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SOME DESIGN PROBLEMS OF SUPERSONIC TRANSPORTS AS IDENTIFIED IN PILOTED-SIMULATOR STUDIES

MAURICE D. WHITE,* RICHARD S. BRAY,* AND GEORGE E. COOPER†

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

INTRODUCTION

The types of airplane currently being considered for use as a supersonic transport have radically different configurations from any now in service, and unusual handling qualities problems are predicted. A requirement therefore exists for evaluating the handling qualities for these types of airplane to determine acceptable limits. Furthermore, existing specifications for handling qualities have been developed largely on the basis of military requirements, and these need to be reappraised and modified where necessary before they can be employed for a supersonic transport.

Piloted simulators are appropriate tools for investigating handling qualities, and a program for this purpose has been initiated at the Ames Research Center of the NASA. In the present paper, some of the results obtained to date are described.

One of the aims of the program is to define the handling qualities in the cruising condition of flight. For this program simulators having different motion capabilities were used in parallel studies, and indications were obtained of the simulator complexity required for such studies and of some limitations of motion simulators.

A second aim is to investigate the handling qualities requirements for the landing approach condition. A fixed simulator has been used to explore the longitudinal handling characteristics in the instrument approach phase of the landing. A visual-landing simulator incorporated in the overall simulator has enabled

* Research Scientist.
† Chief, Operations Branch.

the pilot to continue the landings to the touchdown. From these studies it has been possible to describe in more detail than in previous flight studies some of the important factors contributing to difficulty in the control of the approach and landing.

Preliminary results from both of these studies have been reported in Ref. 1. The present paper includes more recent findings of the program.

PART I. HANDLING QUALITIES IN CRUISING FLIGHT—STATEMENT OF THE PROBLEM

In common with most airplanes designed for efficient high-speed flight at high altitudes, the supersonic transport can be expected to be deficient in aerodynamic damping and in certain static stability derivatives. For example, the large aerodynamic-center shifts that occur between subsonic and supersonic speeds frequently pose a problem in providing longitudinal stability for both ranges of speeds. Similar types of problems are foreseen in relation to the directional stability and the dihedral effect. It appears evident that various stability derivatives of the airplane will require artificial augmentation. Complete reliability could be assumed for the stability augmentation systems, but this would be unconservative. A more practical approach is to assume that failures will occur and to design the airplane to be satisfactorily operable in the event of failure. This is the approach that has been taken in the present investigation, wherein a completely satisfactory airplane, with suitable stability augmentation, has been assumed to suffer a failure of a single stability derivative augmenter, and the level to which that particular derivative could be allowed to deteriorate has been determined. Implicitly, this approach assumes the failure of only one augmenter; if multiple failures were to be considered, the scope of the investigation would have to be expanded. A rational basis for selecting the augmenters that could fail simultaneously might be derived from a detailed review of a particular system; such a selection cannot be made until the design of the airplane is well advanced.

SIMULATION

Three different simulators, a three-degree-of-freedom simulator and a five-degree-of-freedom simulator, and a variable stability airplane were used in the test program. The three-degree of-freedom simulator provided freedom of rotation in roll, pitch, and yaw (Fig. 1). As used in the test program the motions corresponded directly with the rotational motions of the airplane; there was no modification of the angular motions to simulate translational accelerations. The single-place closed cockpit was provided with conventional flight instruments to simulate instrument flight conditions. For convenience, a stick control was used in place of the conventional transport wheel control, and two throttles controlled the two outboard engines of a simulated four-engine airplane.

The five-degree-of-freedom simulator is shown in Fig. 2. It will be noted that this simulator was constructed by mounting the three-degree-of-freedom

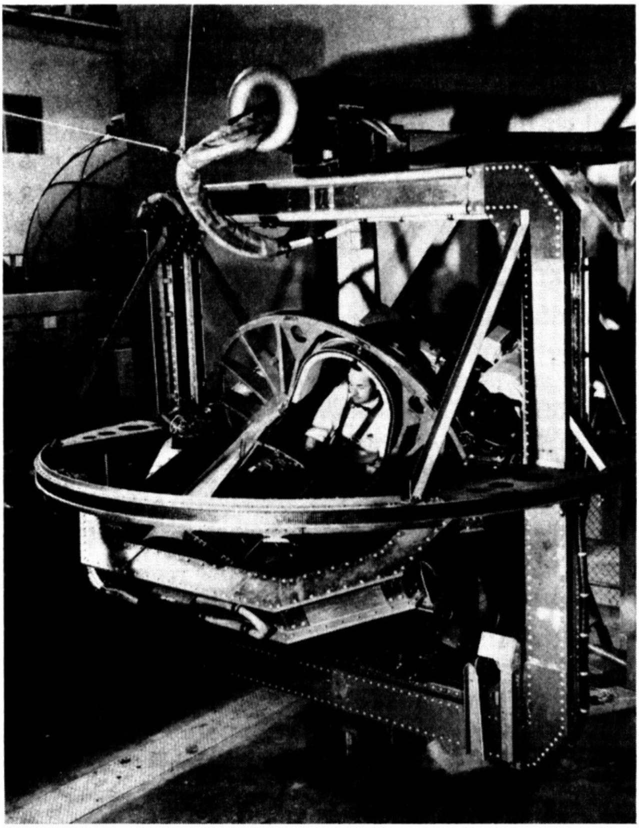

Fig. 1. View of three-degree-of-freedom simulator with cockpit cover removed.

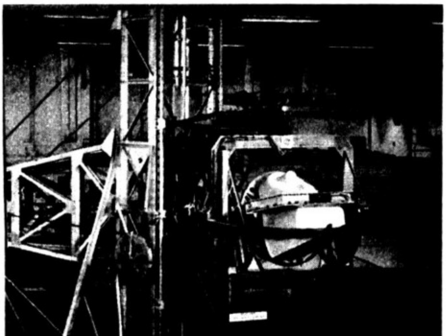

Fig. 2. View of five-degree-of-freedom simulator at Ames Research Center.

simulator on a vertical track that provided 3½ ft of usable vertical travel for these tests. The vertical track was, in turn, mounted on the end of an arm that enabled operation as a centrifuge. The vertical track assembly was supported on a circular rail on the floor rather than by a conventional cantilevered arm. For the present program the cockpit was oriented to face radially outward, rather than tangentially to the track as is customarily done in centrifuge operation. With this cockpit orientation rapid changes in side acceleration at the cockpit (resulting from abrupt loss of thrust of an engine and displacement of the cockpit from the center of gravity, for example) could be represented by motion of the centrifuge arm. The added motion capabilities of the five-degree-of-freedom simulator permit correct representation of the major motion cues, but other motions are neglected or erroneous. Considerable flexibility in the arrangement of motions to provide the desired acceleration cues is possible. The motion arrangements were under continuous study and development through the present test program (Appendix B) and the results reported herein were obtained with arrangements that were acceptable but possibly still not the best obtainable.

Except for the motions provided, all elements (control system, instrument display, etc.) of the five-degree-of-freedom simulator were essentially the same as those of the three-degree-of-freedom simulator.

The variable stability airplane used in the flight validation test is an F-100C fighter airplane (Fig. 3) which has been modified by special control arrangements to enable effective variation of certain stability derivatives. Through activation of the primary control surfaces by signals from appropriate transducers it is possible to vary the coefficients C_n, C_l, and C_m as functions of rotational rates, control deflections, angle of attack, and angle of sideslip. The ranges of derivative values available are enlarged by adjusting Mach number and altitude to the condition best suited for the particular test program. Thus,

Fig. 3. F-100C variable-stability airplane.

rotational motions may, in certain cases, be reproduced faithfully at the expense of flight condition duplication. In the flight tests, of course, it was not possible to reproduce the supersonic transport cruise conditions of $M = 3.0$ at 70,000 ft altitude. The flight tests were actually conducted at $M = 0.8$ at 35,000 ft altitude. No attempt is made to reproduce translational motions in flight tests with the F-100C airplane, but previous experience has indicated that the rotational motions do provide information of considerable value to the pilot.

TESTS AND EVALUATIONS

In the test program the simulated airplane was initially trimmed for flight at $M = 3$ at 70,000 ft. The pilots flew the airplane in entries into turns and precise control of altitude, and in other maneuvers designed to test more thoroughly the particular derivatives of interest. At some point during the evaluation, failure of one of the outboard engines was simulated and the pilot attempted to control the resulting motions. Pilots' ratings were based on general handling characteristics for normal flight, and on the difficulty of restraining the sideslip angles to values less than 5° when the engine failed (5° was assumed to be a structural design value for the airplane). The pilot rating schedule shown in Table I was used in rating the configuration.

TABLE I. PILOT OPINION RATING SCHEDULE

Type	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[1]	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No

* Failure of a stability augmenter.

TABLE II. SIMULATION USED TO OBTAIN RATINGS OF EACH PILOT CRUISE FLIGHT AT M = 3 AND 70,000 FT ALTITUDE

Pilot	Three-degree-of-freedom simulation	Five-degree-of-freedom simulation	F-100C variable stability airplane tests
A	X*	X	
B	X*	X	X
C	X*	X	
D	X		
E		X	

* Results included in part I of Ref 1.

Four NASA test pilots and one company test pilot participated in the program. However, all of the pilots did not fly all phases of the program; the particular phases flown by each pilot are indicated in Table II.

In the three-degree-of-freedom-simulator tests the pilots evaluated the various derivatives over complete ranges of values. In the five-degree-of-freedom-simulator tests, and in the F-100C flight tests, the pilots evaluated only a limited number of values, generally those corresponding to a pilot rating of $3\frac{1}{2}$ and $6\frac{1}{2}$ as determined in three-degree-of-freedom simulations.

The test basis developed in Ref. 1 was used in the present tests; that is, it was assumed that by stability augmentation a set of stability derivatives had been obtained which, in combination, were considered good (pilot rating $1\frac{1}{2}$). With the failure of a particular augmenter, the value of that one derivative would be reduced to the basic aerodynamic level. The task, then, was to determine what this basic aerodynamic value should be in order to be rated acceptable. The test procedure was to fly the airplane with all the derivatives at the level required for the satisfactory airplane, except for the one derivative that was assumed to be affected by failure of the augmenter. This derivative was evaluated at different levels. Limited tests on the five-degree-of-freedom simulator were also made in which the good airplane was maneuvered continuously in navigation turns and climbs, and individual damping augmenters were unexpectedly made inoperative.

Evaluation of Results

The results obtained in evaluations conducted on the three simulators are shown in Figs. 4, 5, and 6 where the pilot rating is shown as a function of the aerodynamic derivative. The aerodynamic derivative is usually presented as a ratio of the basic value for a delta-winged canard airplane. These basic aerodynamic values, although obtained from wind-tunnel tests of a particular configuration, are considered representative of the general class of low-aspect-ratio-wing, elongated airplanes that would be designed for efficient supersonic flight. Some differences are indicated in the results obtained from the different simulators; these differences will be discussed later.

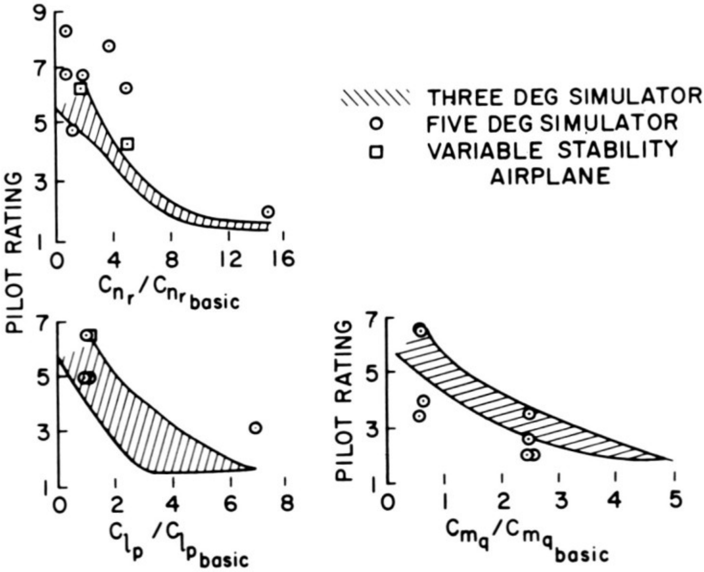

Fig. 4. Effect of variations in stability derivatives on pilots' ratings of handling characteristics in cruising flight. Values for each curve determined with all other derivatives set at satisfactory levels. Damping derivatives varied.

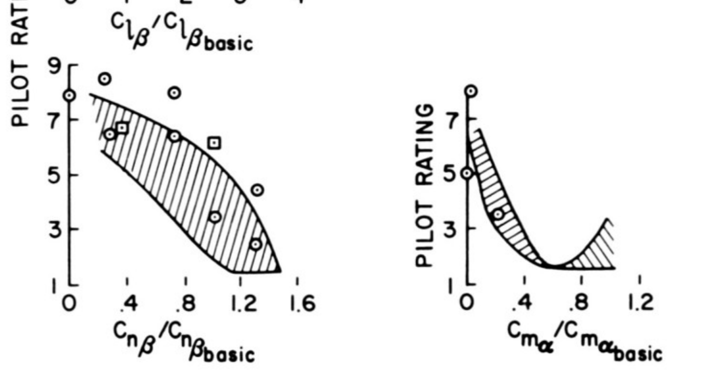

Fig. 5. Effect of variations in stability derivatives on pilots' ratings of handling characteristics in cruising flight. Values for each curve determined with all other derivatives set at satisfactory levels. Static stability derivatives varied.

The results in Fig. 4 show that for the good airplane ($PR = 1\frac{1}{2}$) the yaw, roll, and pitch damping derivatives would have to be augmented to 15, 7, and 5 times the basic values, respectively. Similarly, augmentation to the level that would insure completion of the mission ($PR = 4$) would still require 4, 3, and 2 times the basic damping in yaw, roll, and pitch, respectively, if the average values are considered. Achievement of satisfactory damping levels aerodynamically requires configuration changes that would severely penalize cruise lift-drag ratios. A pilot rating of even $6\frac{1}{2}$ would still require some augmentation of the yaw damping derivative; this pilot rating should be interpreted as permitting the pilot to maintain control until he can change to a more stable region of flight. For example, it has been estimated that the altitude would have to be reduced to 55,000 ft and a Mach number of 2.1 (for $1 = g$ flight) to achieve adequate values ($PR = 4$) for the roll or pitch damping derivatives. For the yaw damping derivative the altitude would have to be reduced to 37,000 ft and the Mach number to 1.4. If there is a limited range of alternative Mach numbers and altitudes that permits completion of the flight (from a performance or range standpoint), then a possible easing of the stability design problem may involve only matching of the aerodynamic damping derivatives to each other to assure that one "emergency" flight condition will suffice for any augmenter failure.

In Ref. 1 the transient effects of stability augmenter failure were shown to be of serious consequence in certain conditions where tight control of the airplane is required. For the tests in which unexpected failure of an individual damping augmenter was simulated during transport type maneuvers of a good airplane, no special difficulties were experienced and the pilot ratings remained unchanged.

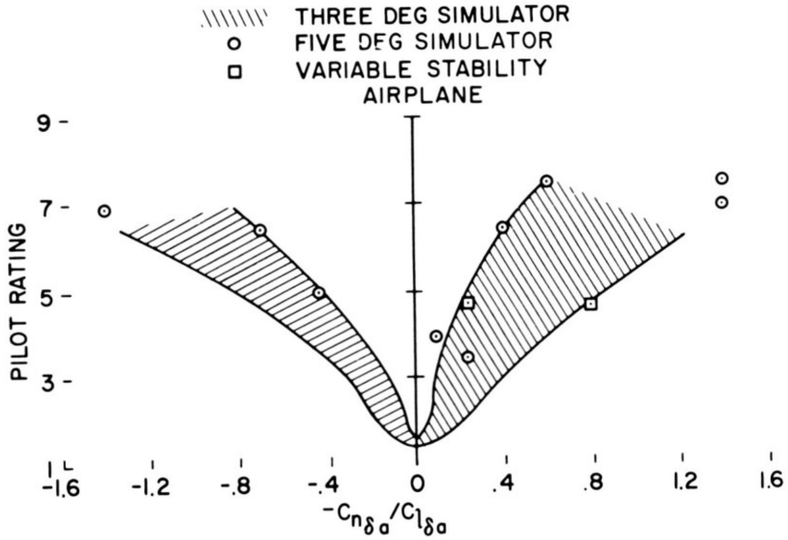

Fig. 6. Effect of variations in stability derivatives on pilots' ratings of handling characteristics in cruising flight. Values determined with all other derivatives set at satisfactory levels. Aileron yaw characteristics varied.

It is inferred that transport operations simply do not call for the tight control techniques that lead to trouble.

In Fig. 5 the variations of pilot rating are shown for several static stability derivatives. In contrast with the clearly defined ratings observed for the damping derivatives, the data for C_{n_β} and C_{l_β} exhibit considerable scatter, which could not be reduced by closer definition of the evaluation tasks. Average values for the observed results would indicate the basic airplane to be satisfactory, but pessimistic values would indicate the basic airplane to be unsatisfactory, and, hence, to require augmentation. Possible sources of the data dispersion are discussed later.

In recognition of additional possible design trends of the supersonic transport, limited ratings were also obtained on the five-degree-of freedom simulator for a negative dihedral effect. Difference in rating from the corresponding positive dihedral levels was obtained only at extreme values, where a rating of 7–8 for negative dihedral was compared with a rating of 6½ for positive dihedral.

The results obtained for the yaw characteristics of the roll control are shown in Fig. 6, where the values of $C_{n_{\delta_a}}$ are referred to $C_{l_{\delta_a}}$ in the absence of basic wind-tunnel data. For the desired operation of a transport, the pilots were in agreement in desiring zero levels of $C_{n_{\delta_a}}$. As shown, any departures from the minimal levels changed the ratings rapidly, although here, too, considerable scatter was evidenced, partly because of differences in the amount of required coordinating rudder that would be tolerated. Because adverse effects of yaw due to aileron were minimized by the low values of dihedral effect with which they were associated in the basic evaluation program, some additional ratings of $C_{n_{\delta_a}}$ were obtained with the value of C_{l_β} that had been rated 3½ (rather than 1½). Intermediate conditions were rated the same, while the value for 6½ was rerated as 8.

The effects of combining degraded values are indicated from this test to be important only at extreme values. This conclusion cannot be extended to all possible combinations of moderately degraded values. This was indicated by a test condition that was a combination of all the derivative values, each of which had been rated at 3½ when all other characteristics were good. The resulting combination was rated approximately 7. This result was not unexpected since other investigations have shown similar results. It does emphasize the fact that the results presented here must be interpreted in the context of the experiment, and denotes possible relaxations in design requirements that can be achieved when the single-failure philosophy is considered.

The general indications of the results presented here are that augmentation will definitely be required for the damping derivatives for all three axes of the airplane. The conclusions with regard to the static stability derivatives are not so clearly defined because of differences in the ratings of the various test pilots. These differences were large enough to leave a question as to whether some of the basic static stability derivatives are satisfactory or unsatisfactory, and were not resolved by discussions aimed at unifying the evaluation criteria. Such dispersions are not unusual, and have frequently characterized pilot evaluation programs, even in flight tests. Subsequent discussion will indicate some sources of the scatter, but experience with such evaluation programs indicates that differences in individual pilot characteristics will always contribute to some dispersion.

Comparison of Results from Different Simulators

The detailed results presented in Figs. 4, 5, and 6, and pilots' observations indicate some differences between results obtained on the various simulators that warrant discussion, not only to aid in the interpretation of the results, but also to indicate some considerations that need to be recognized in simulator testing. One important observation related to the control tasks that were used for evaluation. It was recognized early in the program that control of the airplane motions following the abrupt loss of thrust of an engine might represent a critical condition. Initial tests with the three-degree-of-freedom simulator and later tests on the variable stability airplane both indicate little effect of this task on pilot rating; for any individual pilot the pilot rating for abrupt thrust loss might have been increased over the value for normal operation by as much as 1 rating point, but these differences were submerged in the scatter among different pilots. In these tests, of course, the rotational motions were accurately reproduced but reliance had to be placed on instrument indications to judge the character of the other motions. One, therefore, could not be certain, on the basis of these tests alone, that the pilots were making adequate allowance for the missing motions, even though they were briefed on their character.

In the tests on the five-degree-of-freedom simulator, it was possible to provide, in addition to the rotational motions, a real indication of the side acceleration at the pilot's compartment, which would be a significant effect with failure of an engine.

The results of these tests show concurrence with those obtained with the three-degree-of-freedom simulator except for the derivatives that most directly affect the responses of the airplane to an abrupt loss of engine thrust, C_{n_β}, C_{n_r}, and C_{l_β}. Some of the pilots, unfavorably impressed by the simulated motions revealed by the five-degree-of-freedom simulator, rated these derivatives more adversely than they had in three-degree-of-freedom operation. The changes were quite substantial and would add seriously to the design problems indicated by the three-degree-of-freedom studies. One of the pilots indicated no deterioration of ratings on the five-degree-of-freedom simulator, on the basis that the added motions (side accelerations) provided the cue for prompt and instinctive corrective action to avoid large sideslip angles when the engine thrust was stopped. He observed further that if these added motions were too small to be detected, or small enough to be obscured by atmospheric turbulence or buffeting, a valuable clue for corrective action to limit sideslip would be lost.

A similar observation had been made by another pilot with respect to dihedral effect; too little dihedral robbed the pilot of a valuable clue to the development of sideslip angle. It is apparent from these and other observations that the relatively low limiting sideslip angle of 5° used as an evaluation criterion strongly influenced the pilot ratings. Detection of sideslip angle by the pilot in the absence of aerodynamic clues is a difficult task, since this information is not absorbed easily and rapidly from instrument displays. When it is a critical factor, as in the present investigation, the pilot must develop alternative sources of information, and a compromise must be reached between motions that are strong enough to serve as clues and motions that are strong enough to represent additional control problems. It does not seem unreasonable to speculate that some of the differences observed in the pilot ratings are due to diverse preferences of the pilots for source or strength of sideslip information clues. To the extent that this applies it would indicate a need to include as a factor in the ratings some stability and control parameters that have not been varied; that is, the derivatives C_{n_p}, C_{l_r}, etc.

In considering the effects of side acceleration as a cue for corrective control, it is of interest to note that the dynamics of the simulator drive system resulted in some lag in the response to the rapid commands generated by the computer. The order of this response lag is illustrated in Fig. 7 where the initial commanded side acceleration at the pilot's compartment is compared with the actual side acceleration indicated by an accelerometer mounted on the simulator. It is significant that even when the pilots were observing flight instruments that gave relatively instantaneous indications of the motions, they did not feel that the actual motion time lags of the order of ½ sec were troublesome or detracted from their evaluations.

It has been noted and was strongly emphasized by the pilots that some of the additional features provided by the five-degree-of-freedom simulator enabled them to rate certain variables with much more confidence. In particular, ratings for configurations that had marginal handling qualities were advanced with considerable reservation on the basis of three-degree-of-freedom-simulator evaluations, especially when violent motions such as those associated with engine failures were considered. Exposure to linear accelerations that approximated the actual motions, as on the five-degree-of-freedom simulator, established a

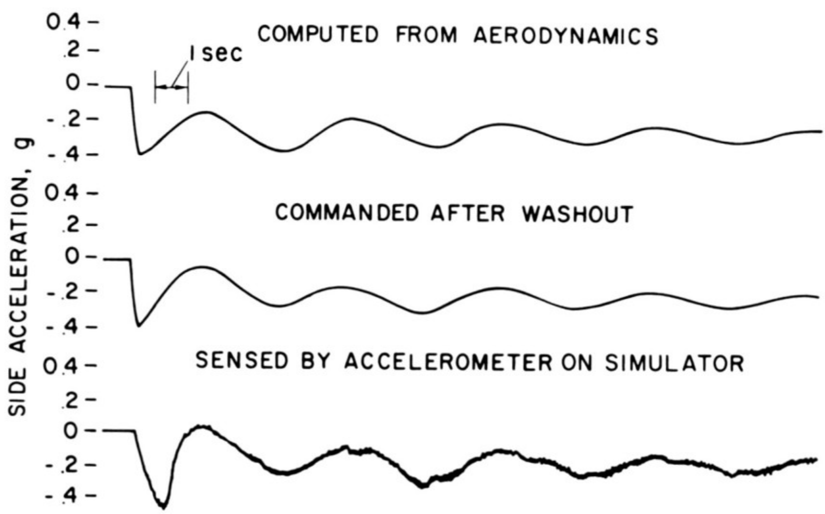

Fig. 7. Time history showing relationship of actual and command side acceleration at pilot's compartment following an uncontrolled engine failure.

much firmer foundation for the evaluations that depended on these motions. At the same time, however, the five-degree-of-freedom simulator did not provide a clear-cut answer to all problems because of unavoidable motion compromises (Appendix B).

Insofar as the variable-stability airplane is concerned, some obvious differences between flight and simulation received comment by the pilots. Aside from the realism of actual flight, it was noted, for example, that the visual environment of the flight tests made it possible to concentrate on observing the airplane response. On the other hand, the instrument flight conditions that would represent some of the transport operations would probably be more critical, and in this limited respect the simulator reproduced flight conditions more closely. It was noted, also, that simulated engine failures, which could be represented on the test airplane mainly by rotational motions, were much milder than those experienced in the five-degree-of-freedom simulator.

The details that would need to be incorporated in a simulator to provide realism equivalent to flight, will probably remain a subject for discussion and investigation for many years, and it would not be altogether unreasonable to expect that an answer completely satisfactory to pilots for all situations will never be found. This is probably not too serious a conclusion, however, since pilots have repeatedly demonstrated their capabilities for developing the required answers on fairly rudimentary simulators for many classes of problems, albeit with reluctance and reservations.

On the whole, it was concluded that the simulator and the variable-stability airplane complement each other well, and the ideal arrangement would be to have a variable-stability airplane available in the immediate location of the simulator, so that the pilot could examine the same problem on both in immediate succession. This would enable the pilot to take advantage of the best features of each with no time delays between evaluations to dull impressions, a factor of no small importance.

In summary of the findings of this section of the paper it appears that for cruising flight of a supersonic transport at $M = 3.0$, difficulty will be experienced in providing the required levels of damping, and possibly of some static stability derivatives, by aerodynamic design. The indicated solution, artificial damping and stability augmentation, would ease the aerodynamic design problems and, for a single-failure design philosophy, may require little enlargement of stabilizing surfaces.

The abrupt loss of thrust of an engine poses a critical design consideration for those stability derivatives that directly affect the resulting airplane motions.

PART II. LONGITUDINAL HANDLING QUALITIES IN THE LANDING APPROACH—STATEMENT OF THE PROBLEM

The low-aspect-ratio wings that characterize efficient high Mach number airplanes result in handling problems in the landing condition. One problem that has been clearly identified with this configuration is the location of approach speeds on the so-called back side of the thrust curve, where required thrust increases with decreasing speed. Military pilots have adapted to this characteristic on high-performance military airplanes by more active use of the throttle as a primary control in the approach. The acceptability of such piloting techniques for civil transport operations needs to be established to determine whether a configuration modification or automatic throttle control is necessary. Further, it has been indicated in previous flight and simulator studies that precision flying at speeds on the back side of the thrust curve was more difficult with low static longitudinal stability. Since trim-drag penalties in cruising flight required the static longitudinal stability to be low in the landing approach, this factor was also varied in the studies.

SIMULATION

The fixed transport-type cockpit used in this investigation (Fig. 8) was equipped with a conventional instrument display and normal flight controls. A Dalto Visual Simulator, a closed-circuit television device using a model runway, and a servo-driven camera were used to present to the pilot a projected picture of the approach lighting and runway as they would be seen in hazy,

Fig. 8. Instrument display and visual view of runway in landing-approach simulator.

half-mile visibility. The view shown in Fig. 8 was supplemented by a horizon representation and narrow-gage runway lights. Six degrees of freedom were provided in the equations of motion used in the simulation. The approach and landing task was studied in two separate phases. The first was that of performing a straight-in approach, on instruments, from a point seven miles from touchdown to less than a mile from touchdown. A standard ILS landing approach system was simulated. In the second phase the transition to visual conditions was made at an altitude of 200 ft and the approach was continued through the flare and touchdown. For the visual phase the display was represented as that seen from a pilot's compartment located 60 ft ahead of the center of gravity for the current turbojet and 100 ft ahead of the center of gravity for the supersonic transport.

TESTS AND EVALUATIONS

To aid in the adaptation to simulator operation it is desirable, initially, to provide the pilots with the characteristics of an airplane with which they have had recent flight experience. For this purpose, simulator studies were conducted first with a representation of a current jet transport. The supersonic transport configuration considered in the basic program was a delta-winged canard. Only the longitudinal characteristics were treated as variable; the lateral-directional characteristics were, therefore, maintained at a constant satisfactory level. The lift-drag characteristics were altered to produce the variations in required thrust with velocity shown in Fig. 9. For the approach speed range considered, 145 to 160 knots, the average value of the parameter $(dT/W)/dV$ was 0.0016

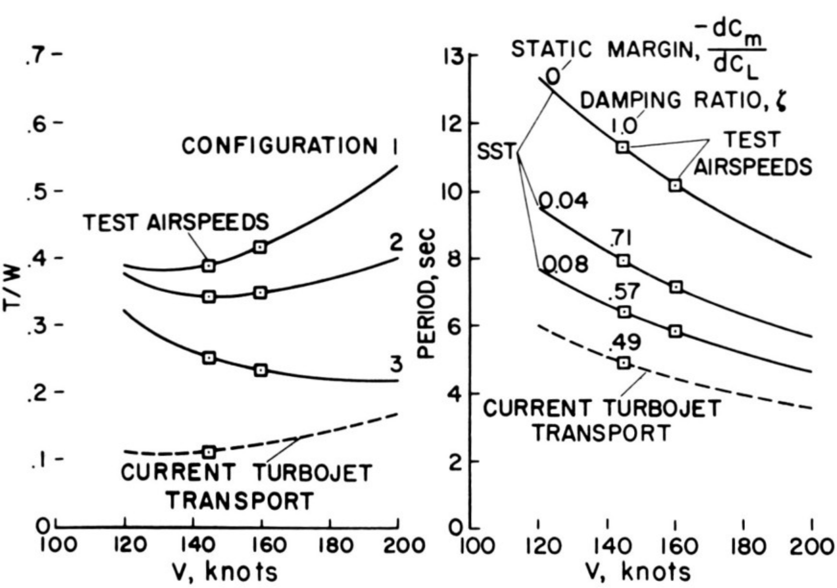

Fig. 9. Longitudinal characteristics of configurations investigated in landing-approach studies.

for configuration 1, 0 for configuration 2, and -0.0014 for configuration 3. For each of these configurations, values of the static margin, $-dC_m/dC_L$, of 0.08, 0.04, and 0 were considered. For the two positive stability cases the control power was set to permit a trimmed lift coefficient of 1.2; for the neutral-stability case the control power was the same as that for the lower stability case. The values of T/W assumed for the current jet transport are shown for comparison in Fig. 9. The ILS approach task was initiated 7 miles from touchdown in level flight at 1,500 ft altitude. Mild atmospheric turbulence and cross winds of small amplitude were included. Additional studies in which the approach was carried to touchdown, with a transition from the ILS display to the visual display provided by the Dalto simulator at 200 ft altitude, were initiated from stabilized conditions at an altitude of 400 ft. Two supersonic transport (SST) cases have so far been evaluated by one pilot in the latter studies, configuration 3 ($d(T/W)/dV = -0.0014$), with static margins of 4 and 8 percent mean aerodynamic chord. Seventy-five runs were made in the flare and touchdown program; this number is not large enough to justify quantitative statistical analysis, but is considered enough to indicate comparative trends.

RESULTS AND DISCUSSION

ILS APPROACH

Preliminary results for the ILS phase of the approach as evaluated by one pilot were reported in Ref. 1 and are repeated here in Fig. 10.* The deterioration in performance index with reduced stability was indicated there to correspond qualitatively with the pilots' ratings, and for stability levels somewhat below those of current jet transports would be considered unsatisfactory. No substantial changes in the results have been observed in subsequent evaluations. However, the final appraisals of approach characteristics are, of course, best defined in terms of touchdown conditions, and the results of such studies are discussed in the next section of this paper.

FLARE AND TOUCHDOWN

A number of different factors are of importance in defining touchdown conditions, principal among them being rate of descent at touchdown, for structural design, and longitudinal location of the touchdown point, which affects, of course, the amount of runway available for braking to a stop after touchdown. Among the secondary factors that need to be considered are rotational rates, lateral displacement from the runway centerline, heading, etc.

In Fig. 11 the results obtained from the landing studies are presented in statistical form. Fig. 11*a* shows the rate of descent at touchdown. For comparison, there is included in this figure and in Fig. 11*b* unpublished data obtained from

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* The error index ϵ used in Fig. 10 is defined as $\epsilon = \sqrt{\int(e_{gs}^2 + e_{loc}^2)}$ where e_{gs} and e_{loc} are glide slope and localizer needle deflections, respectively.

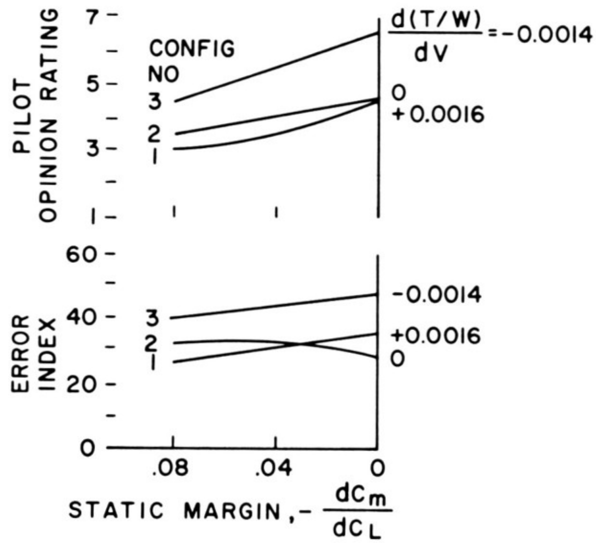
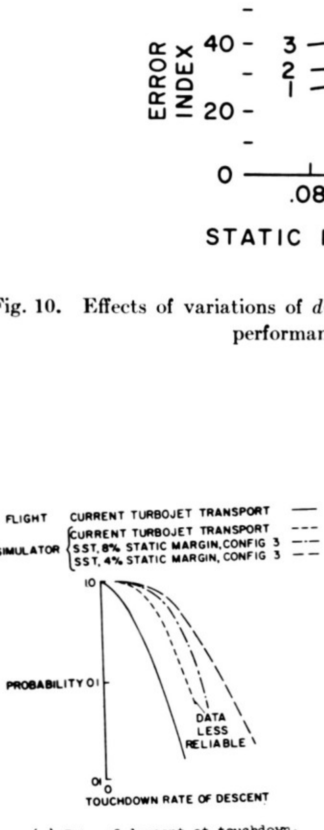
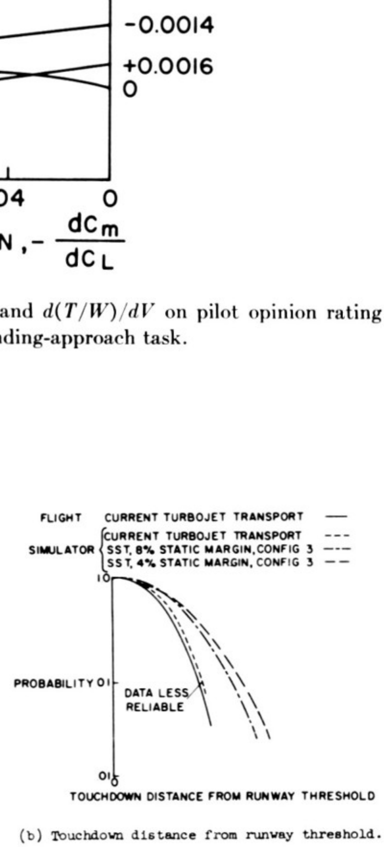


Fig. 10. Effects of variations of dC_m/dC_L and $d(T/W)/dV$ on pilot opinion rating and performance of landing-approach task.



(a) Rate of descent at touchdown.



(b) Touchdown distance from runway threshold.

Fig. 11. Probability distributions of landing performance parameters determined from flight and simulator landings: (*a*) rate of descent at touchdown; (*b*) touchdown distance from runway threshold.

documentation of landings of current jet transports in routine airline operations. Reliable measurements of touchdown conditions have not been obtained on the simulator for the current jet transport. Some crude indications of touchdown conditions, however, have been documented on the simulator, and since these conform somewhat to expected results, they have been included in Fig. 11*a* and 11*b* to serve as a reference for the other simulator results. The indicated touchdown rates of descent for the current jet transport are higher on the simulator than those measured in flight. The difference is not entirely unexpected since it is impractical to duplicate the flight conditions accurately on the simulator. The lack of cockpit accelerations and customary visual cues, and the difference in pilot motivation from that which is a normal part of any real landing maneuver would all contribute to higher values.

Substantially larger touchdown rates of descent are indicated on the simulator for the supersonic transport (SST) configurations than for the current jet transport. These increased descent rates are large enough to cause concern regarding landing gear structural design requirements. In addition, differences are indicated in the descent rate between the two static longitudinal stability levels for the supersonic transport. These differences are in qualitative accord with previously obtained differences in pilot rating for the two supersonic transport arrangements in the ILS phase of the approach (Fig. 10).

The curves for longitudinal touchdown points shown in Fig. 11*b* indicate that touchdowns were made over a range of distances considerably farther from the threshold for the supersonic transport configurations than for the current jet transport (as determined from operational experience or from the simulator). Increased dispersion of the touchdown points is, of course, unsatisfactory because of the consequent reductions in runway length available for landing rollout. These results are also significant in denoting that the increased descent rates discussed previously did not result only from the efforts of the pilot to force the airplane down within prescribed distances.

In general, then, it appears that the unsatisfactory longitudinal handling characteristics that resulted in poor pilot ratings for the ILS portion of the landing approach would also degrade the ratings for landing touchdown conditions. The full extent of the degradation may not be accurately indicated by the simulator results shown here, because these runs were initiated at an altitude of 400 ft, in alinement with the ILS beam. In the remaining short interval before "going visual," there was insufficient time to deviate as much from the beam as indicated in Fig. 22 of Ref. 1. The effects of initial offset (at 200 ft altitude) on the touchdown conditions have not been documented, but they would certainly be expected to be unfavorable.

Some indications of the basic roots of the problem can be obtained from the pilots' observations and from recorded data for the flare and touchdown task.

The general pattern indicated by the flare time histories is that of a large fairly linear decrease in rate of descent, of the order of 10 ft per second change, occurring over a time interval of 6 to 9 sec (Fig. 12). The pilot observed that sluggishness in longitudinal response had a detrimental effect in several ways.

First, it made it necessary to start the flare earlier at altitudes where visual judgment capabilities were less.

If the pilot did not initially judge and perform the flare accurately, he then had to make secondary flight path adjustments to let down to touchdown at a greatly reduced flight path angle; times ranging from 0 to 6 sec were used in this phase. For an airplane with fairly rapid longitudinal response (low value for period of short-period oscillation), the pilot is able to initiate and control secondary adjustments for large errors in the initial flare. He can thereby shorten the distance required to let down to ground contact and, perhaps, reduce the rate of descent in the last few seconds before touchdown. Accurate control of secondary adjustments becomes increasingly difficult as the period of the longitudinal motion increases, because of the increased lead in applying control required and the small time available for accomplishing the adjustments. It would appear that rapid responsiveness of the airplane for secondary adjustments makes the airplane forgiving of errors in the initial flare. Where this responsiveness is lacking, greater demands are made for accuracy of the initial flare.

The overall problem seems to be increased by lack of a consistent piloting technique for controlling the maneuver. Examination of the time histories of the flares for a given configuration revealed basic inconsistencies in the angle-of-attack variations that are interpreted as inconsistencies in the management of the flare and which failed to diminish with experience even under the systematic conditions of repeated simulator testing. Figure 12 shows comparative time histories of two successive flares that illustrate these inconsistencies. Case (*a*) shows a failure to reduce the rate of sink to desirable value before touchdown, while case (*b*) shows a mild "overflare," a situation which demands rapid reëstablishment of a sink rate if the landing distance is to be minimized. The desirability of rapid longitudinal response is obvious in this case.

Insofar as airspeed changes are concerned, these did not seem to represent a serious problem in the flare for the magnitudes of thrust-required gradient tested. Even for flare times of the order of those indicated, airspeed reductions were not large enough to require increases in thrust, and, in fact, for many runs the pilot actually decreased the thrust during the maneuver. However, in earlier phases of the approach the long period of the phugoid motion made airspeed control

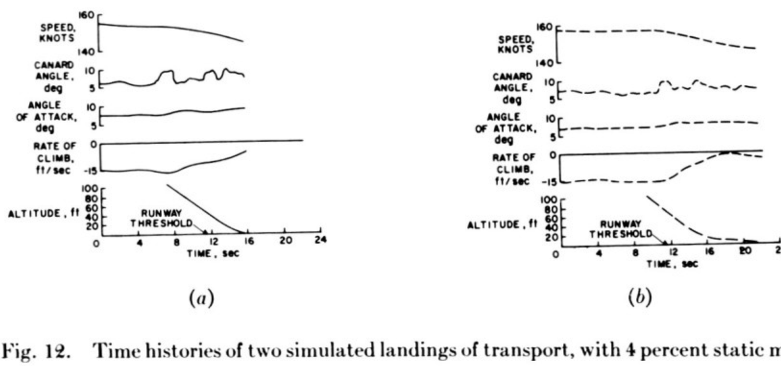


Fig. 12. Time histories of two simulated landings of transport, with 4 percent static margin.

difficult. The effects of a thrust adjustment for airspeed error could not be ascertained for a long time after the adjustment. By then the airspeed, undetected, would have changed greatly because of attention being given to flight-path corrections.

Management of the flare has frequently been described as an art rather than a science. While the present results may exaggerate the problem, because of the extreme longitudinal control characteristics being investigated, the fact cannot be ignored that the problem does exist in some degree with all high-performance airplanes. As a part of a long-range program directed at providing all-weather landing capabilities for the supersonic transport, the Ames Research Center is considering means for improving landing consistency.

One aspect of this problem which may have had some influence in producing the poorer landing performance of the supersonic transport shown in the present results in that of visual judgment. The pilot's compartment is substantially higher than in current jet transports, and at flare initiation, is subject to motions that do not accurately reflect those of the airplane center of gravity.

Limited simulator tests of a delta-winged canard configuration of a supersonic transport have indicated that poor longitudinal handling characteristics in the landing approach will be reflected in the flare and touchdown characteristics. Thus, for two configurations which were rated unsatisfactory in the approach, touchdown rates of descent and touchdown points (distance from runway threshold) were considerably greater than corresponding values for current jet transports. Augmentation of the pilots' visual judgment capabilities and simplification of the control task, possibly through provision of director-type information, should be investigated as an alternative or supplement to improvement of the basic longitudinal characteristics.

APPENDIX A

NOTATION

b = wing span, ft
C_{l_p} = roll damping derivative, $\partial C_l/\partial(pb/2V)$
C_{l_r} = roll-due-to-yawing derivative, $\partial C_l/\partial(rb/2V)$
C_{l_β} = effective dihedral derivative, $\partial C_l/\partial\beta$
$C_{l_{\delta_a}}$ = roll control power derivative, $\partial C_l/\partial\delta_a$
$C_{m_{C_L}}$ = $\partial C_m/\partial C_L$
C_{m_q} = pitch damping derivative, $\partial C_m/\partial(\theta c/2V)$
C_{m_α} = static longitudinal stability derivative, $\partial C_m/\partial_\alpha$
C_{n_p} = yaw-due-to-rolling derivative, $\partial C_n/\partial(pb/2V)$
C_{n_r} = yaw damping derivative, $\partial C_n/\partial(rb/2V)$
C_{n_β} = static directional stability, $\partial C_n/\partial\beta$
$C_{n_{\delta_a}}$ = aileron yaw derivative, $\partial C_n/\partial\delta_a$
$\bar{c}$ = wing mean aerodynamic chord, ft
e = deviation of airplane from ILS beam, percent of full-scale indication
g = acceleration due to gravity, 32.2 ft/sec^2
PR = pilot rating
p = rolling velocity, radians/sec
r = yawing velocity, radians/sec
S = wing area, sq ft
T = thrust, lb
t = time, sec
V = velocity
W = airplane gross weight, lb
α = angle of attack
β = sideslip angle
δ_a = aileron deflection
δ_e = elevator deflection
ϵ = resultant rms error in ILS indication, percent full scale
θ = airplane pitching velocity

SUBSCRIPTS

basic basic airplane value
GS glide slope
loc localizer

APPENDIX B

MOTION SIMULATION WITH A FIVE-DEGREE-OF-FREEDOM MOTION SIMULATOR

The investigation reported here represents one of the first known attempts to simulate handling qualities problems around 1-g base level with a five-degree-of-freedom motion simulator oriented as described. As mentioned earlier, difficulties were experienced in developing satisfactory arrangements for limiting the motion of the simulator. Because these difficulties were not completely resolved during the program, they may have influenced the test evaluations by the pilots to some degree. Also, some rather fundamental problems associated with such motion simulations were illuminated, and for these reasons it appears worthwhile to review the problems.

Basically, of course, the purpose of a motion simulator is to supply kinesthetic cues to enable the pilot to appreciate and control handling qualities problems more realistically. It has been fairly well established that only the accelerations of the motions are sensed by the pilot. Thus the approach taken is to try to apply realistic accelerations where they contribute to the handling and to "washout"* these accelerations slowly so that the pilot is unaware of the washout, or at least unaffected by it.

In the present program there appeared to be little cross coupling of longitudinal and lateral-directional problems, so that it is possible to discuss them separately.

First, in the longitudinal motion, fairly strong washouts were required for the vertical travel because of the limited motion available — 3½ ft. For the evaluation tasks considered (controlling a poorly damped airplane, holding altitude, initiating climbs, leveling off, etc.) this motion, in conjunction with pitching rotation that was comparably washed out, contributed significantly to the realism of the "feel," although it was not required for evaluation.

The main difficulties centered around the lateral-directional motions. As already noted, the cab orientation was selected to enable side accelerations to be represented by motion of the cab around the circular track. (The scheme of using cab bank angle to supply high-frequency side accelerations through orientation of the gravity vector was discarded after a quick appraisal, because the rapid changes in side acceleration (occasioned by asymmetric thrust losses, for example) produced roll motions that could not be differentiated from aerodynamic roll motions.) In theory, this arrangement permits side accelerations (or at least the component of side acceleration represented by motion around the track) to be sustained until limiting arm velocities are reached. In practice it was found that the large velocities attained with sustained accelerations became apparent to the pilot through the noise levels, the centrifugal acceleration (0.37g at limiting velocity), and possibly other factors, tending to obscure the acceleration cues of primary interest.

Since these effects in some cases contributed to nausea of the pilot, some washout of the motion around the track was necessary. The degree of washout

* "Washout" describes simulator drive signals that are superimposed on those commanded by the pilot in order to return the simulator to zero conditions after some time delay.

required appeared to be somewhat a function of the particular task being evaluated. A strong washout was desired to minimize the discomforting effects of large velocities around the track, and this seemed to be quite acceptable for the higher-frequency oscillations ($P = 4.5$ sec). With low frequency motions ($P = 12$ sec), however, the strong washout damped the cab motions at a frequency that appeared different from the airplane frequency, as evidenced by flight instruments, and the cab motions were considered actually detrimental by some pilots. A solution to this problem was to use washout on the arm motion and apply bank angle for gravity orientation to replace the accelerations canceled by the washout. If a moderate arm washout were applied, which would permit moderate motions around the track, the necessary bank angles would be applied at a relatively low frequency or roll rate so that they might remain undetected by the pilot. No completely satisfactory arrangement could be found in reproducing side accelerations accurately; in oscillations the pilot sensed the roll motions as an apparent negative dihedral effect. A final solution, it appears, may require adjustment of the washout arrangement for the particular task, and in all likelihood, acceptance of accelerations which, though erroneous in magnitude, still vary in proper phase with the correct accelerations. The limitations described here, it will be noted, do not arise peculiarly from the fact that a centrifuge was being used for the tests. Restrictions of the side motion, to limit discomfort in a centrifuge, would be imposed by practical design considerations for most other types of motion simulators that operate over a limited travel. The considerations that dictated the washout arrangements in the present studies will, therefore, be found widely applicable in motion-simulator studies.

REFERENCE

1. White, Maurice D., Melvin Sadoff, Richard S. Bray, and George E. Cooper, "Assessment of Critical Problem Areas of the Supersonic Transport by Means of Piloted Simulators," *IAS Paper 62–20*, Jan. 22–24, 1962.