Criteria for Determination of Minimum Usable Approach Speed

G. A. PATTERSON JR.*
Naval Air Test Center, Patuxent River, Md.

Until recently, the landing approach requirements have not been delineated in the design specifications for U.S. Navy carrier-based airplanes. The minimum and/or optimum approach speeds have been determined qualitatively. This did not provide a quantitative base from which desirable and undesirable characteristics could be assessed. This paper discusses the development of the present tests and techniques utilized for determining the minimum usable approach speed. Six major factors were isolated, i.e., longitudinal acceleration available, stall speed, field of view from the cockpit, ground clearance, stability and control requirements, and glide slope correction capability. Several existing airplanes have been evaluated against these factors and the results are discussed. All new carrier-based airplanes, plus a few already flying, must comply with the stated requirements for establishing the minimum usable approach speed. Additional experience will be necessary to conclude finally that the values of the requirements are valid.

I. Introduction

THE carrier landing is one of the more demanding maneuvers required of pilots today. It is a precision maneuver at the minimum usable airspeed, with little margin for error. This report describes the flight tests and the resulting requirements presently used for determining the "minimum usable airspeed," $V_{PA_{\min}}$, for the carrier landing approach.

Carrier Landing Environment

About ten years ago, the optical landing aid system, shown in Fig. 1, was installed on all aircraft carriers. Subsequently, the Fresnel Lens Optical Landing System replaced the original optical landing aid system. This type of equipment provided the pilot with the visual information required for making constant glide slope approaches to the desired touchdown point. The piloting technique used is to fly along this visual path while maintaining the appropriate angle of attack, which gives the proper approach speed. The difficulty of maintaining the desired angle to attack and flight path can be accentuated by such items as gusty air, rain, night conditions, and/or turbulence behind the ship.

The ease or difficulty with which the airplane can be landed is directly affected by the control system characteristics, the flying qualities, and by the performance characteristics of the particular airplane being considered. The landing accident rates of different aircraft reflect to a large extent the landing approach characteristics.

Landing Approach Airspeed

For several reasons, the landing approach should be made at a low airspeed. Among these reasons are reduced structural loads imposed on the aircraft, reduced wind over deck requirement or reduced loads imposed on arresting gear, and increased time for pilot reaction.

Historically, a minimum approach airspeed has been implied only in the airplane design specifications. The flying qualities and performance requirements were not specifically stated. As a result, the approach speeds were determined by qualitatively establishing the minimum speed for acceptable flying qualities. Experience has shown that the limiting factor could be one or more of several items, restricted visibility, minimum tail clearance at touchdown, low lateral control power, and insufficient wave-off performance, to mention a few. Several studies have been made which defined factors affecting approach speed.[1–4] In order to establish a quantitative base for some of these qualitative limits, a program was set up to develop flight test techniques and to determine minimum acceptable levels from the flight-test results.

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* Supervisory Aerospace Engineer, Flying Qualities and Performance Branch, Flight Test Division.

II. Flight Tests

Three factors that required definition of minimum values for satisfactory approach characteristics were 1) flying qualities criteria, 2) an altitude correction capability, and 3) wave-off performance. Initially, tests were conducted on five current carrier-based aircraft, two fighter and three attack designs.

Flying Qualities Criteria

From experience gathered over the years, it has been concluded that the flying qualities requirements of the military specification MIL-F-8785[5] need to be updated. Work is going on in that area at present. For our purposes, however, the power approach (PA) configuration requirements at the approach speed were generally adequate for the minimum requirements during landing approaches. A requirement for acceptable stall warning and stall characteristics in wave-off(WO) configuration should be added.[6] A modification to the lateral control effectiveness requirement is expected when the specification is updated. One study of several carrier-based jet aircraft concluded that the lateral control effectiveness should

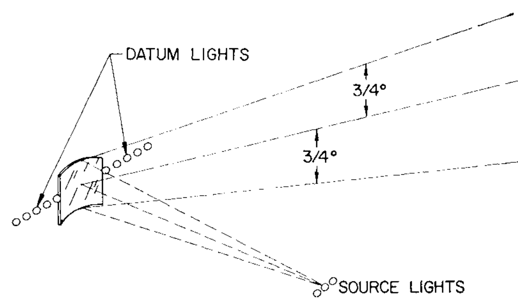

Fig. 1. Optical landing aid system.

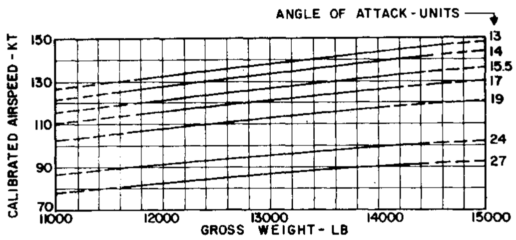

Fig. 2 Angle-of-attack relationship.

by sufficient to produce a 20° bank angle change in the first second.[7] Another study concluded a minimum steady roll rate of 15°/sec was required.[8] Some of the more critical flying qualities requirements for the landing approach are elevator-fixed static stability, elevator-free static stability, lateral-directional damping, static lateral-directional stability, adverse yaw, lateral control effectiveness, and stall warning.

Altitude Correction Criteria

An altitude correction capability maneuver was developed which was based on the results of a theoretical study that concluded that the approach speed correlated with the ability to correct a 50-ft altitude error.[1] It was considered that this error must be corrected in 5 sec while using no more than one half of the maximum normal acceleration capability. To determine the available maneuvering capability, flight test evaluations of the gross weight, airspeed, and angle of attack, relationship up to stall angle of attack was required. Figure 2 presents a typical graph of these parameters. Next, accelerated stalls were performed throughout the approach speed range of each aircraft. Figure 3 shows typical results of such tests. Step-up maneuvers were then performed at several airspeeds, or trim angles of attack, using various g levels. Figure 4 shows the results of such tests. From this, the minimum approach speed at which the requirement is met can be ascertained. Initially, the 50-ft step-up in altitude was performed from level flight; however, this was not satisfactory. Because of the airspeed system position errors and lag problems, the pilot was unable to control the aircraft accurately and the resulting data were questionable. Subsequently, two mirror landing systems were set up along one runway to provide two parallel glide paths that were separated by a 50-ft altitude difference. Figure 5 is a sketch of this installation. This provided the pilot with cues needed to perform the step-up maneuver successfully, which was termed a "glide slope transfer." Pilots opinion suggests that the time requirement of 5 sec or less for executing the pull-up and accomplishing the 50-ft glide slope transfer is valid. Of course, the time required to stabilize on the new flight path will require an additional time increment. This portion of the maneuver generally entails one overshoot, and then the airplane gradually "settles" down to the new glide path. The

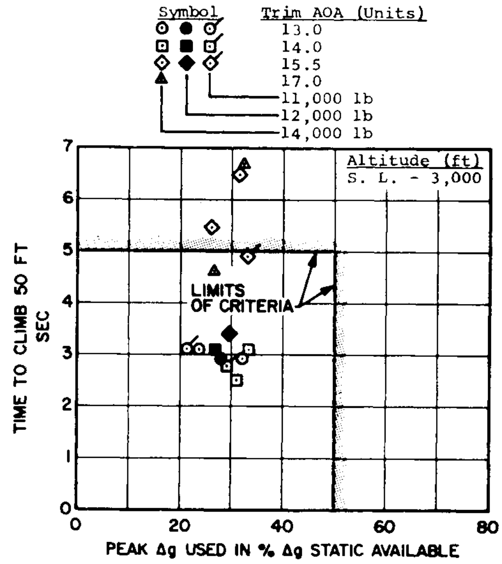

Fig. 4 Step-up capability.

requirement of restricting the pull up to 0.5 of the maximum normal acceleration is considered by the pilots to be an arbitrary limit, and some pilots suggest that the normal acceleration should be allowed up to stall warning. Such a maneuver would require a suitable reduction in the time allowed for execution.

The glide slope transfer maneuver is accomplished without changing the throttle position: therefore, the speed loss during the maneuver may become a critical factor. Originally, the throttle position was maintained until stabilized on the new glide slope. The intention behind this requirement was to insure that the aircraft would be flown at a speed in which the aircraft exhibited positive speed stability. This requirement proved to be impractical since the tests showed that the initial airspeed would not be required after the pull-up. The procedure was modified to permit normal throttle movements after attaining the 50-ft increment and the push-over to the new glide slope is initiated. In consideration of the aforementioned tests, the detailed specification of a current fighter-type airplane requires the following:

> The aircraft will be capable of making an altitude correction from established flight on a four (4) degree glide slope at $V_{PA_{min}}$ to a new altitude 50 ft above the initial flight path and will be capable of maintainng this new flight path after such altitude correction has been made. The aircraft will come to or above the new altitude within 5 seconds after initiation of the maneuver. The maneuver will be performed without change in the engine thrust, and the maximum positive incremental load factor during the maneuver will not exceed 0.5 of the incremental load factor which would be attained by rotation to steady state $C_{L_{max}}$ at $V_{PA_{min}}$.

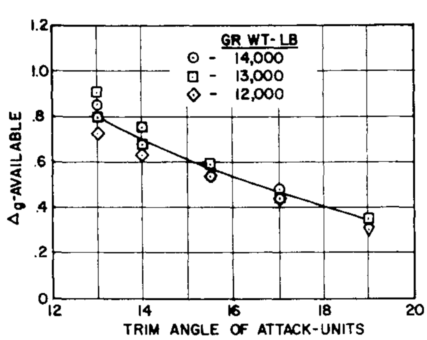

Fig. 3 Load factor available.

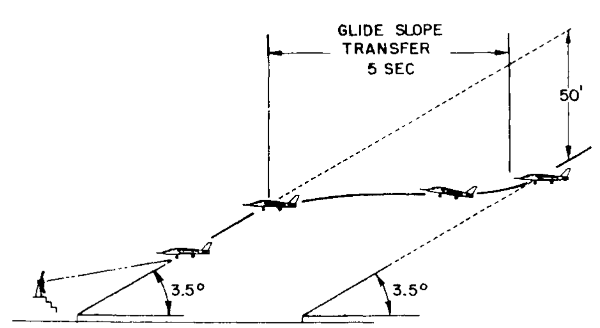

Fig. 5 Glide slope transfer.

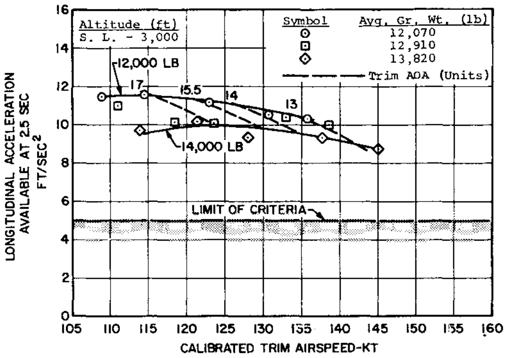

Fig. 6 Longitudinal acceleration.

Wave-Off Criteria

Military thrust wave-offs were conducted on each type of aircraft, both from level flight and from steady glide slope approaches. Although a wave-off from a steady glide slope approach is the most realistic, it is also more difficult to define accurately and to test. The level flight acceleration test is simple to perform and measure. Experience has shown that the level flight acceleration capability is a good indicator of wave-off capability. Since a late wave-off may be initiated only 3 sec prior to the impending touchdown, a quick response to throttle movement is vital. Because of this, 2.5 sec after the initial throttle movement to the military thrust positions is used as the time base. A longitudinal acceleration of at least 5 ft/sec^2 in 2.5 sec was determined to be the minimum acceptable value. Figure 6 presents some results obtained during these tests.

As a result of these tests, the detailed specification of a current fighter airplane requires the following longitudinal acceleration capability at the minimum usable approach speed:

The longitudinal acceleration of at least 5 ft/sec^2 on a hot day (90°F) in a level attitude at zero flight path angle will be available within 2.5 seconds after initiation of throttle movement to the military thrust position while in a stable speed approach $V_{PA_{\min}}$.

Stall Speed

The approach speed should not be less than 110% of the stall speed. Ten % above stall is considered to be the minimum safe increment of speed for the approach.

Visibility Criteria

The field of view from the pilot's position must be "adequate" for both day and night operations. This requirement is necessarily qualitative in nature; however, the ability to see the optical landing aid located on the left of the landing area or in an emergency, to see the mechanically operated Visual Landing Aid System, which is located on the right side of the landing area, is mandatory throughout the approach, including nose-up pitch changes as are normally required to maintain the glide path. Additionally, the angle deck centerline and the stern of the ship must be visible so that the pilot can readily effect and maintain the proper lineup. Drop line lights are positioned down the stern of the ship and are required for night operations.

Clearance Criteria

The ground clearance also must be "adequate." This requirement remains a qualitative item until a "quantitative dent" appears because of contact between the empennage and the deck or cable.

Comparison of Findings with Safety Records

Table 1 presents a comparison of the relative landing accident rate with the results of these tests. The comparison is quite encouraging with one possible exception, aircraft E.

Pilots state that it is difficult to maintain the proper speed in aircraft E. To investigate further the speed/flight path control problem, a series of GCA tests was conducted on aircraft A, B, C, and E. Two types of approaches were made, 1) correct flight path errors with longitudinal control only (throttle fixed), and 2) correct flight path errors with throttle control only (maintain optimum angle of attack with longitudinal control). In each approach using longitudinal control only, the speed varied considerably from the optimum, generally resulting in a fast approach. During the throttle control-only approaches, the speed, and flight path could be maintained reasonably well in all aircraft with one exception. Aircraft E exhibited a divergent long-period oscillation in height. This suggests that some consideration is required for stability of the "pilot input-engine response-rate of climb" loop. In practice, the pilot of aircraft E modifies the oscillation in height with longitudinal control inputs, however, this ultimately results in speed variations, or poor speed control, as noted in pilots comments. A "closed-loop" systems analysis had shown similar results.[9]

Two carrier-based aircraft that are presently in their development programs have specification requirements for establishing $V_{PA_{\min}}$. The actual recommended approach speed will be compared with the guaranteed $V_{PA_{\min}}$. Similarly, the pilot opinion of landing approach characteristics of the new aircraft will be obtained and the landing accident statistics when available, will be analyzed in an attempt to provide a basis for revising the $V_{PA_{\min}}$ requirements.

Augmented Control Systems

In order to improve some deficient approach characteristics that are inherent in some current aircraft, additional control systems are being developed. These systems include 1) the approach power compensator, an automatic throttle control that improves the speed control; 2) direct lift control, a wing lift control system that improves the altitude correction capability; and 3) speed-modulated afterburner thrust system, another throttle control system that improves the wave-off capability. Each of these systems helps reduce the pilot's task while performing the critical landing approach maneuver.

Conclusions

The requirements for establishing a minimum usable approach speed $V_{PA_{\min}}$, have been defined and are applicable to carrier-based aircraft currently in their development program.

Table 1 Safety record comparison

Aircraft	FY-65 Relative landing accident rate—embarked (scale of 1.00 for highest rate)	Comments on $V_{PA_{\min}}$ requirements at recommended approach speed
A	0	Meets all requirements
B	0.21	Meets all requirements
C	0.31	Fails to meet glide slope transfer requirement. Low lateral control power.
D	0.63	Fails to meet longitudinal acceleration requirement.
E	1.00	Meets glide slope transfer and longitudinal acceleration. Low lateral control power.

Additional experience is required to insure that the present requirements are optimum. Also, some consideration is needed for other factors that affect height control.

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Navy Variable-Stability Studies of Longitudinal Handling Qualities

John A. Eney*
U. S. Naval Air Development Center, Johnsville, Warminster, Pa.

A study of longitudinal handling qualities in the simulated carrier approach was performed at Princeton University in a North American Navion so equipped as to vary its static and dynamic longitudinal stability characteristics. Five Navy pilots flew "meatball" approaches in 24 configurations and gave ratings using the Cooper scale. Short-period dynamics with frequencies greater than 1.4 rad/sec and damping ratios greater than 0.2 were found to be satisfactory. Control sensitivity was variable and was found to be a critical parameter for some configurations. Stick force per g ranged to extremes and was found to be of little consequence in visual landing approach. A comparison is made with several proposed longitudinal handling qualities criteria, with little agreement. Further work in landing approach, as well as high-speed flight, is currently in progress at the Naval Air Test Center, using a variable-stability F-8D. Short-period frequencies ranging from 0.2π to 4π rad/sec are being flown through typical tactical mission profiles. The handling qualities of higher-order dynamics, typical of augmented aircraft, are of prime interest, and data will be compared with numerous criteria that have been proposed for the longitudinal dynamics of aircraft.

Nomenclature

α = angle of attack, rad
δ_{es} = stick deflection, in.
F_s = stick force, lb
g = gravitational acceleration, 32.2 ft/sec^2
M_α = dimensional pitching moment due to $\Delta\alpha$, 1/sec^2
$M_{\dot\alpha}$ = dimensional pitching moment due to $\dot\alpha$, 1/sec
$M_{\delta_{es}}$ = dimensional pitching moment due to δ_{es}, rad/sec^2/in.
$M_{\dot\theta}$ = dimensional pitching moment due to $\dot\theta$, 1/sec
ω_{sp} = short period frequency, rad/sec
s = Laplace operator
ss = steady state
θ = pitch attitude, rad
V = airspeed
Z_α = heave acceleration due to $\Delta\alpha$, 1/sec
$Z_{\delta_{es}}$ = heave acceleration due to δ_{es}, 1/sec
ζ_{sp} = short-period damping ratio
$(\dot{\ })$ = time rate of change, $\partial/\partial t$

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* Aerospace Engineer, Aero Mechanics Department, Flight Analysis Division. Associate Member AIAA.

Introduction

In the Fall of 1965, the Naval Air Systems Command contracted Princeton University to conduct an in-flight study of longitudinal handling qualities in a simulated carrier approach task.[1] The objectives of this undertaking were as follows: 1) to determine if, and to what extent, the Princeton variable-stability Navion was suited to studying the longitudinal handling qualities of carrier-type aircraft, and 2) to compare Navion pilot-opinion ratings with a) results obtained in a similar program using a variable-stability jet trainer[2] and b) various proposed criteria on longitudinal flying qualities.

Flight Program

Description of Airplane

The airplane used was a North American Navion (see Fig. 1) modified to provide 3-axis variable stability and control. In the pitch axis, angle of attack (α) and pitch rate ($\dot\theta$) were fed back to the elevator servo to effectively alter the M_α and $M_{\dot\theta}$ derivatives and thereby vary the short-period dynamics.

Evaluation pilots flew from the right seat (see Fig. 2), which was equipped with a center stick in place of the original yoke