SIMULATOR REQUIREMENTS DEDUCED FROM COMPARISONS OF PILOT'S PERFORMANCE IN GROUND SIMULATORS AND IN AIRCRAFT

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ABSTRACT

Research experience with piloted, ground-based simulators and comparisons with flight results are reviewed. Three specific research investigations are reported: (1) jet transport landings, (2) takeoff certification tests, and (3) STOL handling qualities in landing approach, in which both simulator and flight results were obtained. Comparison of these results provides further information on simulator requirements.

It is shown that in piloted ground research simulation (1) visual cues and task objectives are important in jet transport landings, (2) only visual cues are required in many takeoff certification maneuvers, but are not sufficient for all maneuvers, and (3) sophisticated motion simulation is important in STOL airplane landing-approach studies.

INTRODUCTION

Piloted flight simulation is a significant avenue of research on new types of aircraft. Its importance has been emphasized by the revolutionary characteristics of some aircraft designs and the extreme costs of revisions after flight tests. Making correct design decisions prior to flight tests is particularly difficult where handling qualities are concerned and in certain areas of performance and mission accomplishment in which the requirements are not fully established for many new classes of aircraft. Thus the role of the research simulator in allowing piloted research "flight" for studying requirements in general and specific vehicles in particular is vital to the integration of man and machine in advance of actual flight.

In any piloted simulator, the pilot must extrapolate mentally from the behavior of the simulator to actual flight conditions, since, in any situation other than real flight, the task representation must be artificial to some degree. Thus the requirements of the simulator, in terms of such factors as motion and visual cues needed to obtain meaningful results, have been the subject of considerable investigation. Reference 1 makes a critical review of a number of reports relating to comparisons of flight and simulation results, and concludes that (1) relatively simple fixed-base or angular motion simulators provide results that substantially agree with flight results for general handling qualities assessment; (2) kinesthetic motion cues are essential for realistic assessment of such things as abrupt damper failures of aircraft and the handling qualities requirements of supersonic transport configurations in cruising flight; and (3) motion cues are of secondary importance in problems, such as approach and landing of aircraft, where strong external visual cues apparently are more important. Information obtained more recently on the value of cockpit motion in landing approach, however, indicates that the last conclusion of Ref. 1 should be qualified, as will be discussed in this paper. Reference 2, while touching on simulator requirements for valid simulations, also discusses piloting requirements and the need for defining the simulation task so that the results will be valid. And Ref. 3 presents several tables in which simulator sophistication and realism are considered with relation to the problem to be studied and with relation to whether qualitative or quantitative results are desired.

The purpose of this paper to is examine recent directly comparable flight and simulator tests so that more can be learned about simulation requirements in specific types of investigations. In particular, the material will be reviewed to determine the importance of the following: (1) the degree of sophistication of the simulation equipment in such respects as (a) external visual scene, (b) motion capabilities, (c) control system characteristics, and (d) cockpit instrumentation and interior arrangements, (2) the pilot background experience and familiarization with the simulator and the task, and (3) the nature of the simulation task. To accomplish this, comparative simulation and flight results are presented and discussed for investigations in three areas: (1) jet transport landing performance, (2) takeoff certification maneuvers, and (3) STOL transport-handling qualities requirements.

RESULTS AND DISCUSSION

For most of the cases discussed, the investigations were carried out by experienced test pilots who were given ample familiarization time in the simulator. In the jet transport landing comparisons, where this was not the case, the possible effects of lack of familiarization and different pilot background will be discussed at the appropriate time. In each case, also, the pilots who flew the simulators had flown the aircraft and were able to verify the correctness of the whole simulation setup including errors in mechanization.

JET TRANSPORT LANDING STUDIES

In the past several years simulator landings of jet transports have been compared with flight results (e.g., Ref. 4) for the purpose of calibrating the simulator results for use as an appropriate reference in judging the landing characteristics of future types of aircraft, such as the supersonic transport. The results of simulator studies of Refs. 5 to 9 are compared with flight results in Figs. 1 and 2 in terms of the probability of exceeding a given touchdown rate of descent and a given distance from the runway threshold on landing. Since these two quantities appear to be interdependent variables, any assessment of landing performance requires that both criteria be considered. A considerable difference will be noted in the results from the various simulations. The results of Ref. 8 are close

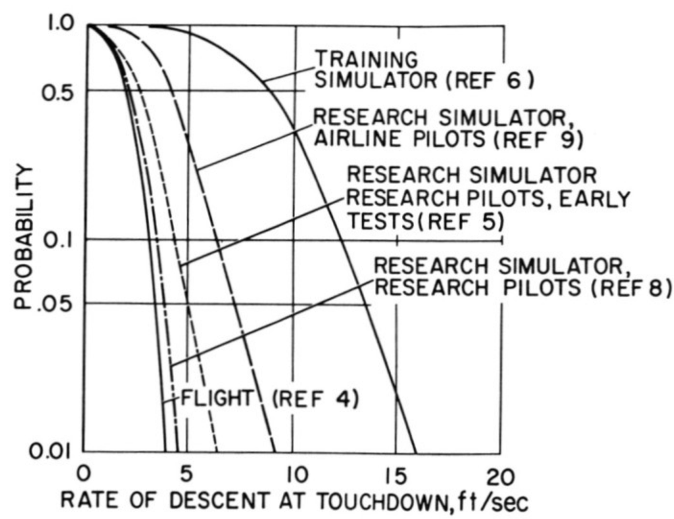

Figure 1. Comparison of jet transport landing descent rate for flight and simulator.

to the flight results for rate of descent at touchdown, and the results of Refs. 5 and 9 are close to flight results for the distance of the ground contact point from the runway threshold.

Although none of the simulator results exactly duplicate flight results, several are close enough to serve as a reference from which to judge results of landing investigations of future designs of this general type. However, from the standpoint of choosing simulation techniques that adequately approximate flight results, it is of interest to examine the various factors that could affect the simulation.

Basic elements of the various simulations. Figure 3 is a pictorial block diagram of the basic elements of landing-approach simulators.

In the Ames landing simulation studies of Refs. 5 and 8, the cockpit was fixed; the interior was a generalized version of a transport airplane cockpit; the pilots were experienced test pilots, and were allowed ample time to become familiar with the simulator and the landing problem.

In the simulation of Ref. 6, the simulator was the type used by airlines for training or proficiency checks of flight crews. Cockpit motion cues in pitch and roll were limited, and cockpit instruments and control systems were identical to those of the airplane. The "flights" were made by airline personnel.

In the investigation of Ref. 9, the cockpit had limited pitch-and-roll angular motion; the interior was a replica of the actual airplane instruments, control layout, and dimensions. The simulated landings were made

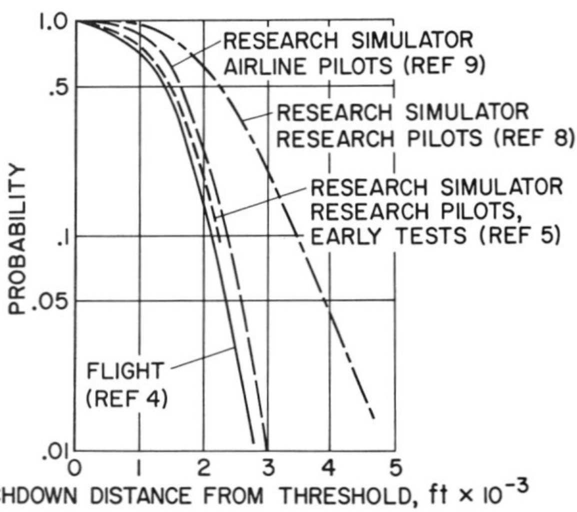

Figure 2. Comparison of jet transport touchdown distance for flight and simulator landings.

by airline pilots, and "flight" time allowed the pilots to become familiar with the simulator and the simulated landing problem was quite limited.

Effect of cockpit motion. It might be concluded from Figs. 1 and 2 that cockpit motion is not required in the landing simulation inasmuch as the simulations without cockpit motion (Refs. 5 and 8) gave results close to flight values, whereas the simulations with limited pitch-and-roll motion (Refs. 6 and 9) gave results no closer to flight values. Ames experience does not fully bear out this conclusion; we have found that pitch motion is definitely helpful to the pilot in the landing task. Also, pilot adaptation time is reduced by cockpit motion. As will be discussed later, in STOL aircraft studies cockpit motion is almost mandatory in order to reduce pilot adaptation time when the lateral control of the vehicle being studied is critical. In the jet transport landing study lateral characteristics were satisfactory and presented no problem to the pilot, so motion, although desirable in providing added realism, did not significantly affect pilot performance.

Effect of familiarization time. As noted earlier, the airline pilots who flew the simulation of Ref. 9 were allowed only limited familiarization time (several landings) in the simulator before data were taken; in contrast, the research pilots in the investigation of Ref. 8 and three to 10 hours. This difference in time could account for the difference in the results.

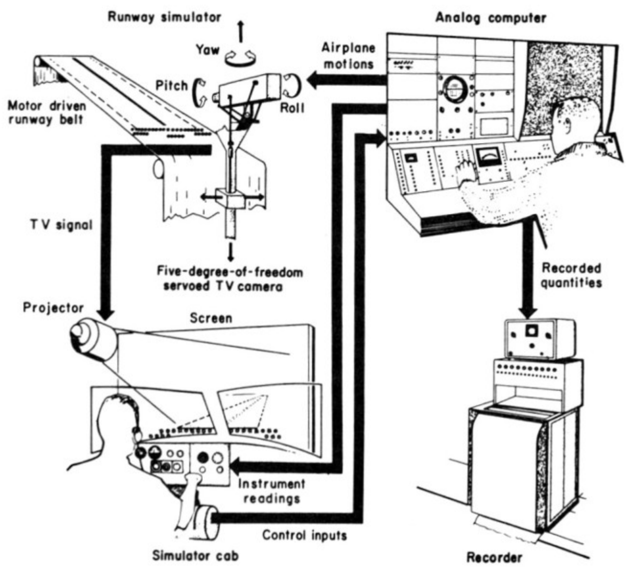

Figure 3.

According to Ames pilots, considerable familiarization time is required to learn how to deduce from the simulator visual scene height and height-rate information that will correspond to height and height-rate cues received in normal visual landings. This is the most time-consuming part of the familiarization process.

Airline pilots are, of course, familiar with "flight" in training simulators, but training tasks differ from those presented to them in this research simulation. In the training task the pilot follows the ILS beam, and landing touchdown descent rate is not a factor in the training or simulator proficiency check. This background may have caused them to adopt a different criterion for the landings than that used by the research pilots. Figure 2 shows that the airline pilots attained touchdown distances over the threshold on the simulator very nearly the same as in flight, but the rates of descent (Fig. 1) were almost twice as great. Based on experience gained at Ames, the touchdown descent rate is the important criterion for judging the landing performance of future designs, as it reflects pilot ability to deal with undesirable vehicle characteristics to a greater extent than does landing at the target touchdown point. Obviously, both factors must be considered, but results could be different, depending on the relative emphasis given.

Effect of visual presentation. It is possible, also, that differences in the clarity or definition of the television scene of the runway caused variations in landing performance. Since the scene as presented to the pilot most closely resembles a landing at dusk in thick haze, any slight improvement in the visual scene could affect landing performance. In the opinion of Ames pilots, the definition of the runway in the Ames simulation was better than in others, and some features of the Ames visual presentation might be mentioned in this regard.

Compared to other simulator runway models, the Ames model is fairly large ($\frac{1}{300}$ of full scale) and extra lighting has been added to that furnished with the original equipment. Both of these features account for the better runway definition. Focus distance of the televised picture, an item of some importance, was set for 2,000 feet down the runway. Also, a hazy horizon was provided at the end of the runway, at the request of the pilots, to make the scene more representative of normal visibility conditions (the view of the runway was limited to $\frac{1}{2}$ mile). It became apparent in the course of early investigations at Ames that performance of the television camera transport system was not acceptable to the pilots. The improved transport system has the frequency response characteristics shown in Fig. 4. These are minimum acceptable values to the pilots, and lead terms in the computer were required as an aid. The improvement in the transport system is partially responsible for the difference in touchdown velocity results in Fig. 1, the latest results from Ref. 8 being obtained with the improved response system. Another factor that may be responsible for better performance in the later tests is the daily check and adjustment of the televised picture and the camera drives; daily monitoring was not scheduled at the time of the earlier tests.

The poor performance of the training simulator of Ref. 6 is thought to be related to the visual scene since runway definition was poorer than in the Ames simulation. Also camera transport operation may have been poor because of the difficult computer scaling problem in the training simulator. Because it must simulate the entire flight range of the aircraft, the training simulator may not normally have computer scalings appropriate to the operation of the camera transport, which may lead to noisy drive signals.

Summary of jet transport landing studies. In summary, it may be concluded that flight results of jet transport landings can be closely duplicated on piloted ground simulators. Deficiencies in the television presentation of the outside world can prevent the attainment of exactly comparable results. The results appear to be influenced by the amount of familiarization time allowed pilots, and how well the pilots understand the task objectives. Cockpit motion, although helpful to the pilot in adapting to the simulator and in providing realism, does not appear to be important in this specific jet transport landing task.

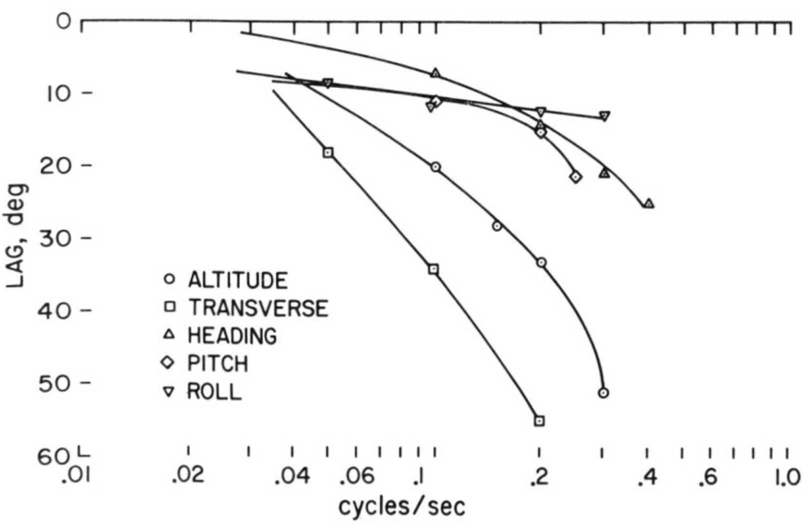

Figure 4. Frequency response of Ames television camera drive system.

STUDIES OF TAKEOFF CERTIFICATION MANEUVERS OF JET TRANSPORTS

Recent piloted simulator studies of takeoff certification maneuvers at Ames have attempted to duplicate actual certification flight tests for a current jet transport to determine the degree of simulator sophistication required for valid results. The simulation task was that of making maneuvers given in the FAA regulation [10].

Description of the simulation. A fixed cockpit simulator was used with a televised external scene, similar to that used in the jet transport studies and shown in pictorial block diagram form in Fig. 3. Since the simulation included ground reactions as well as stability, control, and performance parameters (through large excursions in angle of attack), it required a considerably more complex analog computer program than does the typical handling qualities simulation. Accurate values of the influence of the presence of the ground on aerodynamic parameters was an important requirement.

Determining refusal speed. Figure 5 illustrates the agreement obtained in determining refusal speed. The results in Fig. 5 show that the distance to stop after engine failure on takeoff agreed with the flight tests. This maneuver also serves to illustrate the potential value of piloted ground simulators in certification testing. For example, it was possible for the pilots to study the effect of delay in initiating the stopping of the airplane

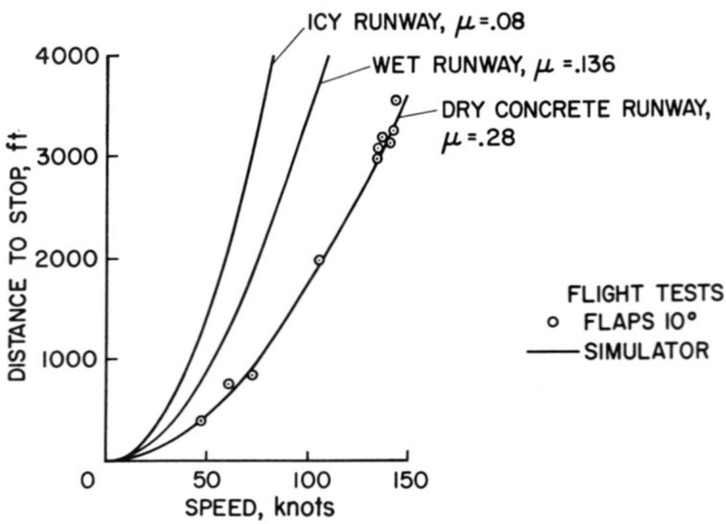

Figure 5. Distance to stop after engine failure on take-off.

following an engine failure on takeoff in such details as (1) cutting remaining power, (2) applying brakes, and (3) extending spoilers. The effect of stopping the airplane under different runway conditions such as icy and wet runways was investigated. In this study the simulator was improved to the extent of using aircraft toe brake pedals and the value of braking coefficient (0.28 on a concrete runway) for the nonskid brakes used in the actual tests.

Determining minimum ground control speed. The comparison of simulation and flight results in Fig. 6 illustrates a maneuver in which simulation sophistication must be improved, inasmuch as simulation and flight results did not agree. In determining the minimum ground-control speed the pilot attempts to minimize the deviation of the airplane from the runway center line. He does this by applying full rudder upon recognition of an engine failure. The speed at which the pilot can limit the maximum lateral deviation to 15 ft is taken as the minimum ground-control speed. Both in flight and in the simulator many runs were made to establish a faired line, as shown, by means of which the minimum control speed is determined. As can be seen in Fig. 6, in the simulated tests, when the pilot used the television scene of the runway as the primary cue in recognizing engine failure, he could not keep the airplane within 15 ft of the centerline (following engine failure) until his ground speed reached about 130 knots, which is far above the value of 99 knots for the flight tests. However, when a verbal cue was given at the precise time of engine failure, he obtained a

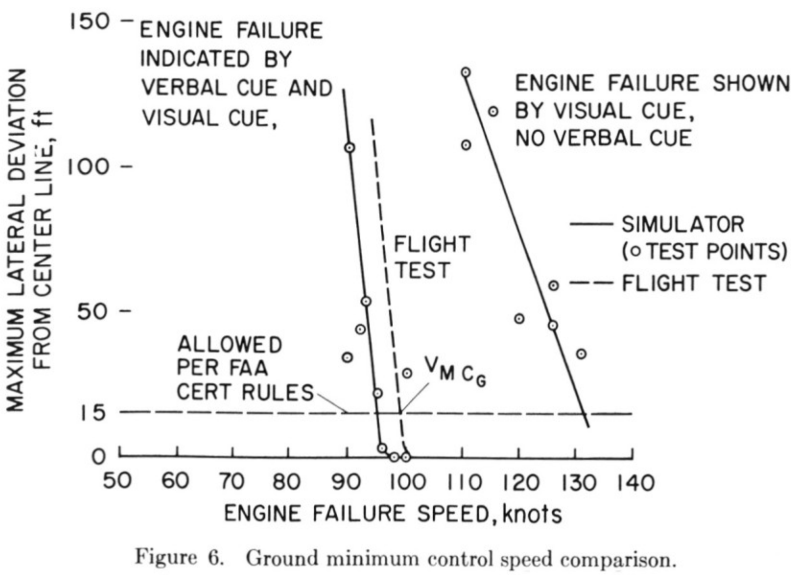

Figure 6. Ground minimum control speed comparison.

minimum ground-control speed of about 95 knots, which was lower than obtained in the actual flight tests. It is apparent that the simulator as set up lacked the ability to simulate realistically the cues by means of which the pilot quickly recognizes engine failure. It may be that yawing motion and lateral acceleration would help. It is also possible that the effects of the verbal cue indicate the need for accurate simulation of engine noise. Further investigation of this maneuver is required in a more sophisticated simulator to determine simulator requirements.

Determining minimum unstick speed. In the takeoff run the pilots indicated that lack of motion was a deficiency. The feeling of motion was supplied by a pulse to the pilot's pneumatic seat cushion each time the simulated aircraft supposedly passed over one of the divider or tar strips separating the standard 25-ft squares of runway concrete. Another addition to realism was the use of an engine-sound generator commanded in intensity by the engine rpm.

In the simulation of the minimum unstick speed, V_{MU}, in which the airplane is rotated as soon as possible to take off at the minimum speed, the pilots noted that a control column shaker and the vibrations to a pneumatic seat cushion distinctly improved the realism of the simulated maneuver. In the opinion of the pilots these cues would be a valuable addition to the use of the simulator in the study of this maneuver.

Summary of takeoff certification studies. Good comparison between simulation and flight results for a number of maneuvers was obtained with a fixed cockpit and the television scene of the runway. Some maneuvers, however, require motion, aural, and buffet, and other cues which must be investigated on more sophisticated simulators.

STOL TRANSPORT HANDLING QUALITIES STUDIES

As noted in Ref. 11, flight tests have been made of a Breguet 941 STOL transport to study STOL flying qualities requirements. Part of the program included a simulation study to better understand the optimum STOL flying qualities and their acceptable lower limits. This study has afforded information on simulation techniques required in the study of STOL aircraft.

Equipment. The cockpit used has a limited movement in roll of ±9°, and pitch of 14° up and 6° down. A screen in front of the pilot moves with the cockpit. The television projector is mounted on top of the movable cockpit, and the runway scene is generated and mechanized in the same manner as shown in Fig. 3 for the fixed cockpit.

Results. Some of the simulation results are shown in Fig. 7. This figure shows that the same pilot rating* of 3 was obtained for the simulation as

* The pilot rating schedule, based on Ref. 12, is provided in Table 1.

TABLE 1

PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No

[1] Failure of a stability augmenter.

was obtained in flight, and also gives information on how pilot rating of the airplane flying qualities varied as yawing moment coefficients were varied singly from the value noted for the basic airplane.

Motion requirements. A requirement for roll motion in the simulation is demonstrated in Figs. 8 and 9. The figures also illustrate the task used by the pilots for the various conditions studied. It consisted in flying an IFR approach using the ILS glide path set for 7½° STOL approach. At 250-ft altitude the runway came into view, and the pilot made a VFR landing. At initiation of the IFR approach the pilot was required to correct for a 170-ft offset due to localizer error, and when the runway came into view, the pilot had to correct back 170 ft to land on the center line of the runway. It can be seen in Fig. 8 that with motion off, the pilot was unable to perform the task. The high adverse yaw that resulted from lateral control with this marginal configuration caused the pilot to devote his complete attention to controlling the large bank angle and sideslip excursions. However, when the runway came into view he was just able to gain control and make a successful landing. In Fig. 9, with motion on, the pilot was able to perform the task IFR, but with some difficulty. In the VFR part he had little trouble correcting the offset and in performing the landing.

The absence of, or decrease in, stability and damping as airspeed is reduced is probably one of the main reasons for motion requirements in the STOL aircraft landing simulation. Unless bank angle is kept quite small at low speeds, a large turn rate will develop. In addition, if a small bank-angle error is present, and directional control is reduced to avoid turning,

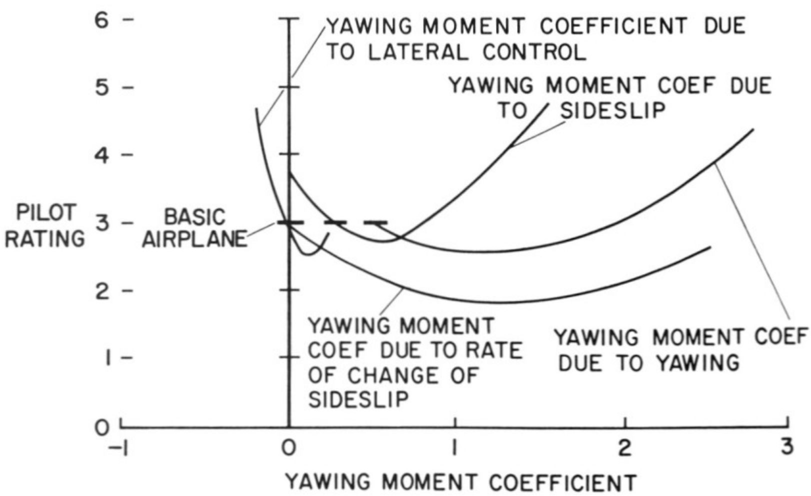

Figure 7. STOL transport simulation results.

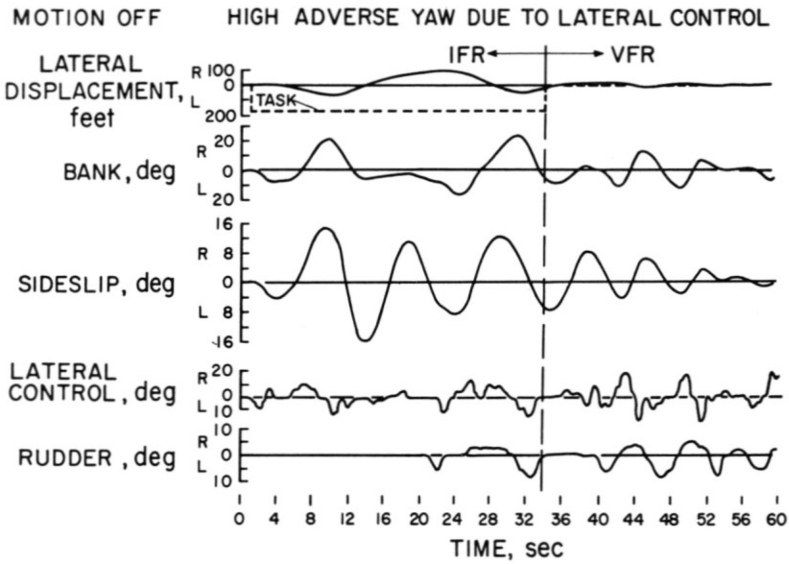

Figure 8. Simulator landing of STOL transport.

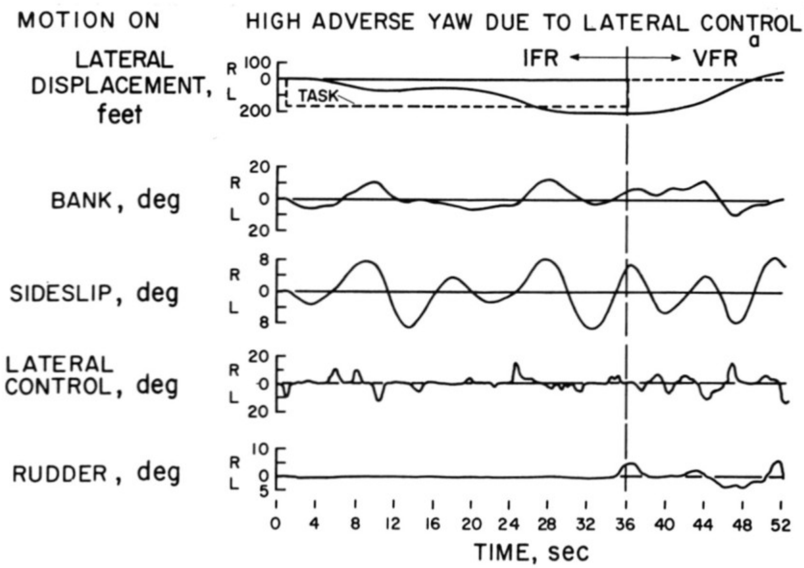

Figure 9. Simulator landing of STOL transport.

sideslip will build up. Figure 10 shows the variation of the sideslip to bank-angle ratio with airspeed. It can be seen that at lower speeds, the steady-state sideslip for a given bank angle is much larger than at higher speeds. These characteristics make it essential for the pilot to detect very small bank angles as well as roll rate to control STOL vehicles. This information must come from the motions and display of the simulation.

A major problem in the use of simulator motion is that of programming roll motion. To detect bank-angle error and roll angular acceleration, a 1-to-1 ratio of input bank angle to cab motion is desirable, but when large bank angles, typical of STOL operation, are used, the pilot feels an unrealistic side force and the cab reaches the stops too soon. In the simulation of the Breguet 941 a compromise was used. The motion was adjusted so that 13° of commanded bank angle was required for the cab to reach its stops at 9°. However, this was not entirely satisfactory, since the pilots often wanted to use more than 13°. It seems likely that what is required is a motion generator having long lateral travel, so that side acceleration can be combined with bank angle to give a more realistic motion simulation of true flight. Of course, the washout of the lateral movement and bank angle then becomes a problem. As indicated in the study of Ref. 13, however, some initial study of the combination of lateral travel with bank angle to obtain more realistic motion has been carried out with acceptable results in the Ames five-degrees-of-motion simulator. This is an area requiring further investigation. The pilots felt that yaw angular motion should have been

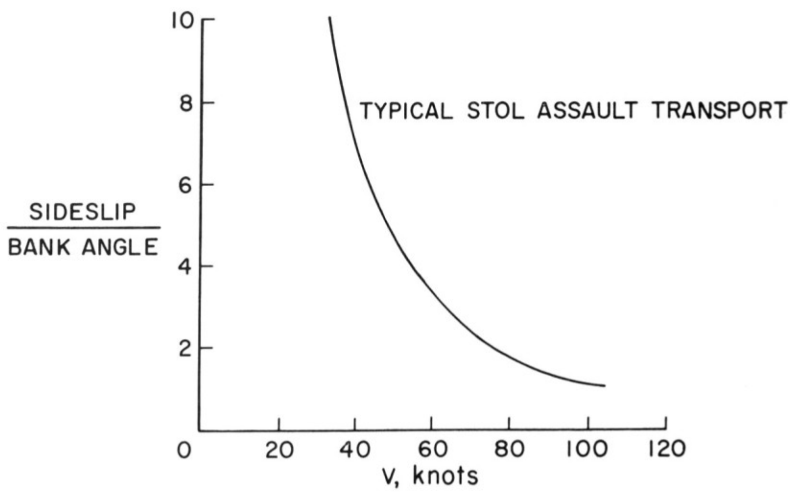

Figure 10. Variation of steady state sideslip to bank angle ratio with airspeed.

incorporated in the simulation so that the lateral-directional problems of STOL operation at low speeds could be studied more effectively. Ames is now placing in operation a six-degrees-of-motion simulator and it is hoped that V/STOL studies on this simulator will identify critical motion and motion-washout requirements for V/STOL simulations.

Control system and instrument requirements. Figure 11 shows the simulator cockpit interior arrangements with the Breguet type control stick and left-hand throttle installed in the typical transport cockpit. The cockpit also included angle-of-attack indicating lights above the instrument panel as well as normal instrumentation. This duplication was found to be necessary before the pilots could "fly" the simulation satisfactorily and examine the effects of changing various aerodynamic parameters of the design.

Correct duplication of the control system characteristics on the simulator was a problem. The simulator control system did not permit exact duplication of the control system parameters as measured in flight, and, as shown in Fig. 12, when these characteristics were first approximated on the simulator, they were unsatisfactory. The pilots objected to the control characteristics and could barely "fly" the simulated airplane. It was only when the characteristics were changed to the "simulator satisfactory" curve that the simulated airplane was regarded as flyable and reasonably simulating the airplane.

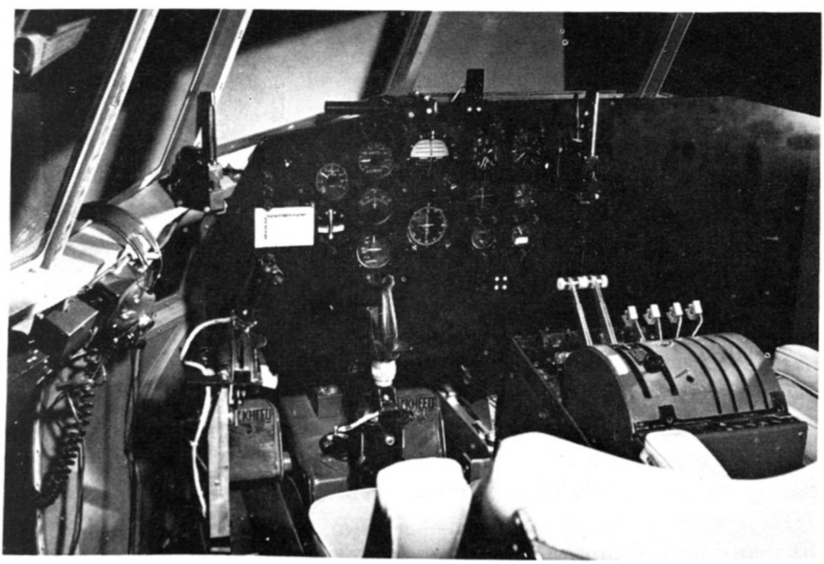

Figure 11. Cockpit interior for Breguet 941 simulation.

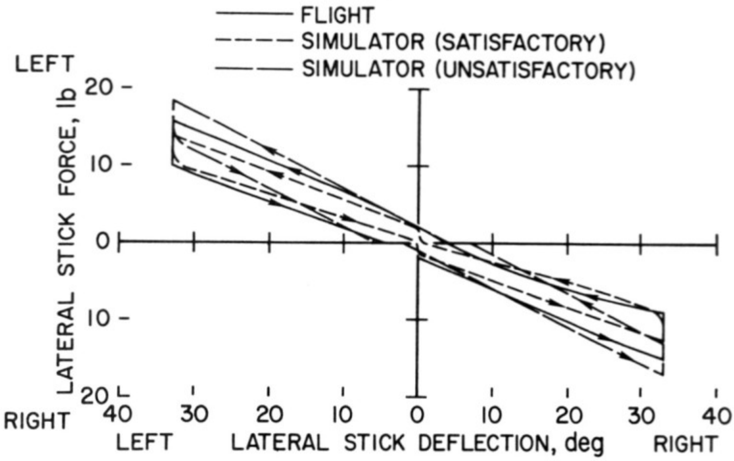

Figure 12.

Summary of STOL simulation results. The same pilot rating of three was obtained for the simulated airplane as was obtained in flight tests. It was demonstrated that simulator motion was required to obtain this good comparison. Roll motion particularly was required, but other motions might be required to eliminate certain banking problems. Lack of yaw angular motion was a deficiency. Correct duplication of control system characteristics and cockpit instrumentation was important.

CONCLUSIONS

Several simulation studies have been compared with flight results. It was shown that in jet transport landing studies the external visual scene and task criteria were important factors in obtaining results comparable to flight results. In takeoff certification studies a fixed cockpit with external scene gave results comparable to flight results for many maneuvers, but motion cues, aural cues, and cockpit sophistication may be required for some of the maneuvers. However, further research is needed to establish requirements. For STOL transport-handling qualities studies in landing approach, simulator motion was important. Lack of yaw angular motion was a deficiency, and roll motion, although definitely required, created a problem by preventing flight at large bank angles as would be desired in STOL studies. It would appear that translational lateral travel combined with bank and appropriate washout provisions may be required to adequately study lateral-directional problems of STOL operation at low speeds.

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COMMENTARY

D. K. M. MENDELA (*Hawker Siddeley Aviation, De Havilland Division, Hatfield, Herts., England*):

(a) Could the lecturer give an approximate indication of the cost involved in providing the six-degrees-of-motion simulator, indicating separately the cost of providing visual display?

(b) How big is the computer used to solve the equations of motion? Is it analogue or digital, or a hybrid type? Also, how are various nonlinear functions provided?

(c) Has consideration been given to providing less sophisticated visual display, produced by solely electronic means, where the display gives the picture of a runway fitted with the Calvert type of lighting system? This was produced at De Havilland Division at a very low cost, of the order of only £3,000, and was found by at least twenty pilots participating in the investigation as very realistic. One of them, Mr. Drury Wood (American pilot) commented that it is a very good representation of Edwards base, California. Pictures of the display could be forwarded if necessary.

REPLY

(a) The six-degrees-of-freedom motion simulator cost approximately $650,000 for the motion generating equipment alone. The cost of computers and visual display are additional. The cost of providing closed circuit television visual display in front of the pilot would vary depending on the type used. No visual display has been provided yet, but it is estimated the cost would vary from $100,000 to $300,000, depending on the model used for the TV camera and whether or not black and white or color television is used.

(b) Depending on the complexity of the simulated problems, one or two Electronic Associates 231 analog computers are used. Nonlinear functions are usually provided by use of diode networks in the feedback of an operational amplifier, using up to 20 straight-line segments to make up a curve. A digital arbitrary function generator has recently been acquired for the generation of nonlinear functions, and it is expected this will be used extensively in the future.

(c) During the course of simulation studies at Ames less sophisticated visual displays generated solely by electronic means have been used, and are continuing to be used particularly in the study of symbolic display of the runway for actual landings by instrument. However, the electronic display is not sufficiently realistic for some simulation studies in which simulation of actual landing performance under visual conditions is desired.

COMMENTARY

J. C. WIMPENNY (*Hawker Siddeley Aviation, De Havilland Division, Hatfield, Herts., England*):

1. On the moving cockpit the projector screen appears to be rather close to the pilot's eyes. We have found in similar situations that a collimating lens is essential. What is your experience?

2. Your display has a limited sideways view. Have you found this a limitation, and are there situations in which peripheral vision is essential?

REPLY

1. On the moving cockpit the projector screen is about 12 ft in front of the pilot. At this distance a collimating lens is not required. In some of our simulations a television monitor has been used that is about three feet in front of the pilot. In this case a collimating lens has been found to be very helpful and is used.

2. The limited sideways view is a limitation, and there are situations in which we would like the sideways view to be simulated. We are interested in learning of ways to provide this without great expense.