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Man-Machine System Simulation for Flight Vehicles*

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Summary—A procedure for conducting a meaningful simulation of a man-machine system is presented and illustrated by various specific examples. The relationship of the various types of simulators to their use is outlined and desirable detailed characteristics are delineated. The tradeoffs between simulator complexity, realism and the interrelation of various feedback sensing cues (motion, visual or tactile) are discussed and the necessity of validating the simulation by use of a variable stability and variable control system aircraft is noted. It is shown that as the problem to be studied becomes more complicated or the questions asked of the simulation become more quantitative, the simulator characteristics must become more flight-like, since in the last analysis the best place to ask the question is when the pilot and the vehicle are immersed in the true environment (*i.e.*, flight).

Introduction

IN ANY SYSTEM that is to be operated by man the system element being controlled must respond in some desired manner to the man's (operator's) wishes. In addition, some restraint must be placed on the characteristics of the controlled system so that it will not destroy the operator. To guarantee these necessary properties of the integrated system, it is desirable to assess at the earliest possible stage of the design the effectiveness and compatibility of man's control over the system.

This compatibility can be investigated both analytically and experimentally. As in most engineering activities, a combination of techniques is most appropriate. However, analytical predictions are limited in their scope to only a few of the many tasks involved in man-machine systems (*e.g.*, tracking operations), so an empirical approach is inevitably the primary technique used when overall system evaluations involving may part tasks are required. Still, analytical studies of man-machine systems are handy adjuncts to a predominantly empirical program, especially in initial planning and during the final stages of data interpretation. Such studies are particularly helpful in the original identification of potential problems.

The ideal experimental approach, in application, requires control of the process to be studied to the extent that one can systematically define problem areas, identify significant variables, and assess the effects of these variables on the over-all system and its degree of acceptability. For man-machine system studies involving complex machines and diverse tasks, this ideal experimental approach is difficult to attain. The most fruitful way out of many difficulties introduced by the over-all complexity is the use of highly skilled experts as the active human element in the system—thereby introducing, as it were, an additional experimenter into the actual experimental situation. This procedure has some serious practical and theoretical deficiencies, but these are more than offset by the expanded scope of experimental activity. Especially in flight vehicle systems, the use of expert pilots as measuring and problem defining "instruments" is time honored, and has been the main way the man-machine compatibility problem for such vehicles

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has been attacked. This approach will be taken as axiomatic in what follows. Also to be considered axiomatic is the use of physical models to define the response characteristics of the machine. In the flight vehicle field this machine model is termed a "flight simulator." These simulators have been successfully used for years both as experimental devices and as trainers [1], [2].

The use of simulators to aid the designer must be viewed in the same light as the use of any model, whether structural, aerodynamic, or other, to provide the necessary information for design purposes while the design decisions are being made. A classical example of this process is the technique used by the Wright Brothers in the designing of their successful airplane (see Fig. 1). The Wrights' testing phase involved testing of models in a wind tunnel as well as flying unpowered gliders to investigate the pilot control problems. As they uncovered problems solutions were worked out and the machine redesigned. Here the man-machine problem was solved in full scale flight. Today a similar full scale procedure would be economically and temporally impossible.

Using models or simulators expedites the experimental approach by replacing the vehicle with analog elements, as can be seen by reference to Fig. 2. This block diagram also indicates other relationships that must be considered during the design process. In this simulation process we must use man himself as the *controlling element*—not a mathematical representation of him. What we want to do is to present the problem to the pilot-experimenter in such a form that he can identify and assess its specifics, and give us a subjective rating of his ability to carry out the analogous problems in flight [3]. We must be able to represent the response characteristics of the machine (controlled element) and to vary them at will; we must also be able to control those factors represented by extra vehicular disturbances. The vehicle response quantities must be fed back to the operator in such a fashion as to readily indicate the status of the vehicle and to provide the necessary cues for conducting the required task. These response quantities fall in the categories of visual, kinesthetic and aural cues. In addition, the environment stress effects must be included to properly represent the requirements of the task or mission.

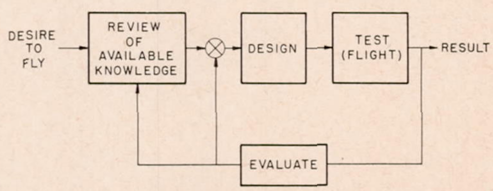


Fig. 1—Technique used by the Wright Brothers in designing their airplane.

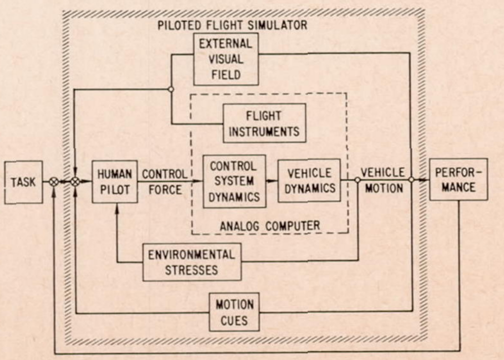
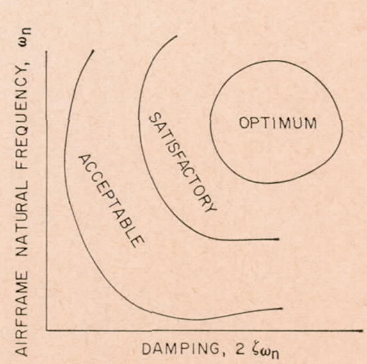


Fig. 2—Block diagram of piloted flight simulator.

This paper discusses ways of achieving these ends from a general point of view, noting that they must be based on use of a highly motivated subject with experience as an experimental test pilot to provide the subjective information required.

Preliminary Analysis

In designing vehicles that are to cope with large variations in the operating environment, such as aircraft or spacecraft, it is necessary to consider the effect on the human pilot of the variation of the vehicle's response characteristics over its operating envelope. To decide whether these response characteristics are acceptable from the pilot's standpoint, they must be interpreted in terms that can be applied directly to the human. This is accomplished in a rough sort of a way by considering the vehicle response characteristics as functions of time and expressing the response characteristics in terms of those quantities that directly affect the pilot's assessment of the motion. These include such things as angular and linear accelerations, rotational velocities, etc., as well as the time dependence of the motions and the interactions of all the forces imposed on the pilot. For example, the longitudinal stick-fixed response characteristics of an aircraft are approximated by a fourth-order constant-coefficient linear differential equation. This equation describes motions which are ordinarily the combination of two oscillations, so it can be factored into two second-order equations which can be expressed in terms of gains, natural frequencies and damping ratios. These latter quantities are the actual dynamic descriptors of the vehicle. Generalized experimental and/or analytical determinations of the allowable ranges of these factors for various tasks have built up a body of knowledge that enables the designer to predict whether the expected operation of his vehicle is close to or far away from regions of unacceptability and to spot the vehicle characteristics on a diagram of the type shown below. This approach has led to definitions



of flying qualities requirements on a static and dynamic parameter basis [4]–[10].

If, for all expected conditions, the characteristics of the vehicle are in a good area well away from the unacceptable boundary, then adequate performance is assured and there is no need to conduct further simulation; however, if the expected characteristics are close to a boundary, then the precise task to be performed by the pilot must be considered before the location of the boundary can be determined. In other words, the general shapes of the boundaries can be determined from a simulation and analysis of the problem on a generalized task basis but precise definition of boundaries is dependent on the exact task expected. So, in those cases where comparable operational experience exists, or prior simulation has defined or mapped the regions of acceptable or unacceptable behavior, simulation should be used with an objective mind to investigate those areas of operation where predicted operation indicates expected concern. Otherwise, only the general shapes of the boundaries can be determined from simulations of the problem on a generalized task basis.

Basic Technique

In those cases where a simulator is to be used to define new problem areas, or to investigate old problem areas under a new task definition, the problem must be set up so that a logical attack can be made. This requires that the formulation of the problem should provide fidelity of the dominant interrelationship of all active elements including the human operator. The overall objectives of the problem should first be clearly stated. From these objectives the experimental team composed of the designer and the operator will be able to determine the area of application of the results and the desired nature of the results (whether qualitative or quantitative). These considerations lead to an indication of the task complexity required to define the problem and of the type of simulator that must be used.

It has been found possible to correlate the type of results and the application of these results with the complexity of the task required to provide proper evaluation and with the simulator complexity. This correlation has been made in a paper by Cooper [1] and is presented in slightly modified form in Table I. 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 a 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 more precise and realistic (in a flight sense) type information is required, the more complete must be the simulation with the ultimate limit being reached in the actual flight situation.

Following this selection process, the actual setting up of the simulation must begin. The equations of motion defining the kinematic relationships of the system must be determined. Practical methods of setting up the equations of motion for use on analog computers are available [11]–[13]. The equipment to provide both the vehicle response computation and the vehicle response feedback information must be assembled and checked out. At the same time the test procedure is outlined by the designer working with the operator (pilot). Following a response check of the analog computational setup, the over-all simulation scheme must be validated by the operator to bridge the gap between the real life situation and the simulator situation. It is at this point that the real worth of the pilot (operator) comes to the fore—for he

TABLE I
Classification of Piloted Simulators

	Rudimentary	Basic		Advanced
Application	Handling qualities (Basic parameters) For general understanding, determination of feasibility and problem areas	Gross determination of trends Defining boundary shapes First order interrelationships Cockpit display development	Minimum acceptable handling qualities Operating problems Cockpit display effectiveness	Potentially useful for closer definition and solution of operating problems, minimum acceptable handling qualities and certification aspects
Results	Qualitative (Quantitative if sufficient elements of problem included)	Qualitative	Quantitative (Relatable to flight)	Quantitative (Directly applicable to flight)
Task complexity	Generally part task	Part task (Pilot initiated short term tasks involving discrete parts of problem)	Whole task (Specific operational longer term tasks including greater percentage of problem)	Whole task (Complete mission capability)
Sophistication and realism	Minor . . . . ➤Increasing computational complexity and degrees of freedom . . . . ➤Maximum feasible (Symbolic display) (No motion)	(Basic inst. only) (Ext. visual display and motion if avail.)	(More complete cockpit inst.) (Ext. visual display and motion as required)	(Most complete representation of vehicle)
Method of evaluation	Subjective pilot opinion from pilot initiated tasks	Primarily subjective pilot opinion from pilot initiated tasks	Subjective pilot opinion plus task performance, longer term	Primarily task performance based on fairly complete criteria plus subjective pilot opinion

may be relied on to determine whether the simulation as set up reproduces the essence of the problem to an extent sufficient for a meaningful evaluation to be made. If necessary, at this point modifications to the simulation setup or a reduction in objectives can be made. Following a successful completion of this process, *i.e.*, the simulation is validated, then the outlined test scheme can continue. As the simulation test program proceeds, the data must be analyzed on a "how goes it" basis by observation of the recorded quantities and subjective pilot comments.

Discussion

The approach outlined has been applied to numerous studies of flight control problems. Consideration of the various factors involved in these studies led to the interrelationship of type of simulator and its intended use as delineated in Table I. This table is, in essence, an abstract of the experience gained during these studies. A more comprehensive tabulation that expands the data presented in Table I to include considerations of the environmental effects as well as a breakdown of the desired and required motion feedback quantities is presented in Table II (next page).

To illustrate the scope of this approach several examples will be covered in sufficient detail to point out some of the important interrelationships shown in Table II.

Increase in Simulator Complexity

The first series of examples to be discussed concerns the interrelationship between quality of results and simulator complexity and realism. The problem to be considered involves the landing of aircraft. It will be shown that as the simulation complexity and realism are increased, the results increase in quality from Qualitative to Quantitative (applicable to flight).

Landing Approach Speed Determined: The first study [14], reported by White and Drinkwater, was a comparison of the carrier-approach speeds as determined from flight tests and from a pilot-operated simulator.

The speed used in the approach is important since it can influence the way the pilot flys the aircraft and hence, from a practical view, can limit the precision with which he can control the flight path and his sink-rate at touchdown as well as his touchdown point. Research in flight on many aircraft has indicated [15]–[24] that there are several possible reasons why pilots are reluctant to make landing approaches at speeds below a selected speed. These include proximity to the stall, poor visibility from the cockpit, unsatisfactory stability and control characteristics, and inability to control altitude or check sink rates satisfactorily. Of the reasons listed, inability to control altitude is by far the most prevalent, being given for about 70 per cent of the configurations tested.

As part of a general program to obtain a better understanding of the problem, an analog simulator was devised to enable a detailed study of some of the factors that influence the choice of approach speed. This simulator permitted the pilot to maneuver an airplane longitudinally, using the control stick and throttle as he would in flight, and thereby to arrive at a selected approach speed. Simulator evaluations would be comparable with flight evaluations only for airplanes for which the flight approach speed was limited by ability to control altitude or check sink rate, rather than by other factors as visibilty from the cockpit or adverse stability and control characteristics.

The pilot perceived airplane altitude as the vertical displacement of a horizontal line on the oscilloscope, at a scale of 0.1 in/ft of displacement. Air speed was indicated on a meter located beside the oscilloscope, and a stall warning was provided by an audible buzzer that sounded continuously at lift coefficients greater than a preset value. A second, shorter horizontal line on the oscilloscope was available to indicate vertical acceleration of the airplane by vertical movement on the display. The simulator is shown in Figs. 3 and 4, and the oscilloscope display presentation is illustrated in Fig. 5. This arrangement is considered to be a "rudimentary simulator" in the context of Tables I and II.

It was concluded from this study that the minimum comfortable approach speeds for carrier-type landings can be determined by the use of a "rudimentary type" landing approach simulator which incorporates the basic performance parameters of the airplane (lift, drag, weight, and thrust) for those cases wherein the flight approach speeds were limited by ability to control altitude and flight path. Flight tests indicate that the approach speed so determined must be revised upward if on the aircraft any other detrimental factors appear; that is, poor stability or control characteristics, restricted visibility from the cockpit, etc. In the simulator evaluations by three NACA test pilots, average approach speeds for four airplane configurations were determined which agreed with flight values within 3 knots (see Fig. 6).

This illustrates how a simulation with a limited task (evaluations made on the simulator representing constant altitude flight rather than flying down the flight path) can yield meaningful information which is comparable on a qualitative basis and has possible application, because of the ability to validate the simulation, in yielding quantitative results.

Quantitative Landing Parameters Determined: By increasing the complexity of the simulation to increase the realism of the situation, it is possible to obtain by the use of simulators information ordinarily considered accessible only in actual flight. For instance, such quantitative items as touchdown rate of descent and landing distance from runway threshold have been obtained using the NASA Ames Research Center landing approach simulator (Fig. 7). This simulator, with a two place fixed-base transport-type cockpit, is equipped with a visual display that gives a view forward which approximates conditions at night during periods of reduced visibility (Fig. 8). The runway light pattern represents at all times the relative attitude and position of a real life runway (as viewed by one eye) as it would be seen from a real aircraft. The aircraft and instrument response to control

TABLE II

CLASSIFICATION OF MAN-MACHINE SYSTEM SIMULATORS

	Rudimentary	Basic		Advanced	Air or Spacecraft
Application	Determining 1st order requirements for controllability about and of the flight path Feasibility studies of new control problems and techniques Delineation of potential control problem areas	Gross Handling Quality Trends Defining Boundary Shapes Determining 1st-order interrelationships between modes of motion and control of and about the flightpath Cockpit Display Development	Minimum Acceptable Handling Qualities Defining Operational Problems, Navigational & Guidance Cockpit Display Effectiveness	Over-all operating problems; definition and solution Certification problem; definition Definition of minimum acceptable Handling Qualities Display aids analysis	Over-all operating problem; definition and solution Certification questions Minimum acceptable Handling Qualities Display aids evaluation
Results	Qualitative (Quantitative if sufficient elements of problem included)	Qualitative	Quantitative (Relatable to flight)	Quantitative (Directly applicable to flight)	Quantitative
Task Complexity	Generally part task	Part task (Pilot initiated short term tasks involving discrete parts of problem)	Whole task (Specific operational longer term tasks including greater percentage of problem)	Whole task (Complete mission capability)	Whole task or whole mission
Sophistication & Realism	Minor →	Increasing to →		Maximum Feasible	
A. Operators B. Cockpit Layout	Pilot (one) chair—simple controllers	Pilot and/or co-pilot any cockpit with representative controllers	as required any cockpit with required controllers	crew as on aircraft as on aircraft; controllers designed for job.	Complete Complete crew complete; controllers designed for job.
C. Vehicle response representation a. Controlled element dynamics & kinematics (as represented on analog computer) b. Parameter variation c. Extra vehicular disturbances	Complete, but simplified (linearized) and to include cross-coupled terms (all 1st order effects in) plus control system augmentation failures yes, systematic as required	complete, plus second-order effects to increase realism plus representative nonlinearities plus control system augmentation failures yes, systematic as required	yes, systematic as required	Complete plus all non-linearities known. Represents aircraft or spacecraft responses as close as possible plus control system augmentation failures not a primary requirement but highly desirable as required	Basic aircraft characteristics plus variable dynamics, plus control system augmentation failures on variable stability aircraft only as required
D. Vehicle response feedback to Operator a. visual b. kinesthetic c. aural	Symbolic tactile-spring restraint fixed base as required	Instruments-normal or simulated projection }depends on peripheral }task tactile-representative force feedback on controls moving base-modes of motion depending on task requirements as required	Instruments-simulated projection }depends on peripheral }task but with increased field of view as in VFR Flight as required	Instruments as on aircraft for max. realism projection }as required peripheral }for VFR flight tactile-expected force feedback moving base-as required to maximize realism complete	Instruments-prototype ——— tactile-expected force feedback complete complete
Environment- A. biophysical B. psychophysiological C. operational	None as required as required	as required as required as required	as required as required as required	as required as required as required	——— ——— ———
Method of evaluation	Subjective pilot opinion from pilot initiated interrogations	Primarily subjective pilot opinion from pilot initiated interrogations	Subjective pilot opinion plus task performance measures over the longer term	Primarily measured task performance criteria plus subjective pilot opinion	Primarily measured task performance criteria plus subjective pilot opinion

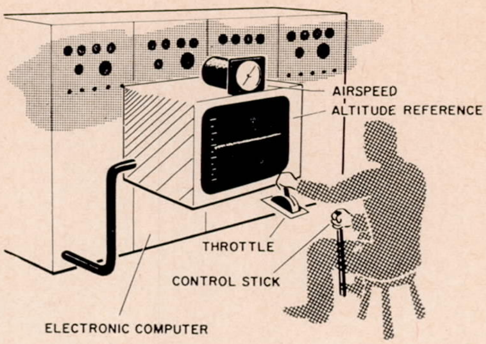


Fig. 3—Rudimentary simulator.

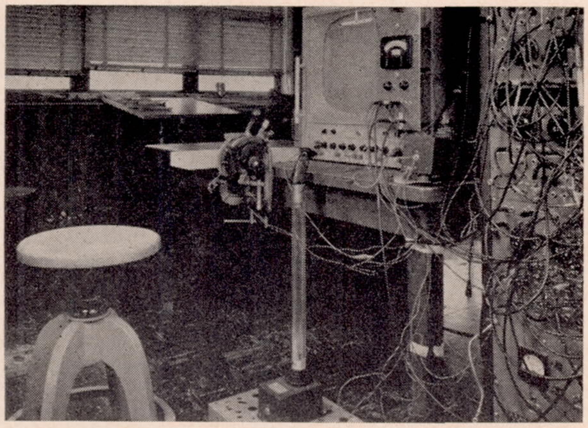


Fig. 4—Physical arrangement of the rudimentary landing approach simulator.

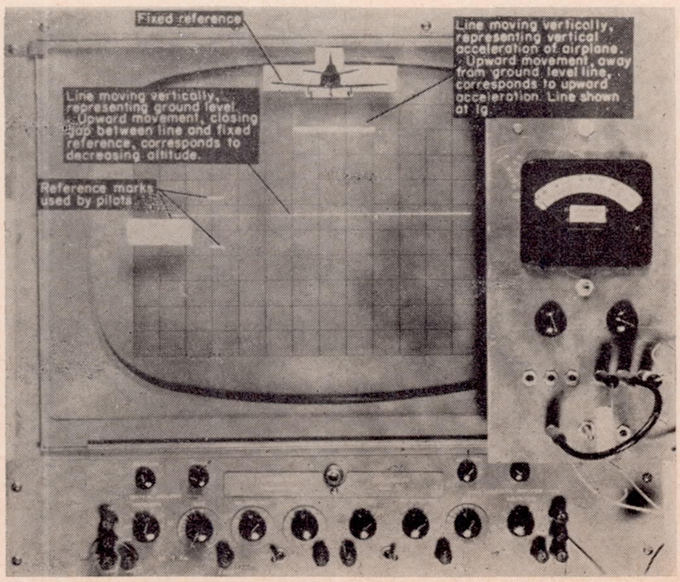


Fig. 5—Visual presentation to the pilot in the rudimentary landing approach simulator.

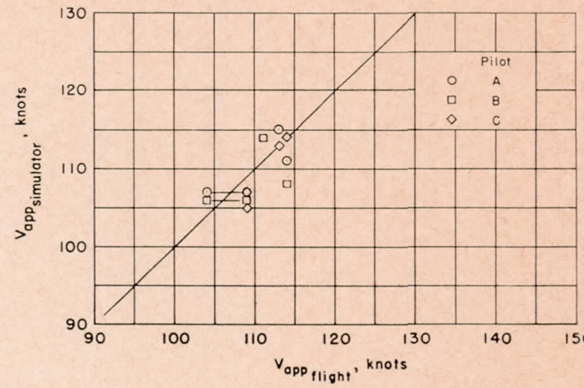


Fig. 6—Comparison of carrier approach speeds determined from flight and from simulator tests.

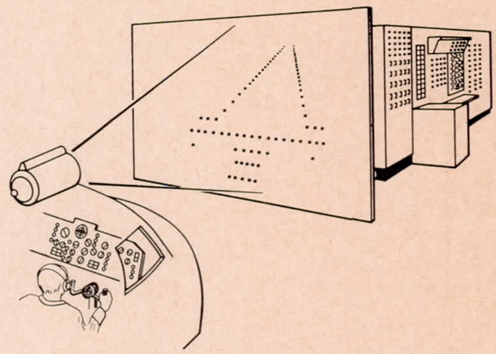


Fig. 7—Transport landing simulator

Fig. 8—Pilot's view of the instrument panel and runway projection in transport landing simulator.

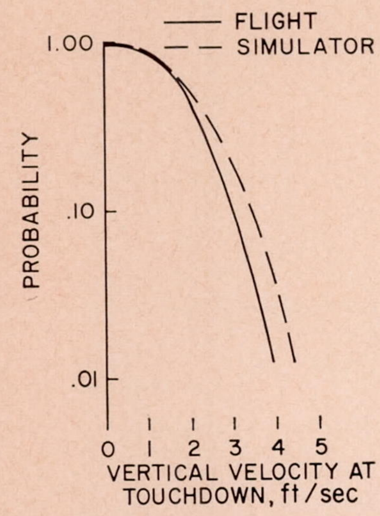


Fig. 9—Probability distribution of landing parameter, rate of descent at touchdown.

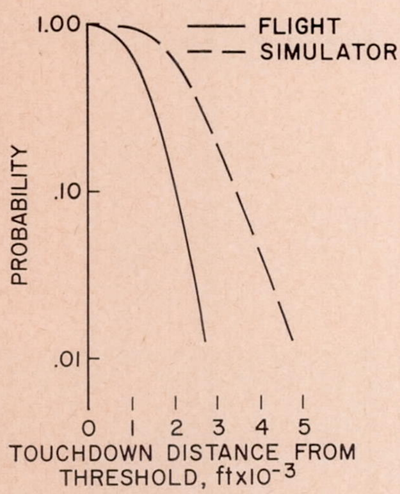


Fig. 10—Probability distribution of landing parameter, touchdown distance from runway threshold.

inputs are computed by an analog computer wherein all 6 degrees of freedom of body motions in response to controls and disturbances are represented. The pilots consider this visual presentation very realistic [1], [24].

Comparisons of data taken from a series of landings on the simulator with in-flight data under daytime operations with normal visibility are shown in Figs. 9 and 10. Although the touchdown rates of descent (Fig. 9) as measured on the simulator are higher than in flight (2.0 fps mean rate compared to 1.9 fps), the shapes of the curves are similar and indicate that the difficulty of the task has been represented to a fair degree of accuracy on the simulator. The data for the comparative longitudinal touchdown points (Fig. 10) indicates good agreement as well. Thus, as the sophistication and realism of the simulation increases, it is possible to obtain data of a more quantitative nature and if the realism and accuracy is sufficiently great obtain data comparable to the real life situation.

Response Feedback Characteristics

Because the pilot will use all the information available to achieve and maintain control of the vehicle, it is extremely important to properly represent the response feedback quantities for him. These factors include visual (instruments), kinesthetic (tactile and body forces) and aural feedback quantities. The use of forces on his body to increase realism and to augment the visual cues is so important that several examples of the use of this factor are presented below.

Motion Feedback that Helps Pilot Control: Two specific examples [25] illustrate the helpful effects of motion cues which are phased such that they augment rather than conflict with visual cues.

The first example occurred in the study of transition characteristics for a deflected slipstream VTOL vehicle. Fig. 11 shows the range of flight conditions studied, from 0 to 55 knots. From wind-tunnel tests, made previously on the prototype of one flight vehicle itself, the variation of angle of attack with airspeed was determined for several flap deflections. Any point on any of the curves represents a steady level flight condition. The upper boundary is fixed by wing stall and control available to balance the pitching moments. The lower boundary is imposed by the structural limits of the flap. From wind-tunnel results alone, it would be concluded that the vehicle could operate anywhere between these boundaries. Prior to flight the transition was studied using a fixed cockpit simulation. The pilots found it very difficult or impossible to complete the transition. To check whether the omission of motion cues caused this result, the simulation was repeated with pitch and roll motion of the cockpit added. With these motion cues, the pilots were able to explore the transition region and to establish a comfortable transition boundary which with the flap limit boundary designated a corridor through which the aircraft could be flown by careful attention to flaps, speed and angle of attack. The gray area was to be avoided because it was too near the upper boundaries to allow sufficient control. Subsequent flight experience supported the pilots' conclusions regarding this corridor.

In reviewing the results of this simulation, the need for cockpit motion was readily apparent. Without cockpit motion, the transition was very difficult to perform, even in the limited three-degree-of-freedom case of the longitudinal mode only, because of the multiplicity of quantities which had to be monitored. The addition of roll and yaw modes and their visual indications, to give six-degree-of-freedom simulation, made the task impossible and it was necessary to add pitch and roll motions to the cockpit to achieve satisfactory pilot performance.

A second example of the effects of motion feedback can be illustrated in some results obtained from the simulation of a large tilt-wing vehicle in hover. The study was concerned with roll control and the simulation was limited to three degrees of freedom, including vertical and lateral translation and roll. The pilot was given the tasks

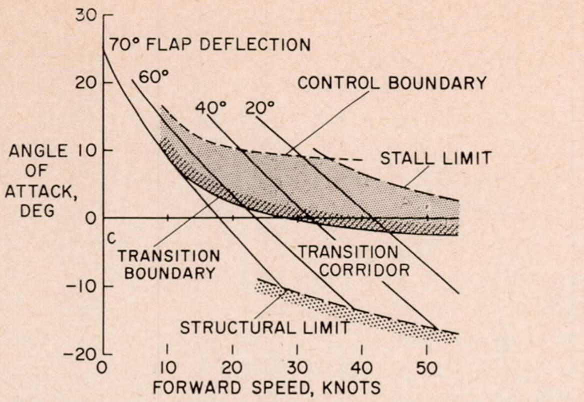


Fig. 11—Transition boundaries of deflected slipstream aircraft from simulator studies.

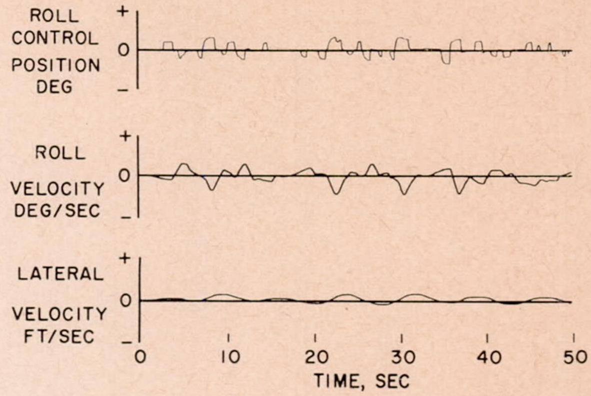


Fig. 12—Lateral control in hover—fixed cockpit.

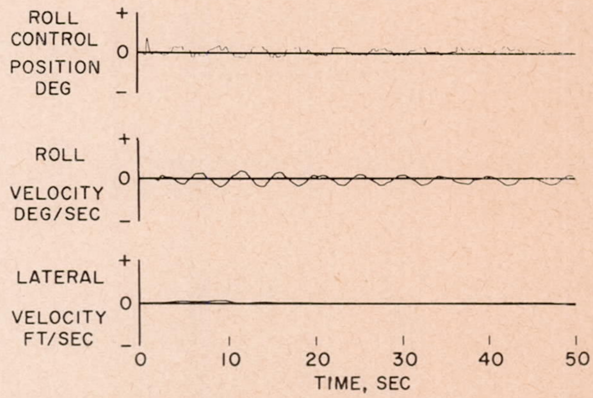


Fig. 13—Lateral control in hover—moving cockpit.

of lifting off into hover, of landing and of moving laterally. Some conditions were compared with the cockpit fixed and with it moving in roll. As the characteristics became worse, a definite difference appeared, as shown in Figs. 12 and 13. Fig. 12 presents representative time histories of the roll control position, rolling velocity, and lateral velocity for fixed-cockpit simulation, and Fig. 13 shows the same quantities for the moving cockpit. The erratic movements and larger lateral velocities of the fixed-cockpit simulation are compared with the more regular movements and lower lateral velocities with the roll motion feedback. Even in this simple case, the pilot found the added motion cues in roll to be an aid since they gave him a more realistic picture of the onset of lateral velocity. He remarked that he found it possible to remove his hand from the control stick for brief periods of time with the moving cockpit and still regain control—something he could not do with the cockpit fixed.

This example illustrates that fixed-cockpit studies alone tend to be conservative. It emphasizes that when a pilot finds he can cope with a short-term stabilization problem on a fixed-cockpit simulator the problem can probably be considered unimportant. However, when he cannot cope with the problem even when visual saturation is not suspected, serious consideration must be given to increasing the realism of the simulation to obtain valid pilot opinion especially if operation near a boundary between acceptable and unacceptable regions is under study. Another example [26] of helpful motion feedback involved the favorable effects of providing side force and roll degrees of freedom in studying the effects of engine failure on the ability to control a supersonic transport configuration using the Ames Research Center's five-degree-of-freedom motion simulator (see Fig. 14). Although strong visual cues can substitute in part for motion cues as shown in Vomaske, *et al.* [27], one must proceed with caution since a complete reliance on visual cues in development of instrument displays can lead to problems when the system is evaluated in flight [28]. It is considered necessary to provide motion feedback at least about the rotational axes when proper representation of the instrument flight situation is required.

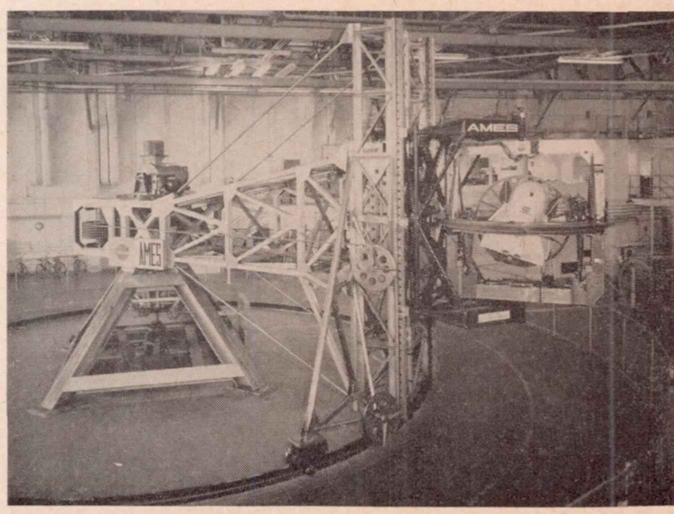


Fig. 14—View of the five-degree-of-freedom motion simulator at the NASA Ames Research Center.

Motion Feedback that Deters Pilot Control: In some cases the presence of motion cues renders control of the vehicle more difficult even though these motion cues result in a more realistic flight situation being presented to the pilot. This next section discusses these types of problems.

The ability of the pilot to quickly change the angle of bank of an aircraft from one value to another has been a consideration that has established the size of the ailerons

TABLE III
PILOT OPINION RATING SYSTEM

	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*	Doubtful	Yes
No Operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable—Dangerous	No	No
		9	Unacceptable—Uncontrollable	No	No

* Failure of a stability augmenter

and affected the overall maneuverability of an aircraft for decades. For this lateral mode it has been determined [29] that the equations defining the roll response can be approximated by a first-order system with a time constant T_R, and a gain L_{δ_a}. The boundaries defining ranges of satisfactory, acceptable and unacceptable characteristics (the ratings on the boundaries are described by the pilot rating schedule given in Table III) can be presented in terms of the maximum aileron control power, $L_{\delta_a}\delta_{a_{max}}$, and the roll time constant (see Fig. 15). Special areas of concern are at values of $L_{\delta_a}\delta_{a_{max}} \gtrsim 10$ rad/sec^2 where the effects of motion feedback reduce the acceptable region. It is surmised that the large angular accelerations in roll hinder the pilot's ability to control precisely. The overall comparison of the results of these moving simulator texts compared very well with flight results.

Another example of conflicting cues occurs in a longitudinal control situation. The control parameters of the longitudinal case can be represented by a second-order system where the oscillatory roots are defined by ω_n, the undamped natural frequency of the motion, and $2\zeta\omega_n$, the total damping. Boundaries on this $\omega_n - 2\zeta\omega_n$ plot, determined from simulator tests [30] using a pitch and roll chair, are presented in Fig. 16. Our concern is in the region of low damping and high natural frequency where the aircraft is considered sensitive to control inputs. Here the motion is rapid and has a tendency to throw the pilot around the cockpit unless he is adequately restrained. For this case adding only angular motion to the visual cues gave enough realism in the simulator to yield a reasonable correspondence with the flight results.

Some flight control problems, such as "pilot induced oscillations," have as yet not been duplicated on motion flight simulators, for as the over-all pilot-airframe system approaches the condition of neutral stability, the subtleties of all the motion cues plus any control system nonlinearities tend to dominate the problem [31]. When regions of sensitive control are suspected, it is always conservative to plan to include motion around the axis of the expected control problem.

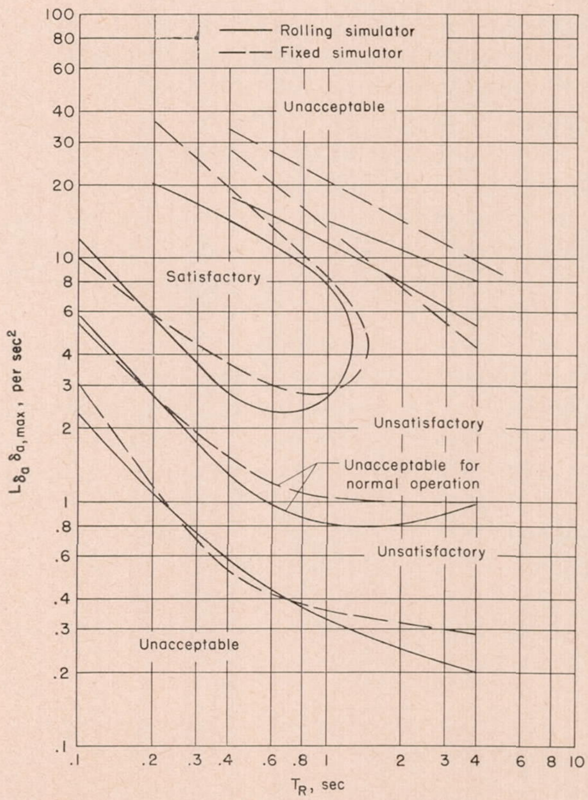


Fig. 15—Comparison of pilot opinion boundaries obtained from fixed and moving flight simulators.

It has been shown that the presence of motion cues can both help and hinder the pilot in performing his task. The use of motion feedback will always increase the realism to the pilot and unload him so that a better assessment of the flight task can be made. However, it is important to remember that in the use of motion feedback, motion artifacts (such as unwanted motion about an axis perpendicular to the axis of concern) can compromise the problem and decrease the region of acceptability [30].

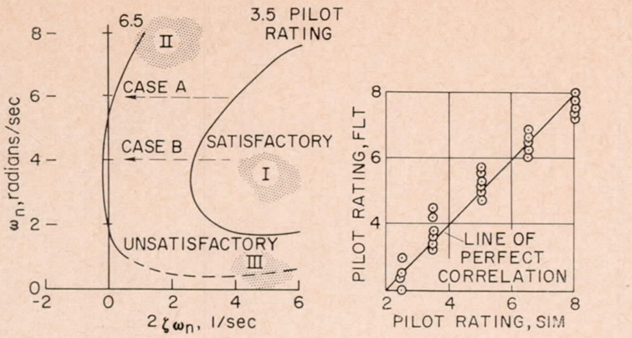


Fig. 16—Simulator derived longitudinal handling qualities and correlation with flight for conventional aircraft.

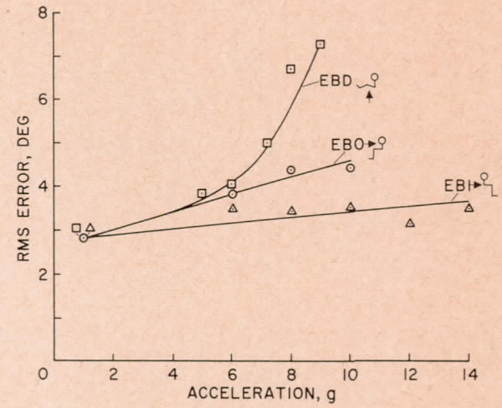


Fig. 17—Effect of acceleration on pilot performance.

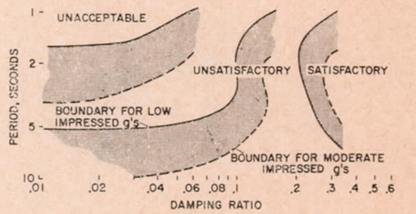


Fig. 18—Effect of acceleration on pilot opinion boundaries of longitudinal handling qualities.

Fidelity of Control System Representation

Because of the importance of stick force feedback in indicating to the pilot the well-being of his aircraft, stringent requirements have been placed on the stick force response characteristics both as to variation with aircraft condition and with time [4], [5].

Flight tests made with a variable control system airplane [31] indicate the extreme importance of changing the control system irrespective of the airframe dynamics. This suggests two things: 1) that the over-all response is the important quantity to represent, and 2) that in a simulation the control system responses both time-wise and force-wise should be faithfully reproduced. This is why, as indicated in Table II, for any other simulator than the rudimentary type representative force feedback on the controls is necessary.

Failure of stability augmentation systems can result in dangerous out of trim conditions (hardover failures) or divergent oscillatory closed-loop system behavior that can result in exceeding structural limitations of the airframe before the pilot has time to adapt to the new dynamic situation [32]. It is therefore extremely important to represent the control system in all its functional complexity so transients inherent in the system to be controlled can be assessed by the pilot in judging the over-all controllability characteristics of the air or space craft.

Environmental Stress Effects

The task required of the pilot must be analyzed accurately enough to determine if any stresses will be imposed on the pilot which will degrade his performance. From a flight point of view, these stress effects during aerobatics have defined limits on the maximum acceleration that can be imposed on the pilot before he will black out and lose control. In addition, there has been some suspicion that moderate values of acceleration can reduce the pilot's performance capabilities.

In an NADC Johnsville Human Centrifuge simulation study [33], [34] designed to investigate the effects of large values of steady acceleration such as would be encountered during decent from orbiting or translunar flight, it was found that over a certain range of acceleration levels the pilot's tracking performance did not decrease appreciably. However, above a certain acceleration value, which depended on the orientation of the acceleration vector with respect to the pilot, a noticeable reduction in performance was noted (see Fig. 17). In addition, for the longitudinal control case, the presence of a moderate acceleration vector (about 7 g) reduced the acceptable controllability regions (see Fig. 18) compared with the 1-g case. This investigation indicated that the method of restraining the pilot as well as the type of controller used could play an important part in the over-all usability of the man-machine system. If the body of the pilot is not to be supported or restrained against the inertial forces, then the position of the body with respect to such loads must be represented correctly [30].

Any untoward effects or restraints on the pilot's operation or ability to manipulate the controls, *i.e.*, any consequence of the environment imposed on the pilot such as pressure suit configuration, orientation of seat, position of controls, etc., should be represented if a true interaction between the environmental factors and the pilot's ability to control the vehicle is to be obtained. Each environmental factor such as biophysical, psychophysiological and operational must be examined to assess the necessity for providing it in the simulation to enable the desired type of conclusions to be drawn.

Concluding Remarks

A procedure for conducting a meaningful simulation of a man-machine system has been discussed. The relationship of the various types of simulators to their use as well as some detailed characteristics have been outlined in Tables I and II. The various examples given have been aimed at showing that as the problem to be studied becomes more complicated or the questions asked of the simulation become more quantitative, the simulator characteristics must become more flight-like, because the best situation in which to ask the questions is when the pilot and the vehicle are immersed in the true environment (*i.e.*, flight). Although to our knowledge the "advanced" simulator does not now exist and may never exist in the eyes of the critical pilot, we can provide most of the characteristics desired by using a simulator such as the present Ames Research Center's jet transport training simulator, which provides limited motion cabability along with strong visual cues. However, rather than provide complete fidelity for all problems, a more sensible attack is to provide devices that are responsive to certain types of mission, advanced aircraft, space vehicles, hovering (VTOL) craft, etc., and which will reproduce the dominant motions required for the problem at hand. It should be borne in mind that whenever possible use should be made of variable stability and variable control system aircraft (the "ultimate" flight simulator in the research sense) to validate the results obtained with the ground based equipment.

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