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MEMORANDUM

USE OF FLIGHT SIMULATORS FOR PILOT-CONTROL PROBLEMS

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and Joseph G. Douvillier, Jr.

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**NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION**

WASHINGTON
February 1959



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SUMMARY

Comparisons have been made between actual flight results and results obtained with fixed and moving flight simulators in a number of phases of flying airplanes with a wide range of characteristics. These results have been used to study the importance of providing motion stimuli in a simulator in order that the pilot operate the simulator in a realistic manner. Regions of airplane characteristics where motion stimuli are either mandatory or desirable are indicated.

INTRODUCTION

Since real flying is becoming more complicated and expensive, it is necessary to look to flight simulators for an economical means to train pilots and give them realistic practice to maintain their proficiency. Such simulators are finding increasing use in aeromedical research, airplane and systems design, and training; however, they vary widely in type - from a man on a chair in front of an oscilloscope to multimillion-dollar centrifuges. For example, there are two types of training simulators. One, called a procedure trainer, is an exact duplicate of an existing cockpit and is used chiefly to teach instrument layout and specific operating procedures. The other, the type discussed herein, might be called a proficiency trainer because its object is to give the pilot realistic practice in operating the flight controls and in observing the airplane response. Obviously, the value of this equipment to the pilot being trained is greatly enhanced if the right type is chosen, that is, the equipment which makes him use the same inputs and develop the same responses that he would in actual flight. A number of factors which affect this choice have been encountered in various research projects which will be reviewed in order to discuss the extent of simulation required to present certain flying tasks realistically.

DISCUSSION

General Considerations

Figure 1 is a diagram of a typical pilot-operated simulator. The solid-line upper portion shows the basic elements of the fixed simulator and shows the pilot in a cockpit with controls he can move. These control motions are fed into a computer which computes the proper airplane response and the corresponding display information which is then shown to the pilot by the instruments in the cockpit. These visual cues from the instruments are the pilot's only input.

The next stage of refinement is indicated in figure 1 by the dashed-line lower portion. The computer supplies the computed airplane motions to a device which provides motion cues in addition to the visual cues from the instruments. This device can take several forms, with the most common form being a servodriven cockpit or centrifuge which fully reproduces some combination of the correct angular and linear motions. Another less complicated device is a restricted-travel cockpit which supplies a much smaller initial movement but in the correct sense to help the pilot's judgment. Also, there are fixed simulators enclosed in spherical screens on which a moving outside world and horizon are projected. The pilot is given a strong visual illusion of motion like the effect of Cinerama.

In each of these devices the principle is the same; that is, the pilot is shown the instrument display as it would be in actual flight, and he is also placed under motion conditions that may or may not be near those of flight depending on the capability of the simulator. The main problem in choosing a particular training simulator then is the extent of completeness necessary to give the pilot the information he needs to solve his flight problem. Typical questions that might arise concern the extent that the motion stimulus affects the pilot's ability to control bank angle or to damp out a pitching motion and the extent that a given instrument display is influenced by the presence of a motion stimulus as well as by a visual stimulus.

Up to the present time these problems have been examined at the Ames Research Center with the aid of three pieces of motion-simulation equipment. In addition to using numerous production airplanes, variable-stability airplanes have been used in flight to subject the pilot to all six freedoms of motion over a wide level of oscillatory and steady-state conditions. The pilot's capabilities in flight then have been compared with those on various fixed simulators where no motion inputs are present. Also, these tasks have been repeated with, to date, two degrees of rotational motion of the cockpit (pitching and rolling). Although this work is being extended to other more complete motion simulators,

the present results have shown that the importance of motion input is directly a function of the type of task presented to the pilot.

The various piloting tasks where comparisons have been drawn between flight and simulators are landing approach, longitudinal dynamics, longitudinal control, lateral dynamics, instrument presentation, and simulation of particular airplanes. In some of these cases, motion inputs were not necessary. In others, the motion cues were useful and helped the pilot solve his problem more realistically. In still other cases the use of a motion stimulus was mandatory; without it completely wrong or reversed answers were obtained.

Landing-Approach Problem

The landing-approach problem is considered first. Approaches made with the Instrument Landing System were simulated in a wide variety of dynamically stable airplanes in order to study the factors affecting the pilot's choice of approach speed. With regard to the simulator the situation is fairly straightforward. In a landing-approach simulation the critical piece of information that must be given to the pilot is his rate of sink. This can be done by visual instrument alone and no motion inputs are necessary. This does not mean that the pilot would not like motion or use it if given to him. It means that he can get by without it. Here and elsewhere the emphasis is on the distinction between a mandatory stimulus and a merely desirable stimulus.

The degree of correlation between actual flight and the fixed simulator is illustrated in figure 2. The speed chosen when performing the approach on the simulator is shown plotted against the approach speed chosen by the pilots in flight. This correlation was obtained through tests covering 12 airplane configurations and several research and service pilots. There are two qualifications: First, these tests did not cover airplanes with unstable or significantly nonlinear aerodynamics in the landing-approach configuration; and second (a more general qualification), in this and other simulator studies the pilots found it valuable first to simulate an airplane that they had actually flown recently so that they could get the feel of the simulator and then calibrate themselves to build up their confidence. These results and the others discussed were obtained following such a conditioning process, and it appears to be an important step in getting the pilot's cooperation and in using a simulator really successfully.

Longitudinal Dynamics

In the study of longitudinal dynamics numerous studies of flying qualities are made in which test pilots are asked to fly widely different airplane configurations and rate the different combinations according to their desirability. In doing this they fly various standard maneuvers and perform such precision tasks as tracking and formation flying. By comparing their ratings from flight and simulators, some insight is given as to how well the simulator reproduces actual flight in these areas. A typical result is shown in figure 3 which is a cross plot of longitudinal-dynamic-stability parameters with the short-period frequency plotted against the damping ratio. The solid-line curves show the results of a study (ref. 1) made by the Cornell Aeronautical Laboratory on a variable-stability airplane. The pilot has designated regions where he regarded the short-period frequency and damping combinations as good, acceptable, poor, and unacceptable. The broken lines show the results of a similar study on a fixed simulator at Ames with different pilots.

The agreement between the two studies is good in the region of moderate frequencies and good damping corresponding to present-day conventional airplanes; therefore, the fixed simulator appears to be very realistic. At short-period frequencies above 0.6 cps, however, the simulator becomes much easier to fly than the airplane and is obviously not realistic. Such a high natural frequency implies a rapid airplane response to the controls, which then feed back to the pilot motions which become increasingly difficult to cope with as the frequency increases and the damping deteriorates. It is interesting to take a data point in this region of high frequency and low damping and quote the full opinion of the Cornell pilot: "Initial response fast and abrupt. Constant short-period oscillation which pilot excites. Must let go of stick to damp out oscillations. Overshoots load factor. Requires constant attention." These comments are typical effects of motion feedback that is too rapid for the pilot to cope with. A moving cockpit with sufficient performance to operate in this region is just now being completed; thus, whether adding the pitching motion alone without vertical or longitudinal accelerations will result in a satisfactory simulation has not yet been determined. However, it is apparent that a fixed simulator is not adequate to train the pilot to cope with airplanes which fly in this region.

Longitudinal-Control System

Considerably intertwined with this subject is the question of the characteristics of the longitudinal-control system. A modified airplane has been flown at the Ames Research Center in which the pilot can vary the static stick gearing or stick force per g, the time constant of the dynamic response, and the breakout force and again select the preferred combinations. A portion of these results is shown in figure 4 where for

two different pilots the maximum-acceptable, the best-available, and the minimum-acceptable time constants have been plotted against stick force per g. This is the equivalent first-order time constant of the control system, the time required for the control surface to reach 63 percent of the steady-state response to a step input of stick force. Broadly speaking, the maximum-acceptable time constant is the value above which the pilot considers the control response too sluggish and the minimum-acceptable time response is the value below which it is too sensitive. It should be pointed out that these results are for constant airframe aerodynamics which appear in the "poor" range in figure 3. The flight results are shown by solid-line curves and, again, the companion fixed-simulator study is shown by dashed-line curves.

In comparing the two pilots, it is interesting to note that the honest difference in opinion between them in flight, shown by the solid-line curves, is accurately reflected in their simulator results, shown by the dashed-line curves. Also, it appears that the fixed simulator is reasonably realistic in the range of interest. One exception must be emphasized in the lower left-hand corner of these figures where the pilot has a rapidly responding control and very high control sensitivity or low stick force per g. In actual flight with pitching motion and acceleration feedback present, the pilot-control-system-airplane combination became unstable and a pilot-induced oscillation was encountered which again could be stopped only by releasing the stick. In the fixed simulator with the motion feedbacks not present, although the pilot correctly derated the combination with a low opinion, he did not encounter any self-induced oscillations. If this problem is of particular concern, then motion or acceleration feedbacks appear to be mandatory. These results were obtained on highly maneuverable fighters; but, even with transports, if it is desired to train pilots to cope with upset maneuvers or damper failures, the regions in figures 3 and 4 where the airplane in question appears should be determined.

Lateral Dynamics

The next pilot task considered is lateral dynamics. A recent study (ref. 2) suggested that two important parameters influencing pilot opinion were the roll-damping and roll-control power. Pilot-opinion boundaries based on these two parameters were derived from tests which stressed two very important phases of lateral control: the maximum roll acceleration and rate capabilities desired by the pilot, and the precision of roll control in terms of ability to change bank angle rapidly and stabilize.

The results of the lateral-dynamics study are shown in figure 5. The constant pilot-opinion boundaries are shown as a function of a roll-damping parameter and a roll-control-power parameter. Flight results are shown by a solid-line curve, the moving simulator by a dash-dot

curve, and the fixed simulator by a dashed-line curve. The agreement between all three is satisfactory in the desirable normal operating region where most of the real airplanes that were flight tested appeared. However, the two simulator results diverge very rapidly at higher rolling accelerations, a result indicating that the fixed simulator becomes very unrealistic. It should be noted that a logarithmic scale is used in figure 5. Pilot opinions indicate that, in the region where the fixed simulator is not realistic, the primary difficulty is in obtaining precise control of the bank angle. As this region is entered, the control movement that the pilot has to make to change his bank angle precisely is changing from a simple pulse to a rapid sinusoid. It is easy to conjecture that, at these rolling accelerations, of the order of 500° per second², the actual environment of a rolling cockpit is mandatory in order to reproduce the difficulty of the control problem realistically.

Another point of interest is that, at very low rolling rates encountered in a sluggish airplane, the moving simulator is easier to fly than the fixed simulator because the motion cues, particularly the acceleration, help the pilot considerably. Again, in order to make these results meaningful in connection with the simulation of a transport airplane, it would be necessary to examine possible critical maneuvers such as collision avoidance or emergency corrections to the Instrument Landing System, to determine the rolling performance actually used, and to see where a particular airplane appears in figure 5.

Instrument Presentation

Instrument presentation is as interesting as it is controversial. The simulator work discussed concerns presentation of the attitude of the airplane, especially bank angle, to the pilot. The example shown (see fig. 6) consists of two alternative fire-control-system presentations shown to the pilot on an oscilloscope. The one on the left consists of a reference circle fixed with respect to the instrument case and a moving target dot displaced from the center of the circle according to the position of the target relative to the attacker. The pilot tracks the moving target dot with the fixed circle the same as he would track a visual target with a fixed sight ring. In the presentation on the right the target symbol, indicated by a small dash, is fixed in the center of the scope. The attacker is represented by an inverted T displaced from the fixed target according to their relative positions. The pilot tracks by flying the "drone" on to the fixed bar. The matter of concern is the bank-angle presentation. In the case on the left side of figure 6 the bank angle is presented by an artificial gyro horizon; that is, the bar remains parallel to the true horizon while the instrument case (with its reference marks, the pilot, and the airplane) rolls around it. This is called an inside-out presentation. In the case on the right side of figure 6 the bank angle is indicated by the angle between the wings of

the drone and the fixed line across the instrument case which, of course, rolls with the airplane. This is called an outside-in presentation, the view that the pilot would get from a platform behind his airplane. The essential difference between the two is shown by imagining the relative motions involved in the lower two sketches of the presentations in a right-wing-down bank angle of 45° with the target on the horizon to the right. In the inside-out case the target dot is on the horizon but it is displaced to the right, the view that the pilot would get from his window. In this version of the outside-in presentation the drone is banked 45° with respect to the reference bar but 90° with respect to the true visible horizon and is displaced to the left.

As shown in figure 7 both of these presentations have been compared by using flight tests, a moving simulator cockpit driven in pitch and roll, and a fixed simulator. Each of the curves is a composite time history of the radial aim error averaged over about 15 tests. A vertical line divides the time into two regions of the tracking maneuver, a straight nonmaneuvering tail chase and a breakaway into an accelerated turn. It can be seen that in the fixed-simulator results no differences between the presentations appear. The type of presentation did not affect the pilot's performance. In the flight tests during the nonmaneuvering portion the results were the same. In the maneuvering portion of the flight, however, the pilot's performance deteriorated markedly with the outside-in presentation, and the fixed-simulator results are obviously not realistic. In fact, with the use of two experienced test pilots thoroughly trained in standard instrument-flying techniques, the outside-in presentation in some cases actually produced symptoms of vertigo in the maneuvering portion of the test. The pilots attributed the vertigo to the fact that they were getting a visual cue in conflict with the motion stimulus, which was, of course, not present in the fixed simulator. In the rolling-cockpit simulator the comparison between the two presentations is more like that in flight, but it is still not satisfactory. The specific motion and visual cues which produce this very marked effect have not all been traced as yet. It seems apparent, however, that fixed simulation of certain types of instrument presentations for pilot training in maneuvering flight should be viewed very carefully until more is known about this subject.

Complete Flight Simulation of a Particular Airplane

The final category to be discussed is the complete flight simulation of a particular airplane. This is the stage in which all the piloting tasks discussed previously are combined and the various interaction effects are encountered. Unfortunately, research directly applicable to transport airplanes is very limited since nearly all research projects have involved fairly exotic types such as vertical take-off and landing airplanes, the X-15, the X-18, and various satellite and reentry

configurations. However, one principle that is pertinent has been encountered repeatedly. Either in flight or in a simulator increasing demands are, of course, made on the pilot's concentration as he is asked to control the airplane in three dimensions and perform a number of tasks simultaneously. In flight the pilot meets this challenge by concentrating on the obviously difficult tasks and by taking care of the others by instinctive or set behavior patterns. Some of these instinctive responses can be based on rather subtle inputs; in order to achieve a realistic simulator, the pilot must be given the inputs he actually uses or he may be burdened excessively.

One simple example is a satellite-reentry problem in which the pilot was asked to fly at a specified pitch attitude presented to him by an instrument and at the same time maintain his lateral balance with a rather poor control system. The problem was first studied in a fixed simulator which substituted an artificial-horizon instrument for the actual rolling-motion stimulus. In order to perceive a bank-angle error, the pilot had to wait for it to develop on the instrument, make a corrective control motion, wait to observe its effect on the instrument, and so on. This took so much of his concentration that he found the pitch control unsatisfactory and in some cases impossible to cope with. When just the actual rolling motion was added to the cockpit, the pilot could feel even a small roll acceleration instantly through the seat of his pants and could maintain his lateral balance almost instinctively. This left him free to cope with the identical pitch problem satisfactorily, and his opinion of the longitudinal-control system was quite different.

CONCLUDING REMARKS

Comparisons have been made between actual flights and flight-simulator studies in a number of phases of flying airplanes with a wide range of characteristics. There are regions where some form of motion stimulus is desirable or mandatory in order that the pilot operate the simulator realistically, particularly for pitch- and roll-control systems with a sensitive rapid response to control movements and for instrument presentations in maneuvering flight. In a broad range of airplane characteristics that might be termed conventional, however, the fixed simulator with adequate instrument presentation appears to be a realistic and useful device for pilot-proficiency training.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Nov. 5, 1958

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1. Harper, Robert P., Jr.: Flight Evaluations of Various Longitudinal Handling Qualities in a Variable-Stability Jet Fighter. WADC TR 55-299, July 1955.
2. Creer, Brent Y., Stewart, John D., Merrick, Robert B., and Drinkwater, Fred J., III: A Pilot Opinion Study of Lateral Control Requirements for Fighter-Type Aircraft. NASA MEMO 1-29-59A, 1959.

BLOCK DIAGRAM OF SIMULATOR

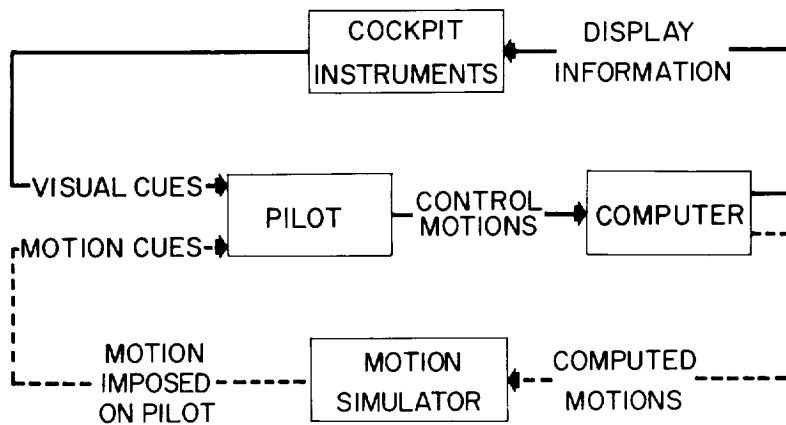


Figure 1

LANDING APPROACH SPEED CHOSEN

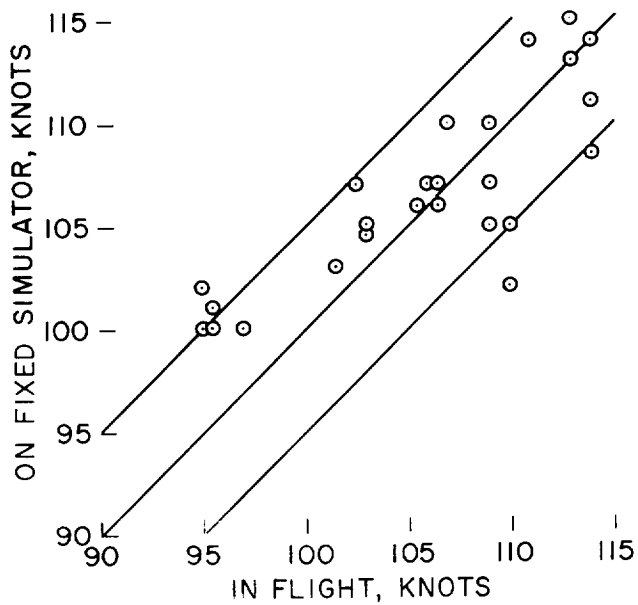


Figure 2

LONGITUDINAL DYNAMICS

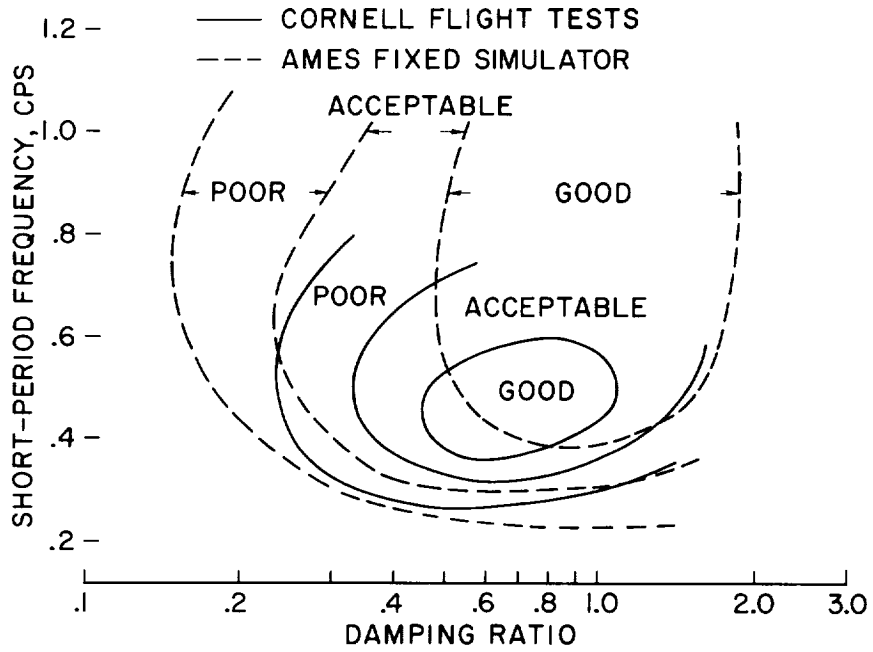


Figure 3

LONGITUDINAL CONTROL

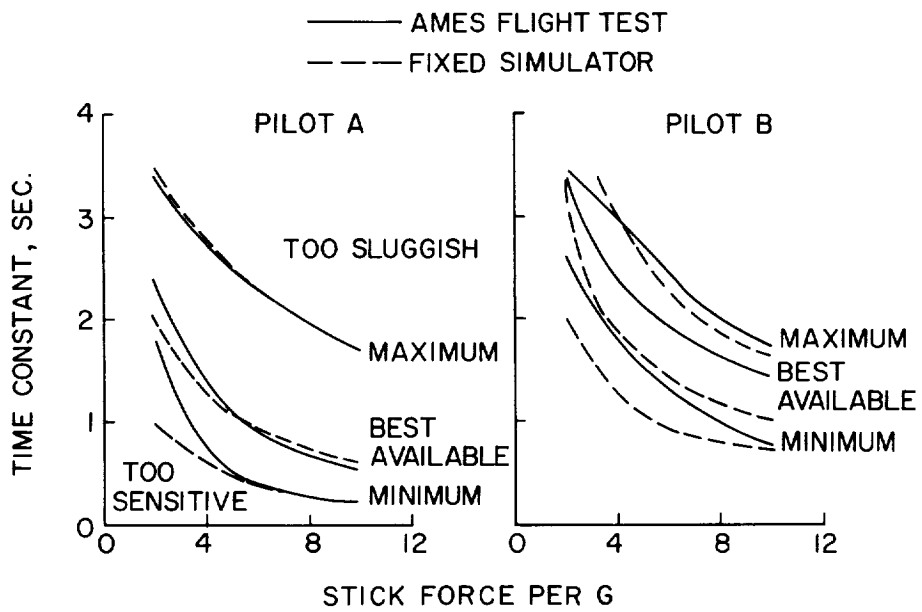


Figure 4

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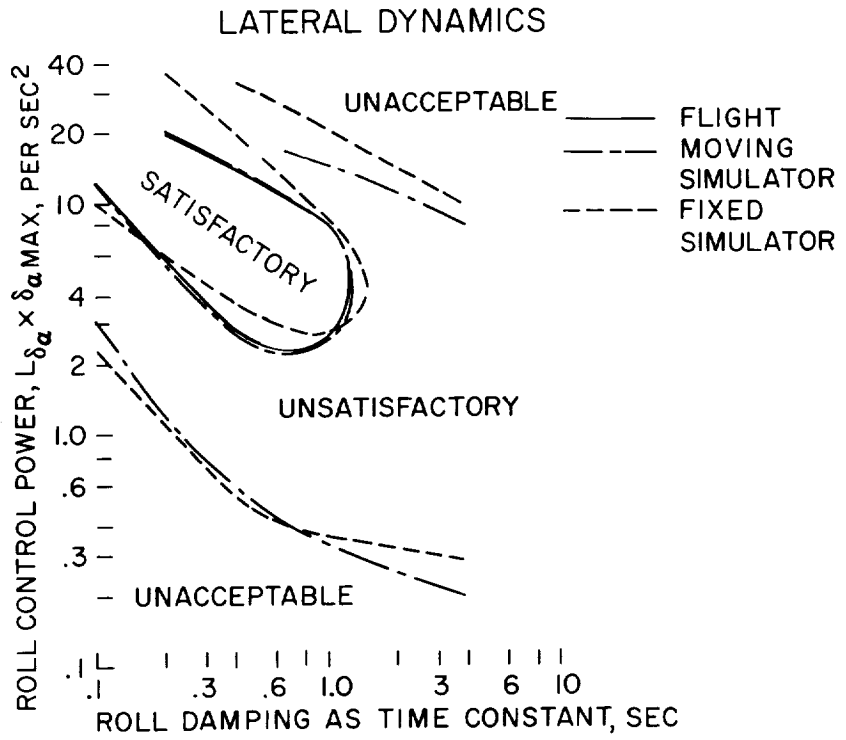


Figure 5

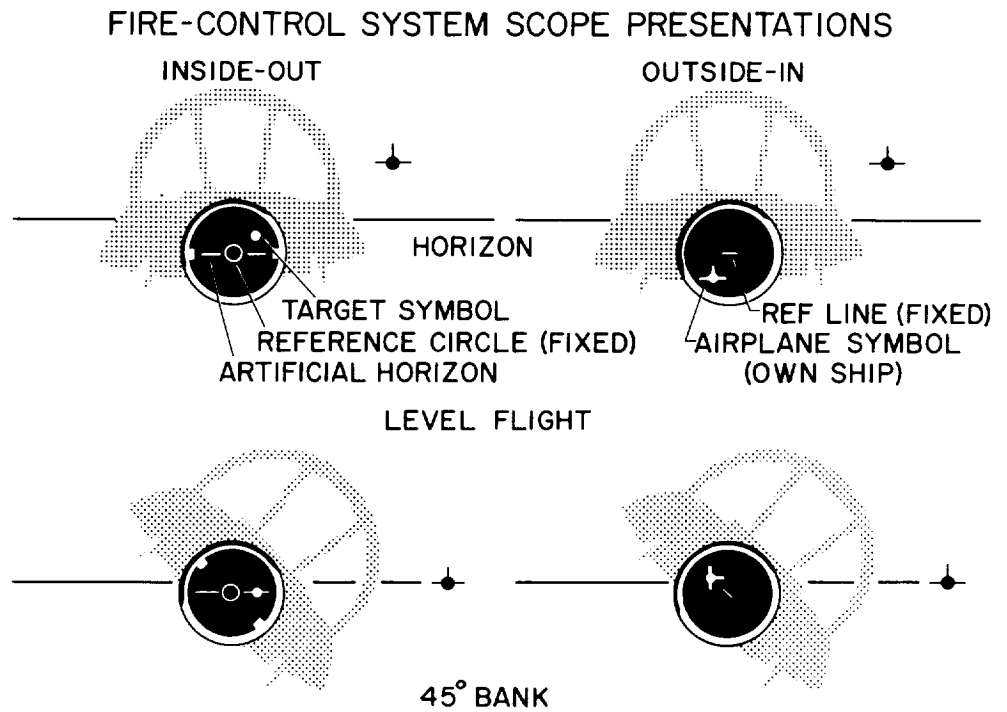


Figure 6

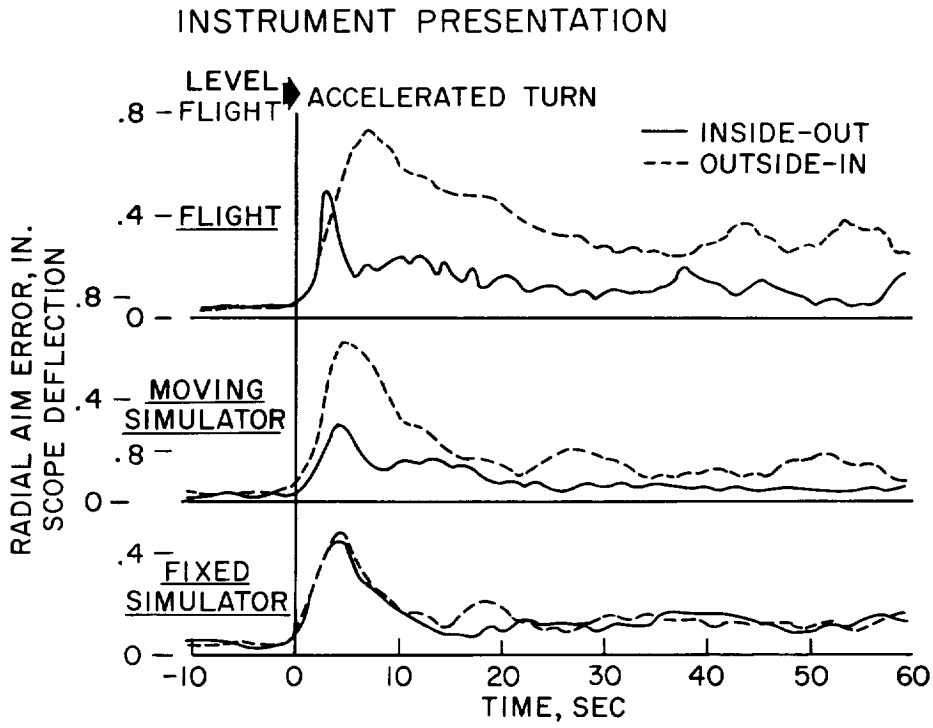


Figure 7

<p>NASA MEMO 3-6-59A National Aeronautics and Space Administration. USE OF FLIGHT SIMULATORS FOR PILOT-CONTROL PROBLEMS. George A. Rathert, Jr., Brent Y. Creer, and Joseph G. Douvillier, Jr. February 1959. 14p. diagrs. (NASA MEMORANDUM 3-6-59A)</p> <p>Comparisons have been made between actual flight results and results obtained with fixed and moving flight simulators in a number of phases of flying airplanes with a wide range of characteristics. Regions of airplane characteristics where motion stimuli are either mandatory or desirable are indicated.</p>	<p>NASA MEMO 3-6-59A National Aeronautics and Space Administration. USE OF FLIGHT SIMULATORS FOR PILOT-CONTROL PROBLEMS. George A. Rathert, Jr., Brent Y. Creer, and Joseph G. Douvillier, Jr. February 1959. 14p. diagrs. (NASA MEMORANDUM 3-6-59A)</p> <p>Comparisons have been made between actual flight results and results obtained with fixed and moving flight simulators in a number of phases of flying airplanes with a wide range of characteristics. Regions of airplane characteristics where motion stimuli are either mandatory or desirable are indicated.</p>	<p>1. Stability and Control (1.8) 2. Control, Longitudinal (1.8.2.1) 3. Control, Lateral (1.8.2.2) 4. Flying Qualities (1.8.5) 5. Instruments, Flight (8.1) I. Rathert, George A., Jr. II. Creer, Brent Y. III. Douvillier, Joseph G., Jr. IV. NASA MEMO 3-6-59A</p>	<p>1. Stability and Control (1.8) 2. Control, Longitudinal (1.8.2.1) 3. Control, Lateral (1.8.2.2) 4. Flying Qualities (1.8.5) 5. Instruments, Flight (8.1) I. Rathert, George A., Jr. II. Creer, Brent Y. III. Douvillier, Joseph G., Jr. IV. NASA MEMO 3-6-59A</p>
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