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SOME COMPARISONS OF AIRCRAFT FLIGHT CHARACTERISTICS WITH THOSE SHOWN BY GROUND SIMULATION

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SUMMARY

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Past literature on piloted ground research simulator results as compared with flight results is briefly reviewed. The results of three specific types of research simulation investigations, (1) jet transport landings, (2) take-off certification tests, and (3) STOL handling qualities in landing approach, are compared with flight results for the purpose of presenting further information on simulator requirements, in terms of simulation equipment, accuracy of parameters, task criteria, and pilot familiarization required for valid results.

It is shown that the important factors in ground simulation are: (1) visual cues and task criteria in jet transport landings, (2) motion cues, visual cues, cockpit sophistication, and exact ground effect parameters in take-off certification studies, and (3) sophisticated motion simulation and control characteristics duplication in STOL landing approach studies.

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INTRODUCTION

The subject of this session is "Scientific Aspects of Simulation of Flight Dynamics on the Ground with Special Reference to Flight Comparisons." I have assumed this to imply discussion is desired on the

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research use of piloted simulators, rather than the discussion of training simulators, as they are considerably different in nature. I have assumed also that emphasis is desired on the technique of simulation rather than on research results.

Before going further it may be appropriate to review briefly the principles and basic elements of the research simulator. These are shown in the diagram of Fig. 1. Pilot inputs are fed to a computer to determine the vehicle motion response which is then presented back to the pilot by some combination of cues, usually visual and motion cues, but others such as aural cues for example could be added, which the pilot utilizes in performing the task he is given. The major problem in research simulation is to provide the pilot with adequate information to judge how well he is performing the prescribed task and what he must do or how the vehicle or its systems may be altered to improve his performance. For this purpose research simulation equipment must be adaptable to representing a wide range of cues to the pilot even though in any one research problem only a few are used so that the problem is manageable. Flight comparisons of simulation results furnish information on the important cues to use in various simulation problems, and the purpose of this paper is to present some further information on this subject. A review of some of the existing literature on flight and simulator comparisons is thought appropriate.

Reference [1], "A Critical Review of Piloted Flight Simulator Research" by Sadoff and Harper summarizes results from a number of references in which the validity of piloted flight simulator research results are discussed, based on comparisons with flight tests. Examples of past experience, obtained on devices ranging from simple, fixed-chair simulators, to complex and costly multi-axis motion generators, such as shown in Fig. 2, and variable stability aircraft, are provided. The use of simulators in defining acceptable handling qualities for a wide variety of aircraft is summarized from references [2-11]. The use of simulation for investigating potential problem areas of a general nature or for specific vehicles is summarized from data in references [11-14]. The use of simulators for determining environmental stress effects on a pilot's control and performance capabilities is summarized from references [15-20], and for conducting research and development programs on specific vehicles from references [13, 21, and 22].

Experience on simulation requirements and techniques of use gained from the foregoing simulator programs and associated programs are summarized in references [23, 24, 25, and 26].

The general conclusions of reference [1] are that for general handling qualities assessment relatively simple fixed-base or angular motion simulators provided results in substantial agreement with flight test. Kinesthetic motion cues are essential for realistic assessment of: such things as abrupt damper failures of aircraft and for assessment of the handling qualities requirements of supersonic transport configurations in cruising flight. Motion cues were considered of secondary importance in problems as approaches and landing of aircraft, where strong external visual cues apparently are of more importance. In general, the comparisons presented in the references mentioned and summarized in reference [1] were of qualitative results that were expressed in terms of pilot opinion, often in Cooper rating numbers as discussed in reference [27], although some comparisons were touched upon that dealt with pilot performance and presented results that were quantitative in nature. The advancement of simulator science toward quantitative answers, and a direct assessment of the pilot performance of specific missions is, of course, a desire of those who design future vehicles. The increasing complexity of simulation equipment and the more rigid definition of the pilot mission to be studied as progress is made toward having simulation predict quantitative results is touched upon in references [25 and 26]. Figure 3, based on information presented in references [25 and 26], correlates the types of results to be expected from a simulation with the complexity of the task to be simulated and with simulator complexity. If the table is entered knowing the use or application required of the results as well as the type of results (qualitative and/or quantitative) desired, one may determine the type of simulator (rudimentary, basic, or advanced) that is required as well as the kind of task that must be considered in order to provide a proper evaluation. It is seen that as need for more precise and realistic (in a flight sense) type of information is required, the more complete must be the simulation with the ultimate limit being reached in the actual flight demonstration.

In this paper, then, I will consider this aspect of simulator use which presently is becoming of more interest as the science of manned simulation advances - the ability to predict quantitative results in a simulation of a particular mission. It is the purpose of this paper to compare flight and simulator performance predictions in several areas for which data have become available in the past several years, and from these comparisons attempt to learn more about simulator requirements for valid answers.

DISCUSSION OF FACTORS AFFECTING SIMULATION VALIDITY

It would appear that the validity of any manned simulation is dependent on four factors as shown in Fig. 4: (1) the nature of the simulation equipment, (2) the accuracy of the parameters used to represent the simulated aircraft, (3) the correct duplication of the flight task, and (4) pilot familiarization with the simulator and the task. As shown in Fig. 4, the nature of the simulator equipment can be subdivided into that required for: (a) external visual simulation, (b) motion simulation, and (c) cockpit interior items, such as instrument displays, control system, etc.

My discussion will deal with three specific simulation investigations: (1) jet transport landings, (2) take-off certification tests, and (3) STOL handling qualities in landing approach. These specific investigations lend themselves well to the comparison of simulation and flight results on the basis of particular factors, i.e., effect of the external visual scene on the transport landing performance, need of additional cues in take-off certification studies, and importance of simulator motion, cockpit instrumentation, and control system validity in the STOL investigation. It is beyond the scope of this paper to deal with each of these studies in detail on all the factors listed, so I will discuss several of the factors in general terms now, and reserve detailed discussion on important factors for each of the specific investigations till later.

Parameters Used

In the investigations I will discuss, parameters used were from wind tunnel tests as corrected from flight tests, and so were considered accurate and not a factor in the comparisons. Further in each case the pilots who flew the simulators also had flown the aircraft and were able to furnish a check of the whole simulation setup including errors in mechanization. The pilot's knowledge of the flight characteristics of the airplane simulated are very important in making certain the simulation is correct. The pilot is important in this regard even in simulations for which there are no previous flight comparisons, such as supersonic transport studies. By "flying" the simulator he will note characteristics that are troublesome, which may on investigation be found to be errors in mechanization rather than troublesome aircraft characteristics.

Familiarization of the Pilot

In Ames experience, thorough familiarization of the pilot with the simulator and the task is essential to valid simulation research results. Because of the part he plays in checking the simulation, an experienced background as a research pilot is most valuable. Since no simulation is correct in all detail, it is necessary for the pilot to extrapolate mentally the simulation setup to a flight condition, and simulation "flight" experience as a background is important for this purpose. Also extensive familiarization time in the specific simulator, for the purpose of adaptation and becoming familiar with the task, is often required. For example, in the landing studies at Ames, pilots took three to ten hours of familiarization to become adapted to the simulator and attain consistent performance. Obviously, the extent to which sophistication of the simulator can reduce familiarization time is a matter of considerable interest, and will be touched upon in the discussion of specific investigations.

SIMULATOR INVESTIGATIONS OF JET TRANSPORT LANDINGS

As reported in references [28 and 29], turbojet transports have experienced significantly higher vertical velocities at touchdown than their predecessors, the piston-engine transports. This result has prompted the consideration of manned simulators to examine future designs of aircraft in this regard. Of course the validity of the simulator for this examination was a matter of concern, and so in the past several years there have been a number of simulator investigations made in which jet transport landing performance on the simulator has been compared with the flight results. References [30, 31, 32, 33, and 34] present results of simulations made of jet transport landings for which flight results are presented in references [28 and 29].

Results on landing performance are generally expressed in terms of at least two criteria: impact velocity and the distance of the ground contact point from the runway threshold. Since these appear to be interdependent variables, any assessment of landing quality requires that both criteria be considered. Comparisons of the results on the probability of exceeding a given touchdown rate of descent is shown in Fig. 5, and of exceeding touchdown distance from the threshold is shown in Fig. 6. It is seen that there is considerable difference in the results from different simulations, with the Ames results of reference [33] being closest to the flight results for rate of descent at touchdown, and the results of reference [34] being closest to flight results in the distance of the ground contact point from runway threshold.

External Visual Simulation

In this type of simulation the equipment used is generally similar to that used at Ames shown in pictorial block diagram form in Fig. 7. A television camera is servo driven in three angular degrees of freedom and in altitude and lateral displacement relative to a runway model that in the Ames simulator is installed on a moving belt. The resulting display resulted in mean error from the target touchdown point from runway threshold being much larger. It is apparent, therefore, that in simulation of the landing task using a television display there is a lack of information, and this prevents the pilot from landing as he would under visual conditions. The restriction of peripheral vision to that within the limits of the 4-inch-wide opening in the windscreen had very little effect on performance once the runway was in sight and the approach was initiated. Flare, flare height judgement, and cross-wind control were approximately the same as with the full view windscreen. ~~It took familiarization time for the pilots to adapt to this, however.~~

In the Ames ground simulation the scene presented to the pilot is shown in Fig. 9. It most closely resembles a landing at dusk in thick haze. It should be mentioned that the photograph of Fig. 9 does not adequately describe the quality of the picture presented to the pilot because of the technical difficulties of photographing a projected television picture. At Ames a great deal of effort has been placed on making the picture as clear and geometrically correct as possible. It was found that a daily check of the television scene by experienced technicians was required in order to obtain satisfactory picture quality. Each day before simulation research was started the scene was viewed on the standard television check picture and adjusted as required. The focal point of the television picture was also an item of some importance. It was set for focus at a point about 2000 feet down the runway.

The transport element of the television camera was found to be a very important factor. The DALTO Corporation equipment used for the Ames camera transport and for the moving belt, as shown in Fig. 7, were intended for use with training simulators, and it became apparent in the television scene is presented to the pilot in the form of a projected image on a screen mounted about 12 feet forward of the simulator cockpit, and provides a horizontal field of view of about 50°, and a vertical field of view of about 30°.

There is obviously a question as to the extent to which the two-dimensional display characteristics of a television display degrade the pilot's landing performance as compared with the actual binocular visual scene which he has in normal landings. Further, his normal vision in flight is not restricted to the small forward angular extent that it is in a television display. Reference [35] presents results of some recent studies that are of interest in this regard, and are useful in judging to a certain extent how simulator results might deviate from flight results due to the television display of the landing area.

An R4D (DC-3) aircraft was used as the test vehicle for this experiment. The television display for the pilot was produced by the use of closed circuit television with the camera installed forward of the windscreen. Using the television display as a substitute for the outside visual scene, and after pilot familiarization as desired, data were taken. The pilots were instructed to attempt to land as close as possible to the target touchdown point, but not to sacrifice smooth contact with the runway for a small error in touchdown distance. Figure 8, taken from reference [35], shows that the measured acceleration at ground contact is about the same whether made by normal vision, restricted vision, or by television display. In fact, when the television display was a magnification of the actual scene through the use of telephoto lens, angular magnification = 1.55, the landing impact velocity was less than occurred in normal visual landings. However, as compared with normal visual landings, the television course of early investigations, such as reported in reference [30], that lags in the servos and jerkiness of the camera had to be eliminated for valid research results. This was done to the extent possible. The pilots said the reworked equipment was acceptable, although not completely satisfactory. The frequency response of the Ames reworked equipment is shown in Fig. 10. Even this response was not satisfactory and had to be compensated for on the computer.

It is thought that the poor results of the simulation of reference [31] may be due to television transport deficiencies, but for a different reason. The training simulator used, because it is required to simulate the entire flight range of the aircraft, may not normally possess computer scalings appropriate to the operation of the visual simulator portion to the accuracy required for research use. Poor performance of the television drive system could result.

Some thoughts relative to methods of improving simulator displays might be mentioned here. Pilots' comments on the actual television landings of reference [35] indicated that a contact analog display of the size and clarity of the type used in the investigation would require additional quantitative information for height and height rate before it would be acceptable for an all-weather landing instrument. Along this line research studies are proceeding at Ames on a symbolic display for all-weather landings as discussed in reference [36]. It may be that a symbolic display for the landing runway might give more information than the television scene gives and could be a method of upgrading simulation landing performance. It is also possible that improvement in the television picture, and the use of color would give improvements.

Cockpit Motion and Interior

In the Ames simulator used in the preceding landing studies (Fig. 7) the cockpit was fixed, and the cockpit instrumentation and control system were a generalized version of those in jet transports.

In the investigation of reference [31], simulators of the type used by airlines for training or proficiency checks of flight crews were used. Cockpit-motion cues in pitch and roll of a limited amount were provided. Cockpit interior in terms of instruments and control system was identical to the airplane cockpit.

In the investigation of reference [34] a moving base cockpit with limited angular motion was used. Roll motion was mechanized to represent side force correctly, at the expense of correct roll acceleration. The cockpit was a replica of the actual airplane in instrument and control layout, cockpit arrangement, interior moldings, and exterior mold lines. Flap buffet and landing impact jolt were incorporated into the cockpit motion. The four engines were mechanized separately, and engine whine varied as a function of throttle position. According to Ames personnel who are familiar with this simulator, touchdown conditions appeared somewhat more difficult to control than in the Ames simulator, and this was tentatively attributed to a greater difficulty in obtaining height and height rate information from the visual presentation. Landings, performed with and without the limited cockpit motion provided, revealed no first-order contribution of the motion to the ease of performing the task, and to a certain extent the manner of mechanizing roll motion was disturbing rather than helpful.

Correct Duplication of the Flight Task

As Cooper has discussed in reference [25], and as pointed out in Fig. 3 on advanced simulations, if task performance is to be used as the method of evaluation, the fairly complete criteria of the task are required. It appears there may have been some variations in criteria for task performance for the investigation for which data are shown in Figs. 5 and 6, and these various criteria may have had a bearing on the results.

In the Ames investigation of reference [33] the simulated landing runs were initiated, on instruments, at an altitude of 500 feet. Small offsets from the ILS glide path were programmed in the starting conditions in an effort to simulate the small dispersions that normally exist at this point in a visual approach, and the pilot used a flight director instrument to converge on the glide path. He transferred to "visual outside world" references at an altitude of about 200 feet. No specific touchdown target point was presented; however, the ILS glide path to which the pilot was controlling while on instruments was adjusted to intersect the runway at a point 600 feet beyond the runway threshold, instead of the normally greater distance, in order to approximate more closely the good visibility flight path.

In other investigations it does not appear that the task was specified as closely, but that the pilots were asked to make visual landings performed in the same manner as in flying in the actual airplane. However, in reference [34] the ILS glide path was set to intersect the runway at 1000 feet from the runway threshold. It is somewhat surprising, therefore, that the airline pilots of reference [34] were closer to flight in touchdown distance over the runway threshold than in other investigations. This may be due to their background, as in actual flight, touchdown probably is attempted to be made at the ILS touchdown point, even in visual conditions. There no doubt is a trade-off between these two performance factors, and more attention to precision in touchdown point can result in higher statistical values for touchdown velocity. It would appear that in future investigations of this type a target touchdown point might be more specifically made a part of the task, as the ability to touch down at a specific point is an important factor to be considered in judging the flying qualities acceptability of an airplane.

Summary of Jet Transport Landing Studies

In summary, it may be concluded that results close to flight results can be obtained of jet transport landings on piloted ground simulators, but that deficiencies in a television presentation of the outside world prevent exactly comparable results from being obtained. Cockpit motion and cockpit sophistication did not seem to be important factors. However, task objectives as presented to the simulator pilots may have been a factor in the comparisons.

SIMULATOR EXAMINATION OF THE TAKE-OFF CERTIFICATION OF JET TRANSPORTS

The NASA and Federal Aviation Agency have cooperated on a program to explore the possibility of using ground-based simulators to examine the take-off certification problem. This is a certification area involving certain hazards in actual flight, and simulation could assist in setting up certification requirements and certification procedures, particularly on advanced designs, possibly even eliminating the need for actual flight tests of some of the more hazardous maneuvers. Further, it is thought that simulation of certification maneuvers prior to actual flight tests, and complementary thereto, could provide supplementary information of value to the certification procedure. A current commercial jet transport airplane for which extensive certification flight test data were available was chosen as a test vehicle.

Nature of the Simulation

The simulation set up used was similar to that shown in Fig. 7. A fixed cockpit was used, although a movable cockpit would have been preferable.

The parameters used were those determined from wind tunnel tests and engineering calculations, with the wind tunnel data corrected as determined from flight tests. It became evident during the course of the investigation that ground effect was a very important parameter in these tests; for purposes of reference, the effects on lift and pitching moment of the presence of the ground, as simulated, are shown in Fig. 11.

The same company test pilot and FAA pilots who participated in the actual certification take-off and climb tests "flew" the same take-off and climb certification maneuvers on the simulator. The simulation test maneuvers were a duplicate of FAA certification maneuvers in actual flight as given in the FAA regulation of reference [37].

Simulation and Flight Comparisons

I will present only a few of the many certification test maneuvers carried out on the simulator that were compared with flight results. In general, simulator results were quite comparable with flight results. However, in a few cases they were not. Since these later cases are of more significance to this paper, I will discuss them in more detail.

One maneuver in which excellent agreement was obtained with flight results is that shown in Fig. 12, dealing with accelerate-stop distance. It may be seen that the distance to stop as obtained on the simulator agreed well with that obtained in the actual flight tests. For this simulation the simulator was equipped with toe brakes as in the actual tests. The value of the braking coefficient of 0.28 was used on the simulation, and was selected for the simulation on the basis of Ames' interpretation of Douglas information and actual dry concrete runway conditions that existed during the tests. It was realized that the assumption of a constant braking coefficient is somewhat in error as the value decreases for higher speeds and is somewhat higher for lower speeds. It may be seen, however, that the distance to stop as obtained on the simulator was within scatter of the actual flight test results. It was possible for the pilots to study the effect of delay in initiating the stopping of the airplane following an engine failure on take-off in such details as the effect in delay in cutting remaining power, the effect of delay in applying brakes, and the effect of delay in extending the spoilers. Also, the stopping of the airplane under different runway conditions was simulated with results as shown, which includes curves for the stopping distances at various speeds for icy runways and wet runways compared with the normal dry concrete runway.

In another maneuver, determination of the minimum ground control speed, V_{MC_G}, the pilot applies full rudder upon recognition of an engine failure, and the speed at which he can limit maximum lateral deviation from the centerline of the runway to 15 feet is taken as the ground minimum control speed. Figure 13 shows the results of the simulation tests compared with the acutal flight tests. As can be seen, 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 feet of the centerline until his ground speed was up to about 130 knots, which is far above the value of 99 knots for the flight tests. However, when he was given an aural cue at the precise time of engine failure, he obtained a minimum ground control speed of about 95 knots that was lower than the actual flight test results. It was found that an 0.8-second delay in the pilot's application of full rudder following the aural cue of engine failure, gave a simulation result for minimum ground control speed that was very close to the flight test value. However, it is apparent the simulation as set up lacked one of the vital elements in studying this particular maneuver, that is, the ability to simulate realistically the cues by means of which the pilot recognizes engine failure. It may be that yawing motion and lateral acceleration incorporated as cab motion would help. It also is likely that better simulation of engine noise characteristics would help.

The minimum unstick speed, V_{M_U}, at various pitch attitudes. or tail clearances, was simulated, and the simulated results agreed within a few knots of the values obtained in flight tests. In fact, the time histories of velocity, pitch attitude, elevator force, and tail clearance were quite similar to those of the flight test airplane under the same test conditions and when flown in the same manner. Of particular interest is the necessity to accomplish the acceleration to V_2 within ground effect after lift-off at relatively low thrust-to-weight ratios both in the simulator and actual flight tests. In the simulation as first set up there was a distinct lack of stall buffet noise and the vibration that characterizes the actual V_{M_U} speed on the airplane, and the pilots objected to this lack. This was later introduced to a certain extent by installing a control column shaker and by programming in random vibrations to a pneumatic pilot seat cushion. These additional cues added a distinct improvement to the realism of simulating piloting an airplane at minimum unstick speed in the opinion of the pilots, and would probably be a necessary addition to the simulation if realistic determination of minimum unstick speed is to be determined by simulation in advance of actual flight tests.

The pilots said the continuous take-off maneuver on the simulator was realistic to a certain extent, but that lack of motion in the simulation was a deficiency and that more realism was desired. With the simulation as set up, there was a distinct lack of feeling of proper speed when moving down the runway, resulting from the lack of the near visual field out the front quarter and side windows. The longitudinal acceleration motion cue, of course, was not present. A notable addition to the feeling of motion was given to the pilots by providing a pulse to the pilot's pneumatic seat cushion each time the simulated aircraft passed over one of the divider or tar strips separating the standard 25-foot squares of runway concrete. Another addition to realism that the pilots liked was the use of an engine-sound generator, which although not authentic jet noise was definitely missed if switched off. Engine sound was simulated by "white noise" only, and was commanded in intensity by the engine RPM.

In summary, it has been stated without qualification by the FAA representative in this study program that if programs of this type had preceded the certification programs of all the subsonic jets, many hours of flight test and much risk could have been avoided, and that the actual demonstrations would have been much more to the point insofar as examining critical conditions is concerned. Studies in this area are continuing. It appears from the results of the investigation that simulation equipment for this type of simulation requires sophistication in certain respects. Motion cues would be helpful, aural cues are needed, and control system characteristics have to be fairly accurately simulated. Precise definition of ground effect is a requirement.

STOL TRANSPORT HANDLING QUALITIES IN LANDING APPROACH

As noted in reference [38], flight tests have been made of a Breguet 941 STOL airplane in a cooperative program of the NASA with the French Air Force and the Societe Anonymes des Ateliers d'Aviation, Louis Breguet. As part of the cooperative program it was agreed a simulation of the Breguet 941 would be set up on simulation equipment at Ames so that design variables relating to STOL flying qualities in general, and also to the Breguet 941 in particular, could be investigated to better understand STOL flying qualities optimization and acceptable lower limits, and to determine possible improvements to the airplane.

Nature of the Simulation

Simulation equipment.- A cockpit with some limited movement was available for this simulation that was not available at the time of the NC-130B STOL airplane simulation investigation of reference [39]. The cockpit used is shown in Fig. 14. It has a screen in front of the cockpit that moves with the cockpit and on which the television projector, mounted on the rear of the cab, projects the scene of the runway during approach and landing as generated by the equipment shown in Fig. 7. Prior to this investigation some question had existed as to how to incorporate a visual scene with a moving cockpit. This has not turned out to be a problem. Although the projector rolls and pitches with the movement of the cockpit, the computer is programmed to roll and pitch the picture in the opposite direction as may be required by motion washout so that to the pilot the horizon in the picture remains steady. The cockpit movement is limited to 9° roll to either side, to pitch motion of $+14^\circ$ and -6°, and to a very small amount of heave.

A major problem in the use of simulator motion was that of programming the 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 are used, which are typical of STOL operation, 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. It required 13° of commanded bank angle for the cab to reach its stops at 9°. However, this was not entirely satisfactory, since the pilots often desired to use bank angle in excess of 13°. It would seem likely that what is required here 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, then the washout of the lateral movement and bank angle becomes a problem. As indicated in the study of reference [40], however, some initial study of the combination of lateral travel with bank angle to obtain more realistic motion was carried out with acceptable results using the Ames five degree motion simulator shown in Fig. 2 in studying the handling-qualities requirements of supersonic transports in high-speed cruising flight. This is an area requiring further investigation. The pilots felt that the lack of yaw motion was a real deficiency in the simulation and should have been incorporated to more effectively study the lateral-directional problems of STOL operation at low speeds. Ames is now building a six degree of motion simulator, as shown in Fig. 15, having in mind that it would be required for valid study of many VTOL problems. It is hoped that STOL studies made on this simulator will identify critical motion and motion washout requirements for STOL simulations as well.

Figure 16 shows the simulator cockpit interior arrangement used. It is apparent that the Breguet-type control stick and left-hand throttle control have been installed in the typical transport cockpit. The cockpit also included the angle-of-attack indicating lights above the instrument panel as well as normal instrumentation. This duplication was found to be absolutely necessary before the pilots could "fly" satisfactorily the simulation and examine the effects of changing various aerodynamic parameters of the design.

Parameters used.- It was planned from the start to make full use of the flight data and opinions of the pilots who flew the airplane to make the ground simulation correspond as truly as possible to flight of the real airplane.

There was considerable thought and discussion spent in arriving at what was deemed to be the correct value of yaw damping used in the simulation. Yaw damping values as determined in flight from rudder pulse maneuvers were about two times as large as determined from the damping in yawing oscillations. Since the response to rudder input seemed more important in the flight conditions being investigated, the damping as determined from a rudder step was used, and with this value the simulated airplane was rated by the pilots as being very nearly the same as the airplane.

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. 17. 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 shown in Fig. 17 that the simulated airplane was regarded as flyable and reasonably simulating the airplane.

Pilot familiarization.- The pilots who flew the simulator also had flown the airplane. Familiarization time with the simulator was required, however.

Duplication of a flight task.- Task criteria chosen called for the pilot to fly an IFR approach using ILS glide path set for a 7-1/2° STOL approach to 250-feet altitude where the outside world runway came into view and then make a VFR landing, sometimes after making a series of S turns over the runway. At initiation of the IFR approach the pilot was required to correct for a 170-feet offset due to localizer error, and when the runway came into view, the pilot had to correct back 170 feet to land on the centerline of the runway. Figures 18 and 19 show time histories of two of these approaches. These time histories are for a configuration of the airplane with high adverse yaw which the pilot considered unacceptable for normal operation. Figure 18 is with the motion off, and Fig. 19 is with the motion on. With motion off during the ILS portion, it was impossible for the pilot to perform the task; he devoted his complete attention to controlling the large bank angle and sideslip excursion. However, when he became VFR, he was just able to gain control and make a successful landing. Figure 19 shows the same task with the motion on. In this case 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 performing the landing. As contrasted to the tests on the NC-130B BLC airplane (ref. [39]) on which simulation runs were made with a fixed cockpit at 70-knots speed, in the Breguet 941 simulation, tests were made at 58-knots speed, and at this slower speed cockpit motion was found to be mandatory for performance of simulation tasks with any degree of validity.

The evaluating French pilots, who had many hours and many landings in the Breguet 941, felt that once the task was determined, a large variation in parameters could be tested. During the tests, as parameters were being changed at random, the basic configuration would be inserted every few runs without the pilot knowing it. It was interesting to note that the pilot rating of this basic airplane changed very little during the whole series of tests for the pilots who were very familiar with the airplane. Their rating of the basic configuration on the simulator was the same as on the airplane.

Discussion of V/STOL Simulation

Figure 20 shows the type of results obtained in the simulation of the Breguet 941. These data were obtained to determine which lateral-directional parameter made the most significant improvement. The results are very similar to those of reference [39], which showed that sideslip rate damping was the most effective parameter in improving lateral-directional handling qualities. Although results were obtained that were of value, the strong influence of motion simulation of the simulation of V/STOL aircraft was shown. Problems of banking were indicated that might be resolved if a simulator were used that had a long lateral travel, so that side acceleration could be combined with bank to give a more realistic simulation of flight motion.

CONCLUSIONS

I have listed four factors important to simulation validity, (1) simulation equipment, (2) parameters used, (3) task criteria, and (4) pilot familiarization. Several simulation studies were compared with flight results in terms of these factors. It was shown that in jet transport landing studies the external visual scene and task criteria were the important factors related to obtaining results comparable to flight results. In take-off certifications studies motion cues, aural cues, cockpit sophistication, and exact ground effects parameters are of importance. Task criteria were already defined by regulation, or the investigation itself could be one of the determination of better criteria. In STOL transport handling qualities studies in landing approach, simulator motion requirements were very important, as was correct duplication of the aircraft control system characteristics, and cockpit instrumentation. 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 is required to adequately study lateral-directional problems of STOL operation at low speeds.

APPENDIX

NOTATION

a	aileron position, radians or degrees
b	wing span
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
C_{L_∞}	lift coefficient in the absence of ground plane influence
C_m	pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$
C_n	yawing-moment coefficient, $\frac{N}{qSb}$
C_{n_p}	$\frac{\partial C_n}{\partial(pb/2V)}$, per radian
C_{n_r}	$\frac{\partial C_n}{\partial(rb/2V)}$, per radian
C_{n_β}	$\frac{\partial C_n}{\partial \beta}$, per radian
$C_{n_{\dot{\beta}}}$	$\frac{\partial C_n}{\partial(\dot{\beta}b/2V)}$, per radian
$C_{n_{\delta_a}}$	$\frac{\partial C_n}{\partial \delta_a}$, per radian
N	yawing moment, ft-lb
p	rate of roll, radians/sec
q	free-stream dynamic pressure, lb/ft^2
r	rate of yaw, radians/sec
r	rudder position, radians or degrees
S	wing area, ft^2
V	velocity, ft/sec
β	sideslip angle, radians or degrees
$\dot{\beta}$	rate of change of sideslip, radians/sec
φ	angle of bank, radians or degrees
ψ	yaw angle, deg

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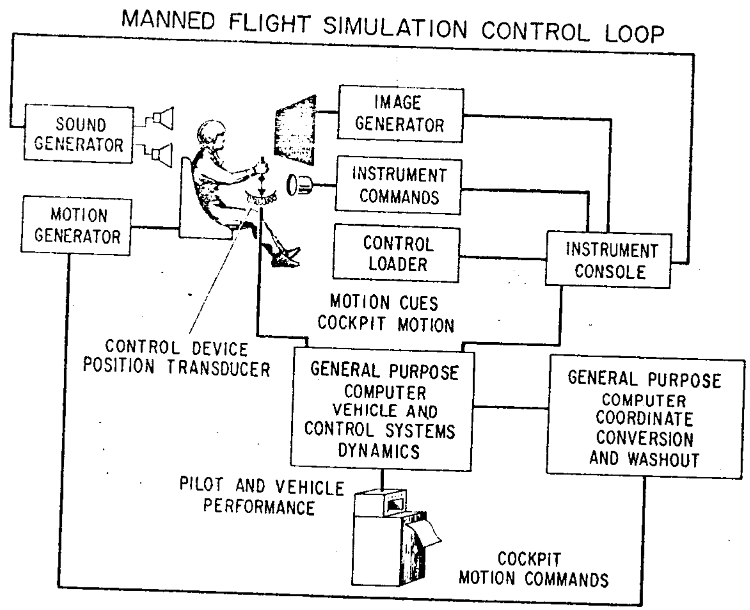
MANNED FLIGHT SIMULATION CONTROL LOOP
SOUND GENERATOR
MOTION GENERATOR
IMAGE GENERATOR
INSTRUMENT COMMANDS
CONTROL LOADER
INSTRUMENT CONSOLE
MOTION CUES
COCKPIT MOTION
CONTROL DEVICE
POSITION TRANSDUCER
GENERAL PURPOSE COMPUTER VEHICLE AND CONTROL SYSTEMS DYNAMICS
GENERAL PURPOSE COMPUTER COORDINATE CONVERSION AND WASHOUT
PILOT AND VEHICLE PERFORMANCE
COCKPIT MOTION COMMANDS

Figure 1.

Figure 2 Piloted simulator having five degrees of motion freedom, as revised with removable cab.

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CLASSIFICATION OF PILOTED SIMULATORS

	Rudimentary	Basic	Advanced
Application	Handling qualities	Minimum acceptable handling qualities Operating problems Cockpit display effectiveness	Closer definition and solution of operating problems Minimum acceptable handling qualities Certification aspects
Results	Qualitative	Qualitative and quantitative, relatable to flight	Quantitative, directly applicable to flight
Task complexity	Generally part task	Part task and whole task	Whole task, complete mission capability
Sophistication and realism	Minor	Fairly complete;- cockpit instrumentation, external visual display, and motion as required	Maximum feasible
Method of evaluation	Subjective pilot opinion from pilot initiated tasks	Subjective pilot opinion plus task performance	Primarily task performance based on fairly complete criteria

Figure 3

FACTORS AFFECTING SIMULATION VALIDITY

1. Nature of the simulation equipment
   (a) external visual simulation
   (b) motion simulation
   (c) cockpit interior items, instrument displays, control system, etc.
2. Accuracy of parameters used
3. Correct duplication of the flight task
4. Pilot familiarization with the simulator and the task

Figure 4

COMPARISON OF JET TRANSPORT LANDING PERFORMANCE
FOR FLIGHT AND SIMULATOR LANDINGS

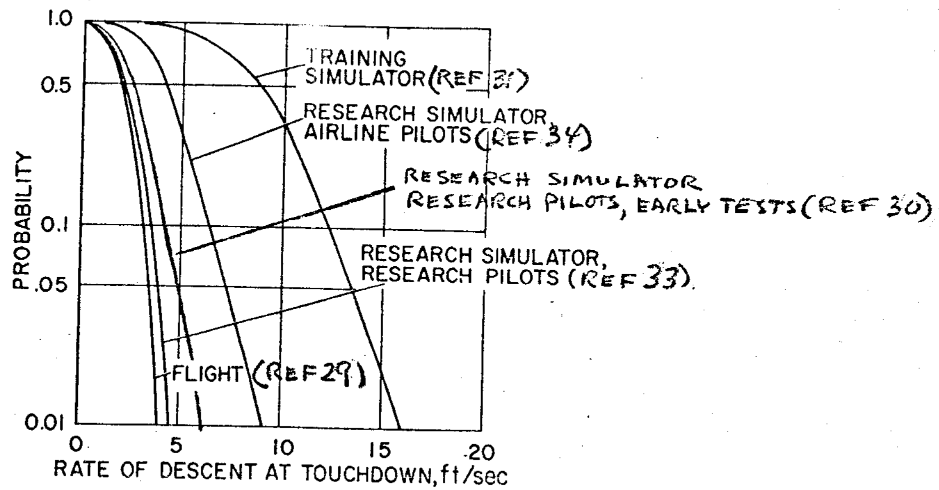

Figure 5

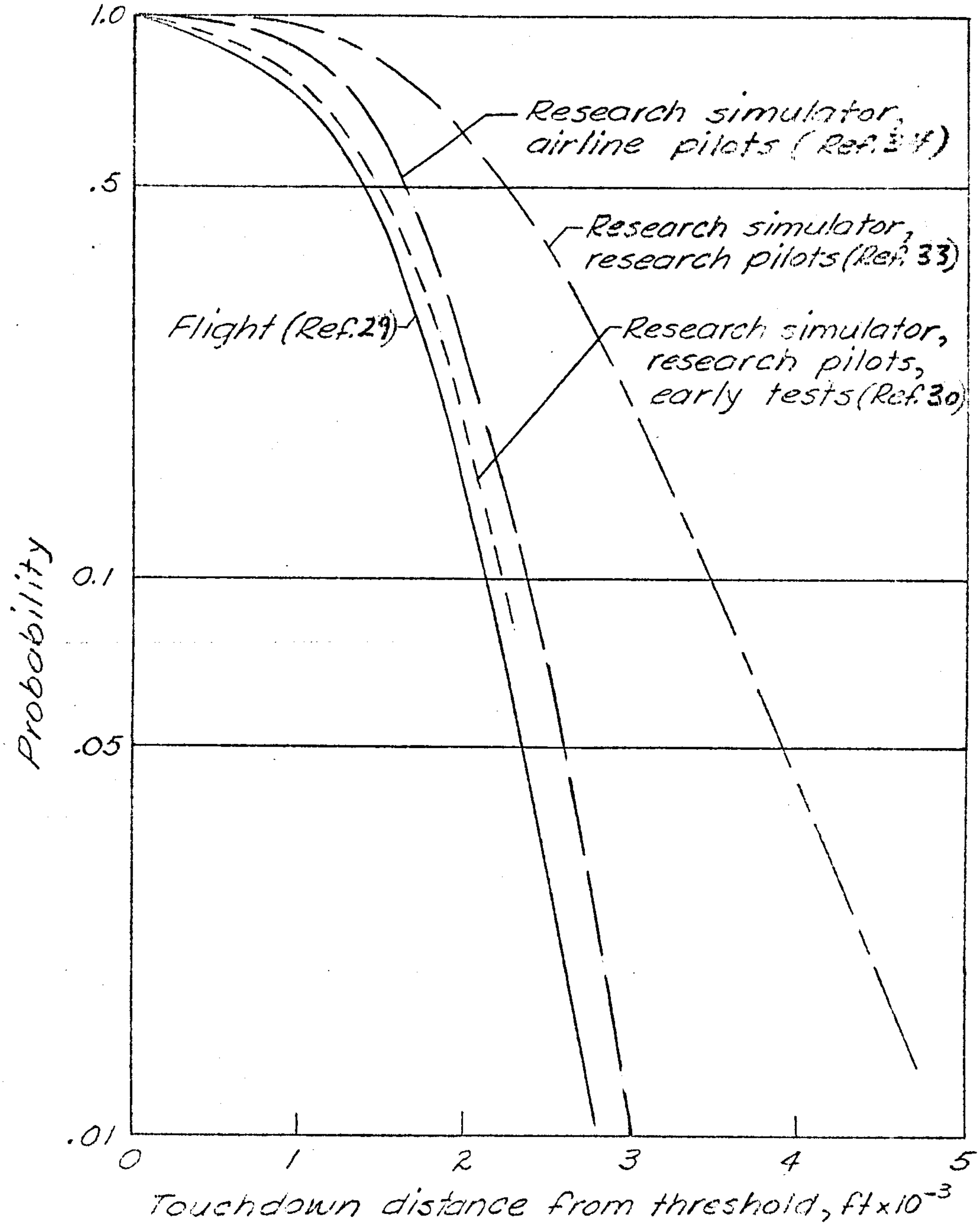

Figure 6.— Comparisons of jet transport touchdown distance for flight and simulator landings.

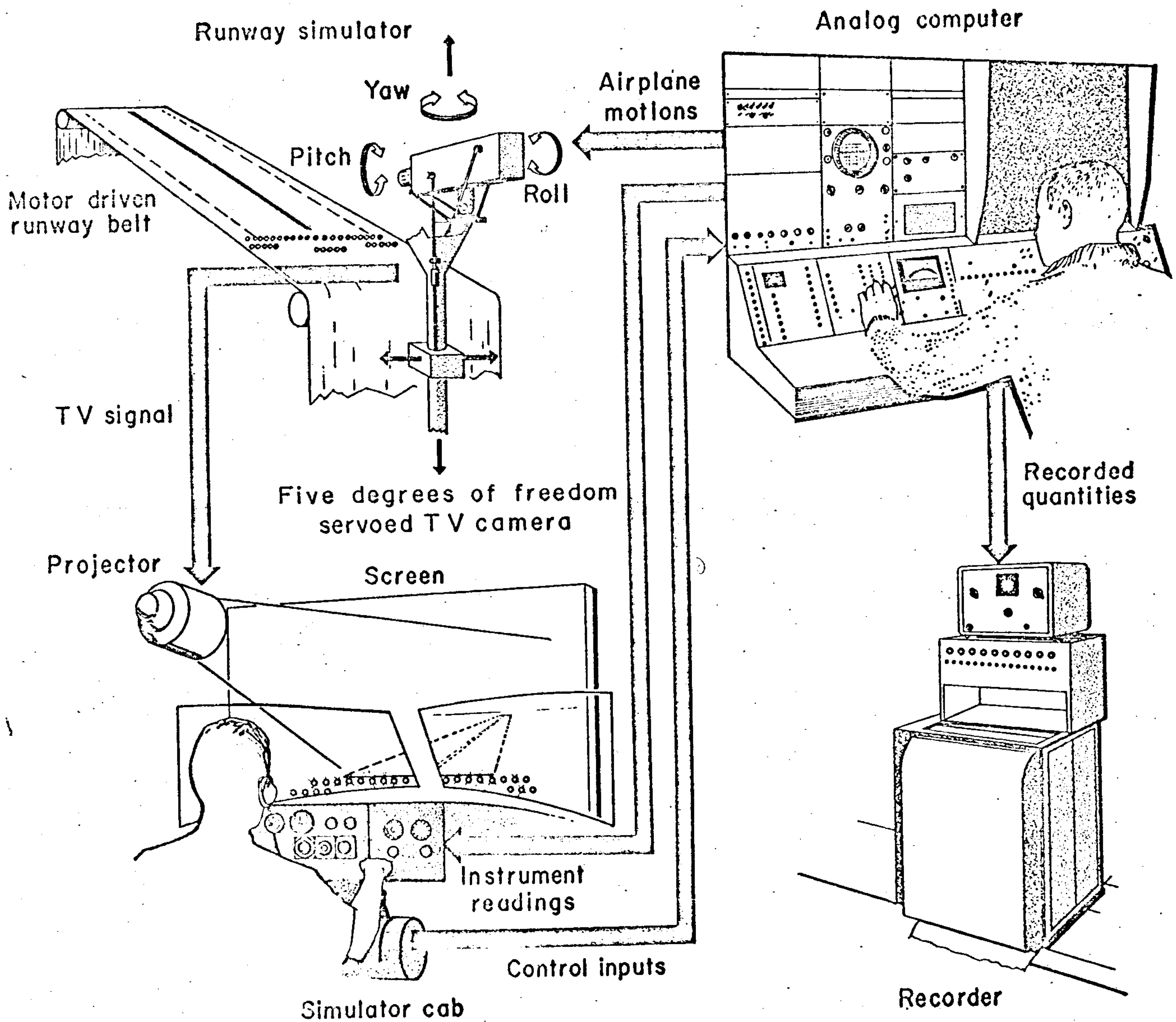

Figure 7.- Pictorial block diagram of the landing approach simulator.

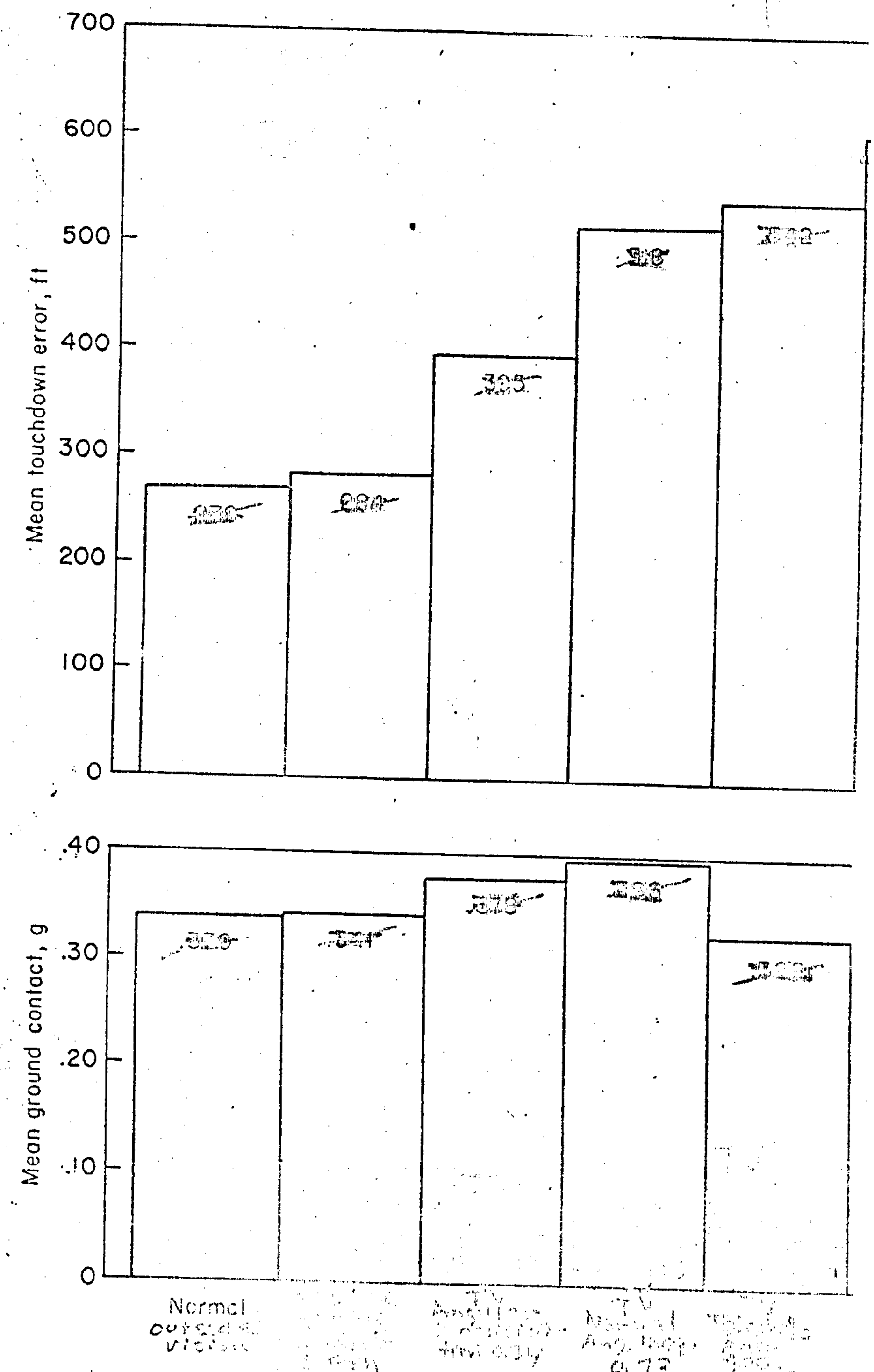

Figure 8.- Comparative mean values for touchdown error and contact g. for landings

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INSTRUMENT DISPLAY AND VISUAL VIEW OF RUNWAY
IN LANDING APPROACH SIMULATOR

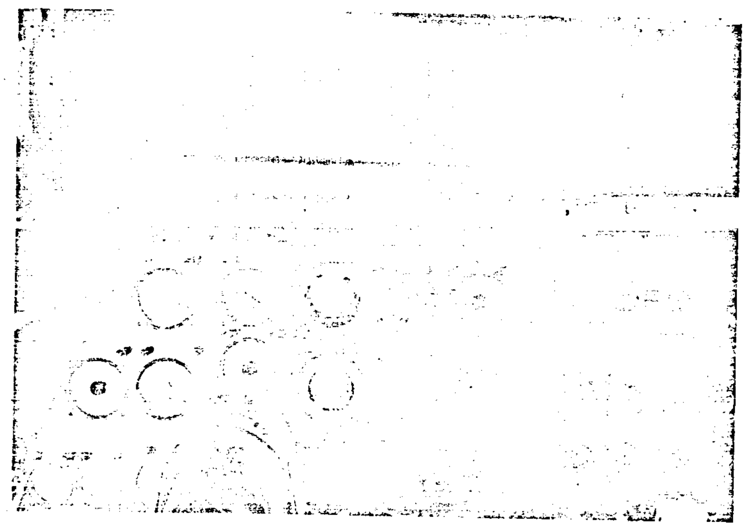

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Figure 8 9

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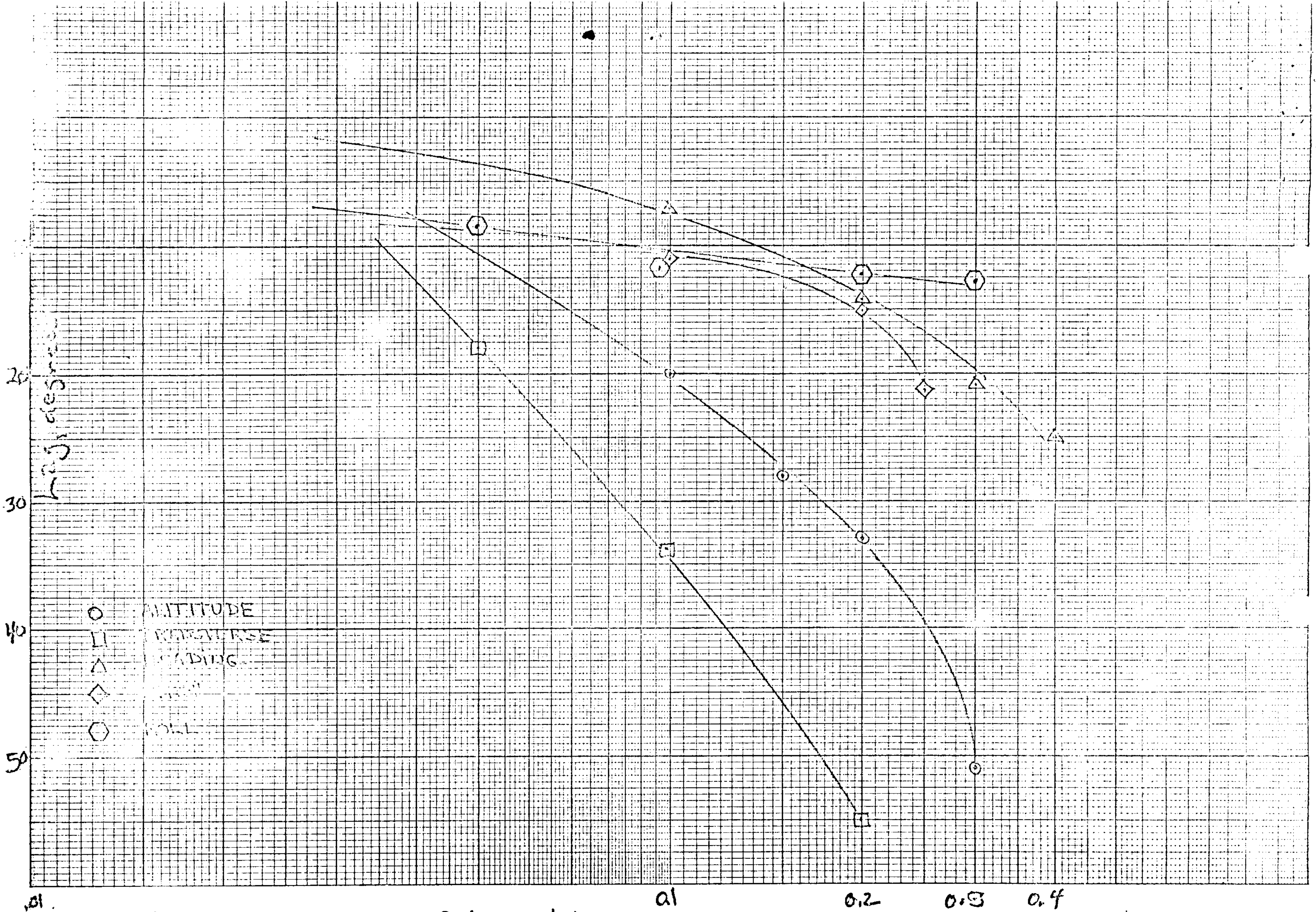

Figure 10. Frequency response of Ames television camera drive system

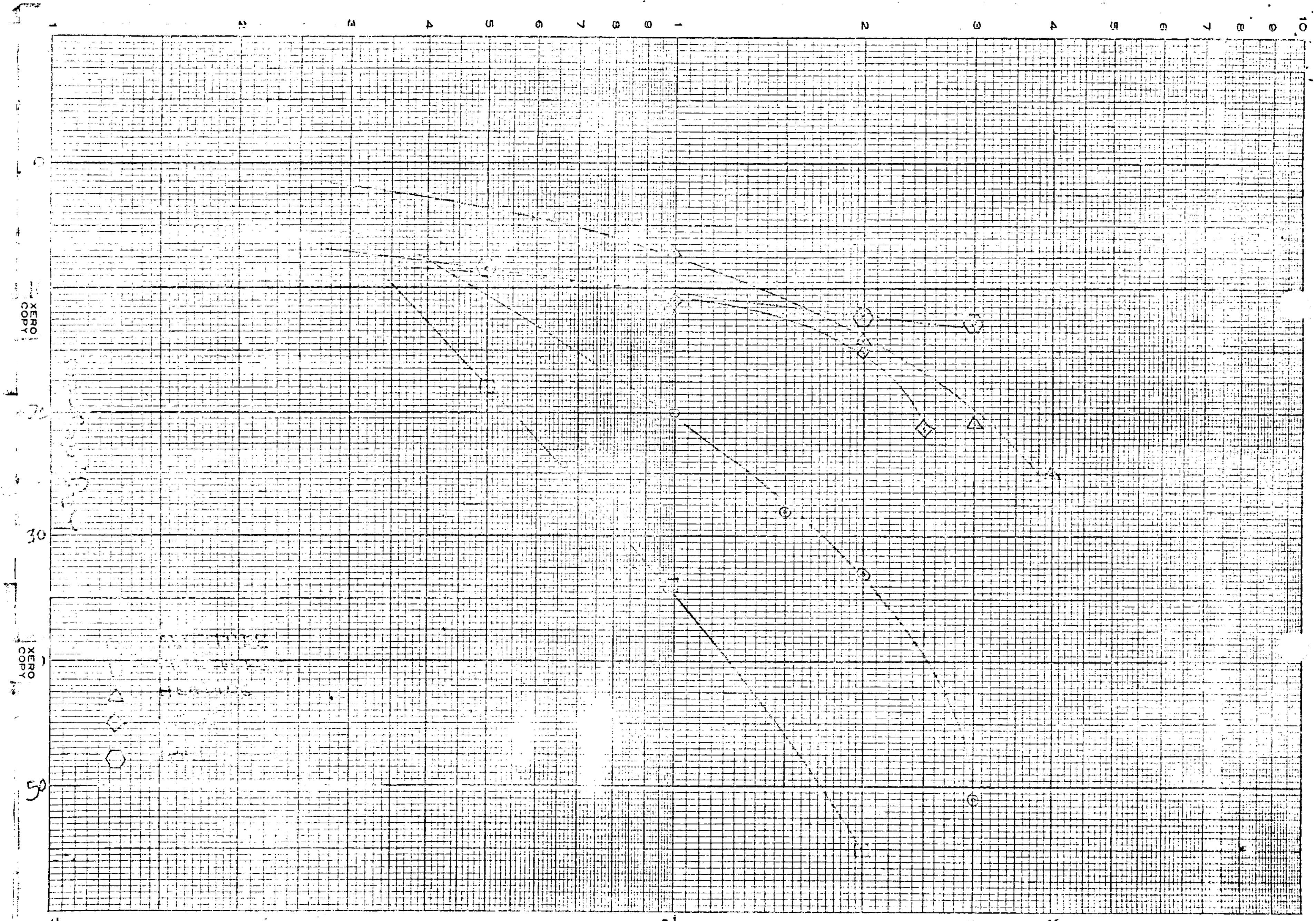

Figure 1a, Frequency response of Ames television camera drive system

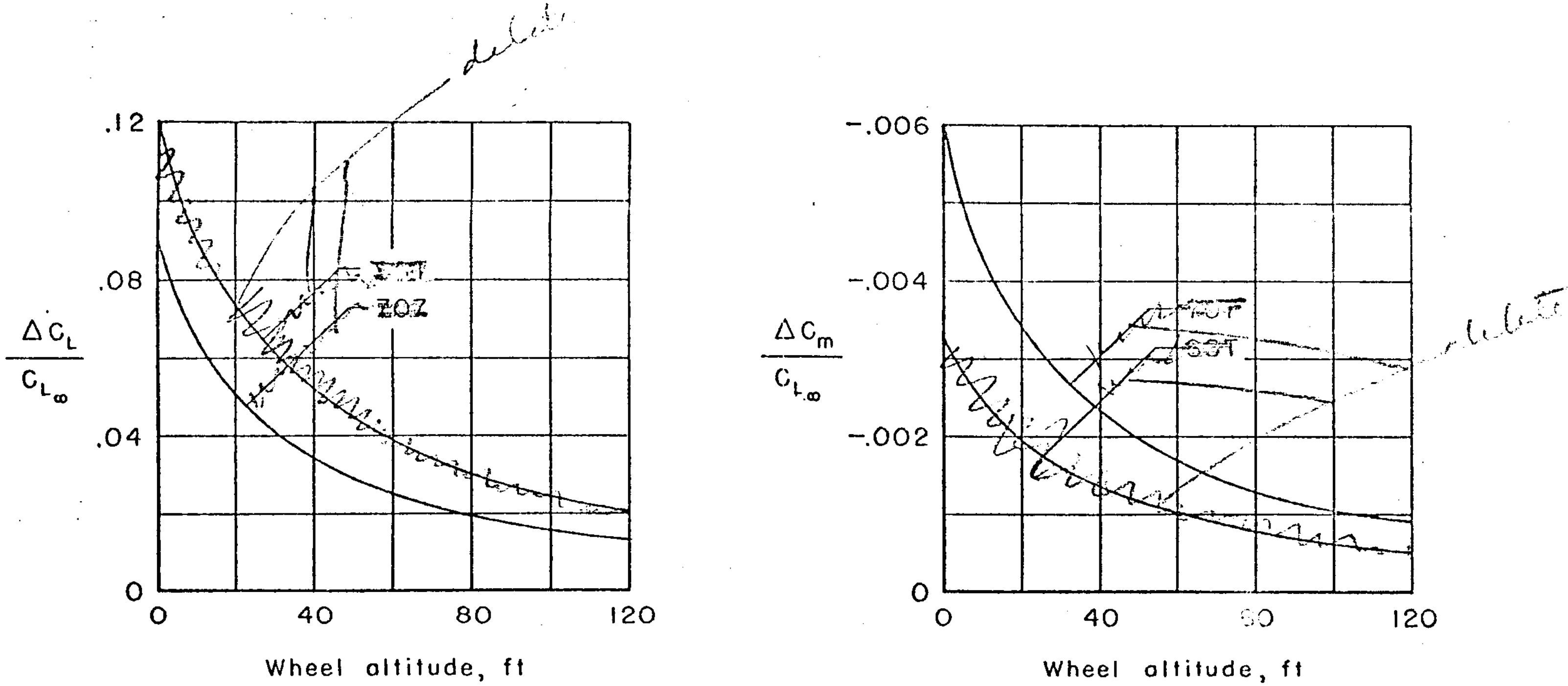

Figure 11.- Effect of presence of the ground plane on the aerodynamic characteristics of the ~~test~~ jet transport ~~configuration as~~ simulated. ~~for the landing tests.~~

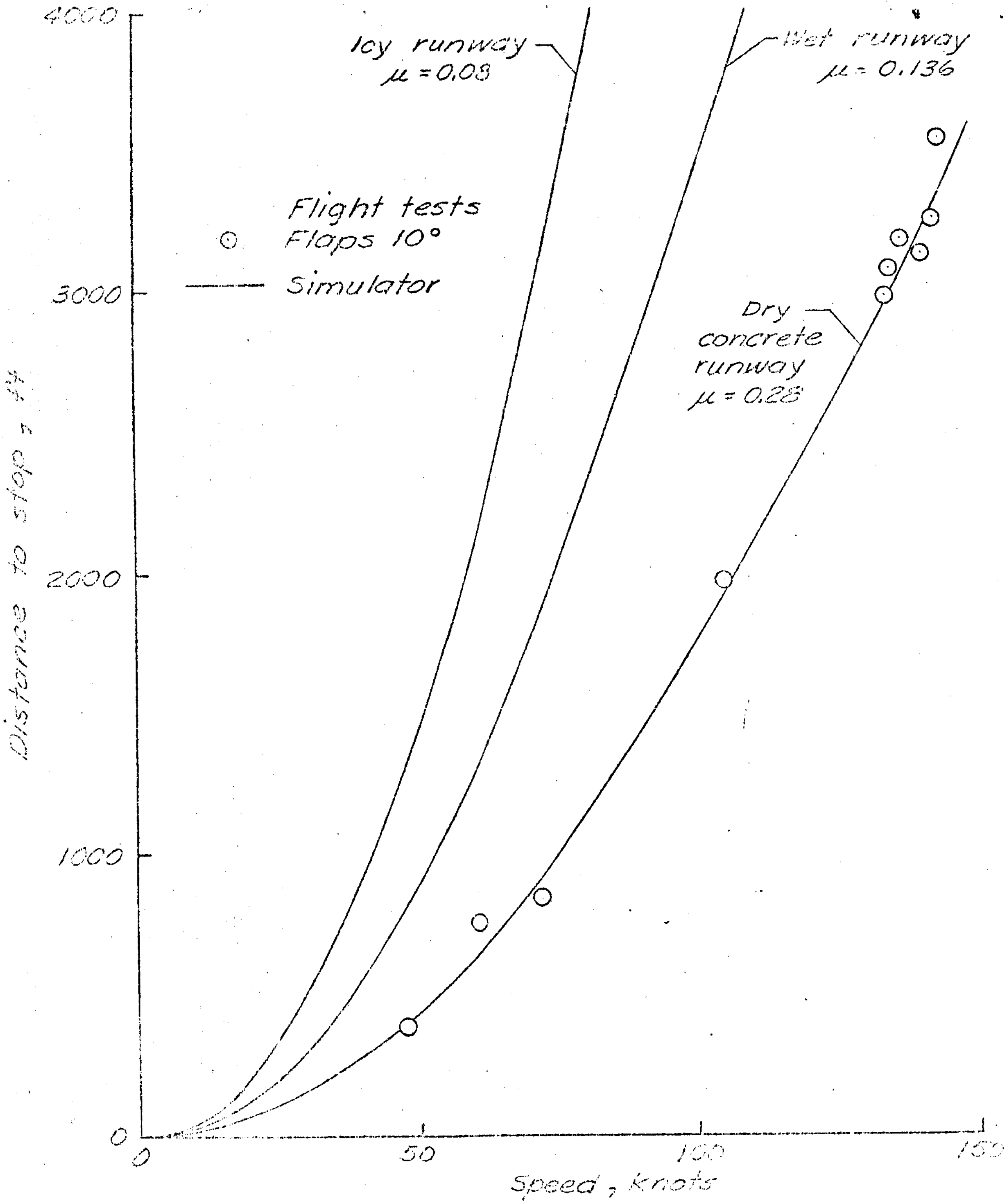

Figure 12.- Effect of runway conditions on distance to stop after engine failure on take-off.

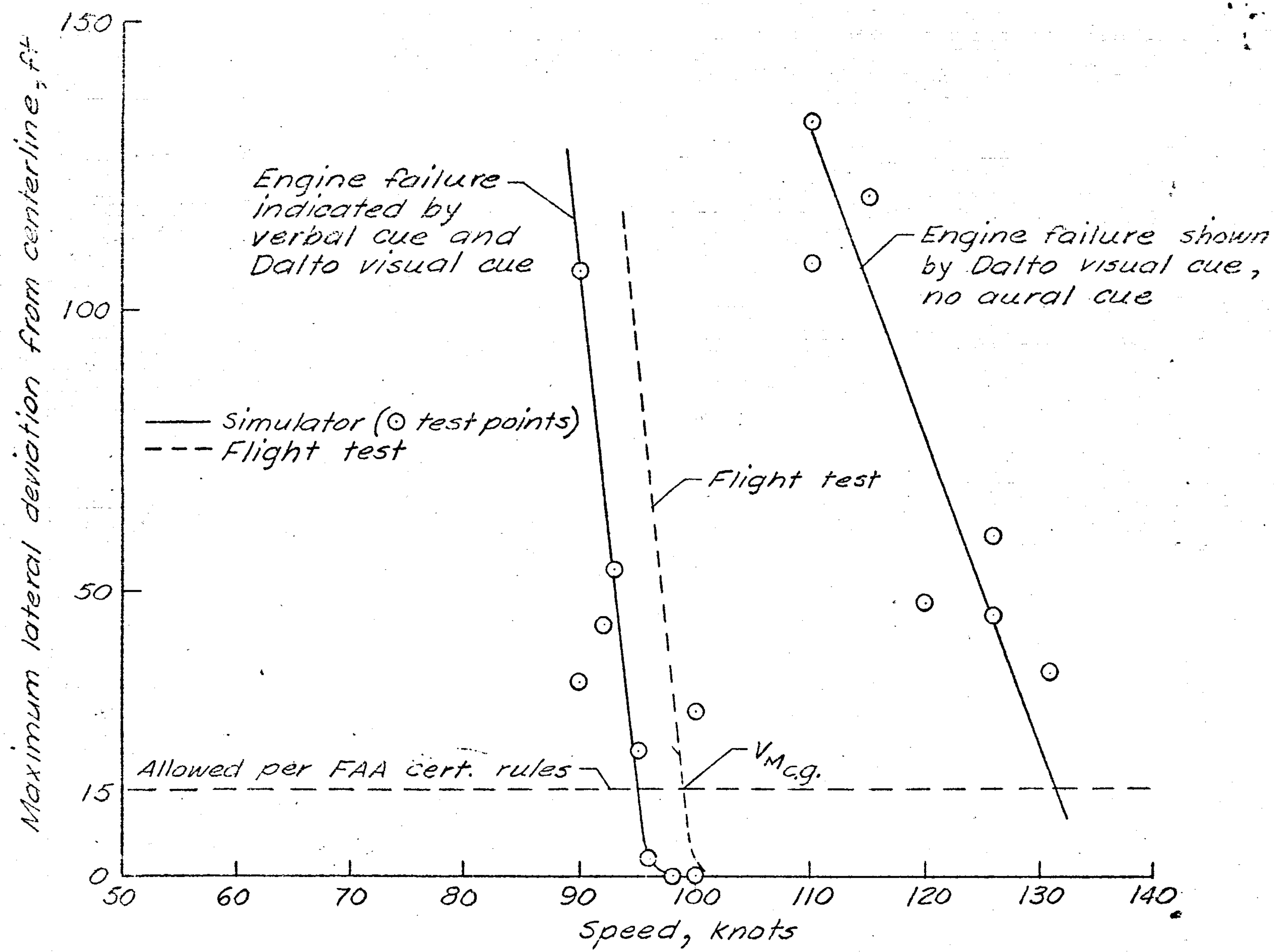

Figure 13. — Ground minimum control speed, $V_{M_{c.g.}}$, as shown by simulator and flight tests.

Figure 14. External view of cockpit used in simulation of Breguet 941 STOL airplane, showing screen on which TV scene is projected that moves with the cab.

AMES ALL-AXIS MOTION GENERATOR

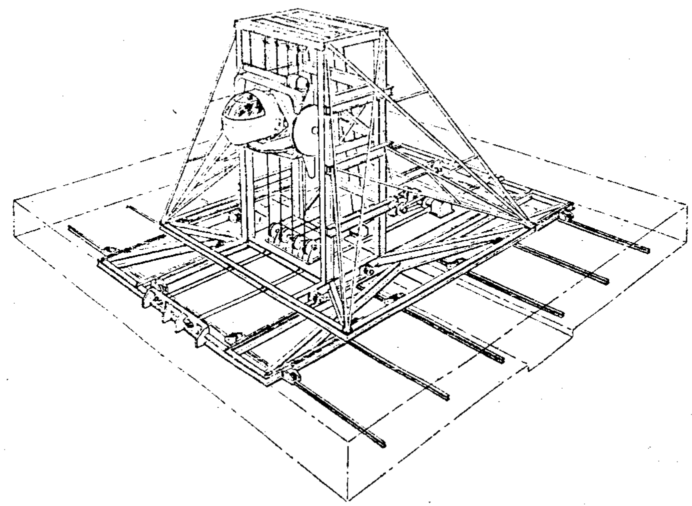

Figure ~~8~~. 15

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COCKPIT INTERIOR FOR BREGUET 941 SIMULATION

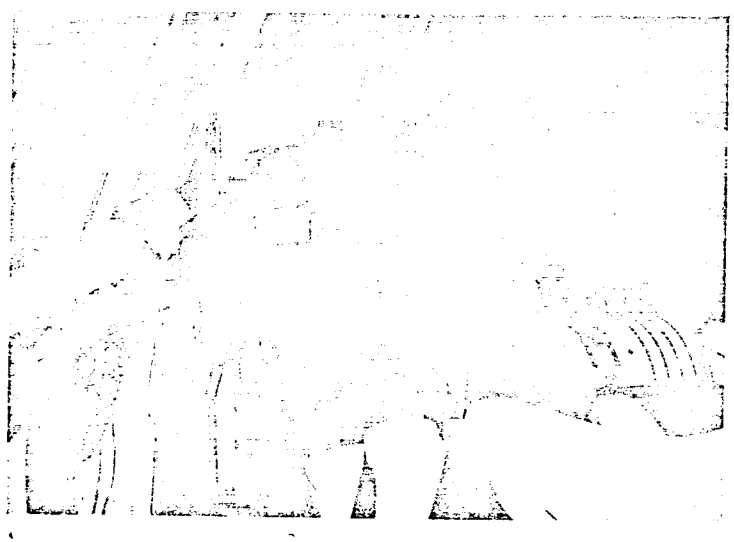

Figure ~~X~~. 16

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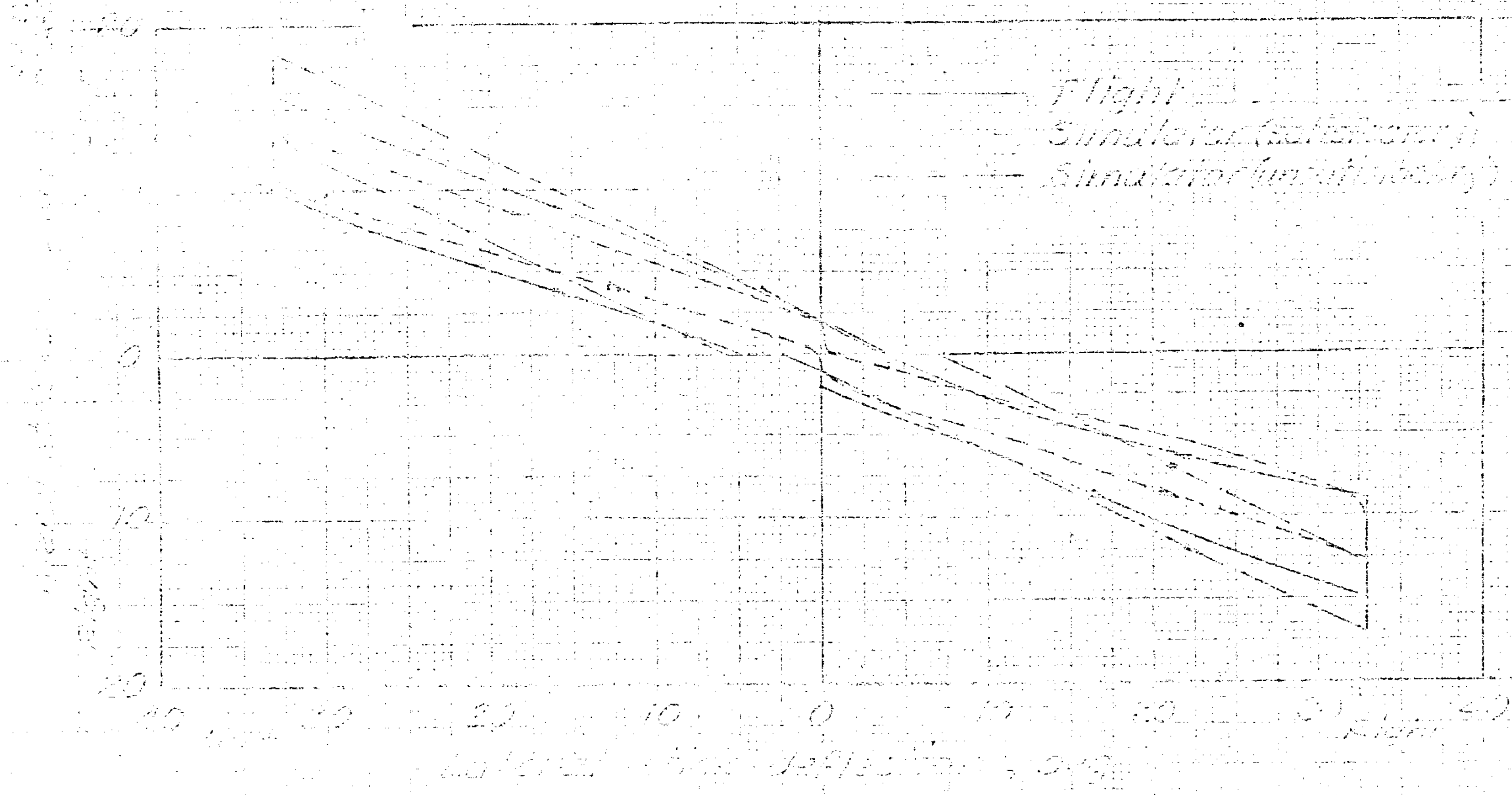

Figure [illegible].- Lateral control system qualification required for [illegible] simulation of Breguet 941 STOL airplane.

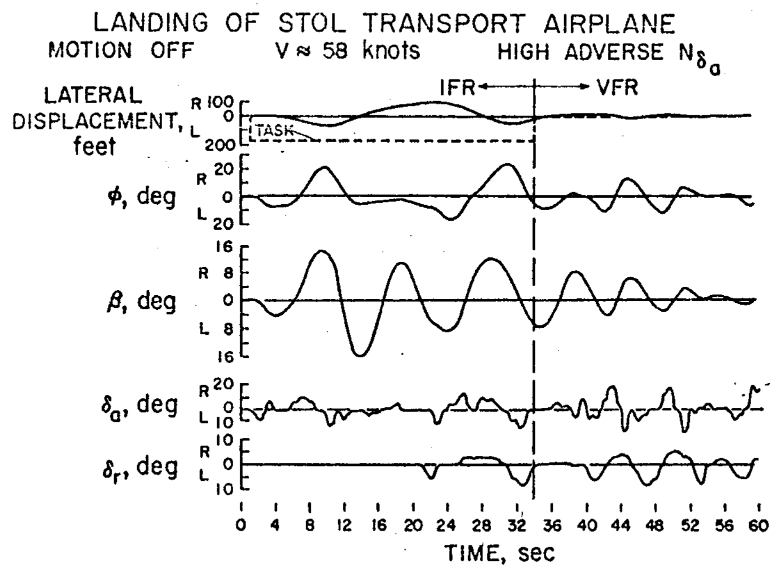
LANDING OF STOL TRANSPORT AIRPLANE
MOTION OFF
V ≈ 58 knots
HIGH ADVERSE N_{δ_a}
IFR
VFR
LATERAL DISPLACEMENT, feet
R 100
0
L 200
TASK
ϕ, deg
R 20
0
L 20
β, deg
16
R 8
0
L 8
16
δ_a, deg
R 20
0
L 10
δ_r, deg
10
R 0
L 10
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60
TIME, sec

Figure ~~7~~. 18

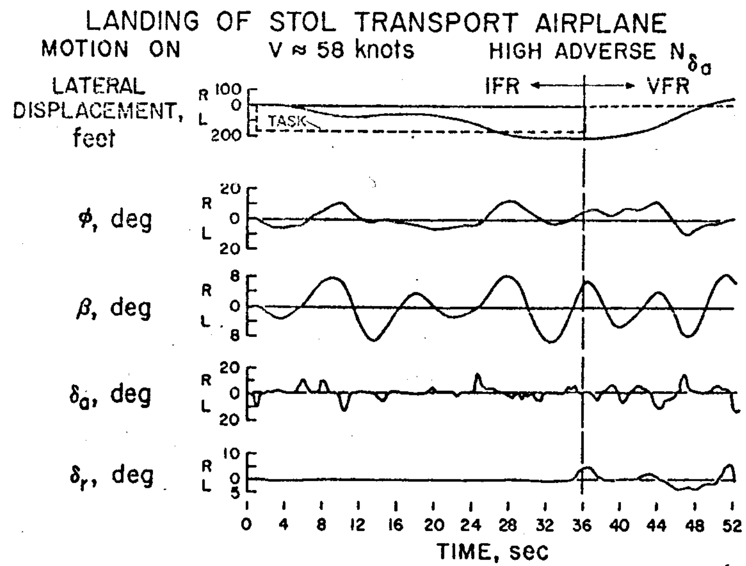
LANDING OF STOL TRANSPORT AIRPLANE
MOTION ON
V ≈ 58 knots
HIGH ADVERSE N_{δ_a}
LATERAL DISPLACEMENT, feet
R
L
100
0
200
TASK
IFR
VFR
φ, deg
20
0
20
β, deg
8
0
8
δ_a, deg
20
0
20
δ_r, deg
10
0
5
0 4 8 12 16 20 24 28 32 36 40 44 48 52
TIME, sec

Figure ~~8~~. 19

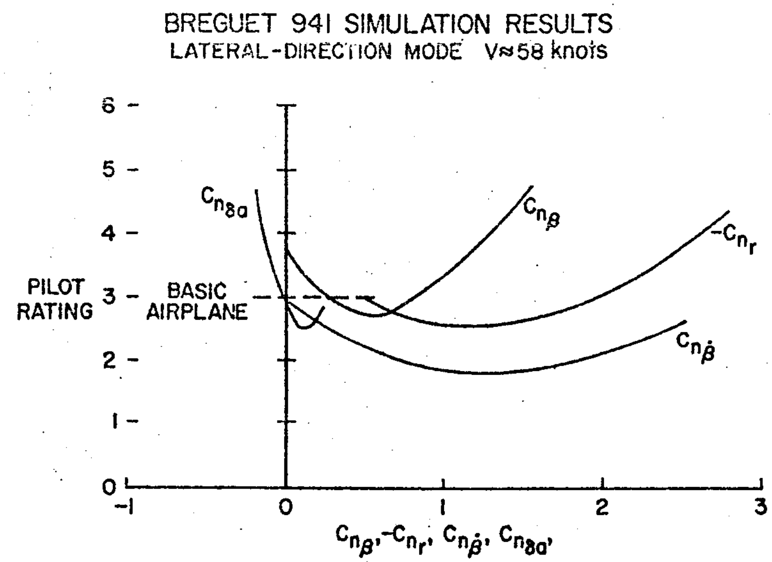

Figure ~~16~~. 20

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