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MEMORANDUM

A FLIGHT EVALUATION OF THE FACTORS WHICH INFLUENCE
THE SELECTION OF LANDING APPROACH SPEEDS

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A FLIGHT EVALUATION OF THE FACTORS WHICH INFLUENCE
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SUMMARY

The factors which influence the selection of landing approach speeds are discussed from the pilot's point of view. Concepts were developed and data were obtained during a landing approach flight investigation of a large number of jet airplane configurations which included straight-wing, swept-wing, and delta-wing airplanes as well as several applications of boundary-layer control. Since the fundamental limitation to further reductions in approach speed on most configurations appeared to be associated with the reduction in the pilot's ability to control flight path angle and airspeed, this problem forms the basis of the report.

A simplified equation is presented showing the basic parameters which govern the flight path angle and airspeed changes, and pilot control techniques are discussed in relation to this equation. Attention is given to several independent aerodynamic characteristics which do not affect the flight path angle or airspeed directly but which determine to a large extent the effort and attention required of the pilot in controlling these factors during the approach. These include stall characteristics, stability about all axes, and changes in trim due to thrust adjustments.

The report considers the relationship between piloting technique and all of the factors previously mentioned. A piloting technique which was found to be highly desirable for control of high-performance airplanes is described and the pilot's attitudes toward low-speed flight which bear heavily on the selection of landing approach speeds under operational conditions are discussed.

INTRODUCTION

Aviation progress, as measured by the increased speeds and altitudes of flight, has led to concurrent increases in landing speeds. Furthermore,

*Title, Unclassified

almost half of the jet airplane accidents occur during landings and these have been accompanied by increases in both the cost per accident and the fatality rate. Consequently, the Ames Aeronautical Laboratory of the NACA has undertaken a general program to study the problems associated with the landing approach. This program may be divided into three phases.

The first phase is the study of how to reduce approach speeds through basic research in the application of boundary-layer control as a means of increasing lift and improving flight characteristics at low speeds. The results of flight and wind-tunnel studies of several boundary-layer-control installations have been reported in references 1, 2, 3, and 4.

The second phase is a study of the basic aerodynamic characteristics that influence the choice of landing approach speeds in order to develop a prediction method. The first results of the work on this phase were reported in reference 5, which is a comparison of pilot-selected approach speeds and the speeds predicted by several criteria for 41 airplane configurations.

The third phase is concerned with the investigation of methods to improve the pilot's control of airspeed and flight path angle during the landing approach. A quote from reference 6 serves to indicate the importance of this phase.

"The most critical component of the pilot's job, as determined from all sources, is that involving the skills of establishing and maintaining a proper angle of glide, rate of descent and speed of glide on the approach. Failure to perform this part of the job adequately was found to result in three times as many accidents as does failure to perform any other part of the job."

Of equal importance to changes in airplane configurations to achieve better control, are the procedures and techniques used by pilots for landing high-performance airplanes. The absence of information on this subject is quite unusual, considering its importance to the safety of flight. Reference 7, which describes motion picture techniques which may be used to simulate the landing approach, notes that there exists no uniform method for teaching students what to observe in landing an airplane.

The purpose of this report is to present an analysis from the pilot's point of view of the factors which either influence his choice of landing approach speed or affect the safety and precision of the approach, and to relate these factors to various control techniques. The discussion of these points is based upon the experience of four pilots during the landing approach evaluations reported in references 3, 4, and 5.

A detailed description of the airplane configurations involved is presented in reference 5 along with pertinent aerodynamic data. The airplanes included straight-wing, swept-wing, delta-wing, and tailless configurations. Additional evaluations were conducted on a large multi-engine jet transport airplane and on several fighters of advanced design not included in reference 5.

NOTATION

B.L.C.	boundary-layer control
D	drag
$\frac{dV}{dt}$	rate of airspeed change, ft/sec ²
g	acceleration of gravity, 32.2 ft/sec ²
GCA	ground controlled approach
ILAS	instrument landing approach system
L	lift
T	thrust
V _{PA}	approach airspeed, knots
V _S	stalling airspeed, knots
W	weight
β	sideslip angle, deg
γ	flight path angle, positive for descending flight, radians
δ_a	aileron angle, deg
ρ	rolling velocity, radians/sec
ϕ	bank angle, deg

RESULTS AND DISCUSSION

The order in which the various factors which influence the selection of landing approach speeds are considered in this report is as follows. The landing patterns together with the conditions that make up the environment under which the approach is conducted are discussed first. Second, the basic parameters through which the pilot controls the flight path angle and airspeed are considered in order to provide an understanding of just what control is available to the pilot. Third, attention is given to several independent aerodynamic characteristics which do not affect the flight path angle or airspeed directly but which determine to a large extent the effort and attention required of the pilot during the approach. Fourth, pilot control techniques are related to the type of approach and the airplane handling characteristics. In the last section the pilot's attitudes toward low-speed flight are discussed briefly to indicate some reasons why pilots tend to use speeds in excess of the minimum comfortable approach speed under operational conditions.

Landing Approach Patterns

One of the most important factors affecting the approach speed used for high-performance airplanes is the type of approach. Although an unlimited variation in landing approach patterns is possible, they are separated into two basic types for simplification: the tactical and the constant-angle, constant-airspeed approaches. These are illustrated in figure 1.

Tactical approach.- The tactical approach (British "circuit") is executed in a race-track pattern in which airspeed is decreased to the touchdown point and the approach path angle is not held constant (fig. 1(a)). It is used for several reasons during clear weather or when operating under visual flight rules. It provides the pilot with a reference starting point over the runway at a given altitude; it allows the control tower to maintain visual contact with the landing traffic; and it allows the pilot to adjust the approach path angle by varying his turn radius.

In the tactical approach the pilot tries to arrive at the minimum comfortable speed just over the runway threshold prior to the flare. With proper judgement this is possible and the touchdown speed should be the same as would be obtained with a constant-angle, constant-airspeed approach. The problem here is pilot judgement. The variable speed tactical approach is an exacting task and pilots take pride in their ability to judge speed and approach path so that the touchdown occurs near the beginning of the runway. Increasing the runway length, of course, allows more room for error. However, at higher approach speeds the effects

of airspeed and flight path errors are more serious and errors are more likely to occur since the time of flight in the region close enough to the runway for adequate visual judgement of flight path angle and projected touchdown point are very short. In addition the adverse aerodynamic characteristics of many high-speed airplanes make the task more difficult. The pilot, therefore, tends to fly the approach at even higher speeds so that a misjudgement in the rate of speed decrease will be less likely to result in landing short of the runway.

The minimum speed used in the tactical approach is determined almost exclusively by the aerodynamic characteristics which determine ability to reduce the sink speed prior to touchdown. On the other hand for the constant-speed, constant-angle approach the airplane response to thrust, for flight path angle control, and those factors which make it easier to maintain constant airspeed must be considered in addition to the aerodynamic flare capability. For many airplanes the minimum comfortable speeds tend to be the same for either type of approach but, in general, they should not be assumed to be equal.

Constant-angle, constant-air-speed approach.- The relatively constant-speed, constant-angle, straight-in approach (fig. 1(b)) is started from a reference point such as a radio navigation fix or an altitude and distance aft of an aircraft carrier, and it includes aircraft-carrier type approaches and approaches made during instrument flying conditions. Approach path angles from 2.5° to 3.5° are in general use and the pilot is usually presented with supplemental flight path angle information such as is given by the ILAS (instrument landing approach system) cross pointers, the GCA (ground controlled approach) controller, or the mirror landing system. This information relieves the pilot of much of the necessity to judge the approach path angle by visual perception of the ground. Reducing the number of variables the pilot has to contend with in the approach simplifies his task. Maintaining a relatively constant airspeed even in the tactical approach allows more time for judging the flight path angle and the projected touchdown point. This technique was found to increase the accuracy of touching down at the desired point, and the addition of supplementary flight path angle information such as given by the mirror landing system resulted in even greater landing accuracy. This has also been verified through the success of this system for aircraft carrier landings. This constant-speed type of approach was used for the determination of the minimum comfortable approach speeds and of the limiting factors discussed in reference 5.

Environmental Conditions

Landing approach environment.- Part of the difficulty in determining approach speeds arises from the complex relationship between airplane

characteristics and the variety of environmental conditions under which the airplane is to be landed. Some examples of these conditions which the pilot must consider are: rough air (particularly behind the stack of an aircraft carrier), poor visibility, cross winds, other traffic, asymmetric loads, obstacles, experience in airplane type, and runway conditions. These factors will not be evaluated in this report, but they are present in some degree on every approach. The pilot's judgement of the approach environment determines whether he will make the approach faster or slower than a speed that previous experience indicated was safe.

Role of visual cues.- In the absence of supplemental flight path angle information, the pilot must rely upon his visual perception to judge the approach. Improvements in the pilot's ability to control airspeed and flight path angle will be of little value if the pilot is not able to perceive errors so that he may initiate corrective control action. Some valuable techniques for extracting approach path information from available visual cues are discussed in references 8 and 9 and it is the opinion of the Ames pilots that much of this information should find an immediate place in any flight instruction syllabus. The demands made on the pilot's visual perception are continually increasing and a process of learning almost completely by trial and error can no longer be tolerated.

Some examples of the effects of the lack of visual cues are: (1) the difficulties in judgement often experienced in landing at unfamiliar airports having different runway widths and lengths in addition to strange terrain features; (2) the inability to judge a projected touchdown point or altitude when landing on calm water or featureless, flat-textured terrain, such as an unmarked desert dry lake bed. In addition there are strong indications that one aspect of the abrupt increase in sink rates which appear to develop during the landing approach is that only when the pilot has approached relatively close to the ground can he perceive the high sink rate he previously established. For example, a steady 3° (ILAS) glide path seems very shallow when 10 miles out from the runway. Indeed, the instruments have to be monitored to detect the sink. However, if 3° is held down to 50 feet altitude the angle appears very steep and the sink rate appears to increase. When pilots first use the mirror landing system on which they maintain about 3° to ground contact, they have a definite tendency to flare at the last second because of an instinctive reaction to the appearance of an abrupt increase in sink.

Parameters Through Which the Pilot Controls Flight Path Angle and Airspeed

Derivation of simplified equation.- A deterioration in the pilot's ability to control the flight path angle and airspeed was given as the primary reason for not further reducing the approach speeds of a majority

of the configurations tested and documented in reference 5. A better understanding of those factors which determine the pilot's control of flight path angle and airspeed may be provided by a review of the forces acting on the airplane during the landing approach. A simplified diagram of these forces is shown in the following sketch. In this diagram the drag and thrust forces are considered to be parallel and the approach is assumed to be made at 1g normal acceleration since flight path angle changes in the order of only about 1° are being considered.

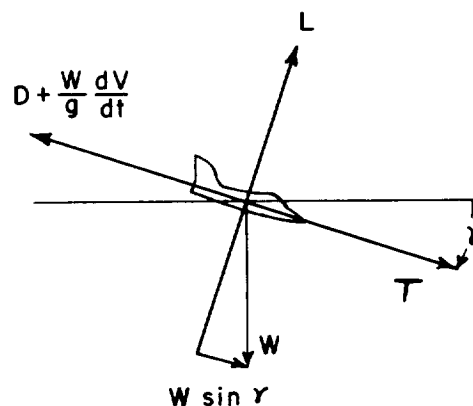
Forces along the flight path are:

$$D + \frac{W}{g} \frac{dV}{dt} = T + W \sin \gamma \quad (1)$$

$$\sin \gamma = \frac{D}{W} - \frac{T}{W} + \frac{dV/dt}{g} \quad (2)$$

Note: For descending flight γ is positive. If 1g flight is specified $L \approx W$, and for small angles

$$\gamma = \frac{D}{L} - \frac{T}{W} + \frac{dV/dt}{g} \quad (3)$$



From this simplified equation it can be seen that the flight path angle γ is determined by the lift-drag ratio at the approach speed, the thrust-to-weight ratio, and the rate of change of airspeed.

Effects of lift-drag ratio.- There are three aspects to the effects of lift-drag ratio on the flight path angle: first, the direct control over this factor which may be provided by spoilers or drag devices; second, the absolute value of the lift-drag ratio at the approach speed; and, third, the variation during the approach of the lift-drag ratio as airspeed or angle-of-attack changes.

The direct control of lift-drag ratio is an effective means of changing flight path angle. However, this type of control is generally used only in the presence of poor response to the primary elevator and throttle controls. Spoiler control has been effectively used by gliders, for instance, since throttle control is not present. The need to avoid reducing maximum lift available for flare often precludes the use of spoilers during the approach and the effectiveness of conventional aerodynamic drag devices at approach speeds is seldom adequate to provide control of the lift-drag ratio.

The existence of lift-drag ratios of less than 4 appeared to contribute to the reduction in ability to control airspeed and approach angle with the elevator. Small deviations from 1g flight caused large

changes in airspeed which also made the final flare difficult to judge. As a result a tendency was noted for pilots who did not usually control the flight path angle with power to do so when determining the minimum comfortable approach speed of airplanes which have low lift-drag ratios. This change in control technique occurred not only because of the abrupt speed changes when the elevator is used but also because the throttle actually commands a greater range of approach path angles (from power-off glide angle to level flight) on an airplane which has a low lift-drag ratio.

Variations in lift-drag ratio are seen, in equation (3), to be an important factor in establishing and maintaining the flight path angle. The variation of lift-drag ratio with lift coefficient and the corresponding drag-airspeed curves for 41 airplane configurations are presented in reference 5. An examination of these curves shows that there are many configurations for which the lift-drag ratio decreases at higher lift coefficients, or, in terms of the drag-airspeed curves, the total drag increases with decreasing airspeed in the approach speed range. This is commonly known as the region of reverse command or the backside of the drag curve, and it is indicated by the left-hand portion of the generalized curves of figure 2. In this figure it can be seen that the variations of drag with airspeed in level flight are such that if the effects of stick-free and stick-fixed longitudinal stability are disregarded, the speed for minimum drag will represent a speed for neutral speed stability, separating a stable region at higher speeds from an unstable region at lower speeds; that is, at speeds higher than that for minimum drag the airplane will return to the trim speed following a disturbance; at lower speeds the airplane will diverge in speed following a disturbance.

During an approach in the unstable region, a flight path angle change made and maintained with the elevator alone results in a continuous increase in the rate of change of airspeed. Therefore, if the pilot uses this technique he must maintain a larger speed margin above the stall speed. If, however, he uses power changes to adjust the flight path angle and he keeps the airspeed relatively constant through the use of the elevator, his control is simplified since the lift-drag ratio also remains constant. This technique not only reduces the possibility of developing inadvertent high sink rates but it also allows the approach to be made with less speed margin from the stall.

On most conventional airplane configurations, as shown in reference 5, the lift-drag ratio increases at higher lift coefficients, that is, the total drag decreases with decreasing approach speed. This is illustrated by the right-hand portion of the generalized drag curves in figure 2. In this stable region a reduction in flight path angle made and maintained with the elevator will still result in a rate of decrease in airspeed (eq. (3)). However, this rate of decrease will diminish as the total drag becomes less until the airplane stabilizes at a more shallow angle and at a lower airspeed. If these changes in airspeed are acceptable to

the pilot he will use the elevator for primary flight path angle control while maintaining a high enough speed margin to allow for the speed changes. The technique of using power to adjust the flight path angle has an advantage even with stable drag-airspeed variation since it reduces the need for a large speed margin by minimizing airspeed changes.

Thrust-weight ratio.- For the conditions in which engine thrust was used (T/W in eq. (3)) to control the flight path angle at the minimum comfortable approach speeds, reductions in the margin of thrust-weight ratio available for climb at military thrust to less than 0.12 gave unsatisfactory control, as indicated in figure 2. Since pilots often compared the airplanes in terms of their response to throttle application in the approach, this factor was examined further. Figure 3 indicates the pilot's opinion rating of the thrust-weight margin in level flight of the airplanes tested. Examination of the data in reference 5 indicated that the thrust-weight ratio required increased with reductions in airspeed on several of the configurations; hence, the pilot could obtain a larger thrust margin by flying at a higher airspeed.

Another adverse thrust-response condition occurs during the landing of a very low-drag airplane (high lift-drag ratio). In this case very little thrust is required to maintain the approach angle and the engines are operated in the low range of rpm where the engine response time constant may be very large. Because of the low variation of drag with airspeed which often occurs along with a high L/D ratio, and the poor engine response at low power settings, it is difficult to select a power setting which will maintain the desired glide angle, and in addition wave-off thrust may not be available for as much as 10 seconds after full power is selected. The drag-airspeed region where this tendency is noticed appears in figure 2. Using a higher airspeed compensates for the slow engine response since a pilot can use up the excess airspeed, $(dV/dt)/g$, to maintain a more shallow flight path angle while waiting for thrust to develop.

Effects of rate of change in airspeed.- If the airspeed is kept constant ($dV/dt = 0$) the pilot must be able to control either L/D with drag or spoiler devices or T/W with the throttle or a thrust reverser in order to adjust the flight path angle (γ). For flight at the minimum comfortable airspeed these methods of flight path angle control become important since very little airspeed deviation can be tolerated.

Airspeed in excess of the minimum comfortable speed is generally used on the approach so that flight path angle changes can be made with the elevator and maintained by the rate of airspeed change $(dV/dt)/g$, (eq. (3)). When the airspeed deviates 5 knots or so from the desired speed, the throttle is adjusted to correct the error. On some types of airplanes this task of correcting airspeed with the throttles may even

be delegated to a second pilot. The control of airspeed with the throttles is considered conventional at least for airplanes having high L/D ratios.

Combined effects.- Low lift-drag ratios and lift-drag ratios which decrease with increasing angle of attack are characteristics which often appear in combination. Examples may be found in reference 5. If the conventional control technique is used on these airplanes a high airspeed margin from stall must be used to allow for large airspeed changes. As these characteristics have become more pronounced the airspeed margin required to compensate for them has become excessive. Previous combat, training, or transport airplanes have not had these characteristics or at least they were confined to speeds very close to the stall speed. If engine thrust is used to control the flight path angle at a constant approach speed in order to minimize these adverse lift-drag-ratio effects, then increased demands are made on the response of the airplane to thrust changes.

Handling Qualities Which Do Not Affect Flight Path Angle and Airspeed Directly

Stalling speed.- The most generally used definition of stall speed is the minimum steady flight speed at which the airplane is controllable (ref. 10). Because of the abrupt loss of lift and stability that generally occurs at the stall, both civil and military regulations require a clear and distinct stall warning to be present. In selecting a minimum comfortable approach speed under ideal conditions, then, the pilot's problem is to fly as slow as possible and yet provide enough margin to compensate for an inadvertent loss of airspeed and to provide a comfortable maneuvering margin. If other factors did not limit the approach speed, and if the airplane was well behaved, the minimum speeds selected in a constant speed type of approach were 1.10 times the power-on stall speed as indicated by the data in reference 5. This limiting condition is shown in figure 2. It is interesting to note that most of the airplanes which were flown at this limiting condition had some form of boundary-layer control which, in addition to the lift gains, noticeably improved lateral control effectiveness and tended to give the pilots a "locked-in" feeling during the approach. The locked-in feeling refers to the ease with which a given approach speed is maintained even when corrections to the flight path angle are being made.

The fact that stall speeds have become more indeterminate in flight is also a matter of concern to pilots. The stall warning of many airplanes having highly swept and/or low-aspect-ratio wings tends to be characterized by the gradual onset of a static instability about one or more axes which contributes to the difficulty in defining the stall speed. Some expressions used to describe these prestall unstable conditions are

"pitch-up," "yaw-off," and "roll-off." Another prestall condition which is relatively indeterminate is an increase in sink rate, which is aggravated by an attempt to reduce it with the elevators. The lack of a well-defined stall warning or the need for an unconventional technique to recover from an incipient stall often results in the use of higher speeds during the approach.

Static longitudinal stability.- The static longitudinal stability contributes significantly to speed stability. The degree of positive static stability determines to a large extent the amount of attention a pilot must give to monitoring his airspeed during the approach. The relative importance, however, of static longitudinal stability will also be dependent upon the type of approach and pilot control technique being used. For example, an approach during which speed is maintained relatively constant allows the pilot to trim for the desired speed and to take maximum advantage of the tendency of longitudinal stability to maintain trim airspeed. If the pilot uses the elevator primarily to control and maintain the flight path angle, the airspeed indicator must be monitored closely to detect the resulting airspeed changes since the longitudinal stability is not given an opportunity to maintain the trim speed. The reason that the static stability tends to effect a choice of an approach speed is that for many configurations the stability decreases with decreasing speed (increasing angle of attack). Figure 4 illustrates the variation in static stability with airspeed and the effect of one boundary-layer-control application on this factor. The reductions in approach speed obtained with the use of this boundary-layer-control installation, as indicated in reference 4, closely paralleled the reductions in speed for neutral static longitudinal stability and the approach speeds were decreased further than the reduction in stalling speed alone would indicate. In no case did the pilots choose a minimum comfortable approach speed in a region of static instability for any of the configurations of reference 5. However, specific tests to isolate this factor have not been made.

Longitudinal trim changes due to power.- In general pilots desire a minimum amount of trim change to result from lowering the landing gear, lowering flaps, or actuating other devices unless the trim change serves a useful purpose. The trim change due to power has been considered satisfactory if peak longitudinal control forces do not exceed 10 pounds (Class I airplanes, ref. 11) for a period of 5 seconds following the change to either take-off power or idle power from that required for level flight when trimmed at an airspeed equal to $1.4 V_S$. Although no consideration is given in reference 11 to the direction of the trim change, this factor superimposed on the static longitudinal stability of the airplane determines the degree to which a change in power alone will affect either flight path angle or rate of airspeed change or both.

An F-86F airplane was flown with small thrust-deflecting tabs located in the tail pipe in order to vary the direction of the trim change with

power. The center of gravity was located near the aft limit in order to magnify the effect. With the jet flow adjusted to give a slight nose-up trim change when power was added, throttle adjustments resulted in fairly rapid changes in flight path angle with little influence on the airspeed. Consequently, once the airplane was trimmed for a particular airspeed, approaches could be made essentially with hands off the stick. This characteristic contributed to the "locked-in" feeling mentioned previously. With a slight amount of opposite trim change, however, (nose-down trim with increasing power) throttle changes resulted in a rate of change in airspeed at a relatively constant flight path angle. It should be obvious at this point that the most desirable of these two types of response to power change will depend upon the individual pilot control technique. That is, if the pilot utilizes the elevator as an airspeed control and the throttle as a flight path angle control, he would like power changes to have a minimum effect on the airspeed. If the pilot uses the throttle as the airspeed control, he would be most satisfied if a change in power changed the airspeed with a minimum effect on flight path angle. These differences in control concepts probably account for some of the differences of opinion between pilots regarding the landing characteristics of certain airplanes.

In any case a slight amount of excess trim change in either direction was found to be undesirable. For example, if power was added and the nose-up trim resulted in a rapid decrease in airspeed unless forward stick was applied or if power was added and back stick was necessary to keep the nose from dropping, the pilots were concerned with the increased attention required to control the airplane. Examples of both types of excess trim changes were found among the airplanes flown and evaluated in reference 5.

Lateral-directional stability and control.- The deterioration of lateral-directional stability and control with the reductions in approach speed was a limiting factor for several of the configurations tested in reference 5. The exact limiting conditions have not been defined. However, poor lateral-directional damping (Dutch-roll) distracts the pilot and increases his work load during this critical phase of flight. Therefore, he has a tendency to select a higher approach speed to provide more maneuvering margin even though the increased speed does not necessarily improve the dynamic stability.

The pilot generally associated the onset of a static lateral or directional instability (roll-off or yaw-off) as speed was reduced with an incipient stall condition. The speed at which these conditions occur is often difficult for him to pinpoint for several reasons. First, the instability may develop gradually with decreasing speed and, second, it is a function of angle of attack which the pilot is seldom able to determine. Experience in a particular airplane makes the pilot aware of the lowest approach speed which will prevent the onset of the instability for the maneuvering ability he desires.

In addition to lateral-directional stability, the control about these axes will influence the choice of an approach speed. The effect of improved lateral control power, which was obtained with a boundary-layer-control installation on an F-100 airplane, on the pilot's choice of approach speed is discussed in reference 4.

The ability to maneuver laterally is also compromised when adverse yaw due to lateral control is coupled with high dihedral effect. At high angles of attack a roll displacement alone will also cause sideslip as a result of the initial inclination of the roll axis to the flight path. In either case the rolling moment due to lateral control tends to be canceled by the opposite rolling moment created by the yaw and dihedral effect, and rolling velocity reversals develop. An example of this type of airplane response to a step aileron input which was considered to be a limiting factor is illustrated in figure 5. At these speeds in this airplane the rudders become a powerful roll control, and aileron deflection primarily develops sideslip. Since the stall on this airplane is preceded by a sideslip angle divergence, aileron control would necessarily be used cautiously at the lowest approach speeds.

Miscellaneous factors.- The reduction in forward visibility at high angles of attack and the marginal ground clearance at the tail were additional reasons given by the pilots for not further reducing the approach speed of several configurations discussed in reference 5. The existence of these factors in conjunction with other undesirable airplane characteristics can complicate the landing approach control problem to the saturation point. Therefore, the occurrence of an unexpected disturbance such as a relatively minor airplane system malfunction can overtax the pilot's judgement and result in a serious landing accident.

Effects of Control Technique and Pilot's Attitude

Pilot technique.- The conventional way to control an airplane is, of course, to use the elevator to adjust flight path angle and to control airspeed with the throttle. Under certain conditions, however, the control functions are not distinctly separable. For example, the importance of using thrust changes to establish the flight path angle (rate of climb or descent) becomes apparent to pilots during precise maneuvers such as instrument practice patterns when airspeed must be held to close tolerances. Therefore, if the airspeed had to be held exactly constant the roles of the two controls would be reversed; that is, thrust would be used to adjust the flight path angle and pitch attitude would be used to control airspeed. These are the two extremes of control technique which are adapted in various ways, depending on the degree of speed of response or airspeed control desired by the pilot. The pilot uses the type of control which gives the best response for any particular flight condition. For general flying the conventional control is used as long as the airspeed variations are less important than maneuvering response. For the

landing approach the conventional technique was found to be satisfactory so long as the airspeed tolerance was large enough or the aerodynamic characteristics of the airplane did not contribute to rapid speed changes while maneuvering.

A technique which was found to permit optimum performance from boundary-layer control and to increase the landing accuracy of low-aspect-ratio airplanes was to make the straight-in approach or the last 90° turn in a tactical approach pattern (circuit) at a fairly constant airspeed (± 5 knots). Throttle changes were then made to adjust the flight path angle and the airspeed was held constant by small changes in elevator angle. The proper thrust setting was thereby established early in the approach through a bracketing technique. When the airplane got closer to the ground where visual perception of angle and altitude changes was improved, more rapid fine adjustments were needed and here the airplane response to throttle was seldom fast enough to make the desired small flight path angle changes. The last fine adjustments to the approach path were then made with elevator control and the small rates of speed change which did occur did not have time to build up large speed errors before touchdown. On airplanes having a low L/D ratio the throttle was not retarded until it was determined that the flare was progressing safely. An exception to this has been noted during approaches when a fully modulating thrust reverser was used which provided more rapid thrust response than the basic engine. In this case the increased thrust response was accompanied by a stable trim change and the pilot had improved flight path control all the way to touchdown.

The importance of the technique of using the throttle for a primary flight path angle control was found to be greater for airplanes with lower L/D ratios and for airplanes on which the L/D ratio decreases as angle of attack increases. This latter trait is characteristic of airplanes having tailless configurations, delta wings, and some other airplanes which do not have landing flaps, as shown in the data of reference 5. As stated in reference 5, the pilots noted that for the airplanes of that investigation, flight under these conditions was not unduly difficult and, indeed, service pilots are often not aware of these conditions. An examination of the drag velocity curves of reference 5 indicates that it is not practical to avoid this region on the F4D, F7U, and F-100A airplanes. These airplanes can be flown in this region because positive static longitudinal stability tends to prevent the airspeed from diverging as the drag velocity curves (ref. 5) indicate it should; that is, the drag velocity instability will not result in an airspeed divergence unless the pilot changes the flight path angle with the elevator and he does not compensate with a thrust change. If the airplane is forced along a particular reduced approach angle by a simple increase in the elevator angle to maintain lg flight, the airplane will not only decelerate but the deceleration will increase (airspeed divergence) as the speed departs from the speed at which the thrust balanced the drag. This situation is avoided if the desired approach path angle is established with the proper

power setting and if the pilot uses the elevator to maintain a relatively constant airspeed, thereby augmenting the effects of the existing static stability of the airplane.

It should be noted that this technique goes beyond the concept of what is usually termed a "power approach;" that is, the use of a somewhat fixed power setting above idle to increase the effective L/D of the airplane. Pilots are gradually accepting the fact that idle-power approaches are not desirable for high performance airplanes and generally concede that it is desirable to use considerable thrust during the approach. By carrying this concept one step further, then, the pilot can actually make flight path angle changes with the throttle and allow the airplane to maintain a relatively constant airspeed for a considerable portion of the approach.

Of the four pilots who participated in this general investigation the two who relied most on thrust for primary altitude control selected considerably lower approach speeds on some airplanes, as reported in reference 4. The reductions in approach speed obtained with this technique moreover were greater than were obtained through the addition of boundary-layer control.

Pilots' attitudes toward low speed flight under operational conditions.- It is a well-known fact that under operational conditions, approach speeds tend to be considerably higher than the minimum comfortable approach speeds determined under test conditions. This report has indicated some of the basic aerodynamic and thrust characteristics of an airplane and certain external conditions, such as approach pattern, pilot technique, or distractions due to turbulence, other traffic, etc., which will influence the pilot's approach speed. In order to complete the picture, however, some consideration must be given to the pilots' attitudes toward low-speed flight.

First of all, he has learned that maneuvering to the angle of attack for stall during the approach is a condition resolutely to be avoided since the altitude required for stall recovery is greater than the landing pattern altitude for most present day fighter airplanes. As a result he finds comfort in remaining as far away from the stall as possible. With this in mind the pilot then tries to fly at a minimum margin from a flight condition which can kill him and at the same time he must alternate his attention from outside the cockpit to an airspeed instrument inside the cockpit which has only a rough relation to the angle of attack. We then have a group of factors which are not well known to the pilot under operational conditions and which prevent him from knowing just what his margin from stall actually is. These conditions are: (1) airplane gross weight after expending ordnance, fuel, etc., (2) unfamiliarity with the stall speed even if the gross weight is known, and (3) airspeed instrument errors. These are all conditions which must be known if the pilot is to fly at a minimum margin from the stall speed. However, the operational

pilot will often add about 5 knots for each unknown condition and then cease to be concerned with them. In effect the pilot is applying the concept that the higher the speed, the less that he has to worry about until he touches down on the runway. Increases in touchdown speed, however, have a greater effect on the stopping distance required for high performance airplanes so that large latitudes in approach speed are no longer tolerable.

There is also another concept that influences the manner in which pilots think of airspeed. This concept is that excess airspeed connotes safety in that it can be traded for time, altitude, and maneuvering ability in the event an emergency situation develops. Pilots then will only decrease airspeed in an approach when they have been convinced that a reduced approach speed increases safety. Changes in airplane characteristics which improve the pilot's ability to control the touchdown point and airspeed, of course, also contribute to improvements in safety. While this tendency to increase speed to gain time and altitude in the event of an emergency appears logical, a point also may be reached, as with high density traffic, where the short time available to observe and avoid other airplanes may actually make it safer to use lower landing pattern speeds.

CONCLUDING REMARKS

An extensive flight investigation of a wide variety of high performance aircraft has revealed the primary reason most often given by pilots for limiting (not reducing further) the landing approach speeds to be the loss of control of flight path angle.

The aerodynamic characteristics which contribute to this deterioration in controllability appear to be low L/D ratio (large increase in drag with angle of attack), T/W margin of less than 0.12 available in the approach, reduced static longitudinal stability, and unfavorable trim change with thrust. An unstable drag-airspeed relation (L/D decrease with increasing angle of attack) was not in itself considered a limiting factor; however, it appeared to magnify the effects of a deterioration in any of the other limiting conditions.

Other characteristics which contributed to the selection of higher approach speeds were unconventional techniques required for stall recovery, poor stall warning, reductions in stability and control about any axis, poor visibility from the cockpit, and airplane-tail ground clearance. In the absence of these limitations or other contributory or secondary factors, it was found that the minimum comfortable approach speed could be reduced to approximately $1.10 V_S$.

The advantages obtained with the constant-speed, constant-flight-path-angle approach in comparison with the standard tactical approach in which speed is continually decreasing throughout the landing pattern are: (1) an increased consistency in arriving at the touchdown point at the desired speed, (2) the decreased tendency to develop excessive sink rates or flight path variations, (3) the decreased requirement for large thrust changes, and (4) maximum advantage is taken of the longitudinal stability for airspeed control. These tend to result in an appreciable decrease in the minimum comfortable approach speed especially when the L/D is low and T/W ratio large as with current fighters.

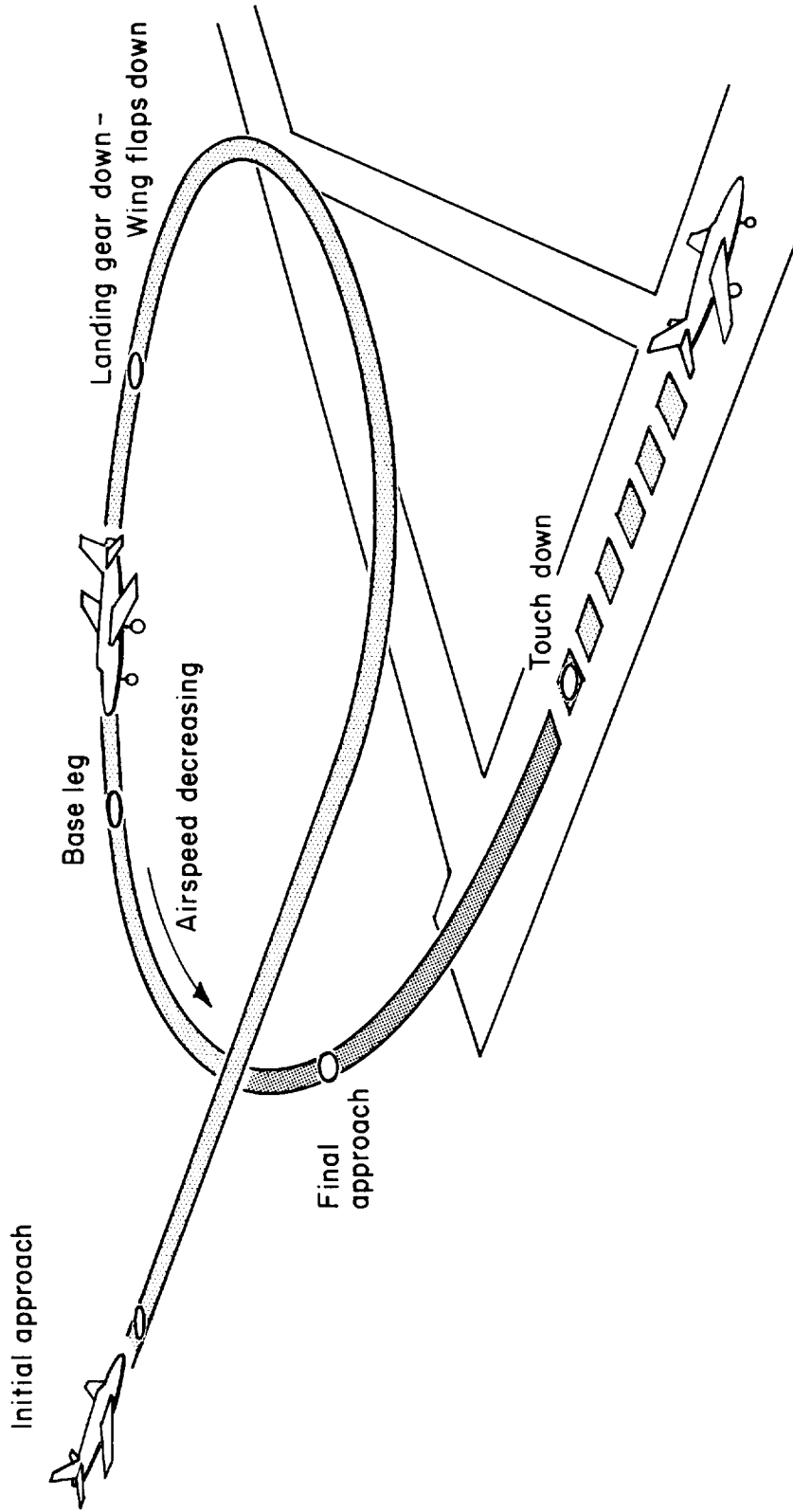
It appears imperative that pilots become more thoroughly familiar with the fundamental concepts discussed herein so that the landing maneuver can be established as more of a science than an art. Minimum comfortable approach speeds of this investigation will be obtained in operational use on high performance airplanes only when, (1) operational pilots obtain and retain complete familiarity with the airplane's low speed flight characteristics, (2) normal variations in gross weight are taken into account in selecting the approach speed, and (3) pilots are convinced that the advantages of using reduced but stabilized approach speeds and constant approach angles are greater than those obtained by using high pattern speeds.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Aug. 25, 1958

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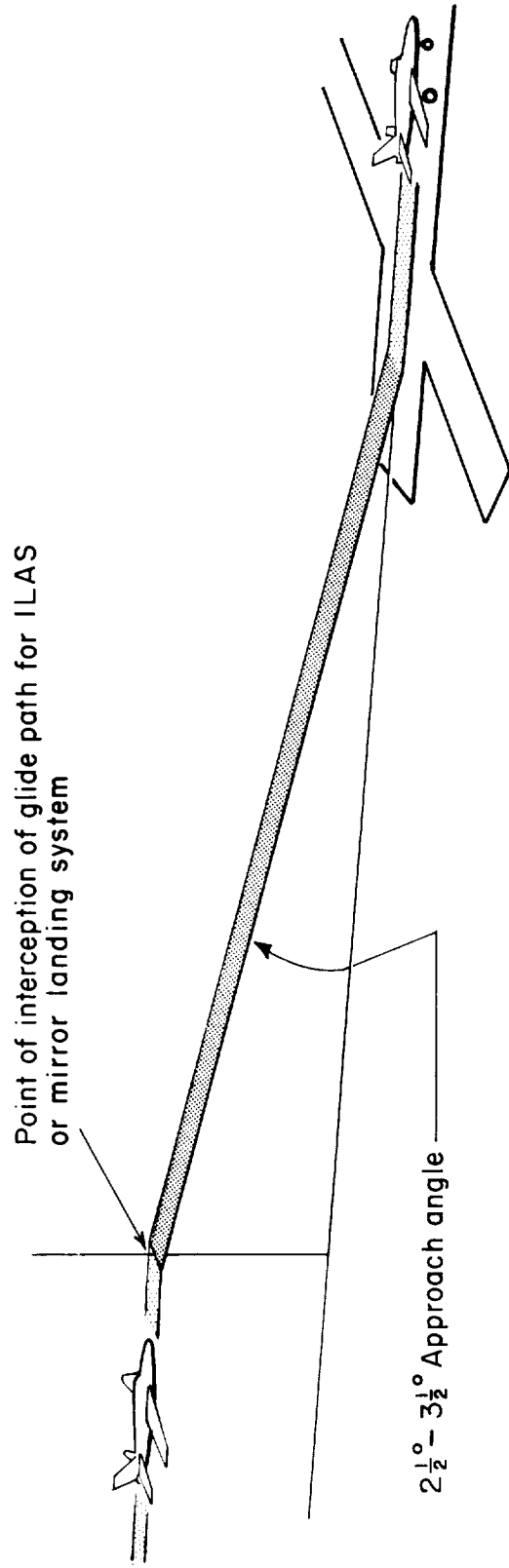
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(a) Typical tactical landing approach pattern.

Figure 1.- Landing approach patterns.



(b) Typical instrument or mirror landing system approach.

Figure 1.- Concluded.

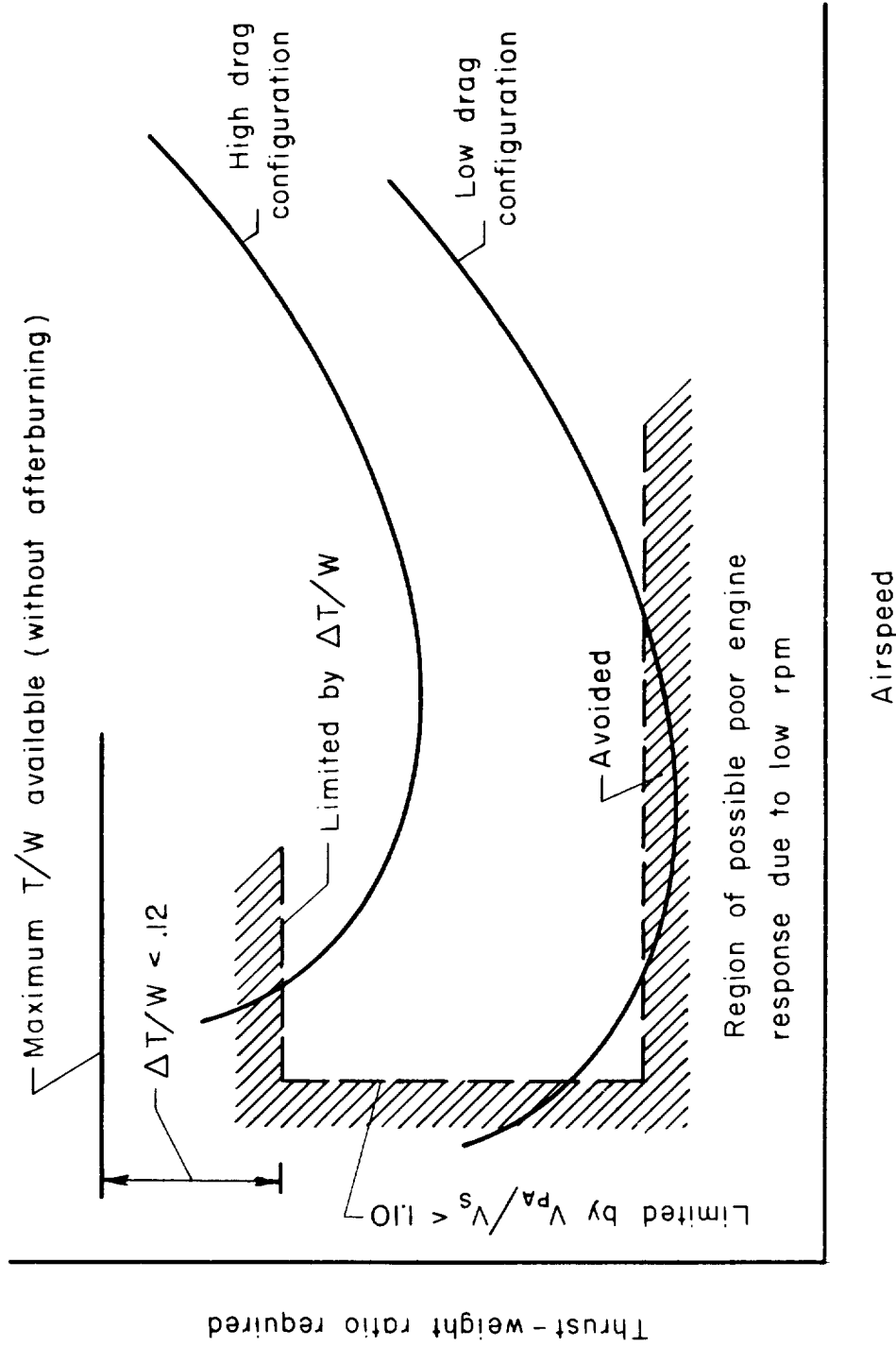


Figure 2.- Summary of limiting factors in relation to generalized drag air speed curves.

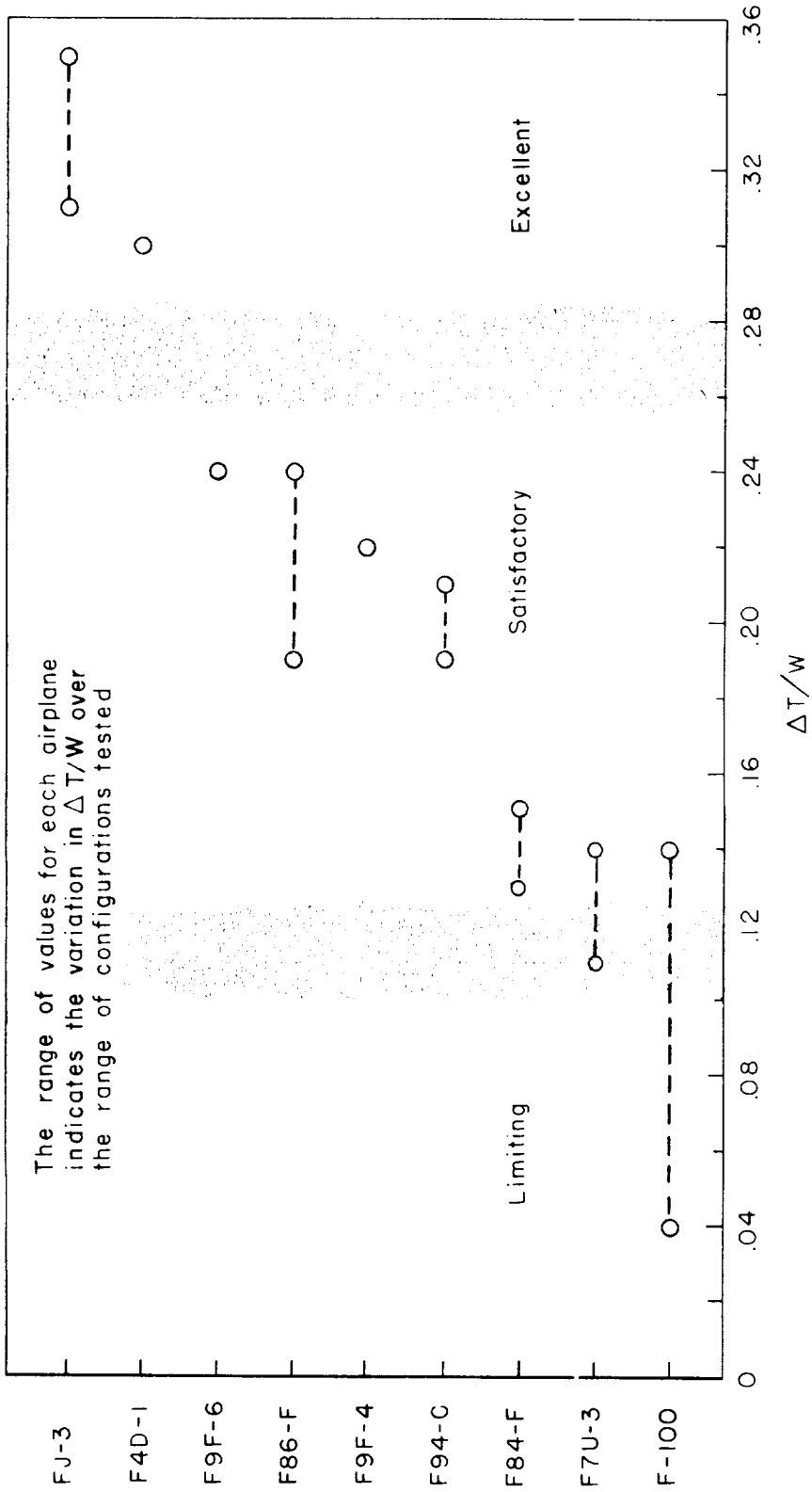


Figure 3.- Pilot opinion of the margin of T/W available at the approach speed (without afterburner).

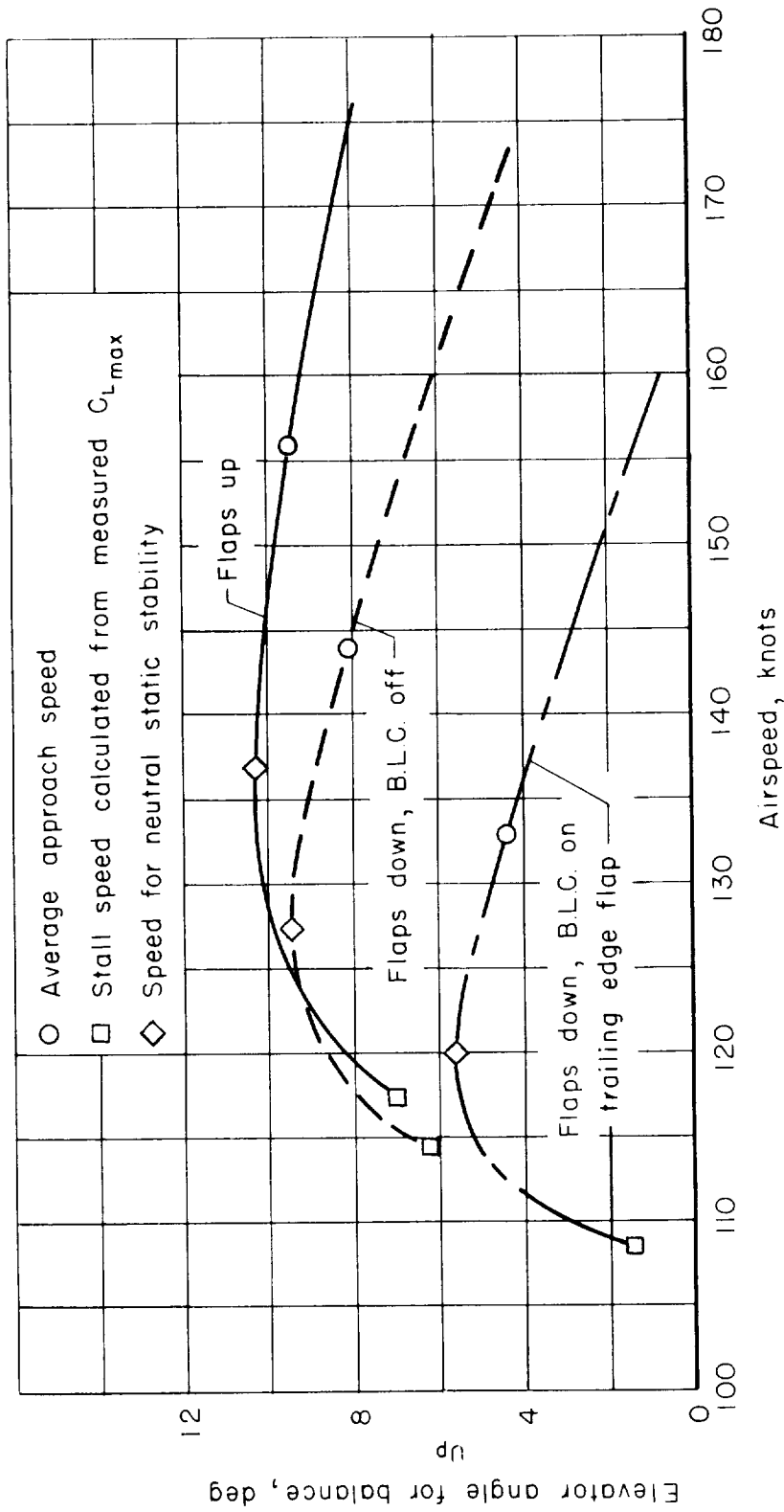


Figure 4.- Reductions in approach speeds compared to reductions in stall speed and speed for neutral static stability for a modified F-100A airplane.

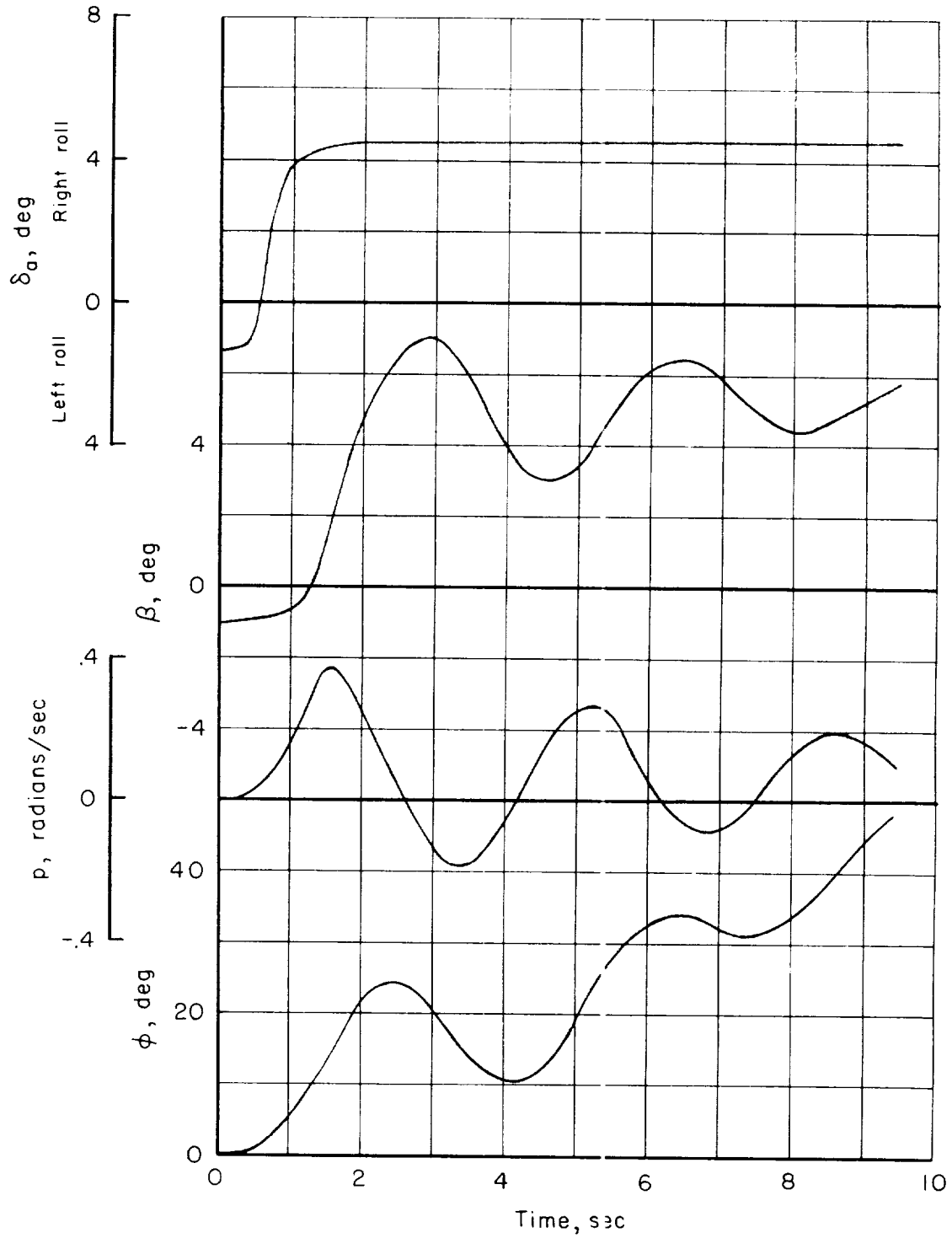


Figure 5.- Response to a step aileron input on an airplane for which lateral control characteristics prevented further reductions in V_{PA} .