26. FLIGHT INVESTIGATION OF METHODS FOR IMPLEMENTING NOISE-ABATEMENT LANDING APPROACHES

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SUMMARY

A flight and simulation investigation has been conducted to determine the requirements that will enable pilots to fly steep two-segment noise-abatement landing-approach profiles with the precision common to conventional instrument landing approaches without an increase in pilot workload. The amount of noise reduction depends on the altitude of intercept of the two segments. Profiles with an intercept altitude of 400 feet resulted in a noise reduction of 10 PNdB or more $1\frac{1}{2}$ nautical miles from the runway threshold and beyond.

The profiles were evaluated by 11 pilots by using a research jet transport. The airplane had improvements over current jet transports including a flight director modified for two-segment profiles, an autothrottle, and both longitudinal and lateral directional stability augmentation. The two-segment approaches could be flown in the modified airplane with the same precision as conventional instrument landing approaches without a significant increase in pilot workload in the nearly ideal conditions of the tests. Further tests are needed to examine the requirements and operational limitations of two-segment approaches in an environment more representative of airline operations.

INTRODUCTION

Operating problems associated with landing-approach profiles that will reduce the noise level of jet transports have been the subject of NASA research for several years. Much of the research (refs. 1 to 3) has concentrated on the problems of steep landing approaches. Reference 1 showed that the use of increased approach angles is a feasible method for decreasing the noise of jet transports. As reported in references 1 and 4 and as shown by figure 1, the approach noise is reduced in two ways when the approach angle is increased. First, an increase in the approach angle requires a reduction in thrust of the engines; and second, a steeper approach places the airplane higher above the ground. The combination of reduced thrust and higher altitude results in a significant reduction in noise.

Another operational method that can reduce the noise in landing approach is the use of a decelerating approach. In the deceleration technique the approach is started at a high airspeed, the engine thrust is reduced to a low value, and the airplane decelerates to the landing-approach speed at a point near the runway. The amount of noise reduction will depend on how much reduction in engine thrust can be tolerated during the deceleration period.

A flight and simulation investigation has recently been conducted to determine the requirements that will enable pilots to fly steep and decelerating noise-abatement landing approaches with the precision common to normal instrument landing approaches without an increase in the pilot workload. The evaluation flights were flown under simulated instrument conditions in daylight and in near-ideal weather. Preliminary results of only the studies on the use of increased landing-approach angle are reported in this paper.

SYMBOLS AND ABBREVIATIONS

h	altitude, feet
T	thrust, lb
V_{APP}	approach velocity, knots
E	instrument landing error, degrees

Abbreviations :

BLC	boundary-layer control
DLC	direct lift control
EADI	electronic attitude director indicator
ILS	instrument landing system
PNL	perceived noise level

AIRPLANE AND SIMULATOR

Test Airplane

A four-engine jet transport, the Boeing 367-80 (707 prototype), was used and is shown in figure 2. This airplane is described in reference 5 except for certain modifications made for this investigation. Details of the modified flap system are shown in figure 3. The modified boundary-layer-control (BLC) flap enabled the airplane to be operated at moderately high lift coefficients in landing approaches with low engine thrust and to provide a means for direct lift control. The main flap and BLC system are described in reference 5. The new slotted auxiliary flap provided additional lift by increasing angle-deflection capabilities and by the impingement of the jet exhaust from the inboard engines on the slotted auxiliary flap. A high-rate actuation system (30°/sec) was installed on the auxiliary flap to provide direct lift control. Maximum travel step inputs (±20°) of the auxiliary flap gave approximately ±0.15g at the landing-approach speed. The normal trim deflection for the auxiliary flap was 10° greater than that for the main flap.

The evaluation pilots flew the airplane from the right seat by a "fly-by-wire" control system which was programed onto a general-purpose analog computer located in the forward section of the fuselage. The computer also provided the computations and drive signals required for the direct lift control, autothrottle, flight director, and flight-path angle on the electronic attitude director indicator (EADI).

The fly-by-wire control system could be used as the basic airplane control system by gearing control inputs directly to the elevator or as a rate command control system to improve airplane pitch response and stability.

The auxiliary flaps for direct lift control were driven in combination with the elevators through a computer interconnection from the control column. Also available was a control-wheel-mounted thumb controller for direct lift control.

The EADI, which was developed by the Boeing Company, was a black and white cathode-ray-tube display with exposed dimensions of 5.4 by 7.2 inches. (See figs. 4 and 5.) In addition to the information usually found on current electromechanical attitude director indicators, the EADI included symbols for digital radio altitude, flight-path angle, potential flight path (proportional to longitudinal acceleration), and a television picture. The television picture was provided by a closed-circuit system with the television camera mounted under the nose of the airplane.

Simulator

The Ames moving base transport simulator, described in reference 5, was used for the simulation studies. The control-force characteristics and pilot instrumentation represented those of the test airplane and included a left-hand throttle arrangement and an electronic attitude director indicator. The simulator was programed with 367-80 aerodynamic parameters by using the equations of motion described in reference 6. These equations were modified to provide for the effects of the modified flap system, proper engine response, autothrottle, rate command control system, and direct lift control. Continuous computations of the noise on the ground directly below the airplane were made on all simulator runs. Approximations of the measured variation of PNdB with engine thrust and with airplane altitude of a Boeing 707-320 were used for the computations.

DISCUSSION

Problem Areas of Steep Landing Approaches

The results of previous tests of steep landing approaches (ref. 1) and the initial-flight and simulator results of the present program have shown that the following problem areas make noise-abatement landing approaches more demanding of the pilot than normal approaches:

(1) Rate of descent near the ground

(2) Flight-path control

(3) Pilot workload

(4) Guidance and display information

(5) Engine response

The first of these problems is of major concern for steep landing approaches because of the higher rate of descent associated with steep approaches. The variation of the rate of descent with approach angle for three approach airspeeds is shown in figure 6 along with the computed noise reduction of an airplane with an approach speed of 115 knots. These data show that the rates of descent for present-day jet transports on normal 2.5° to 3° instrument approaches are between 500 and 800 feet per minute. The curve in the lower part of the figure shows that substantial reductions in noise (approximately 18 PNdB) are possible as the approach angle is increased to 6°. Approach angles of 6° are near the maximum that can be considered for most current jet transports at minimum landing-approach speeds when allowances for overshoots of $7\frac{1}{2}^{\circ}$ to 8° and engine response are considered. An approach angle of 6°, however, will result in a rate of descent of 1600 feet per minute at an approach speed of 150 knots. Evaluation by two NASA pilots in the initial phase of the program indicated that rates of descent greater than 900 to 1000 feet per minute were unsatisfactory at altitudes less than 200 feet above the ground in simulated instrument landing approaches. The data in figure 6 indicate that a reduction in noise of 5 PNdB or more is possible by an increase in approach angle to about 4° without a large increase in rate of descent if approach airspeeds are kept on the low side of the range used by current jet transports. The landing-approach speeds must be reduced to 90 knots or less for the rates of descent to be satisfactory for approach angles of about 6°.

Two-segment landing-approach profiles were used in the earlier tests (ref. 1) to reduce the high rate of descent near the ground. Figure 7 illustrates a typical two-segment approach and shows the computed noise reduction. The two-segment approaches that were considered in this program had an upper segment with an approach angle of 6° which intercepted a lower segment with an approach angle of 2.650. (The angle of the instrument landing system (ILS) at the Oakland International Airport, where the tests were conducted, is 2.65°.)

The noise reduction for a two-segment approach is less than that for a straight 6° approach. At a point 2 nautical miles from the runway threshold in the two-segment approach (fig. 7), the airplane is not as high above the ground; and therefore, the noise reduction is only 12 PNdB compared with 18 PNdB for the straight 6° approach. The noise reduction goes to zero when the airplane intercepts the lower segment of the approach profile because the thrust must be increased to normal approach thrust and the airplane altitude remains the same. The noise reduction on a two-segment approach is related, therefore, to the altitude of the intercept of the two segments. When the intercept altitude is low, the noise reduction is high, but the high rate of descent must be continued closer to the ground. The altitude for the intercept was, therefore, one of-the variables in the program.

The other four problem areas listed at the beginning of this section are related to the pilot's ability to comfortably fly the nonlinear portion of the two-segment approaches. Figure 8 shows a typical flight path of an airplane (solid line) when the pilot is flying a two-segment approach (dotted line) by using instrumentation common to current jet transports. Primarily because of inadequate guidance, the pilot will continue to fly a 6° glide slope at the intercept. The correction of the resulting deviation from the intended flight path is a demanding task and greatly increases the pilot workload. Since the engines are at a low thrust value on the 6° glide slope, the pilot is also concerned about the effect of low response time of the engines. Most jet engines have response times from low thrust to maximum thrust of several seconds; therefore, pilots cannot accomplish a wave-off as quickly as in a normal approach.

The inadequate guidance on the two-segment approach also affects the noise as shown in figure 8. Since a fairly large undershoot error can develop, it is necessary to use thrust values greater than those required for a normal approach. This excess thrust results in more noise. Obviously, the two-segment approaches must be flown precisely and smoothly to alleviate these problems.

Method to Alleviate Problem Areas in Steep Approach

Since the test airplane was a fly-by-wire airplane, it was possible to program the onboard computer to obtain the desired characteristics that would alleviate some of the problems of flying two-segment approaches with the precision and pilot workload of a normal landing approach. To improve flight-path control, a rate command control system on the longitudinal axis and direct lift control were incorporated; to reduce pilot workload, an autothrottle was included; and to improve guidance and display information, modifications to the flight-director computations were made and an advance cathode-ray-tube display was used.

The lateral-directional characteristics of the test airplane were also augmented to give the airplane good lateral-directional handling qualities. The augmentation consisted of roll damping, turn coordination, and directional damping.

Rate command control system.- One of the most important characteristics that the pilots desire for good flight-path control is precise control of the pitch attitude of the airplane. A rate command control system was provided on the longitudinal axis of the test airplane to provide the desired pitch response. Rate command control systems have been demonstrated that give good pitch response. Reference 7 gives examples of early tests of a rate control system. The rate command control system that was used had performance similar to the stick-steering autopilots being installed on some late-model jet transports and was of the general type of control system being proposed for the supersonic transports. With a rate command control system, the pilot's fore and aft control column commands pitch rate as a function of control force. When the control force is returned to zero, the airplane will stay at the new command altitude. This altitude-hold feature of the rate command control system and the ability to command a change in pitch attitude without control reversals helped to reduce the pilot' s workload on the approach. The pilots' evaluation of the rate command control system showed that the system was an improvement over the conventional method for changing and controlling the flight path of the airplane in the approaches. There were, however, some unusual characteristics of the rate command control system which required some change in control technique for flare and touchdown. Further discussion of these characteristics is beyond the scope of this paper,

Direct lift control (DLC).- The direct lift control (DLC) was also incorporated into the airplane to improve flight-path control. Flight tests with other airplanes such as the F-8C (ref. 8) and Convair 990 have shown that DLC provides a more rapid vertical response of the airplane for flight-path control. When the DLC is interconnected to the pitch control as in this program, the DLC affords a quickened vertical response of the airplane to commanded pitch-angle changes. The pilots' evaluation of the DLC in the two-segment approaches indicated that the DLC provided little improvement in the tracking of the ILS on the landing approach for an airplane with good pitch response and adequate guidance. The pilot appreciated the quickened vertical response of the DLC, however, especially in the flare-and-touchdown task. The pilots recognized the potential advantage of DLC to help arrest rates of descent rapidly in case of emergency on a steep landing approach.

Autothrottle.- An autothrottle system was included as a means for reducing the pilot workload on the approach. An autothrottle relieves the pilot of the job of making adjustments in engine thrust to keep the airspeed on the approach within acceptable limits. Autothrottles have been used by airlines and others and have been shown to be effective in reducing the pilot workload. In two-segment approaches where both attitude and thrust changes are required late in the approach, the evaluating pilots considered the autothrottle to be necessary to keep the workload at a level comparable to a normal landing approach.

Flight directors.- Guidance for the pilot on the approaches was provided by a flight-director system. A flight director provides the pilot with computed commands to assist him in flying precise instrument landing approaches. Because computations used in current flight directors are designed for low-angle linear approaches, modifications to the computations were required to provide precise guidance on the two-segment approaches. As in most modern flight-director systems, the airplane attitude and ILS error information were used to compute the commanded flight-director needle displacement. The modifications to the computation and logic provided for the intercept of the 6° upper segment of the approach profile, for an increase in sensitivity, and for guidance on the nonlinear portion of the two-segment approaches by commanded attitude changes. Compensation for the powered-lift effects of the flap and for off-speed effects improved the accuracy of the guidance following transition to the lower segment. A detailed discussion of the modified flight-director computations is beyond the scope of this paper. The pilot evaluation of the flight director will be included in a later section of the report.

Advanced instrument display. - Besides the basic guidance information furnished by the flight director, the pilot requires sufficient additional information to assess the progress of the approach. This information traditionally is provided by several instruments on the instrument panel. The advantages that might be gained by including most of this information along with the flight-director guidance on a single cathode-ray-tube display (EADI) was evaluated in the program.

Although the display contains many elements (fig. 5), after a brief familiarization time on the simulator, the display could be effectively used. The pilots appreciated the expanded scale for much of the information and felt that the information presented was useful on the approach; however, the symbology that was used on the display was not considered optimum by all the pilots. They felt further development of this type of display was warranted. The pilots did not agree on the relevance of the television, but most considered a real-world display useful.

Profiles and Guidance

The two-segment approach profiles that were evaluated by the pilots are shown in figure 9. This figure also shows the computed noise reduction for the profiles. The two profiles have a 6° approach angle for the upper segment and a 2.65° for the lower segment. The intercept altitudes are 250 and 400 feet. The 250-foot intercept altitude was chosen to give a computed noise reduction of about 10 PNdB 1 nautical mile from the runway threshold and beyond. The second profile with the intercept at 400 feet was chosen to give about 10-PNdB noise reduction $1\frac{1}{2}$ nautical miles from the threshold and beyond. These two intercept altitudes also provided the pilots with an opportunity to evaluate a low and a moderately high intercept altitude on two-segment approaches.

Two guidance systems were used on both the 250-foot- and the 400-foot-intercept profiles. The instrument landing systems for the guidance were generated by using an approach radar especially programed for these tests. The two systems are illustrated in figure 10. In the top part of the figure, a system with two separate ILS beams is represented. The upper segment of the profile was a 6° beam generated by the radar system, and the lower segment was the standard 2.65° ILS at the Oakland International Airport. This system required two ILS receivers in the airplane and special flight-director logic for switching near the intercept altitude. The flight-director computations for the two-beam ILS consisted of a capture of the 6° beam at an altitude of about 2500 feet,and a second capture from above of the 2.65° beam near the intercept. The other type of guidance shown in figure 10 represents a single ILS beam that was curved at the intercept point. The radius of curvature was about 40 000 feet which corresponds to a flight-path rate of change of 3.5 seconds per degree at an approach speed of 115 knots. The curved ILS system was generated by the approach radar. The flight-director computation for the curved beam required special logic information from the radar to identify the point where the curvature started. The flight-director computation for approximating the curved portion of the beam was accomplished on board the airplane.

Landing-Approach Speed

Two ranges of landing-approach speed were used to evaluate the benefits of a reduced approach speed on two-segment approaches. An approach airspeed of between 145 and 135 knots was used as representative of current jet transport operation. A lower airspeed of between 122 and 112 was used as representative of a jet transport with special high-lift devices.

Pilots' Evaluation

The two-segment approach profiles were evaluated by one commercial airline, four NASA, and six FAA pilots. The primary objective of the evaluation was to compare the

ILS flying precision and the pilot workload on the two-segment approaches with those on normal 2.650 approaches. Pilot opinion was obtained from the results of both simulation and flight evaluations. The pilots made extensive evaluation of variations in each of the devices incorporated on the simulator to alleviate the problems on two-segment approaches. The results of the simulation were used to determine the airplane configurations for flight evaluation.

Results of evaluation of profiles.- The evaluation by the 11 participating pilots of the two-segment approach profiles has shown that the two-segment approach can be flown with the same precision as a normal approach when the methods to alleviate the problem areas discussed earlier were incorporated into the test airplane. Figure 11 shows a comparison of the tracking of a typical curved two-segment approach having a 400-foot intercept with a normal approach. Comparable magnitude and frequency of glide-slope errors are also shown. The results for an approach with a 250-foot intercept altitude or with the two-beam ILS were similar to those for an approach with a 400-foot interoept altitude (fig. 11). The tracking was within the accuracy required for Category II landing weather minima. The overall pilot workload on any of two-segment approaches was no higher than a normal approach without autothrottle.

The pilots' comparison of the approaches with the 250-foot and the 400-foot intercepts shows that the pilots preferred the higher intercept altitude. The pilots felt that the 400-foot intercept allowed a little more time to become stabilized on the lower segment before initiating the flare. The pilots were slightly rushed on some of the approaches with 250-foot intercepts. Because of the importance of the time element, most of the pilots preferred the lower approach speed. When the approaches were flown smoothly and precisely, the pilots did not consider the low response time of the engines a problem on the two-segment approaches.

The opinion of the pilots was mixed on their preference to the type of guidance for the two-segment approaches. Although either system gave the required guidance, some of the pilots preferred the two-beam system because they felt that having the steep upper segment intercept the lower segment enabled them to determine more accurately their position on the nonlinear portion of the profiles. The transition could be made a little faster, and thus more time on the lower segment was available. Other pilots preferred the single-beam curved profile because they felt that this profile required the least increase in pilot workload. The curved ILS eliminated the discontinuity of the two-beam system and was easier to follow. The transition on the curved ILS was considered to be smoother to fly by most of the pilots,

Requirements for two-segment approaches.- The pilots were asked to evaluate the significance of the various devices incorporated to alleviate the problems of the two-segment approaches. The following list shows what the pilots felt were the primary and secondary requirements for the two-segment approaches evaluated in this program:

Primary requirements

(1) Guidance system for two-segment profiles

(2) Modified flight director

(3) Autothrottle

Secondary requirements

(1) Rate command control system

(2) Advanced displays

(3) Direct lift control

The primary requirements are considered essential for the two-segment approach. A guidance system for two-segment profiles must include the necessary ground-based equipment required for a two-segment instrument landing system and the equipment in the airplane to receive and display the information. The second requirement follows very closely in that a modified flight-director system must be provided that is compatible with the guidance system. The pilots felt that for the two-segment approaches an autothrottle was a primary requirement for keeping the workload at the level of a normal approach.

The secondary requirements are those that the pilots felt were not essential but which gave some improvemeqt. The rate command control system improved flight-path control by providing precise control of pitch attitude. Since the pitch response of the test airplane without the rate command control system was considered satisfactory and the basic airplane control system included automatic trim, the two-segment approach could be flown with or without the new control system without significant change in workload. It should be pointed out, however, that good pitch response is an important requirement and improvement in the pitch-response characteristic would probably be required for some current jet transports for two-segment approaches.

Displays that will improve the method of presenting the information the pilot needs in the approach are definitely required for any landing approach. The advanced cathode-ray-tube display used in the present program was recognized as having the potential to achieve some improvement required for pilots' displays. It was not found, however, to be essential in making the two-segment approach. In one series of approaches made by one pilot, an electromechanical altitude director indicator was used in place of the cathode-ray-tube display. The pilot was able to perform the task equally well with either display.

Since the airplane had satisfactory vertical response to control inputs, the direct lift control was not considered a requirement by the pilots for making the two-segment approach. The benefits of the quickened vertical response were appreciated, however, by the pilots in the flare-and-touchdown task.

CONCLUDING REMARKS

The results of a flight and simulation study have shown that a significant reduction in landing-approach noise can be achieved by flying a steep two-segment approach profile. For the jet transport used in this study, a reduction in noise of approximately 10 PNdB or more at a point 1 nautical mile from the runway threshold and beyond was achieved when a two-segment profile with an intercept altitude of 250 feet was flown. The pilots preferred, however, the two-segment profile with an intercept altitude of 400 feet, which gave a noise reduction of 10 PNdB $1\frac{1}{2}$ nautical miles from the runway threshold and beyond.

The two-segment landing approaches that were evaluated in this program could be flown by a modified jet transport with the same precision as conventional instrument landing approaches without a significant increase in pilot workload. It must be recognized, however, that the research airplane had improvements over current jet transports including a flight director modified for two-segment profiles, an autothrottle, and both longitudinal and lateral directional stability augmentation. The evaluation flights were flown under simulated instrument conditions in daylight and in near-ideal weather. Further tests are needed to examine the requirements and operational limitations of two-segment approaches in an environment more representative of airline operations.

REFERENCES

1. Zalovcik, John A.; and Schaefer, William T., Jr.: NASA Research on Noise-Abatement Approach Profiles for Multiengine Jet Transport Aircraft. NASA TN D-4044, 1967.
2. Hall, Albert W.; and McGinley, Donald J., Jr.: Flight Investigation of Steep Instrument Approach Capability of a C-47 Airplane Under Manual Control. NASA TN D-2559, 1965.
3. Hall, Albert W.; and McGinley, Donald J., Jr.: Flight Investigation of Steep Instrument Approach Capabilities of a T-33 Airplane Under Manual Control. NASA TN D-2775, 1965.
4. Zalovcik, John A.: Effect of Thrust and Altitude in Steep Approaches on Ground Track Noise. NASA TN D-4241, 1967.
5. Condit, Philip M.; Kimbrel, Laddie G.; and Root, Robert G.: Inflight and Ground-Based Simulation of Handling Qualities of Very Large Airplanes in Landing Approach. NASA CR-635, 1966.
6. Jackson, Charles T., Jr.; and Snyder, C. Thomas: Validation of a Research Simulator for Investigating Jet Transport Handling Qualities and Airworthiness Criteria During Takeoff. NASA TN D-3565, 1966.
7. Russell, Walter R.; Sjoberg, S. A.; and Alford, William L.: A Flight Investigation of the Handling Characteristics of a Fighter Airplane Controlled Through a Rate Type Automatic Control System. NACA RM L56F06, 1956.
8. Gralow, R. T.; Peace, J. D., III; and Shipley, J. L.: Evaluation of the Direct Lift Control System Installed in the F-8C Airplane. Final Report, Rep. No. FT-51R-65 (RA1300001), U. S. Naval Air Test Center (Patuxent River, Md.), Aug. 13, 1965. (Available from DDC as AD 468464.)

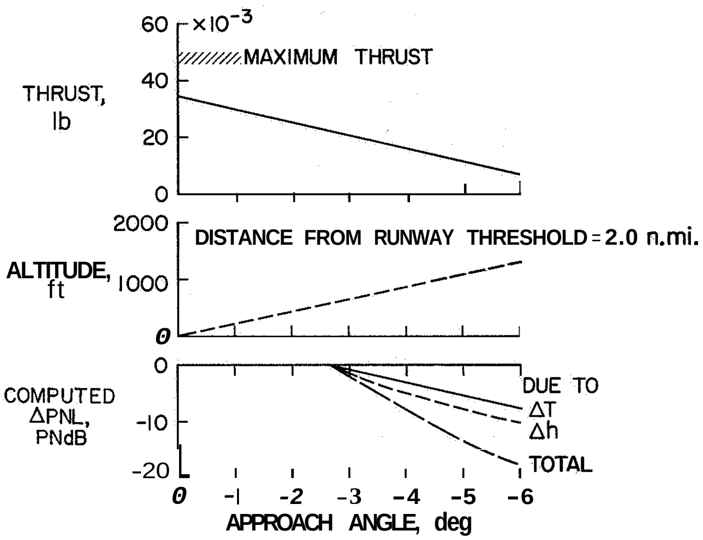

NOISE REDUCTION DUE TO THRUST AND ALTITUDE

Figure 1


TEST AIRPLANE BOEING 367-80

Figure 2

L-68-8580

BOEING 367-80 AIRPLANE MODIFIED FLAP

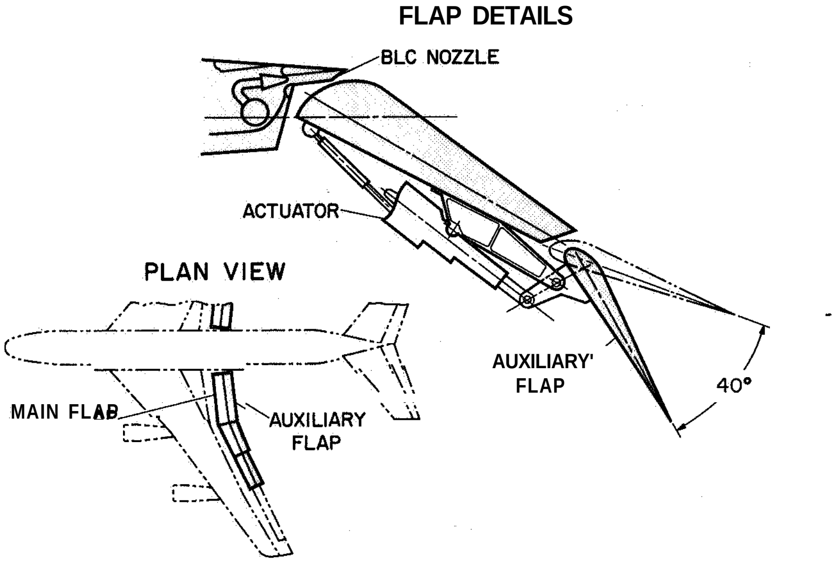


Figure 3

BOEING 367-80 AIRPLANE COCKPIT

Figure 4 L-68-8581

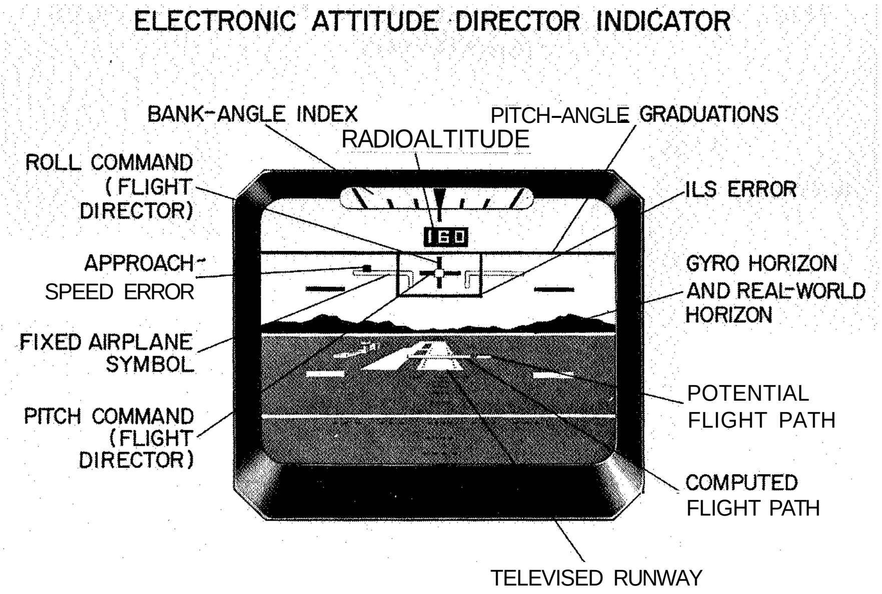


Figure 5

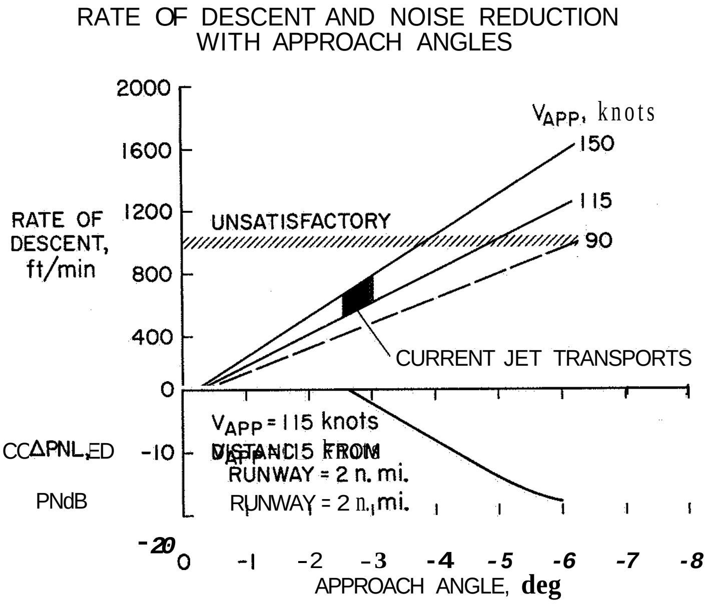


Figure 6

NOISE REDUCTION FOR TWO-SEGMENT APPROACH PROFILES

V_{APP} = 115 knots

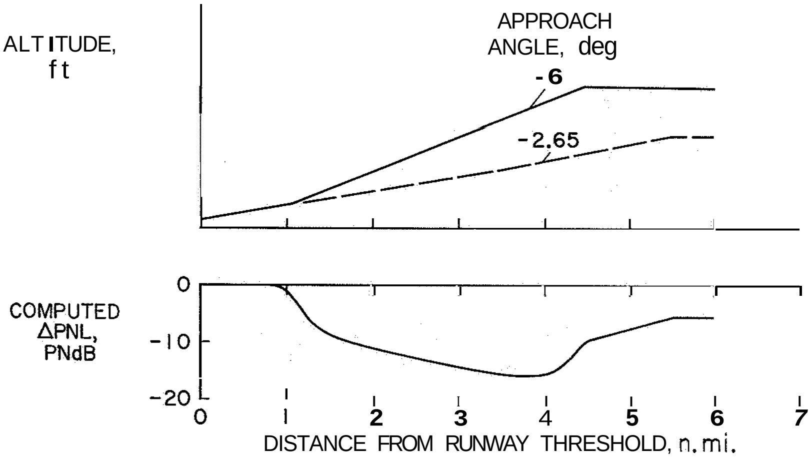


Figure 7

EFFECTS OF INADEQUATE GUIDANCE

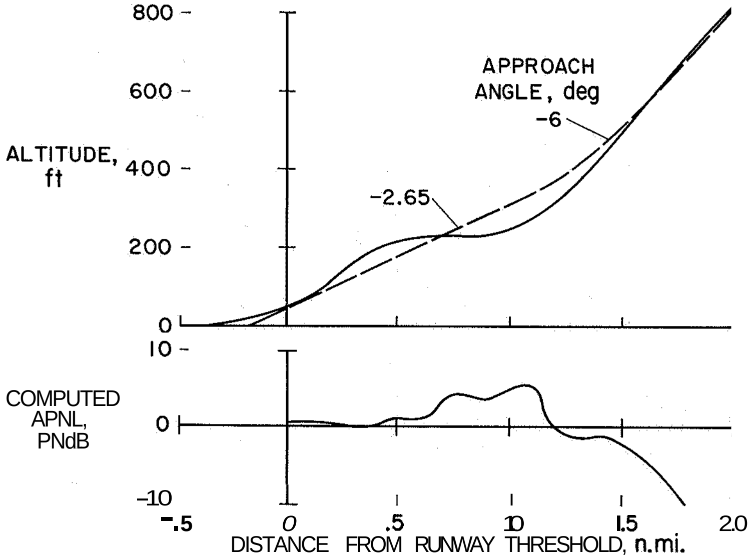
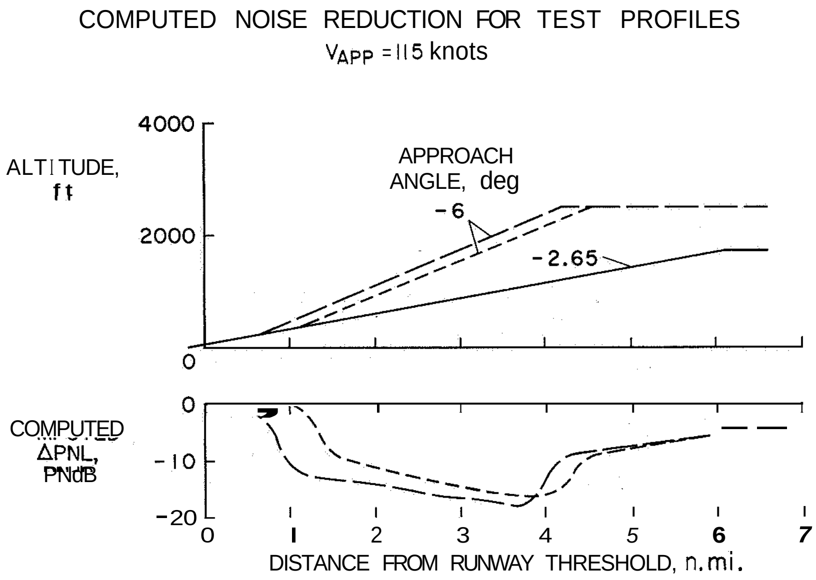
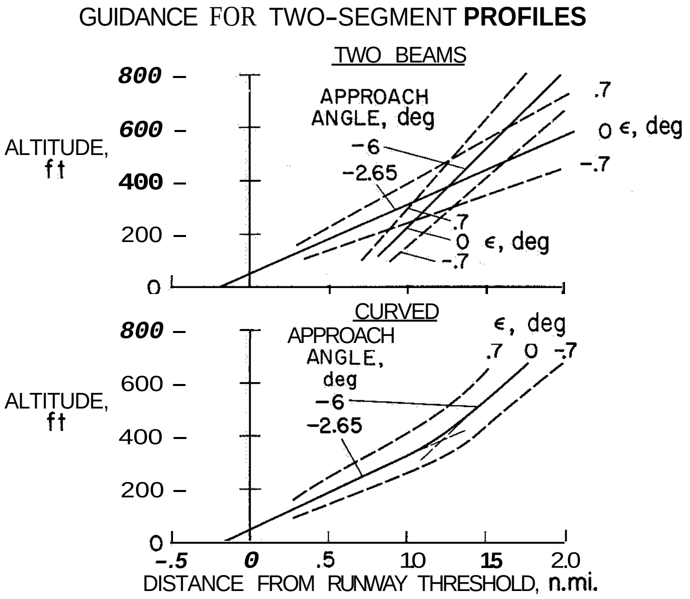


Figure 8


COMPUTED NOISE REDUCTION FOR TEST PROFILES

V_{APP} = 115 knots

Figure 9


GUIDANCE FOR TWO-SEGMENT PROFILES

TWO BEAMS

CURVED

Figure 10

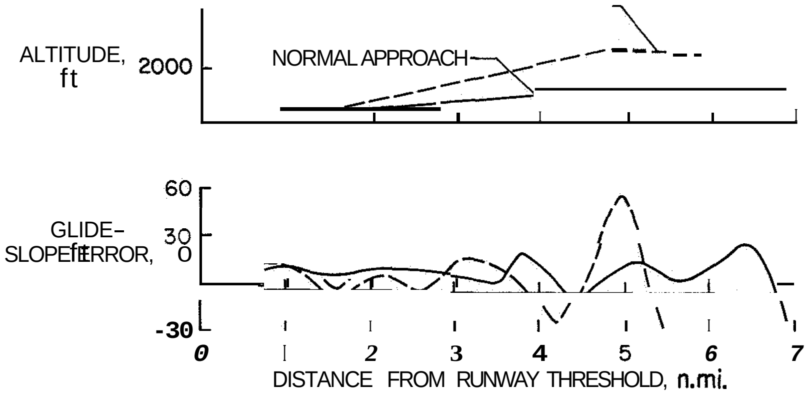

ALTITUDE, ft
2000
NORMAL APPROACH
GLIDE-SLOPE ERROR, ft
60
30
0
-30
0
1
2
3
4
5
6
7
DISTANCE FROM RUNWAY THRESHOLD, n.mi.

Figure 11