angle, γ_A , will require a higher approach speed, or a more abrupt flare, or a combination.

Effect of Speed-Stability

The speed-stability parameter, λ' , tends to rotate the trajectories upwards and to the right, on the diagram, if its value is negative. It has the largest effect at low load-factors, where for the limiting case, $\Delta n = 0$, since $\lambda' \equiv V_o \left(\frac{d\gamma}{dV} \right)_{ss}$:

$$\Delta V \Big|_{\Delta n=0} \equiv \left(\frac{dV}{d\gamma} \right)_{ss} \Delta \gamma \quad (8)$$

This is shown in Figure 2.

Thus an airplane with speed-stability, on the front side, will tend to float and call for gradual flares. Cases with negative speed stability ($\lambda' > 0$), on the back side, will tend to decelerate rapidly and sink, calling for abrupt flares for successful touchdowns.

Effect of Control Drag/ Lift Parameter, $\frac{D'_\delta}{L'_\delta}$

The control parameter, $\frac{D'_\delta}{L'_\delta}$, also tilts the V, γ trajectories one way or another depending on the sign. This has the largest direct effect at large Δn , where in the limiting case $\Delta n = \infty$, the slope is exactly

$$\left. \frac{dV}{d\gamma} \right|_{\Delta n \rightarrow \infty} = -V_0 \frac{D'_\delta}{L'_\delta} \quad (9)$$

Since, however, the speed-stability parameter, λ' , also contains $\frac{D'_\delta}{L'_\delta}$ according to (6a), the effect of $\frac{D'_\delta}{L'_\delta}$ is also felt indirectly at low Δn , even for $\Delta n = 0$.

The usual case of the conventional elevator control has L'_δ and D'_δ of the same sign - mostly due to the angle-of-attack change resulting from control, according to equation (4a). Its effect is toward rapid deceleration in the flare, calling for abrupt flares.

The pure lift control would have $D'_\delta = 0$, and would have a vertical V, γ trajectory for $\Delta n = \infty$. The speed stability characteristic is front side, $\lambda' < 0$.

A spoiler control with proper trim changes would probably have $\frac{D'_\delta}{L'_\delta} < 0$. It would rotate the V, γ trajectories upward to the right, tending to produce a floating characteristic that calls for gradual flares. A throttle control normally has the same effect. But neither of these normally has enough lift authority to be used by itself for the landing flare. It will, instead, be used as a second control, coordinated with the stick or wheel, as discussed next.

Use of a Second Control

In the previous simplified analysis and discussion of the flare maneuver, we have provided for use of only a single control; and by treating load factor as a constant, we have implicitly specified how the control was applied to do the maneuver. As we hinted in the previous paragraph, in this context of the conventional, general aviation light-plane, it is pretty clear that the primary control must be the wheel. It is the only one with sufficient authority and sensitivity, with good enough feel and response, for the demanding task of the landing flare. It is clear from the above analysis and discussion - and of course from experience, also - that landings can be done using the wheel control by itself. It is natural and obvious to consider why and how a second control - like the throttle - would be used in addition.

The landing is a multi-variable control task. The pilot has to control altitude, flight path, airspeed - simultaneously - and the only reason it can be done at all with a single control is that the variables are coupled together by integral relationships like the differential equations (1). It is intuitively and experimentally obvious that a pilot can learn to do a maneuver - in which all the variables change as required - using only one control, if he has it demonstrated to him and if he practices. But it would be surprising if true feedback behavior, with separate sensing and controlling of all the motion variables, were feasible with only a single control, except at a low level of performance. Better performance in the presence of disturbances, like wind and gusts, and better recovery from errors, is possible with two controls.

The primary control, with good authority over the glide path, is the wheel. The throttle, with independent authority over thrust, is normally secondary. It might be used by the pilot to clean up residual deviations in velocity from a reference variation corresponding to a nominal wheel-only maneuver. This possibility - which is perfectly real - has been extensively explored in another project as well (References 2 through 5). In

any case, the wheel-only landing is a very useful reference technique. With only a single control, the action quickly becomes well-defined in experimental landings, and the effects of various parameters are easily seen. The analysis and discussion of V, γ trajectories, previously presented, are quite well corroborated in experiments.

Even aside from countering disturbances or correcting errors, the reference piloting technique can, of course, involve some use of the throttle. One way is to open the throttle in the flare, and then close it at or just before touchdown. Of course this action rotates the V, γ trajectories upward to the right in the diagram, tending to produce floating by (relatively) accelerating the airplane - hence the term accelerate technique. With this technique, the trade-offs with other individual effects would call for lower approach speed, lower flare load factor, or steeper approach angle.

The opposite way to use the throttle is to retard it through the flare. This produces additional deceleration of the airplane in the maneuver, and is called the decelerate technique. With this method, equivalent landings would have higher approach speed, higher flare load factor, or lower approach angle.

With one technique or the other, or perhaps even a combination of the two, a pilot can steer his V, γ trajectory anywhere around the diagram that he wants to go. But many trials in both the other program (Reference 5) and this one have shown that the easiest technique - which gives consistently accurate, comfortable landings and which provides for the easiest accommodation of turbulence and correction of errors - is a particular kind of decelerate technique. It involves a steady retard action of the throttle through the flare to power off at or just before touchdown. It is found that steady rearward action on the wheel is also favorable, and so these two favorable actions are in the same direction, well correlated. In this most favorable case, the two control actions are very directly coordinated - almost as though they were geared together. In some respects, the dual action works just like some equivalent single control.

Most of the experimental landings reported here have been done with the single control, wheel-only technique. They are easier to identify, repeat and evaluate in the experimental routine - involving many landings and many parameters. But it should be kept in mind that any wheel-only landing can be made somewhat more easily by using the "decelerate technique," and by entering the flare from a slightly higher approach speed, V_A . This will be clarified by additional discussion and experimental results in the next sections.

Ground Effect

Airplanes experience changes of aerodynamic forces and moments as they approach the ground. These so-called ground effects are usually an increase of lift, a nose-down moment, and a reduction of drag. They occur late in the maneuver of landing, and they probably do not affect the speed variations appreciably. The drag reduction rotates the fan of V, γ trajectories clockwise, and hence requires a lower load factor for a given flare. It shifts the airplane toward a tendency to float, and hence it makes a floater worse, and improves a sinker. But this effect, occurring late in the maneuver, is considered to be of little significance. The effects of the lift and moment changes are felt in the control actions required for the maneuver. They tend to be opposite and compensating in this respect.

The lift increase, by itself, is a sort of cushion, producing a vertical stability near the ground. The more important effect, however, is to require a nose-down attitude change to maintain lift equilibrium, and this may cause a problem of wheelbarrowing. This could be an important factor, but it was not represented in the experiment reported here. In these experiments, the lift ground effect requires a forward increment of stick control to maintain the required load factor through the flare.

The ground-effect moment change in the nose-down direction tends, by itself, to increase the rearward wheel deflection required through the maneuver. In cases which otherwise require very little control action,

this may be an advantage. An example is the floater, where the required Δn is very small. In any case, the moment change tends to balance the forward control deflection required to compensate the ground-effect increase of lift. Extreme values of nose-down moment, perhaps combined with a sinking situation - where large control action is necessary anyway - would probably be a disadvantage.

EXPERIMENTAL LANDINGS AND RESULTS

A great many (approximately 700) experimental landings have been performed in the variable-stability Navion, N5113K, (Fig. 1) of Princeton University. They have been performed by an expert^{*} experimental test-pilot, who has evaluated their qualities with extensive commentary and Cooper-Harper ratings. Every landing was tape-recorded for play-back and analysis. The various parameters of significance to the landing task were varied over broad ranges by means of the variable-stability features of the airplane. In the following sections, we present the results and their interpretation.

All the landings were good, or successful, since they were all on the runway, did not break the airplane, and would have resulted in reasonable stopping distances. But because of their different aerodynamic and flight parameters, they called for different pilot technique and they varied greatly in piloting difficulty.

Sample landings are shown in Figure 3. In one part of the figure, time histories are reproduced. Initiation of the flare is indicated by

* Extensive recent experience in handling qualities evaluations with in-flight and ground-based simulators; particularly relevant are landing evaluations of spoiler-equipped lightplane, powered-lift STOL transport, and STOL transport with adverse ground effect, as well as subject program. Over 5000 hours total.

stick action, and touchdown by the landing gear strut accelerometer. The time between the two points is used to calculate the average load factor through the flare, according to

$$\overline{\Delta n} = \frac{V_{\text{ave}}}{g} \frac{\Delta \gamma}{\Delta t} = - \frac{V_{\text{ave}}}{g} \frac{\gamma_A}{\Delta t} \quad (10)$$

Of course γ_A was governed by the setting of the approach guidance lights, used by the pilot in every landing to control the approach glide path.

The data are also displayed in the form of control deflection and flight path angle against velocity - the trajectories discussed in the section on flight mechanics.

Of the two landings shown, the first was a floater. There was very little control action and very little deceleration through the flare. The pilot either had to accept a hot touchdown or manage the long, awkward flare. He assigned the relatively poor rating number of 5.

The second landing was a sinker. Positive action on the stick was necessary, and the flare was quite abrupt. The timing of the maneuver was critical, and there was a strong possibility of a hard touchdown. The touchdown was, in fact, short - in front of the designated landing zone. The pilot rating was poor, $4\frac{1}{2}$ to 5.

The accuracy of touchdowns within groups of landings is shown in Figure 4. The black circled points show the averages, with the ranges indicated by the lines. The number of landings in these groups is not large, and so the information is only qualitative.

Figure 4, for one approach angle, $\gamma_A = -.08 \text{ rad } (-4.5^\circ)$, shows clearly that as approach speed and front-sidedness increase, dispersions increase and touchdown occurs further down the runway. These are the typical features of floating, and are downrated by the pilot.

The back-side configuration, S-206, requires a higher approach speed to reduce the sinking tendency. The short landing of Figure 3 is

at the left end of the range shown in Figure 4. These cases that tend to sink rapidly have to be flared very abruptly unless entered at an increased approach speed.

The effect of approach angle is also indicated in Figure 4, where it is clear that the shallower approach shifts touchdowns further down the runway. The effect is toward floating with long touchdowns and large dispersions.

Observed Effects of Individual Parameters

a) Load factor

It is intuitively obvious from the flight mechanics discussions of the previous sections, and also from pilots' descriptions of landings, that the load factor required in the flare is an important parameter. On the one hand, a certain load factor is necessary to make the V, γ trajectory go from the flare point to the touchdown point. Airplane characteristics, approach parameters, or control techniques that tend to produce "floating" - not enough deceleration - call for a long gradual flare and a low load factor. The opposite, where the airplane decelerates too rapidly and sinks too fast, calls for an abrupt flare and a high load factor. And so it seems that the average load factor in the flare might be a convenient measure of a tendency to float, or a tendency to sink. This has turned out to be the case for the data of this experiment. The pilot evaluations of several effects which influence the deceleration through the flare are nicely correlated in terms of average load factor.

Of course the average load factor does not uniquely and completely specify the flare maneuver. A given $\overline{\Delta n}$ could correspond to an infinite variety of time histories of Δn , with different V, γ trajectories. Nevertheless, with the type of time histories typical of the flare maneuver, the average load factor, $\overline{\Delta n}$, does apparently provide a measure of floating or sinking.

The pilot doesn't like the "floater" situation. The corresponding flare is too gradual, too long and drawn out. It has to be started too high and he is exposed to problems of winds and gusts for too long a time. The exact touch-down point is hard to control, and short, precise landings are not consistently achievable. The inexperienced pilot is apt to overcontrol and "balloon," and drop in at the end. An example of pilot commentary is:

"This configuration seems to accelerate as you put in a nose-up pitch input. . . . very delicate control situation. . . ." (S-103, 70 kts)

The opposite case, where the airplane decelerates too rapidly and sinks, is even more difficult. The abrupt flare must be started late, close to the ground, and the timing of it is very critical. The whole maneuver is quick, with little opportunity for the pilot to observe the situation and adjust or correct an error. The control action may be uncomfortably large and the high load factor may even prematurely stall the airplane. Severe cases of this kind will occasionally produce very hard touchdowns and may, of course, damage the airplane. Typical pilot comments are:

"Note here that you can't stop the sink once the deceleration starts. . . . You use a big, continuous stick input, but you just can't stop the sink. It just decelerates too fast. . . ." (S-206, 70 kts)

"Even with the extra 5 knots here, you can't stop the sink. The control movement is a favorable, continuous rearward movement, but I'm getting firm touchdowns; I just can't quite flare the airplane completely. . . ." (S-206, 75 kts)

There is some intermediate load factor that represents the best compromise between these opposite flaws. It is quite clearly shown in the data of Figure 5. Pilot Opinion Ratings, on a Cooper-Harper scale, are shown as a function of the average flare load factor, for various approach path angles. These landings are all wheel-only, and so they correspond in

style to the previous V, γ trajectory discussion. They include amongst the various configurations a wide range of drag and deceleration characteristics, and a range of approach velocities. These data are given in Table 1 for the cases plotted in Figure 5.

The open symbols in the various parts of the figure are cases for which a certain weighted integral of the speed stability parameter is zero. For these cases, speed stability itself ought not to be a factor, and the good correlation against load factor suggests that this is so. The preferred average load factor is about $\overline{\Delta n} = .07$, increasing slightly with approach path angle through the range .05 to .16 rad (3° to 9°). Pilot evaluations degrade gradually for $\overline{\Delta n}$ below the optimum, and sharply for $\overline{\Delta n}$ larger than optimum. These degradations relate to the reasons previously cited: a floating tendency demanding long, awkward flares and a sinking tendency needing abrupt, critically timed flares, respectively.

The pilot opinion ratings at the best load factors are around 3.0 on the Cooper-Harper scale. This is almost the best that can be done with the wheel-only technique. With only the one control, regulation of velocity simultaneously with flight-path is difficult. Deviations of speed that randomly appear cannot easily be corrected, and can only be accommodated by adjusting the flare load factor as either a float or a sink develops.

Allowing for this, and knowing that somewhat better evaluations can be obtained for "decelerate technique," it is of interest to compare these results with those of Reference 5. The preferred average load factors are quite in agreement; and the pilot ratings of the Reference, where the "decelerate technique" was used, are indeed somewhat better. The use of throttle is considered later in this report, and further discussion of it will be deferred to that point.

b) Speed stability, $\left(\frac{d\gamma}{dV}\right)_{ss}$

The shape and various details of the airplane's thrust/drag curves determine the value of the speed stability parameter. On the front side of the γ, V curve, $\left(\frac{d\gamma}{dV}\right)_{ss} < 0$, and its equivalent, of course, $\lambda' < 0$.

The steady-state γ, V curves for two configurations are shown in Figure 6. These are the extensively tested S-103 (Front-side) and S-206 (Back-side). The speed-stability parameter is of course the slope of the curve shown, and varies with speed and between configurations.

In the experimental landings, changes of $(\frac{d\gamma}{dV})_{ss}$ produced tendencies to float or sink. These were manifested by lower or higher average load factors, as shown in Figure 5, with corresponding changes in pilot evaluation.

With configurations for which the flare is partly or fully on the back-side, with $(\frac{d\gamma}{dV})_{ss} > 0$ and $\lambda' > 0$, there appears to be an additional difficulty. This relates to the dynamic instability of speed variations of the airplane constrained to follow a flight path. Based mostly on intuition, we have hypothesized that a measure of this might be

$$I^* \equiv \int_0^{t_f^*} \frac{[|\lambda'| + \lambda']}{2} t^* dt^*, \text{ sec}^2 \quad (11)$$

In words, the parameter I^* is the time integral through the flare of the speed stability parameter, λ' , weighted by the time to go to touchdown and counting only the back-side, $\lambda' > 0$.

Indeed, this weighted integral measure of backsidedness does seem to correlate well the extra penalties in terms of the pilot ratings. The contours faired in the Figure 5 are less than perfectly defined, but they do seem to fit the data pretty well, and there are no glaring discrepancies.

c) Approach Velocity, V_A

Changes of approach velocity affect the load factor required through the flare. The airplane approaching at high speed tends to carry through the flare and to come out too fast, which the pilot counters by reducing the load factor. In the experiment there were cases of this which were downrated as previously shown. And by the same token, slow approaches

are found in the data, downrated by the pilot because they tend to sink. The pilot counters this by flaring more abruptly, with higher load factor. These effects are represented in Figure 5 as a function of $\overline{\Delta n}$ (and in Table 1).

Of course other problems associated with approach velocity are also possible. Particularly obvious are stall proximity and control deterioration with slow approach speeds, and high rate-of-descent and gust sensitivity with high approach speeds. These effects were not represented in this experiment, and presumably did not contribute in any significant way to the evaluations presented herein.

d) Approach angle, γ_A

The change, from beginning to end of the flare, of the longitudinal (along the flight path) force, is proportional to γ_A : the larger γ_A , the larger the decelerating forces in the flare. Beyond that, the time in the flare is more or less proportional to γ_A , and so even if the deceleration was constant, the speed loss would increase with γ_A . This means that for the same flare load factor, the approach velocity would have to increase rapidly with γ_A .

There are, for the pilot, two main disadvantages of increasing γ_A :

The height of the flare point increases, making it more difficult to judge the position and timing of the maneuver; and

the rate of descent in the approach is increased, requiring more accurate timing and lead prediction for initiating the flare.

To reduce these problems somewhat, the pilot compromises on a higher preferred average load factor, for the higher γ_A . The higher $\overline{\Delta n}$ is sometimes cited as a third disadvantage of increasing γ_A .

These factors account for the increase, with γ_A , of the optimum load factor shown in both the data of Figure 5 and in Reference 5. Also, of

course, the pilot ratings degrade somewhat with increasing γ_A . In the range of normal approaches, from about three to six degrees, this effect is very mild, even insignificant. It is important only at the higher approach angles investigated in Reference 5. In that range, the difficulties of single control, wheel-only technique become exaggerated, and the importance of the second control with "decelerate" action is more pronounced.

e) Control technique

The pilot of this experiment consistently reports that the control action he prefers is a steady, rearward movement of the wheel through the course of the maneuver. Again, from pilot commentary:

".....the control movement is a favorable sort of thing, continuous rearward movement....." (S-206, 75 kts)

".....the control input looks more favorable; it's like the 204 at 70 kts, or the 206 at 75 kts. A continuous rearward motion on the control column." (S-103, 65 kts)

He varies, or modulates, this action as required by disturbances or other random occurrences, but he likes the action to be monotonic, without reversals. This has several interesting implications:

- It calls for a minimum level of static stability.
- It suggests that particular ground effects may be beneficial - see later.
- It suggests an additional difficulty for very gradual (low $\overline{\Delta n}$) flares, or for flares with very little velocity change (hence, low approach speed, V_A).
- It suggests an additional penalty for flares involving high load factor near the end, since at that point, near touchdown, reverse (forward) action on the wheel would be needed.

Now in these "wheel-only" landings, we have not been able to separately identify and detail the effects of five principal factors and their numerous

related, dependent consequences. In landings, they all occur simultaneously in a big mix, and it is not possible to pinpoint their isolated influences. There is no inconsistency, however, with the data presented, and it is useful information for the analysis and prediction of the ease of landing, as discussed in a following section.

The use, through the landing, of a second (like throttle) control is an obvious possibility. Several variations have been tried and evaluated. By using "accelerate" action (forward, or open throttle) in the flare, the pilot can handle "sink" situations without excessively large load factors. And with "decelerate" action (rearward, or close throttle) he can reduce the opposite floating tendency. Some of the latter action seems to be the best possible case, where the throttle movement is steadily back through the maneuver - monotonic and correlated with the action on the wheel. The pilot finds the "accelerate" case - with opposite and dissimilar movements of wheel and throttle - to be awkward and unnatural, difficult to manage with consistency and finesse.

"S-206 requires a power addition some place along the line. The only comfortable way to do it is to add power early..... and in the flare perhaps reduce it again if you have too much. Anyway, it turns out to be a rather imprecise sort of maneuver, having to do two things with the throttle, forward then back, and modulate the flare and worry about sinking too much or decelerating too muchI'm uncomfortable about the workload situation." (S-206, 70 kts)

He finds the "decelerate" case - where the throttle and wheel motions are correlated, almost like one action - to be the best of all.

"Basic 203 itself is not a bad airplane - that is, if you use a wheel-only technique on it, you might get just a little float. So the throttle coordination that's desirable is a power reduction. And it works out rather well. You start back with the power right along with the column in the flare, working the two

together, and there's no problem really in figuring out what kind of throttle motion you need to enable you to have a nice, steady pull on the column to complete the landing. I get the feeling right away that I can do things pretty consistently." (S-203, 70 kts)

It is an even better nominal, or reference, action than the wheel-only case. In the latter case corrective actions on the throttle are as apt to be forward as reverse, and he prefers to simply vary - or modulate - the rearward, "decelerate," movement of the lever. With the same average load factor, this action will call for somewhat higher approach speed than for wheel-only technique.

The wheel-only landings shown in Figure 5 exhibit an optimum rating on the Cooper-Harper scale of about 3. The two-control landings shown in Figure 7, and also those of Reference 5, indicate a small improvement - the order of 1/3 to 1/2 a rating unit - with best ratings about 2-1/2. This small but consistent difference relates of course to the better coordination and the preferred throttle action associated with the "decelerate" technique.

f) Coupling of the second control

The lift and moment due to throttle are a coupling which has some effect on the use of the control. The parameter $L'_{\delta_T} / D'_{\delta_T}$ is a measure of their combination, and has been varied over positive and negative values in the experimental landings. The parameter could properly be called the "control position trim change." It determines how much the primary control (wheel) has to be moved to maintain lift equilibrium after a movement of the throttle. It has been shown rather consistently (for example, Reference 3) that for the approach and flight path control, this trim change parameter is best at zero. This makes it easy to maintain speed even while adjusting flight path.

The combination trim change parameter contains two parts, representing the separate, or partial, changes of lift and moment due to power. These are the two parts of the expression

$$\frac{L'_{\delta_T}}{D'_{\delta_T}} = \frac{L_{\delta_T} - M_{\delta_T} \frac{L_{\alpha}}{M_{\alpha}}}{D_{\delta_T} - T_{\delta_T} - \frac{M_{\delta_T}}{M_{\alpha}} D_{\alpha}} \quad (12)$$

It has been shown elsewhere (Reference 4) that the most favorable case for flight path control is

$$L_{\delta_T} = M_{\delta_T} \frac{L_{\alpha}}{M_{\alpha}} \quad (\text{hence, } \frac{L'_{\delta_T}}{D'_{\delta_T}} = 0)$$

and

$$L_{\delta_T} > 0 \quad (\text{hence, } M_{\delta_T} < 0)$$

This characteristic, where advancing throttle lever increases lift and produces nose-down moment, is the natural result of integrating wing spoilers and throttle. It produces a very favorable quality in the response to throttle lever action.

These general effects have been confirmed in further detail in the experimental landings reported here (Fig. 7). Through the flare and at touch-down, the positive value of L_{δ_T} is much appreciated by the pilot. He even prefers, for this task, a small negative value for the combination parameter $L'_{\delta_T}/D'_{\delta_T}$. For this case, the throttle actions to correct both floating (retard) and sinking (advance) produce favorable lift changes to help with the correction. For the opposite case, $L'_{\delta_T}/D'_{\delta_T} > 0$, the lift changes are the wrong way; they tend to defeat the correction, and to compound the problem.

It is possible, however, to overdo the negative value of $L'_{\delta_T}/D'_{\delta_T}$. If the lift change is too large and too pronounced, the throttle begins to compete with the wheel for lift control, and in extreme cases it could even

necessitate opposite, unfavorable, action on the wheel to maintain lift equilibrium. The upshot is that an intermediate negative value seems to be best. This is consistently shown by Figure 7 for several different cases.

The best value of $L'_{\delta_T} / D'_{\delta_T}$ for this task seems to be relatively independent of the other parameters. The indicated optimum is the order of

$$\frac{L'_{\delta_T}}{D'_{\delta_T}} = -.25$$

Considering that in tasks involving speed holding, zero might be preferred, it seems that a compromise in the range

$$-.25 < \frac{L'_{\delta_T}}{D'_{\delta_T}} < 0$$

would be very favorable.

With M_{δ_T} negative, its term in the denominator of equation (12) simply increases slightly the negative sum. It is a small term which may be neglected to perceive limits on the others. Since M_{δ_T} must not be so large as to change the sign of the numerator of equation (12), it is clear that a necessary condition is

$$\frac{M_{\alpha}}{L_{\alpha}} < \frac{M_{\delta_T}}{L_{\delta_T}} < 0$$

This, with the limits on $L'_{\delta_T} / D'_{\delta_T}$, suggests

$$-.25 < \frac{L_{\delta_T}}{D_{\delta_T} - T_{\delta_T}} < 0$$

Translated into words, these conditions are that the partial (constant α) trim changes due to advancing throttle are a moderate lift increase and a small nose-down pitching moment.

These are clearly also the conditions desired for wave-off, or aborted landing. Here the decision to wave-off will be followed by rapid application of full power. Increase of lift and a small nose-down moment are certainly in the correct direction to inhibit settling into the ground or stalling due to increase in angle of attack.

Whereas these favorable tendencies are the natural characteristics of wing spoilers used in the manner of Reference 5, they would be hard to achieve consistently by design of conventional wing-flap-tail configuration details. This, of course, is because the complicated propeller slipstream and flap-tail aerodynamic interactions can only be predicted with powered-model wind-tunnel tests.

g) Ground effect variations

Most of the experimental landings of this project have been done without altering the natural ground effects of the basic Navion airplane. They are more-or-less typical of the conventional general-aviation light aircraft, and they serve as a logical base from which to vary the details.

A series of landings, however, for assorted combinations of the other parameters, have been performed in which the lift and moment ground effects have been varied separately and in combination. These have been simulated, of course, in the variable-stability airplane by sensing height with a radar altimeter, and by using the signals to command lift and moment changes. The changes are represented in terms of the natural Navion effects, which have been estimated by means of a special series of tests. The results of these are shown in Figure 8, for the various parts, under the stated conditions.

The ground effect functions of Figure 8a have arbitrary shapes starting at an altitude of 12 m (40 ft). Although the shapes are arbitrary, the magnitudes of ΔC_L and ΔC_m have been estimated from low passes over the runway with angle-of-attack and elevator deflection carefully compared to up-and-away conditions with the same speed, configuration, and power. Finally, shallow approaches with these functions removed show no tendency for the airplane to flare (from the ΔC_L) or pitch (from the ΔC_m). One such approach, with the Navion ground-effects cancelled is shown in Figure 8b. There is no apparent tendency to change attitude or flight path as the ground is approached.

The drag change due to ground effect was determined in preliminary trials to have negligible influence on the flare. It occurs late in the maneuver, and the small acceleration at the end is of little consequence for the landing. Both pilot reports and runs like the one of Figure 8 indicate that the lift and moment increments adequately represent the Navion ground effects.

The changes to touchdown accuracy by variations in ground effects are shown in Figure 9, for one approach condition and the configuration S-205. It is quite clear that the variations of ground effect do not greatly affect the landing performance, either touchdown point or dispersion. They do, however, affect the control action required, and so they affect the difficulty of the maneuver and the pilot evaluation.

Pilot evaluations for simultaneously varying the lift and moment ground effects are shown in Figure 9 for three cases. For the front-sided configuration, the combined ground effects are apparently a disadvantage since the pilot rating improves when they are removed.

Pilot evaluation results for various combinations of lift and moment ground effects are shown in Figure 10. The back-sided configuration (S-206) shown in Figure 10c exhibits rather small variations in ratings except for the large-moment/ small-lift and small-moment/ large-lift combinations, both of which are degraded compared to the basic Navion levels ($L_G = M_G = 1$). This is reasonable, for the larger nose-down moment further degrades an already-compromised ability to flare the airplane with the elevator; in the other case, decreased nose-down moment and increased lift effect reduce the need for rearward stick motion (which the pilot finds to be helpful in modulating the flare), and introduce a small but noticeable ballooning tendency which makes the landing less predictable. The best case is not sharply defined, but according to the figure would have ground effects on the order of 1/3 those of the basic machine.

The intermediate case with neutral speed stability (S-205) presented in Figure 10b shows similar results. The mix of lift and moment ground effects is about right, but a lower level of each would be advantageous.

For the front-side configuration (S-103) shown in Figure 10a, the rating variations are again rather small and, compared to the other two cases, not so consistent. However, pilot comments indicate that the low-lift, large-moment case was improved over the basic machine because it led to larger, more continuous rearward stick action during the landing. Lift increases, on the other hand, accentuated an already-annoying tendency to float and balloon.

Although the data are not sufficient to establish all the details, it seems clear that, given the right size and mix, these ground effects are advantageous. The usual signs, $\Delta M_G < 0$ and $\Delta L_G > 0$, are favorable. It looks

as though the optimum mix of lift and moment shifts toward pure moment with front-sidedness, and toward pure lift with back-sidedness (Figure 10d). That seems reasonable: since clearly for the floater, nose-down moment is favorable and lift increase is unfavorable; and for the sinker, the lift increase is favorable and nose-down moment is unfavorable. The optimum level of these ground effects is the order of $1/3$ to $1/2$ those of the basic Navion.

Prediction of Airplane Landing Qualities

We now attempt to apply the experimental results and theoretical considerations to the problem of predicting the ease and quality of conventional landings. It is a formidable job, because of the large number of interrelated effects, and the rather subtle interactions between some of them.

The biggest single part of the problem is to predict V, γ trajectories, the character of which determines floating or sinking tendencies and average load factor requirements. But these trajectories are affected by all the parameters of the system, including control technique and approach conditions, as well as the aerodynamics of the airplane. The linearized V, γ equations, previously used as a basis for discussions, are not accurate enough for quantitative predictions. We have therefore devised a step-by-step method of constructing V, γ trajectories. It is a simple routine, and does not require a digital computer.

a) Control for trim

We begin with the lift and drag aerodynamics of the airplane in the form of steady-state γ, V curves for various throttle positions, for flight free of ground effect. We also use, although it is of less significance, static trim curves of pitch control position versus velocity, for various positive load factors, also in flight free of ground effect. For low power levels, we assume these are independent of throttle position.

Static longitudinal stability and trim data would be needed to construct a set of trim curves like those at the top of Figure 11. Flight test or wind-tunnel data would be best, but perhaps estimates of static and maneuver margins would suffice. Starting with a reference control position to trim at $C_L = 0$ (which is the asymptotic value for $V \rightarrow \infty$), the steady-state curve, $\Delta n = 0$, can be given as

$$\delta_e = \delta_{e_o} + \frac{W}{qS} \cdot \frac{(N_o - \bar{x}_{cg})}{C_{m\delta}} \quad (13)$$

At a given speed, the increment due to load factor would be

$$\Delta \delta_e = + \frac{W}{qS} \cdot \frac{(N_m - \bar{x}_{cg})}{C_{m\delta}} \cdot \Delta n$$

The curves illustrated are for

$$\begin{aligned} \delta_{e_o} &= .17 \text{ rad (10 deg)} \\ W/S &= 479 \text{ N/m}^2 \text{ (10 lb/ft}^2\text{)} \\ C_{m\delta} &= -1.43/\text{rad (-}.025/\text{deg)} \\ (N_o - \bar{x}_{cg}) &= .10 \\ (N_m - \bar{x}_{cg}) &= .15 \end{aligned}$$

b) Trajectory

The steady-state γ, V curves can of course be measured in flight tests for the purpose. Or they can be derived from wind-tunnel measurements of drag and thrust. Or, as a last resort, they can be predicted by the method outlined below.

For steady flight, equation (1a) becomes

$$\gamma_{ss} = \frac{T - D}{W} \quad (14)$$

in which D can be based on the quadratic formula for C_D

$$C_D = C_{D_p} + \frac{C_L^2}{\pi e A} \quad (15)$$

As a function of V (or q), this corresponds to

$$\frac{D}{W} = q \frac{C_{D_p}}{W/S} + \frac{1}{q} \frac{W/S}{\pi e A} \quad (16)$$

If thrust were zero, then the negative of this would be γ_{ss} . The two parts, of course, represent the parasite drag and the induced drag. It is well known that the negative γ_{ss} corresponding is a minimum at an intermediate speed where the two parts are equal. At speeds higher than this, the airplane is on the front side; and at speeds below this, it is on the back side. For values typical of general aviation light planes, say

$$C_{D_p} = .030$$

$$W/S = 479 \text{ N/m}^2 \text{ (10 lb/ft}^2\text{)}$$

$$e A = 4.5$$

the minimum is $\gamma_{\min} = -.09 \text{ rad } (-5.3^\circ)$ at about 68 knots.

The variation of thrust with velocity, of course, depends on the type of propeller and the power setting. Usually the propeller windmilling at idle power setting will produce negative thrust that increases negatively with speed. At forward thrust, the thrust will decrease with increase of speed. Rather complete propeller data would be required to predict these variations in detail; and over the small range of speeds of interest in landings, it may be reasonable to assume that thrust is constant for a given throttle setting. The effect of opening or closing throttle, then, on the γ_{ss} vs V curve would be to displace it vertically, as in the family shown in Figure 11.

Now a useful form of equations (1a) and (1b) for a step-by-step trajectory calculation is

$$\Delta\gamma = \frac{\Delta n}{(\gamma_{ss} - \gamma)} \frac{\Delta V}{V} \quad (17)$$

As a way of getting started, we recommend tracing a trajectory backward from a selected touchdown point, using this equation with favorable control variations in accordance with our experimental results.

If the trajectory goes from the touchdown point to a selected approach condition, with favorable control actions, then the landing characteristics would be predicted to be easy. We illustrate this calculation for a case of $\gamma_A = -.08 \text{ rad } (-4.5^\circ)$, $V_A = 70 \text{ kts}$ with touchdown at $\gamma_{td} = -.01 \text{ rad } (-.5^\circ)$ [.3048 m/sec or 1 ft/sec] and $V_{td} = 60 \text{ kts}$.

A favorable wheel action would be steadily backward, not reversing, through the course of the flare. For a $.08 \text{ rad } (4.5^\circ)$ approach, the best average load factor is about 1.07, Figure 5, and so a favorable wheel action would be the one shown as (1) on the trim curves. The corresponding favorable throttle action would be a steady retarding which would vary γ_{ss} along a curve like the dotted line shown on the γ, V graph of Figure 11.

A first trajectory calculation* backward from touchdown, with a $\overline{\Delta n} \doteq .07$ load factor, is shown in the figure, marked (1). The calculation is detailed in Table 2. It is clear that the trajectory misses the approach point on the low side, and that either the load factor or the approach speed must be reduced.

* There is a small error in the above procedure. The induced drag would be a bit larger than contained in γ_{ss} because of the load factor in the flare. It would be relatively simple to correct for this by adding

$$\Delta\gamma_{ss} = - \frac{2 \Delta n}{q} \frac{W/S}{\pi e A}$$

But for the small load factors of this maneuver, considering the other approximations, the extra calculation is probably not worthwhile.

A second trajectory, labelled (2) in the graph and in the table, also falls short of the approach velocity, even though the average load factor has been greatly reduced. It is clear that for the 10 kt margin between approach and touchdown velocities, and for the approach angle of $\gamma_A = -.08 \text{ rad } (-4.5^\circ)$, this airplane is distinctly a floater. In this case of a floater, the following alternatives seem to be available:

- 1) Accept the low approach speed. This may or may not be allowable, depending on stall margins and control characteristics.
- 2) Increase the approach angle γ_A . This may or may not be allowable depending on the training and skill of the pilot.
- 3) Reduce the load factor still further, which would cause the trajectory to have larger ΔV for the given $\Delta\gamma$. This would involve a larger penalty as indicated in Figure 5 by the deterioration of pilot rating.
- 4) Retard throttle more quickly in the flare. This is probably the easiest correction for the pilot to make, but except for high drag configurations or with spoiler controls, this "decelerate" technique may not be very effective.
- 5) The most obvious alternative and perhaps the one that will occur in practice, is to touchdown "hot," well above stalling speed. If the approach conditions are $-.08 \text{ rad } (-4.5^\circ)$, then a $\overline{\Delta n} = .07$ flare will produce a touchdown at about 65 kts. This is all right for the flare, but produces wear on the tires, long roll-outs, and possible wheelbarrowing. Basically this kind of floating tendency may be responsible for service records of hot landings with touchdown speeds elevated over stalling speed.

If, in the opposite case, due to a sinking tendency, the calculated trajectory misses the approach point by a large amount on the high side of V_A , the following alternatives exist:

- 1) Accept the high approach speed. This may be the best solution, depending on rate of descent, gust sensitivity, and runway length.
- 2) Reduce the approach angle, unless restricted by obstacle clearance or approach guidance devices.
- 3) Increase the average flare load factor. A rather severe penalty, as indicated in Figure 5 may be paid for this, because of difficult control timing problems.
- 4) Advance throttle in the flare. This "accelerate" technique may be very effective, but it is awkward and difficult to apply consistently with finesse. Occasional hard landings will result.

In addition to these considerations, the lift and moment changes due to ground effect will play a part. A nose-down moment and a lift increase will be somewhat advantageous to the pilot if they are the right size and mix. More moment and less lift changes are favorable to the floater, and vice-versa for the sinker. Although small improvements are possible with small ground effects of the right kind, rather severe degradations accompany large ground effects of any kind. An airplane with otherwise good landing characteristics can be quite severely downgraded because of excessive levels of this phenomenon.

Implications for Design

Even the crudest use of equation (17), to compute a flare in one big step, would suggest that if V_A is taken 1.3 times V_{td} , then from any likely approach angle, even say 6 degrees, the average load factor would be very low - the order of

$$\overline{\Delta n} \doteq \frac{-\gamma_A^2}{2 \frac{\Delta V}{V}} \doteq .02$$

This, according to Figure 5 would suggest a floating tendency. For optimum landing qualities, the airplane should have higher drag so that the "decelerate" throttle technique can be used, or it should be flown on approach at lower speed. Of course lower stall margins on approach would demand, for safety's sake, very gradual stall characteristics with excellent control effectiveness and plenty of stall warning.

Shallow approaches, like three degrees, will certainly produce floaters unless they are very slow. This may be the reason, along with the tricycle landing gear, that many landings tend to be "hot" and sometimes produce wheelbarrowing or other problems.

The ideal situation, with high drag and deceleration ability for the flare, with the ability to "clean up" safely and easily for go-around, would seem to be spoilers integrated with throttle in the manner described in Reference 5. Small trim changes and other considerations suggest that with spoilers used in this way, low drag part-flap deflection settings may be advantageous for landing.

The ground effect evaluations show that they are advantageous only at a very low level. The low-wing airplane with a short landing gear may well exhibit large values of an unfortunate type, which would be a major disadvantage in landings. For this configuration, with the wing set very low to the ground in landing position, the lift increment due to ground effect might be very large. It would increase any apparent floating tendency, and if the airplane were clean and tended to float anyway with usual or recommended landing technique, it could be a serious handicap. Other factors being equal, the high-wing configuration with smaller ground effects might well be more favorable.

These guidelines admittedly do not add up to a precise formula by which to calculate a pilot evaluation of the landing characteristics of a strange airplane. They do, however, provide a test of favorable characteristics and they do suggest the level of penalty that results from different kinds of problems.

We definitely recommend some trial calculations of flares for any new airplane design. They are bound to reveal the general quality of its landing characteristics, and to suggest the best kinds of pilot technique and approach conditions. They will suggest whether the airplane configuration and style of operation are suited to inexperienced or beginner pilots, or whether they had best be reserved for the professional with high level of qualifications.

CONCLUSIONS

Based on the analysis and the experimental results reported here, the following conclusions are drawn. They apply to landings of conventional style in light general-aviation type aircraft under VFR conditions.

1) An important consideration, for the difficulty of landings, is the airplane's deceleration in the flare. If it decelerates too little or too much, it tends to float or sink. Either extreme is a major problem. The pilot prefers an intermediate quality, where a nice moderate flare ends at the right speed for touchdown.

2) The deceleration, and floating or sinking tendencies, are affected by many parameters. Floating is favored by low approach angle and high approach speed, by abrupt flares with high load factors, by speed stability, and by a lift increase due to ground effect.

3) These various effects can be correlated in terms of an average flare load factor. A value of $\overline{\Delta n} \doteq .07$ is about optimum for low approach angles, increasing slightly with increase of γ_A .

4) With approach stall margins of the order of 30% on speed, most light planes will be floaters. Unless equipped with deceleration devices like spoilers, touchdowns will tend to be "hot," and touchdown accuracy will be poor.

5) An additional penalty for speed instability ("on the back side") can be presented in terms of a weighted integral of the speed stability

parameter. The weighting factor is intended to account for the duration and timing of the speed instability (backside) part of the flare.

6) The easiest, most natural, and most consistently successful control actions required for the flare are steady rearward motions of both wheel and throttle. The pilot finds reversals of direction difficult to gauge accurately and smoothly, and he likes the coordination between actions when both levers go in the same direction with about the same timing.

7) The partial trim changes due to throttle advance should be a lift increase and a small nose-down moment. The former should dominate, giving an overall lift increase. This helps counter, with normal control action, both floating and sinking in the flare, and is favorable for wave-off. For the conventional propeller airplane with flaps down, this is the normal trim change - although it is sometimes much too big. It is also the inherent characteristic of integrated lift spoilers.

8) Ground effects are a help to the pilot in landing, if they are moderate in size, in the correct direction, and in the right "mix." In general, increase of lift and nose-down moment changes due to ground effect are helpful, if they are not too large. The proper ratio depends on other factors tending towards floating or sinking. For the floater, the nose-down moment should predominate; for the sinker, the lift increase should be the larger effect. Very large ground effects are a problem to the pilot, and if they are of the wrong sign or mix, they may be a serious handicap.

9) Given reasonable estimates of the lift and drag aerodynamics, the control characteristics, and the ground effects of a new airplane design, it should be possible to predict the ease or difficulty of landings out of arbitrary approach conditions. A simple procedure for this is given, and it is recommended for application to any new design to identify possible landing problems and suggest favorable approach conditions.

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TABLE 1

FLIGHT DATA

Configurations	Comments	$\left(\frac{\partial \dot{V}}{\partial V}\right)_{ss}$ at $V = 70$ kts (rad/knot)
S-102	Far Front side	-0.0128
S-103	Front side	-0.0074
S-203	Slightly Front side	-0.0030
S-204	Slightly Front side	-0.0028
S-205	Very Slightly Front side	-0.0017
S-206	Back side	+0.0025
S-207	Far Back side	+0.0025

a) $\gamma_A = -0.08$ rad (-4.5°)

V.A (knots)	\bar{n}	P.R.	Γ^0 (sec ²)
69.5	1.036	5.5	0
70	1.039	5.0	0
69	1.041	5.0	0
70	1.042	5.0	0
70	1.043	5.0	0
70	1.044	5.0	0
67	1.045	5.0	0
65	1.047	4.0-4.5	0
69	1.049	4.0	0
62.5	1.054	4.0	0
65	1.055	4.0	0
62	1.062	4.0	0
77	1.046	4.5	0
73.5	1.048	3.5	0
73.5	1.049	4.5	0
54.5	1.052	4.5	0
71	1.060	4.0	0
70	1.064	3.5	0
74	1.065	3.5	0
70	1.070	3.0	0
75.5	1.043	5.0	0.21
76	1.045	4.5-5.0	0.08
67	1.059	4.5	0.46
70.5	1.060	4.5	0.53
68	1.062	4.5	0.62
75	1.082	3.5-4.0	0.0
73.5	1.086	4.5	0.02
73	1.093	4.5	0.04
67.5	1.098	4.5	0.15
70	1.107	4.5	0.08

b) $\gamma_A = -0.10$ rad (-6.0°)

V.A (knots)	\bar{n}	P.R.	Γ^0 (sec ²)
64	1.045	4.5	0
61.4	1.053	4.5	0
70	1.054	4.5	0
65	1.055	4.0	0
61	1.065	4.0	0
60.5	1.067	4.0	0
73	1.071	3.0	0
70	1.073	3.0	0
77	1.051	4.5	0.0
81	1.057	4.5	0.0
80	1.058	4.5	0.0
75	1.059	4.0-4.5	0.0
70	1.066	5.0	0.60
79	1.070	4.0	0.0
77	1.072	3.5-4.0	0.20
74.5	1.079	3.0	0.05
77.5	1.086	4.5-5.0	0.20
72.5	1.088	4.0	0.08
73	1.093	4.5	0.03
70	1.096	5.5	0.64

c) $\gamma_A = -0.16$ rad (-9.0°)

V.A (knots)	\bar{n}	P.R.	Γ^0 (sec ²)
70	1.071	4.5	0
70	1.069	4.5	0
70	1.080	4.0	0
70	1.078	4.0	0
70	1.093	4.0	0
70	1.093	3.5	0
70	1.094	3.5	0
70	1.091	3.5	0
70	1.109	4.0	0
70	1.105	4.0	0
70	1.099	4.0	0
70	1.099	4.0	0
70	1.131	5.5-6.0	0
70	1.131	5.5-6.0	0
70	1.144	5.5-6.0	>0

TABLE 2

SAMPLE TRAJECTORY CALCULATIONS

Step	$\overline{\Delta n}$	ΔV (knots)	V_{ave} (knots)	$(\gamma_{ss} - \gamma)_{ave}$ rad (deg)	$\Delta \gamma$ rad (deg)
	<u>1st trajectory</u>				
1	.020	2.0	61.0	.082 (4.7)	.009 (.5)
2	.060	1.5	62.8	.066 (3.8)	.022 (1.25)
3	.080	1.7	64.5	.052 (3.0)	.039 (2.25)
	<u>2nd trajectory</u>				
1	.01	2.0	61.0	.082 (4.7)	.004 (.25)
2	.03	2.0	63.0	.072 (4.1)	.013 (.76)
3	.04	2.0	65.0	.054 (3.1)	.023 (1.30)
4	.04	1.2	67.0	.0235 (1.4)	.030 (1.70)



Figure 1. Princeton In-Flight Simulator

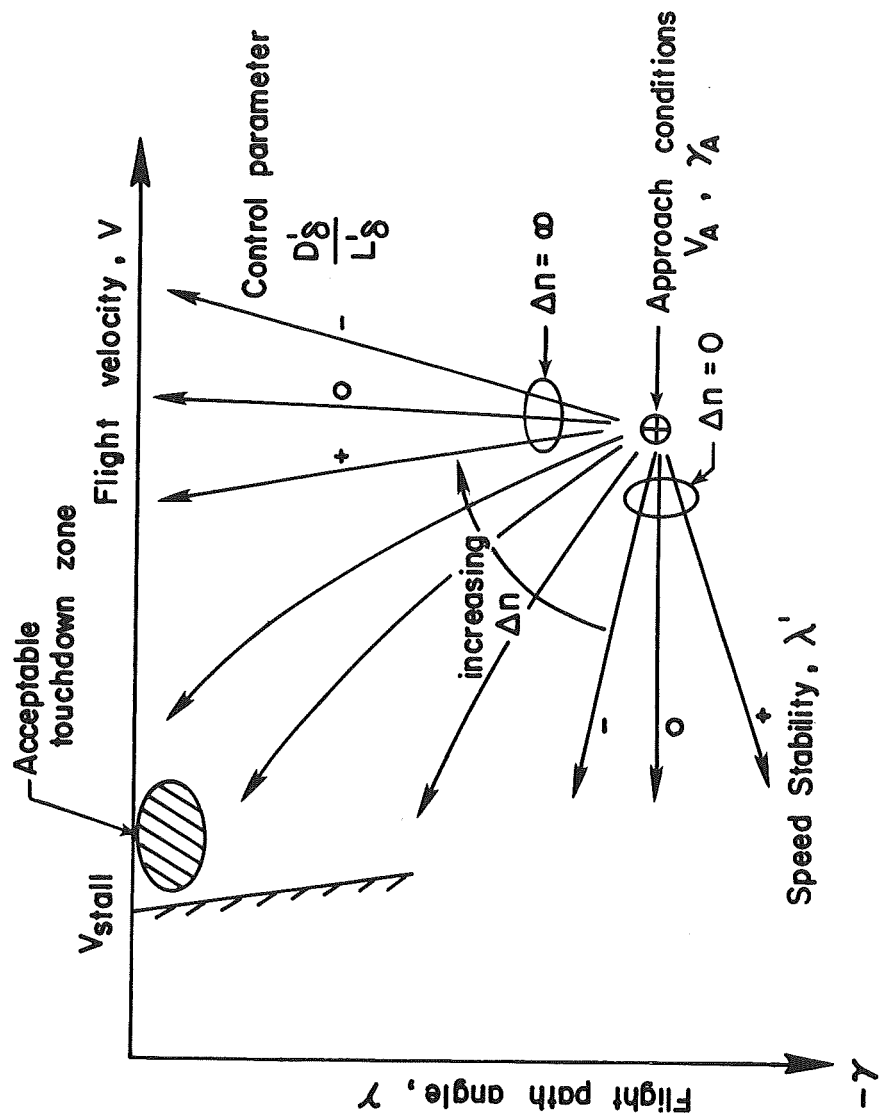
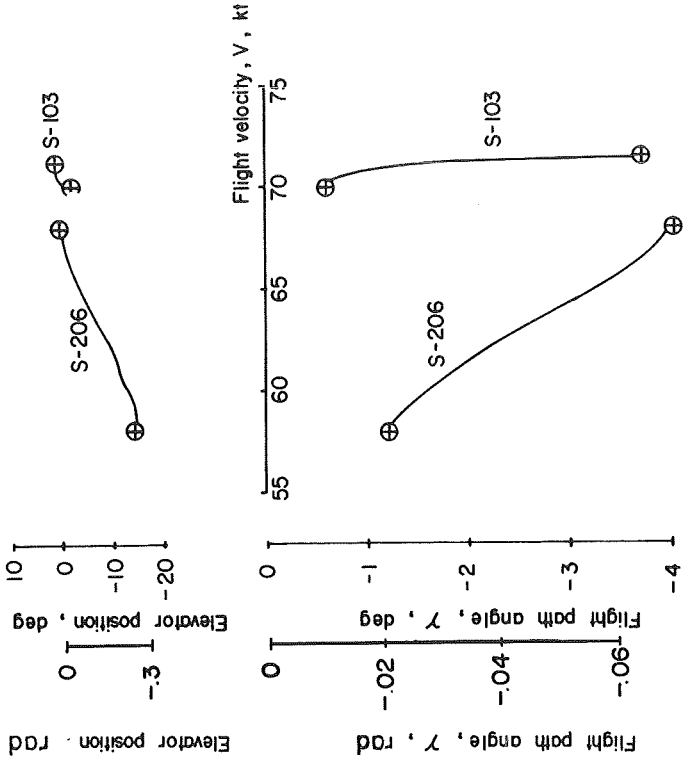
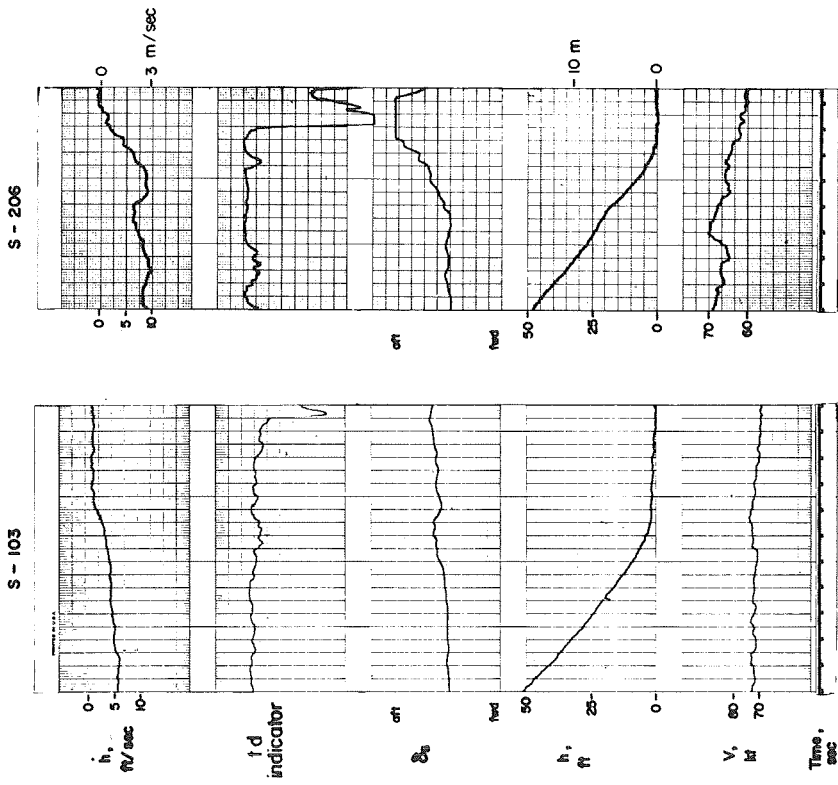


Figure 2. V, γ Trajectories in the Flare; Effects of Load Factor, Control Parameter and Speed Stability



b. V, γ and Control Trajectories

a. Time Histories

Figure 3. Sample Landings for Configurations S-103 and S-206

$$\gamma_A = -.08 \text{ rad } (-4.5^\circ)$$

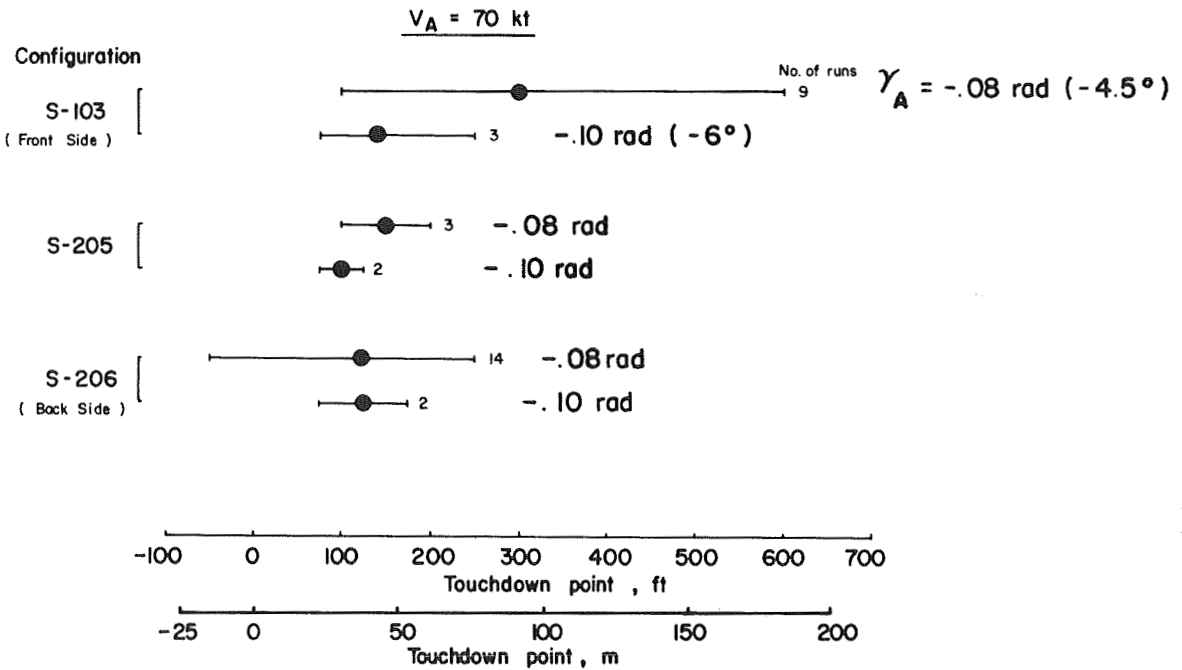
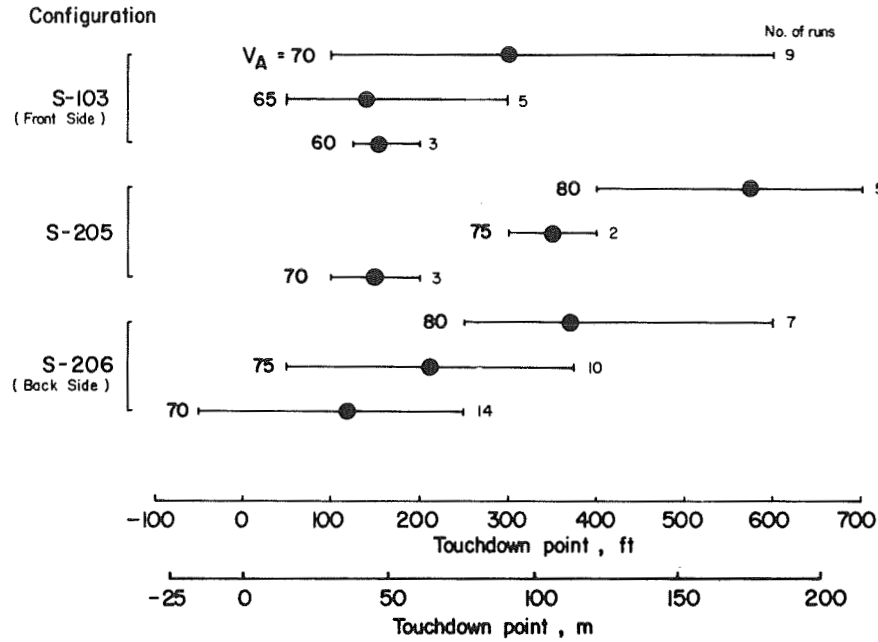


Figure 4. Touchdown Performance for $\gamma_A = -.08 \text{ rad } (-4.5^\circ)$ and also for $V_A = 70 \text{ kt}$

$I^* = 0$ $I^* > 0$ γ_A
 ○ ● -0.08 rad (-4.5°)
 △ ▲ -0.10 (-6°)
 □ ■ -0.16 (-9°)

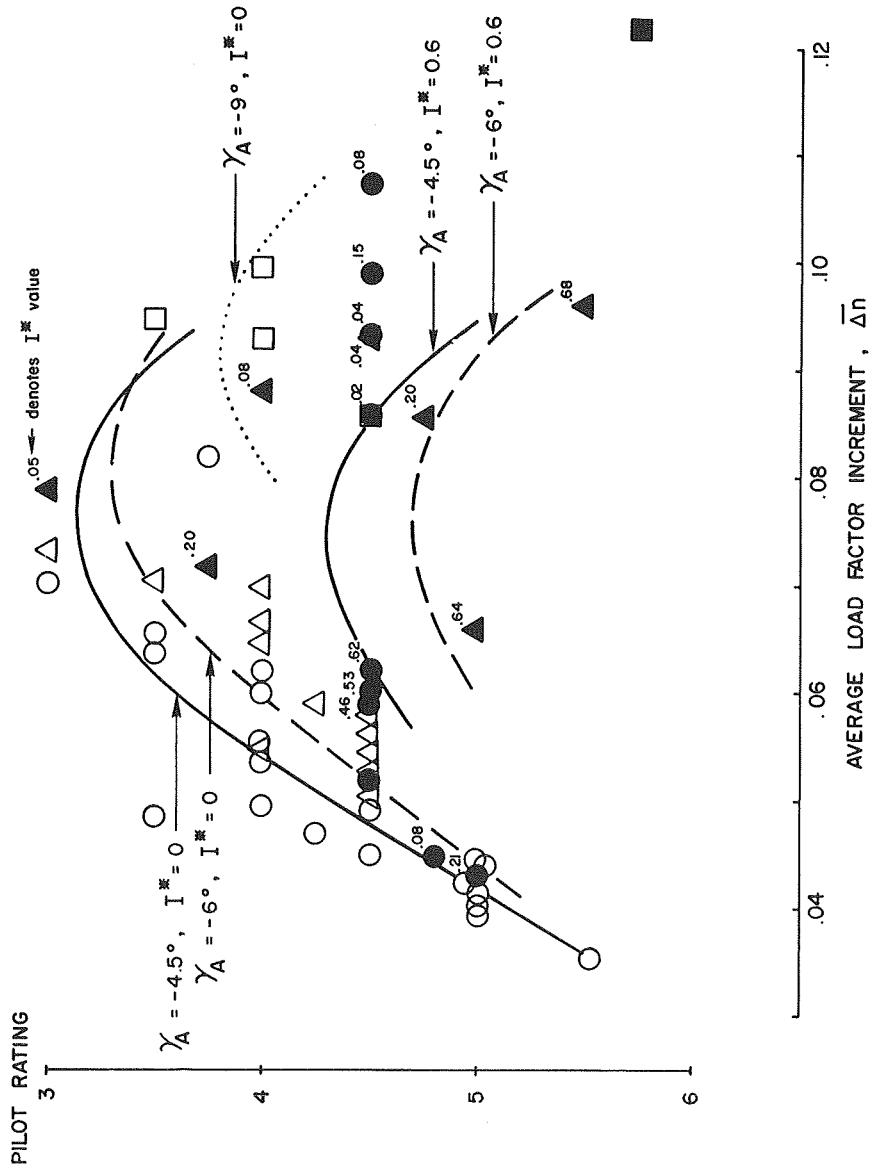


Figure 5. Pilot Rating vs Average Load Factor

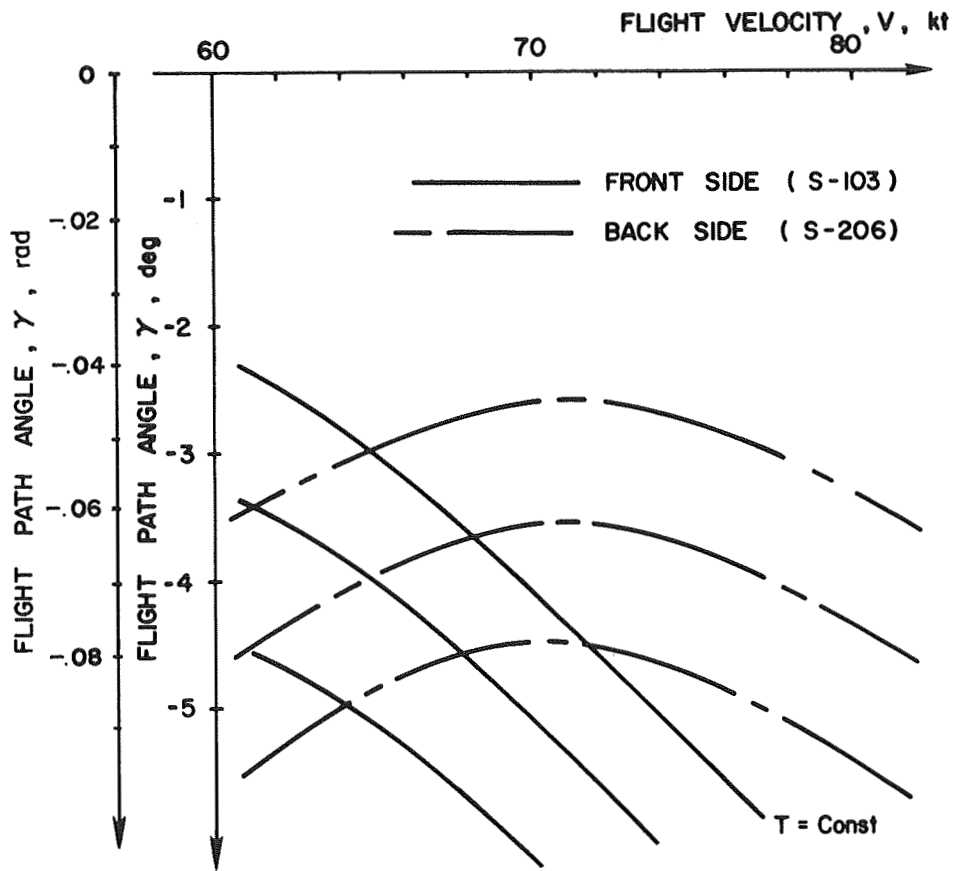


Figure 6. Steady State V, γ Polars

Approach Conditions $V = 70$ kt

○ $\gamma = -.08$ rad (-4.5°)

● $\gamma = -.10$ rad (-6°)

S-102

S-203

S-206

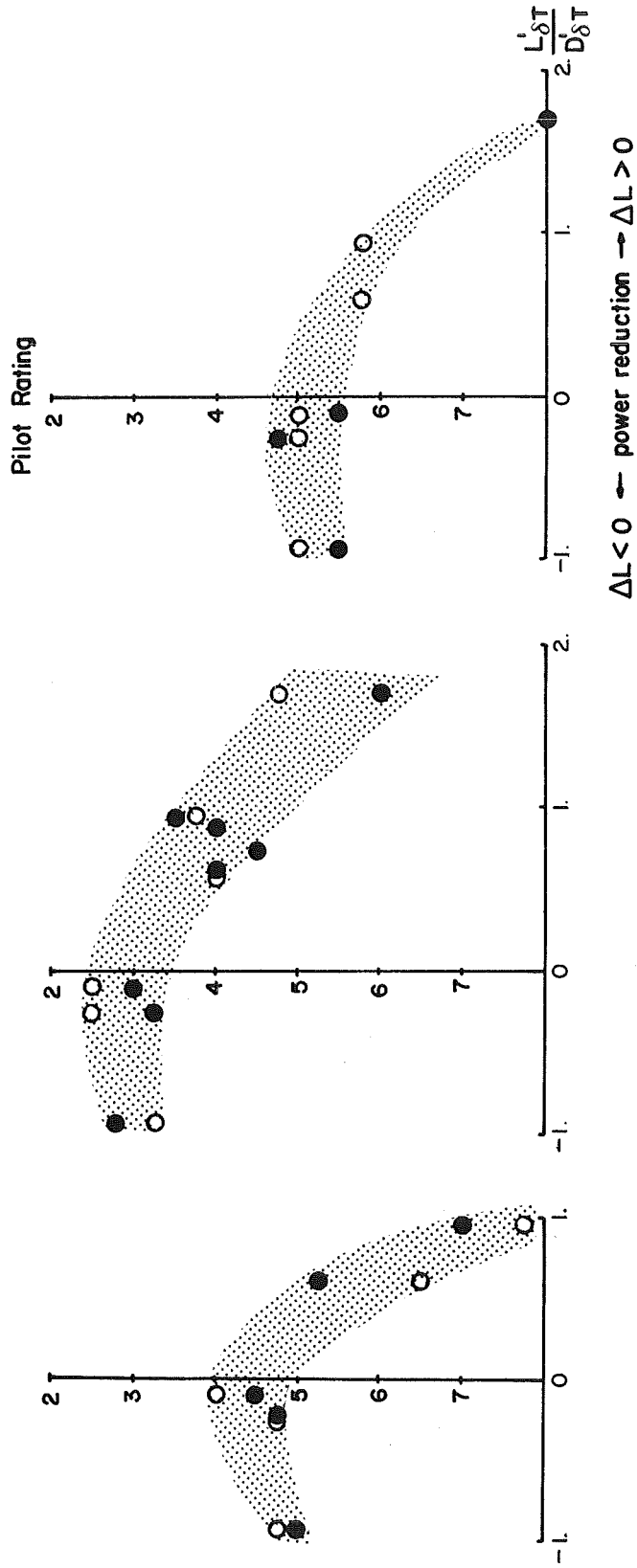
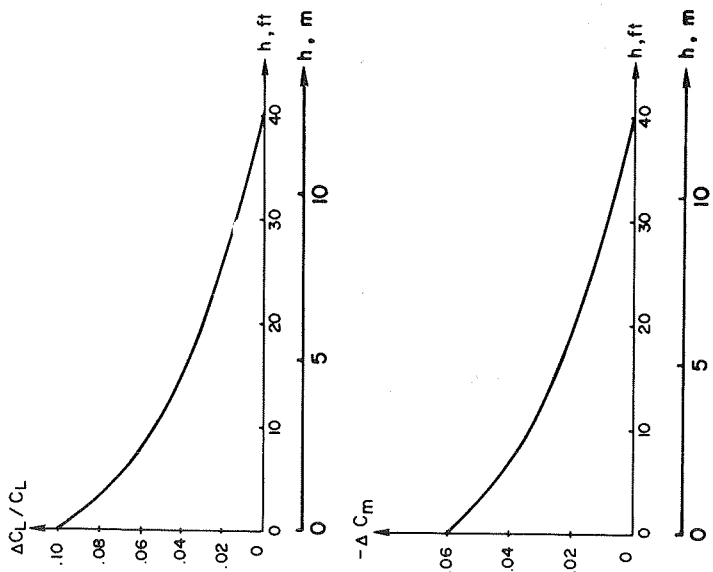
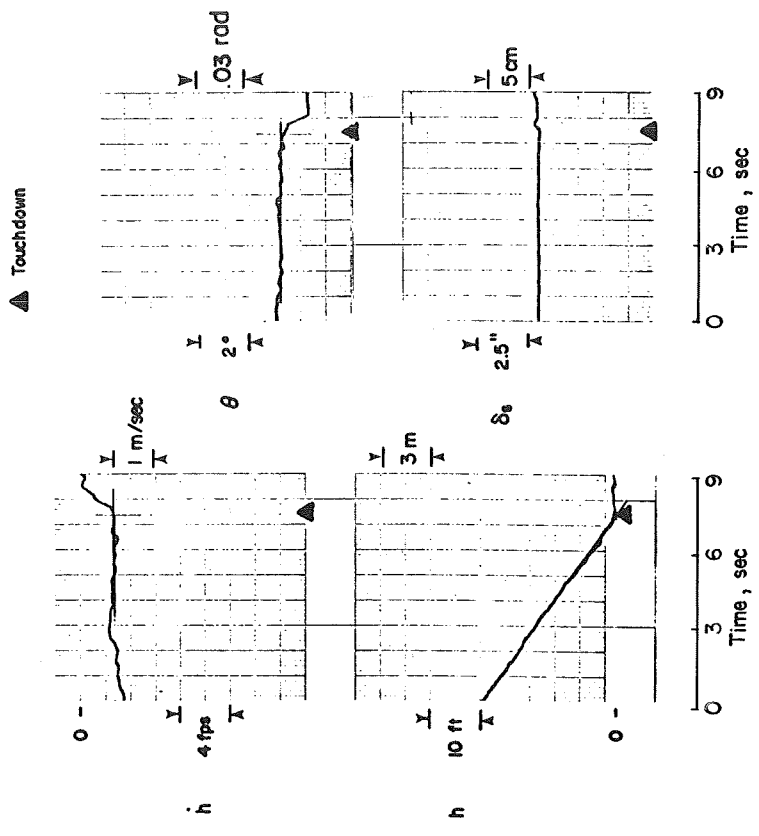


Figure 7. Pilot Rating vs $L'_{\delta T} / D'_{\delta T}$ for Configurations S-102, S-203, and S-206

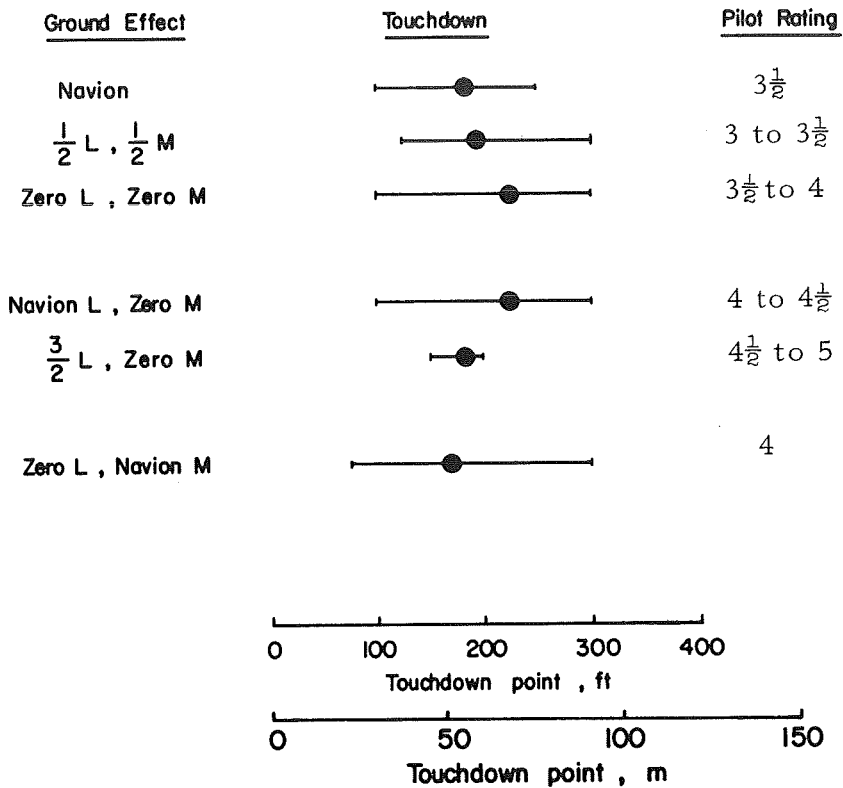


a. Lift and Moment Ground Effect Variations with Altitude

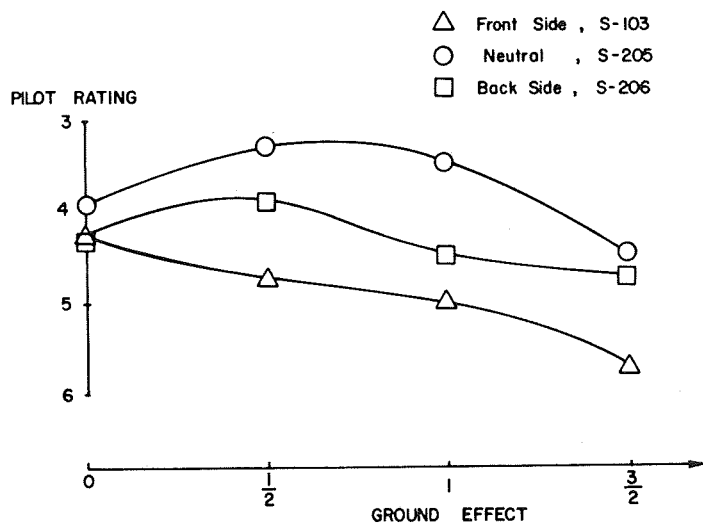


b. Shallow Approach with Ground Effects Cancelled

Figure 8. Reference Ground Effects



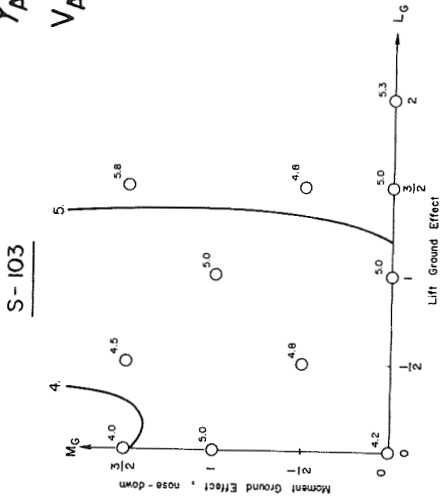
a. Touchdown Performance



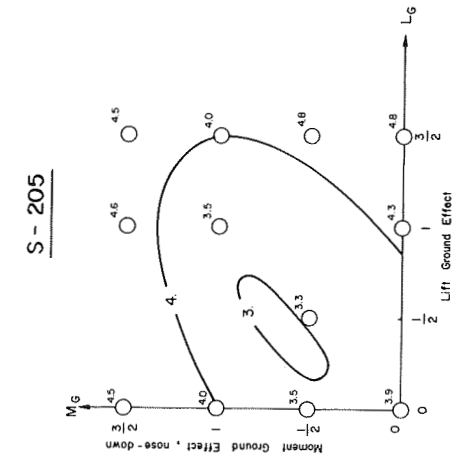
b. Pilot Ratings

Figure 9. Influence of Ground Effects on Landings

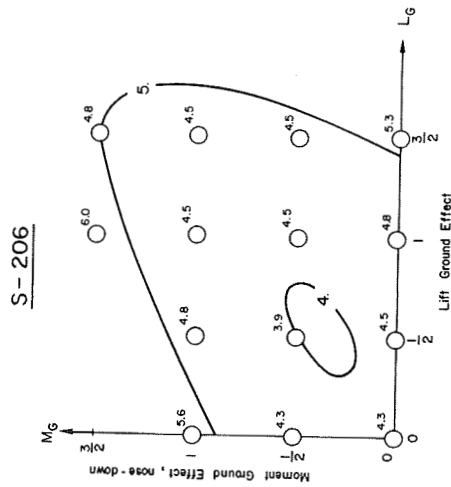
$\gamma_A = -.08 \text{ rad}$
 $V_A = 70 \text{ kt}$



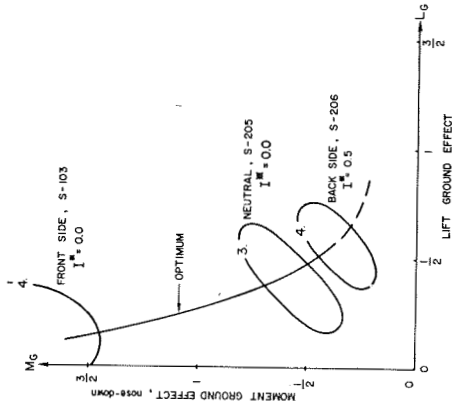
a. Configuration S-103, $(\frac{d\gamma}{dV})_{SS} = -.0074 \text{ rad/kt}$



b. Configuration S-205, $(\frac{d\gamma}{dV})_{SS} = -.0017 \text{ rad/kt}$



c. Configuration S-206, $(\frac{d\gamma}{dV})_{SS} = +.0025 \text{ rad/kt}$



d. Optimum Combinations

Figure 10. Pilot Ratings of Various Ground Effect Variations

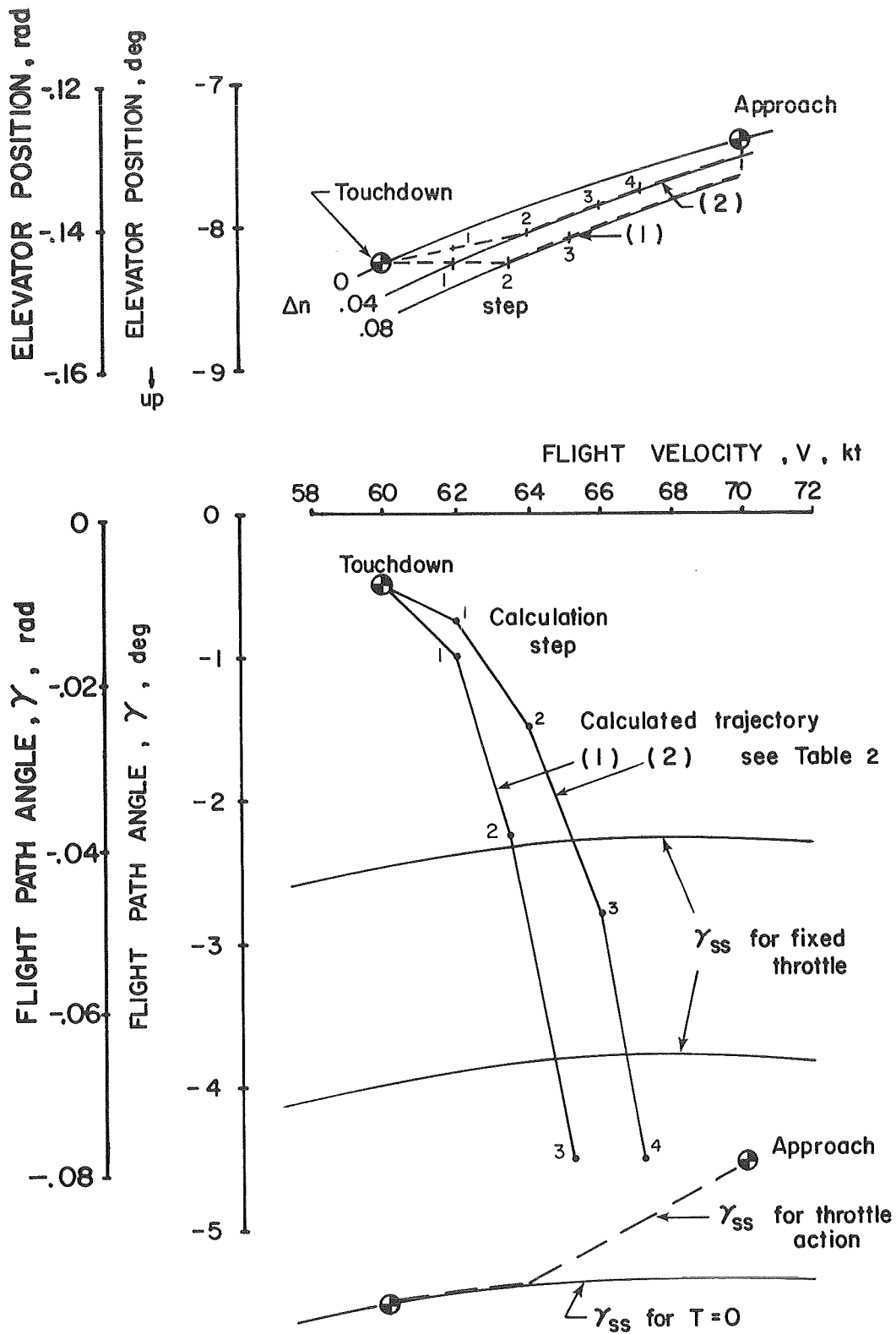


Figure 11. Sample Calculation of Control and V, γ Trajectories



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