SIMULATOR INVESTIGATION OF ARROW-WING LOW-SPEED HANDLING QUALITIES

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SUMMARY

Low speed handling qualities of arrow wings were investigated with a piloted simulator. Existing aerodynamic data were used from NASA SCAT 15F tunnel tests augmented with new Lockheed low speed wind tunnel test data. Two arrow wing planforms were chosen for the simulation effort - a Mach 2.0 design and a Mach 2.7 design. These designs are in the SCAT 15F Mach 2.7 design family, having the same βAR and $\beta \cot \Lambda$.

Piloted simulation results indicate that both the Mach 2.0 and Mach 2.7 planforms have satisfactory longitudinal flying qualities. However, in the control of bank angle the Mach 2.0 planform demonstrates satisfactory handling qualities while the Mach 2.7 planform is unacceptable. This situation applies for crosswind landings at FAA limits and for lineup in heavy turbulence. The low-speed superiority of the Mach 2 planform with its lower sweep and higher aspect ratio is also shown by its ability to approach at least 8 m/s (15 knots) slower than the Mach 2.7 planform without degradation in handling qualities.

INTRODUCTION

Since the development of the SCAT-15F arrow-wing aircraft configuration by NASA in the mid 1960s, supersonic cruise aircraft research has centered around a design cruise Mach number of 2.7. Recent Lockheed studies on the influence of design cruise Mach number on airline utilization, passenger acceptance, aircraft complexity, and operating costs have revealed that cruise Mach numbers as low as M = 2.0 may be competitive. An additional factor, not included in these studies, is the influence of design Mach number on low-speed flying qualities and airport performance. The available low-speed flying qualities data point out two potential problem areas for aircraft designed for M = 2.7. The highly swept, low-aspect-ratio wing, which is cambered and twisted for best cruise performance, does not develop adequate lift even with flaps extended to permit use of approach speeds comparable to current subsonic jets. This problem is further aggravated by approach attitude restrictions imposed by visibility requirements and low tail-scrape angles resulting from the long fuselage inherent in this type of design. In addition, the high rolling moments generated by a highly swept wing in sideslip and the severely limited roll control available from this wing planform restrict the crosswind landing capability.

The primary effects of reduced design Mach number on the aircraft are to increase the wing aspect ratio and reduce the wing leading-edge sweep angle. These parameters improve the lift capability of the wing by increasing the lift-curve slope and flap effectiveness. Roll control is improved by reduced aileron sweep angle, higher wing aspect ratio, and the lower rolling moments induced by sideslip.

These effects may be computed adequately if good aerodynamic data are available for use in the analysis, but the significance of the flying qualities parameters to a pilot attempting to land the aircraft is difficult to evaluate using conventional analysis methods. The objectives of this flight simulation program were to obtain test data on the magnitude of the low-speed improvements offered by a reduction in design Mach number from 2.7 to 2.0, and to qualitatively evaluate the significance of these improvements to a pilot attempting to land a simulated aircraft in various levels of air turbulence and crosswind.

STUDY APPROACH

The approach taken during the flight simulation program was to collect all available data on low-speed flying qualities for arrow-wing planforms and to supplement these data where necessary with wind tunnel data and analysis. Previous wind tunnel testing of various SCR configurations by Lockheed, together with NASA tests of control system effectiveness and basic planform characteristics were accumulated and used as a data base for the M = 2.7 configuration. These data were primarily for the NASA SCAT-15F configuration or for slight variations of that planform. Because there were very little data available for planforms designed to cruise at lower speeds, low-speed tests were deemed necessary to define the characteristics of the M = 2.0 planform. Both planforms were tested to determine the detailed differences between them and to permit the application of an accurate correction to the data for twist and camber effects.

Because the SCR configuration must be balanced to minimize trim drag in cruise, static longitudinal stability in the approach must be negative, which requires a rather sophisticated control system to permit the pilot to use conventional flying techniques. For this study, stability and control augmentation systems were developed based on the results of NASA flight simulation tests from which the control laws required for acceptable approach control were determined. These data, together with configuration characteristics, such as weight and inertia, ground clearance, engine geometry and dynamics, and cockpit location derived from previous SCR configuration studies, constituted a flight simulator data package which was programmed on the Lockheed Developmental Flight Simulator.

A piloted flying qualities evaluation of approach and landing characteristics on the M = 2.0 SCR, the M = 2.7 SCR, and the L-1011 subsonic transport aircraft was conducted in various levels of air turbulence and crosswinds to assess the significance of differences in aerodynamic chafacteristics of the two study planforms.

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STUDY SCOPE

- Testing was limited to general flying qualities in the approach configuration and to an evaluation of controllability and pilot workload during an instrument approach in crosswind and turbulence.

- An existing transport cockpit (L-1011) was used for all testing. No attempt was made to simulate the visibility restrictions that may be present in an SCR design.

- All approach testing was initiated in IFR conditions, and a flight-director similar to the L-1011 system was used for glideslope and localizer commands.

- The flight control system was a control-wheel steering (CWS) system utilizing attitude-hold and rate command logic in pitch and roll. Autopilot inputs were isolated from the control column and wheel to avoid disturbing control system motion that can result from CWS-type systems.

- All approach testing was terminated at main-wheel touchdown.

- Crosswinds up to 15.45 m/sec (30 knots) and air turbulence up to 2.7 m/sec (9 fps) rms were introduced into the aerodynamic equations.

- The L-1011 aircraft was simulated and compared to the two study configurations in all test conditions to provide a reference point for the pilot ratings.

DESCRIPTION OF SIMULATED AIRCRAFT

To evaluate flying quality variations with planform, two wings were designed: one to cruise at Mach 2.7 and the other at Mach 2.0. Wing area, notch ratio, taper ratio, βAR, and $\beta \cot \Lambda$ were held constant for the two designs by varying sweep angle and aspect ratio. A comparison of the Mach 2.7 and Mach 2.0 planforms is shown in Figure 1, where the differences in sweep angle, aspect ratio, and trailing-edge flap configuration can be seen. A tabular comparison of the planform properties is given in Table 1. Pertinent dimensions are listed in the table, showing that the planform parameters are consistent between the Mach 2.0 and 2.7 planforms. All other aircraft dimensions besides wing geometry and engine location were identical for the two test configurations. The engines were located at a constant percentage semi-span location, and thus were farther from the aircraft centerline on the Mach 2.0 configuration because of its larger span. Wing area and landing gross weight were maintained constant, but differences in mass moments-of-inertia between the two designs were accounted for.

Aerodynamic data were derived principally from a low-speed wind-tunnel test of the Mach 2.0 and Mach 2.7 designs in the Lockheed low-speed wind tunnel. These data, derived from flat-plate wing models, were corrected for twist

and camber effects using existing NASA wind tunnel data in which both twisted and flat-plate wing data were available. Basic aerodynamic force and moment data, as well as control surface and high lift system effectiveness were determined from the wind tunnel tests. Flexibility corrections in the roll control effectiveness and effective dihedral parameter are included in the data for the airspeeds evaluated in this study. Ground effects on lift and pitching moment were derived from previous wind tunnel tests of similar configurations. Dynamic stability derivatives were estimated using conventional estimation techniques.

The flight control systems used in this study were developed from the systems described in Reference 1, which reported the results of NASA ground-based and in-flight simulation of a similar configuration. The longitudinal and lateral control systems are attitude-hold autopilot-type systems with control-wheel-steering rate-command inputs for maneuvering. The gains and time-constants in the control systems were chosen to make the systems feel as much as possible like conventional control systems. For the same reason, the control-surface inputs generated by the automatic systems were isolated from the control column and wheel to avoid the disturbing motions that result from CWS-type control systems in current subsonic jets. Because supersonic cruise vehicles operate well on the backside of the thrust required curve at approach speeds, an autothrottle was developed to relieve the pilot of the high workload associated with airspeed control in these conditions.

DESCRIPTION OF FLIGHT SIMULATOR

The Lockheed Developmental Flight Simulator is a hybrid computer facility with peripheral hardware designed to create the illusion of flight. Computational hardware consists of general-purpose digital and analog computers, and special-purpose computers to simulate cockpit control forces and engine noise cues. Several peripheral pieces of equipment, such as a visual display system, a motion generation system, and a cockpit complete with operational flight instruments are available to enhance pilot flight impressions. The digital computer is programmed with the aircraft equations of motion, all aerodynamic and propulsion data, geometric and inertial data, and additional equations to control the peripheral equipment and data recording devices. The analog computer is used to simulate flight control systems, which require high-frequency computing to adequately represent the system dynamics.

The cockpit used for this simulation is a mock-up of the L-1011 cockpit with flight instruments and controls installed in the L-1011 configuration.

The visual system is a single-window television system with a 63.5-cm (25-in.) TV monitor mounted on the pilot's glare shield. The source of the displayed image is a three-dimensional 1500:1 scale model of the Palmdale, California airport and surrounding terrain mounted on a continuous moving belt. The monitor image is generated by a closed-circuit television channel, the camera of which is mounted on a servo-controlled carriage that moves across the width of the model belt and at right angles to its surface. These movements, along with model belt motion, present the true position of the aircraft,

relative to the airport runway. A servo-controlled prism-mirror system, attached to the camera, provides pitch, bank, and heading displacements.

The cockpit is mounted on a 4-degree-of-freedom motion system, providing pitch, roll, vertical, and lateral motions. The motion system provides completely independent motion in each degree of freedom, such that full excursion is available in any axis, independent of the excursions in the other axes. Because of the importance of air turbulence in this evaluation, motion system gains were optimized to present the most realistic turbulence simulation possible within the limits of the actuators.

Air turbulence was simulated by inserting random velocity inputs in the aerodynamic equations. Magnitudes and filtering of the input velocities were controlled according to the Dryden form of the random turbulence equations. In the basic Dryden model the characteristic lengths are reduced as a function of height near the ground. As a result, the peak velocity gusts simulate vertical and horizontal wind-shear bursts on landing approach. Flying qualities were evaluated in levels of turbulence from still air to heavy turbulence. Heavy turbulence is defined for this study as 2.7 m/s (9 ft/s).

Crosswinds were simulated by simply adding a constant value of lateral velocity to the earth-oriented velocity derived from the inertial aircraft equations. This accounted for the lateral movement of the air mass relative to the fixed airport coordinates.

TEST CONDITIONS

The approach speeds evaluated in the flight simulation program were selected from a static analysis of lift and roll control available from both the M = 2.0 and the M = 2.7 configurations at a typical landing weight. In Figure 2, the available approach speeds of the two designs are compared as a function of angle attack for δ_F = 0.35 rad (20 deg). At the maximum allowable angle of attack, the M = 2.0 design can approach 7.7 m/s (15 knots) slower than the M = 2.7 design. If approach attitude is more critical than approach speed, the M = 2.0 design can approach at an attitude of 0.044 rad (2.5 deg) lower than the M = 2.7 design.

Another consideration for approach speed is the control available for a crosswind landing, which usually is degraded as approach speed is reduced.

Figure 3 shows the variation with approach speed of sideslip angle required to land either aircraft in a 15.4 m/s (30-knot) crosswind, assuming the pilot decrabs the aircraft just prior to touchdown and lands with the longitudinal axis aligned with the runway centerline. This is the accepted crosswind landing technique for aircraft without special crosswind landing gear. Also shown in Figure 3 is the sideslip angle which can be controlled at full aileron for the two aircraft designs. At 87.4 m/s (170 knots), the M = 2.7 design requires a full roll control to counter the rolling moment produced by sideslip. For the M = 2.0 design, full roll control is reached at 72 m/s (140 knots), an improvement of 15.4 m/s (30 knots) over the M = 2.7 design.

Figure 4 summarizes the constraints on approach speed previously discussed. From these considerations, test conditions were selected to evaluate each of the aircraft configurations in the flight simulator. Since the roll control constraint is associated only with crosswind landing, approach speed was selected as 160 knots based on scrape angle considerations, and roll control was evaluated at that speed.

RESULTS OF PILOT EVALUATION

Four test pilots evaluated the simulated aircraft including three engineering test pilots from the Lockheed Commercial Flight Test organization and a NASA-Langley test pilot. A total of 50 test hours were completed.

General Flying Qualities In Approach Configuration

In order to evaluate the general flying qualities of each configuration in the approach flight condition, several flight test maneuvers were executed and pilot ratings were obtained. The evaluation maneuvers included level turns and step roll inputs to evaluate roll control, cockpit control doublets to evaluate aircraft dynamics, small heading changes and steady sideslips to evaluate directional control, and engine transients to evaluate asymmetric conditions and control for missed approach. The Cooper-Harper pilot rating scale was used to quantify the pilots' opinions of the test configurations. Figure 5 is a simplified version of the rating scale.

The evaluation pilots were asked to rate the workload and controllability for each of the test maneuvers and to comment on any other flying quality characteristics that became apparent during the simulated flight. The following comments are a summary of those received from all evaluation pilots.

For the Mach 2.7 design, roll control sensitivity and roll rate capability were judged to be lower than current subsonic jets and possibly inadequate, particularly in turbulence. Other lateral directional characteristics such as adverse yaw and dutch roll damping were excellent. Pitch dynamics and pitch response were rated good, with a slight tendency to overcontrol pitch inputs. Because of the low roll response, control force harmony was not optimum. In a steady heading sideslip, roll control was good up to 2/3 pedal travel, where lateral control limits were reached. Beyond this point bank angle control was unacceptable. Control for engine failure was excellent in all axes.

For the Mach 2.0 design, roll control sensitivity and rate capability were much improved over the Mach 2.7 design. Because of the improved roll characteristics, control force harmony was good. In a steady sideslip, roll control was good up to full pedal, where about 2/3 of the lateral control was used.

Figure 6 presents an average of the pilot ratings obtained for the test maneuvers previously listed. In most maneuvers, the M = 2.0 SCR was rated easiest to fly, and the L-1011 and M = 2.7 SCR were rated slightly more difficult. In level flight turns, both of the SCR designs were rated slightly

better than the L-1011 because of the attitude hold control system, which simplified the pilot's task of holding altitude. Pitch dynamics and workload during waveoff also were rated better for the SCR designs for the same reason. The roll sensitivity of the M = 2.0 SCR was rated better than either the L-1011 or the M = 2.7 SCR because of a nonlinearity in roll response in the L-1011 and because of inadequate roll control power in the M = 2.7 SCR. Similar ratings and comments were given for control in steady sideslip. The M = 2.0 SCR could be controlled in a full pedal sideslip with 0.43 rad (25 degrees) of wheel and the L-1011 with about 1.05 rad (60 degrees) of wheel. In the M = 2.7 SCR, full pedal sideslips could not be controlled with full wheel. The average rating of 4 given this condition is a compromise between the relative ease of controlling sideslips up to two-thirds pedal and the inability to control full pedal sideslips. Dutch roll dynamics were rated good for all configurations, and control for engine failure also was easy in all configurations, but slightly more difficult in the L-1011 because of the lack of attitude hold.

Control for Approach in Turbulence

The workload and controllability of the three aircraft during a landing approach in turbulent air were evaluated by each of the four pilots. Turbulence was introduced into all three aircraft axes at levels up to 2.7 m/s (9 ft/s) rms. The effect of increasing turbulence was evaluated by attempting to execute an instrument approach to a typical airport. The simulation was initiated with the aircraft located 9.66 km (6 miles) from the runway threshold on the extended runway centerline. The aircraft was trimmed in level flight at 305 m (1000 ft) AGL at the specified approach airspeed with landing gear extended and trailing edge flaps extended to the landing position. In the L-1011, flap changes were made during the approach in accordance with established airline procedures for that aircraft. The pilots flew the simulated aircraft at the initial altitude, following the localizer inbound until the glideslope was intercepted. The glideslope was then captured, and glideslope and localizer were tracked to touchdown. The pilots transitioned from instrument flight to visual references at about 60 m (200 ft) above the runway and made final adjustments in lineup and glidepath.

For the Mach 2.7 design, pitch control and pitch response were good. The attitude-hold function in the control system handled the turbulence quite well; however, at high turbulence levels, a higher gain in the attitude loop would make the aircraft feel more stable. Roll response was sluggish in all levels of turbulence, but was totally inadequate in high turbulence. Bank angle and line-up corrections close to touchdown could not be made in a timely manner. It was necessary to supplement roll control with rudder inputs to pickup a downgoing wing close to touchdown.

For the Mach 2.0 design, pitch control was more precise than the Mach 2.7 design, and pitch control and glideslope control were precise even in high turbulence levels. Roll control was much improved over the Mach 2.7 design. Late line-up and bank angle corrections were much easier to accomplish and roll sensitivity was much higher, making control harmony better. The improvement in roll control lowered the overall workload sufficiently to permit more precise control of pitch attitude and glideslope.

Figure 7 shows the average pilot ratings assigned to the task of landing approach in turbulent air. The pilots' preference for the attitude-hold system is apparent from the ratings of glideslope control, where both SCR configurations were rated better than the L-1011. The severely limited roll control capability of the Mach 2.7 configuration is reflected in the poor ratings assigned to the lineup control task. The good overall controllability and low workload for the Mach 2.0 SCR can be seen from the overall rating, where the Mach 2.0 SCR was rated as satisfactory even in heavy turbulence. The other configurations were rated more difficult to fly for reasons previously stated.

Control for Crosswind Landing

Evaluation of workload and controllability of the aircraft in a crosswind approach was accomplished using a test technique identical to that for approaches in turbulent air, except for a steady crosswind component 1.57 rad (90 deg) from the runway heading. Crosswinds of 10.3 and 15.45 m/s (20 and 30 knots) were evaluated first with no air turbulence and then with 1.82 m/s (6 ft/s) of turbulence. In this manner, the combined effects of the two tasks could be evaluated. The 15.45 m/s (30 knots) crosswind corresponds to the FAA requirement for commercial aircraft.

In the 10.3 m/s (20-knot) crosswind, the aircraft was crabbed about 0.12 rad (7 deg) into the wind direction and the new heading was maintained until an altitude of about 60 m (200 ft) was reached. At this point, the pilot visually aligned the aircraft with the runway and dropped the upwind wing slightly to avoid drifting downwind. In all the aircraft evaluated, this was a relatively easy task as shown by the ratings in Figure 8. When 1.82 m/s (6 ft/s) air turbulence was added, the ratings were degraded by about one pilot rating unit in the L-1011 and the Mach 2.0 SCR, and by about two units in the M = 2.7 SCR. The ratings assigned to this task are nearly identical to those assigned for this turbulence level with no crosswind, indicating little increase in workload due to the crosswind. When the crosswind was increased to 15.45 m/s (30 knots) with no air turbulence, the pilot ratings increased only slightly from the 10.3 m/s (20 knots) case for the L-1011 and Mach 2.0 SCR, but the rating for the Mach 2.7 SCR increased significantly, into the unacceptable range. The pilots reported that they were unable to align the aircraft with the runway from the 0.21 rad (12-deg) crab angle required in this level of crosswind without exceeding lateral control limits. The pilots quickly adopted a technique whereby they determined the maximum controllable rudder pedal input and landed the aircraft with about 0.90 rad (5 deg) remaining crab angle at touchdown. This situation was definitely unacceptable, because of the workload required to ascertain the control limit and the probable landing gear loads developed at the high crab angles. When 1.82 m/s (6 ft/s) of turbulence was added, the workload increased proportionately, producing pilot ratings of 4.0 and 4.5 for the L-1011 and Mach 2.0 SCR, and an average rating of 8 for the Mach 2.7 SCR, which is totally unacceptable.

Controllability at Reduced Approach Speeds

Because of the lateral control problems encountered by the Mach 2.7 configuration at 81.4 m/s (158 knots), no attempt was made to approach at lower air speeds. In the Mach 2.0 SCR design, approaches were flown at 73.6 m/s (143 knots) with no apparent degradation in either pitch or roll control.

CONCLUSIONS

Based on test results from this flight simulation program, the following conclusions have been reached concerning pilot acceptance of low-speed flying qualities and controllability in landing approach:

- Longitudinal flying qualities of both the Mach 2.0 and Mach 2.7 SCR configurations were satisfactory even in heavy turbulence.

- Pitch control and pitch response were slightly better in the Mach 2.0 SCR than in the Mach 2.7 configurations.

- Roll control and response were satisfactory in the Mach 2.0 SCR configuration in all levels of turbulence and crosswind.

- Roll control was not sufficient in the Mach 2.7 configuration for acceptable control of bank angle and line-up in heavy turbulence or for a crosswind landing at FAA limits.

- Crosswind landing gear could eliminate the requirement to decrab in a crosswind, but roll control would still be marginal in heavy turbulence for the Mach 2.7 SCR.

- The Mach 2.7 SCR approach speed is limited to at least 81.4 m/s (158 knots) by both attitude limits and roll control capability. The Mach 2.0 SCR has acceptable flying qualities down to 73.6 m/s (143 knots).

Throughout this study, the planforms have been identified by reference to design Mach numbers of 2.0 and 2.7. It should be emphasized that these results are applicable to the planforms, regardless of design Mach number. The wing sweep angles and aspect ratios of the study configurations were the significant variables in the study, and these results are applicable to any configuration with equivalent planform characteristics.

REFERENCE

1. NASA Technical Paper 1240 - "Ground-Based and In-Flight Simulator Studies of Low-Speed Handling Characteristics of Two Supersonic Cruise Transport Concepts", Grantham, William D., Nguyen, Luat T., Deal, Perry L., Neubauer, M.J., Smith, Paul M., and Gregory, Frederick D.; July, 1978.

TABLE 1. SIMULATION PROGRAM PLANFORM PARAMETERS

WING PARAMETER	DESIGN MACH NO.	
	2.7	2.0
Span ~m(ft)	31.7 (103.9)	38.1 (125.1)
mac ~m(ft)	26.2 (85.9)	22.6 (74.3)
$\Lambda 1$ ~rad (deg)	1.29 (74.0)	1.19 (68.2)
$\Lambda 2$ ~rad (deg)	1.24 (70.8)	1.11 (63.7)
$\Lambda 3$ ~rad(deg)	1.05 (60.0)	0.84 (48.2)
AR	1.61	2.23
β AR	4.03	4.03
β cot Λ	0.72	0.69

F   =   FLAP
FR =   FLAPERON
A   =   * AILERON
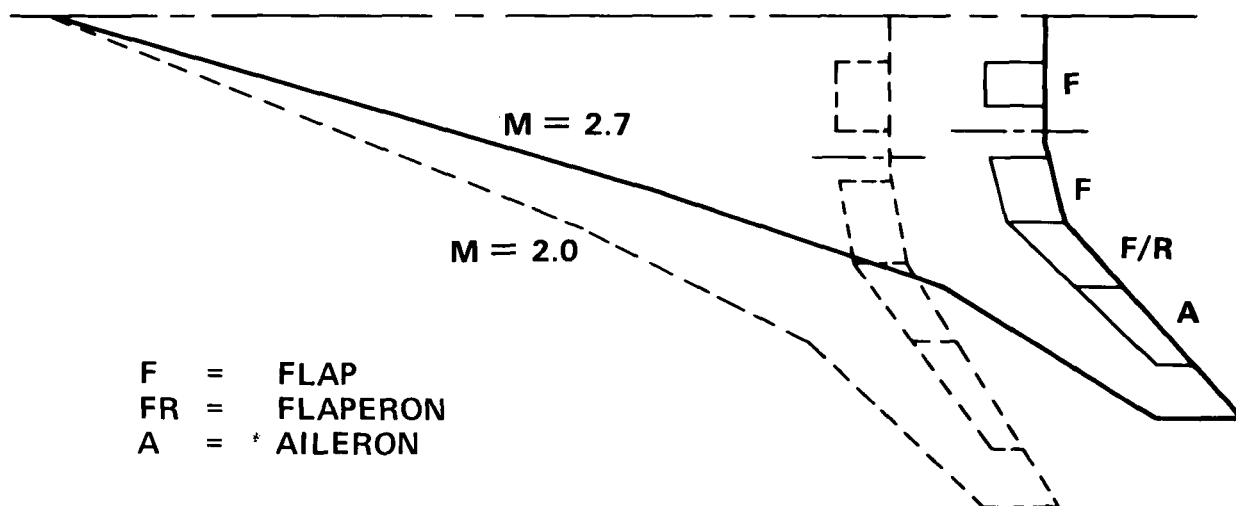
Figure 1.- Planform comparison.
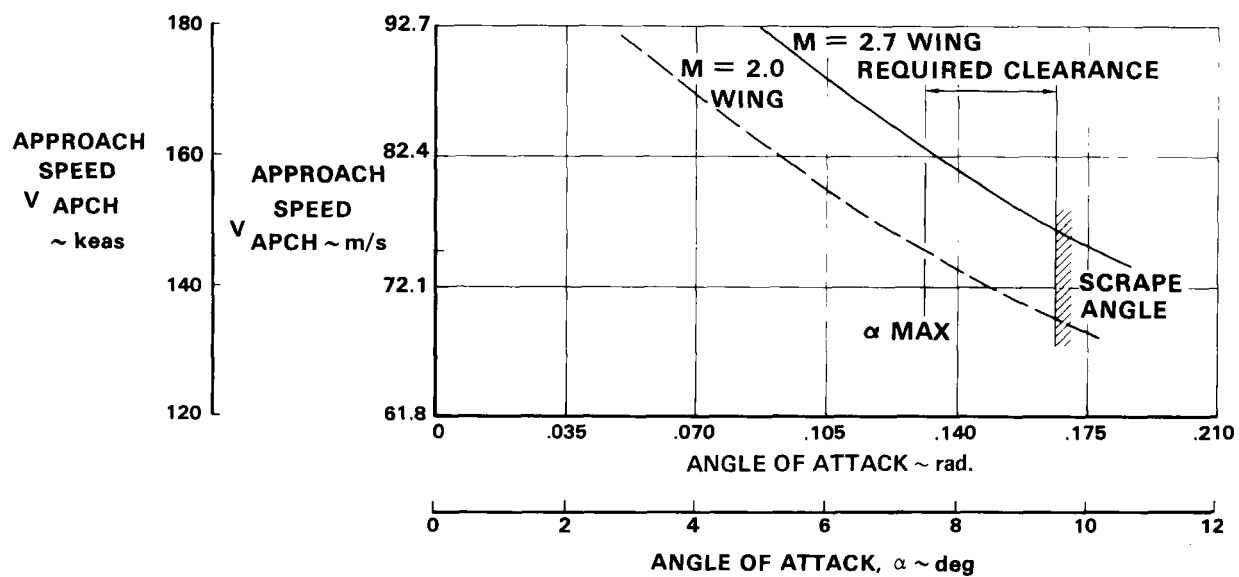
Figure 2.- Approach speed comparison, $\Delta_F = 20^o$.
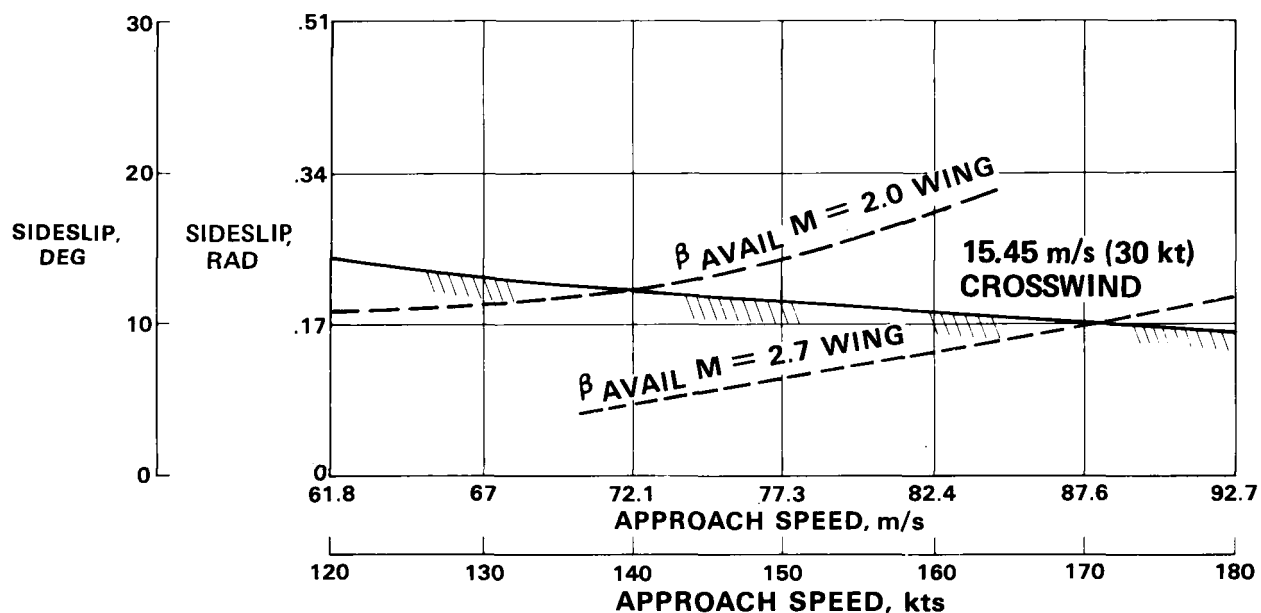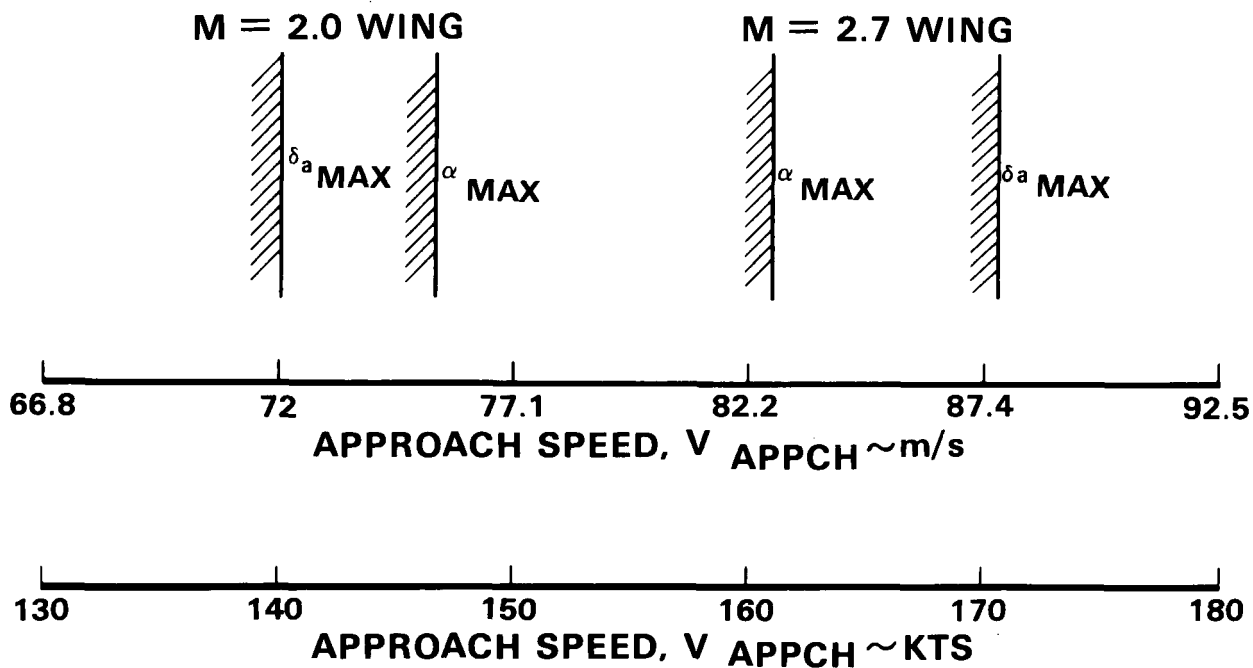
Figure 3.- Crosswind capability.

Figure 4.- Approach speed constraints.

1. EXCELLENT ⎫
2. GOOD   ⎬   SATISFACTORY
3. FAIR   ⎭

4. MINOR DEFICIENCIES   ⎫
5. MODERATE DEFICIENCIES   ⎬   ACCEPTABLE
6. VERY OBJECTIONABLE   ⎭

7. ⎧   ⎫
8. ⎨ MAJOR DEFICIENCIES   ⎬   UNACCEPTABLE
9. ⎩   ⎭

10.   UNCONTROLLABLE

Figure 5.- Pilot rating scale.
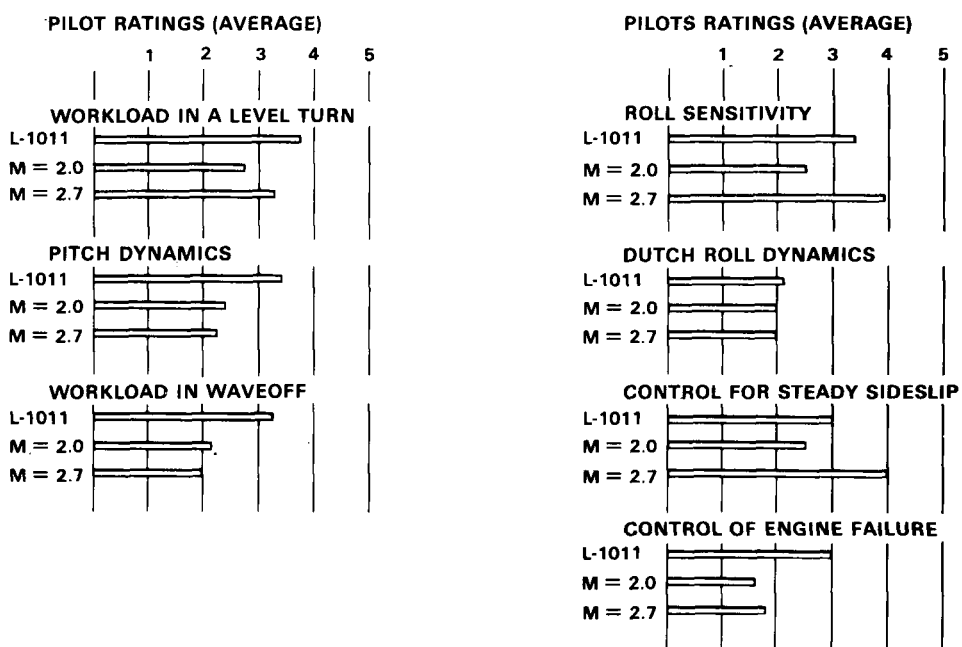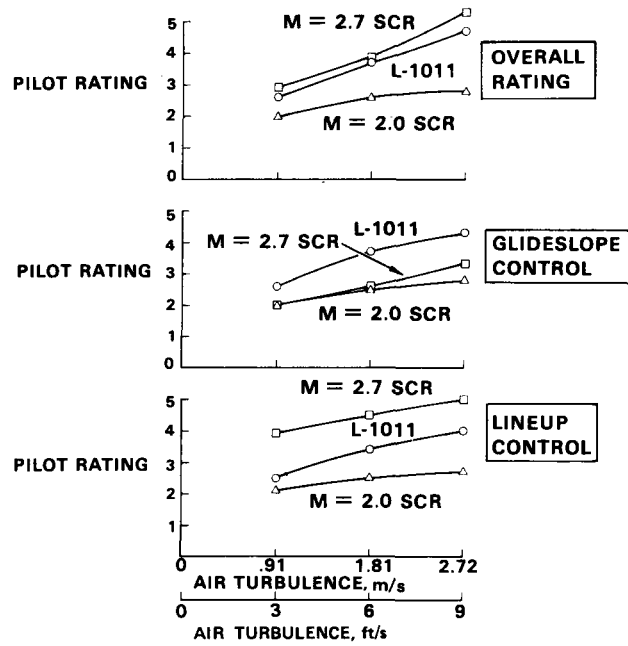

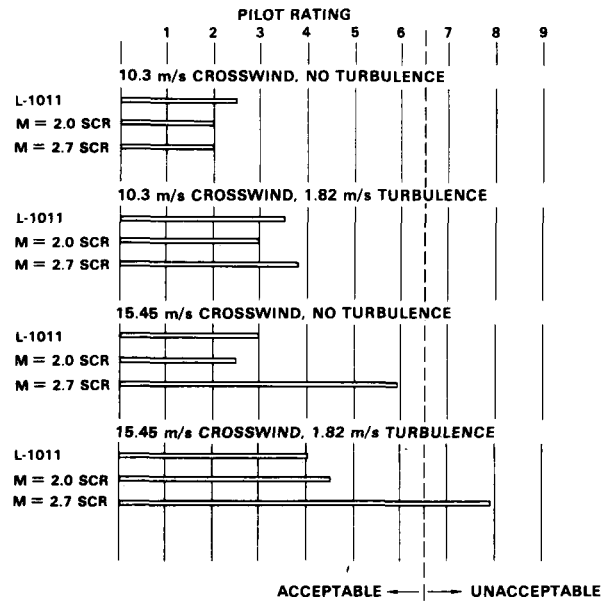Figure 6.- General flying qualities ratings.

Figure 7.- Effect of air turbulence on approach.

Figure 8.- Control for crosswind landing.