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U.S. Naval Air Development Center

Johnsville, Pennsylvania

Aviation Medical Acceleration Laboratory

NADC-ML-6411 13 August 1964

Simulation and Effects of Severe Turbulence on Jet Airline Pilots

Bureau of Medicine and Surgery
Subtask MR005.13-0005.10 Report No. 1

Bureau of Naval Weapons
WepTask RAE 20J 043/2021/F012 10 11
Problem Assignment No. 043AE25-1
WepTask RAE 13J 012/2021/R005 01 01
Problem Assignment No. J04AE13-2

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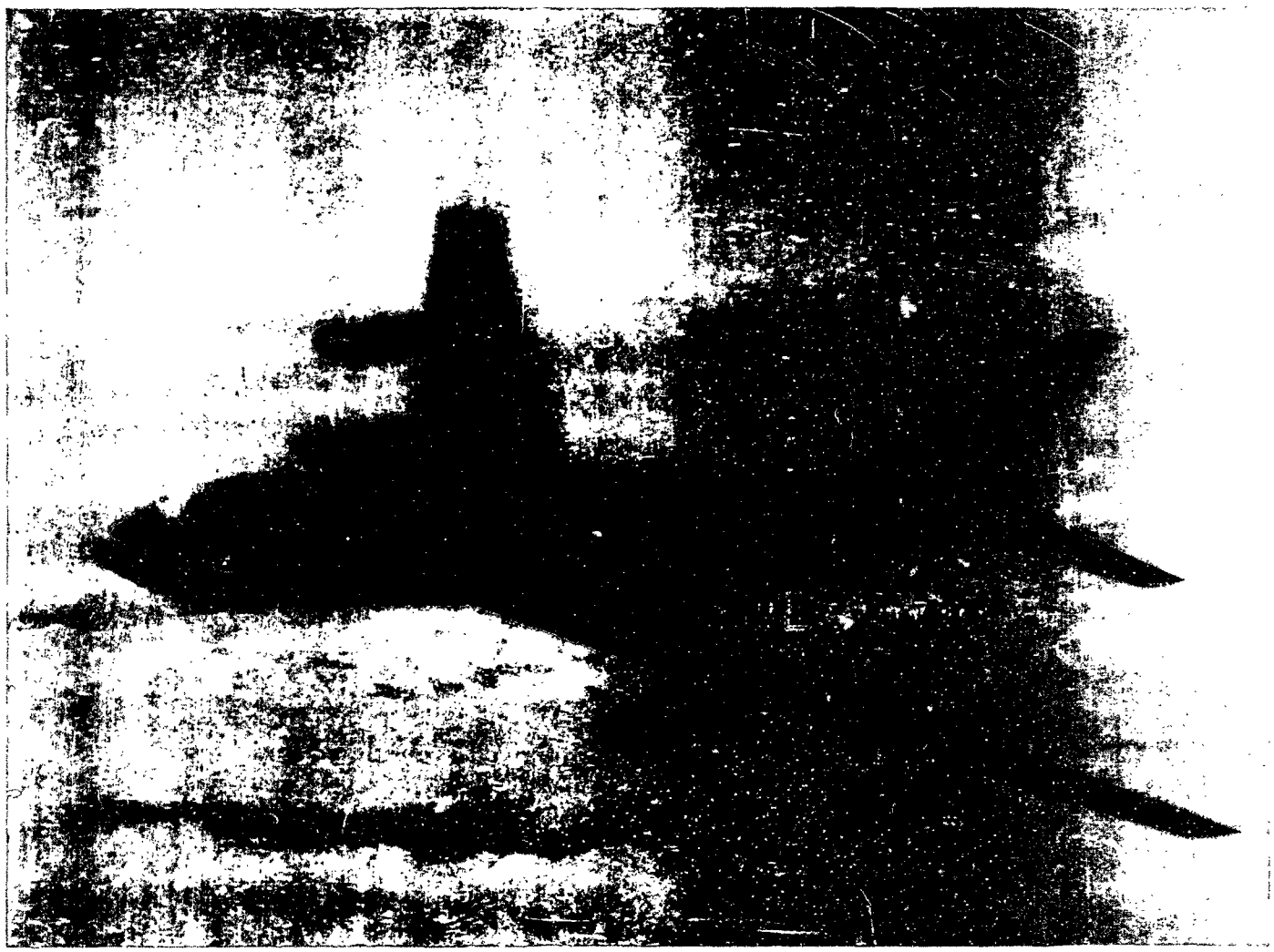

United Air Lines B-720.

SUMMARY

The Aviation Medical Acceleration Laboratory of the U. S. Naval Air Development Center, Johnsville, Pennsylvania, was requested by the Federal Aviation Agency, Washington, D.C., to utilize the human centrifuge to investigate factors contributing to commercial jet aircraft crashes associated with severe air turbulence. The problem undertaken was to determine (1) whether or not an adequate simulation of the physical events taken from the flight recorder of a United Airlines Boeing 720-B could be reproduced with the centrifuge, and (2) to determine if there were any effects upon pilots under these circumstances detrimental to the safe control of the aircraft.

The first portion of the problem was successfully accomplished by programming on the centrifuge the acceleration profile in the G_z axis of UAL 720-B, Flight 746, N7213U, which had encountered severe turbulence in the cirrus portion of a thunderstorm at 37,500 feet over O'Neill, Nebraska, on 12 July 1963. The events that ensued were taken from a Fairchild Flight Recorder #1127 installed aboard the aircraft. In this case the aircraft had dived from 37,500 feet to 12,000 feet before being brought under control. The simulated turbulence produced accelerations that fluctuated from a maximum of +3.5 G_z to a maximum of -2 G_z at a random frequency average of 1 cps. The pilot and copilot who had flown the actual flight were the first to experience the centrifuge simulation. They pronounced it excellent. Subsequently, eight other airline pilots were exposed to the simulation and adjudged it realistic based on their personal experiences in turbulence during their pilot careers.

Effects upon pilot performance detrimental to safe control of the aircraft are thought to have been observed and recorded. On the basis of this limited pilot study, it appears that there is a consistent tendency to experience a kinesthetic illusion which causes the pilot to make inappropriate pitch control movements. When negative G_z was encountered for the first time, an initial movement of the yoke in the wrong direction was the rule rather than the exception. Some stick movements that were thought to be involuntary resulting from jostle were made, but these were not considered to be of a magnitude sufficient to hazard normal aircraft control. The use of a shoulder harness as well as a secure lap belt made control easier and made the pilots feel more secure psychologically. There was some blurring of the instruments. However, if the pilot concentrated upon the artificial horizon, he could maintain his orientation with regard to that instrument but was unable to maintain a useful panel scan. All pilots felt the Lear 3-inch face model 4003 G, Type MM3 artificial horizon used in the simulation was easier to interpret than the type instrument

employed in their commercial jet aircraft which may become unreadable in unusual attitudes. Although the simulation lasted only six minutes in each case, it was obvious that the rate of onset of fatigue was much higher than in normal instrument flying. Disorientation was not a prominent feature in this experiment and motion sickness did not occur. No abnormal physiologic responses were encountered.

These data strongly suggest that by responding to a strong kinesthetic illusion of climb or dive after correcting from an unusual nose up or nose down attitude pilots are creating ever increasing deviations from normal flight pitch attitude in both directions alternately, somewhat analogous to pilot-induced oscillations, until the aircraft stalls and falls off into a steep dive that is difficult to recognize or to recover from because of the limitations inherent in the types of artificial horizons frequently employed in their aircraft.

RECOMMENDATIONS

The results of this study indicate a need to investigate further the problems associated with turbulence in jet transport aircraft with special regard to crew performance, crew responsibility, and flight instrumentation utilizing a sophisticated dynamic simulator. The duties and interaction of pilot and copilot should be thoroughly studied under these conditions in order to determine operational procedures that will avoid loss of control or to regain it once it is lost. In the meantime it is suggested that the results of this study be disseminated among commercial air carrier personnel and that the lessons to be learned from it be included in appropriate company flight bulletins. Artificial horizon indicators that can be easily interpreted in unusual attitudes should be installed in all commercial air carriers at the earliest opportunity.

ACKNOWLEDGMENT

The authors wish to acknowledge the technical efforts of Mr. Joseph Cunningham in the computer programming of this study.

TABLE OF CONTENTS

	Page
SUMMARY	ii
RECOMMENDATIONS	iii
INTRODUCTION	1
MATERIALS AND METHODS	3
RESULTS	15
Integrated Absolute Error in Pitch and in Roll Performance	17
Control Stick Reversals	23
Effects of Practice	30
Pilot's Control Motions when Visual References Were Not Available	34
Effects on Vision	38
Pilot's Evaluation of Their Own Performance	39
Adequacy of the Centrifuge Simulation	43
REFERENCES	45

LIST OF FIGURES

Figure	Title	Page
1	Flight Recorder Data UAL B-720, Flight 746 N7213U	2
2	Cutaway View of Centrifuge Gondola	5
3	Human Centrifuge at Aviation Medical Acceleration Laboratory	6

LIST OF FIGURES

Figure	Title	Page
4	Main Centrifuge Control Center	7
5	High Frequency Portion of Desired G-Profile	10
6	High Frequency Portion of Desired G-Profile	11
7	Mean G or Low Frequency Portion of Desired G-Profile	12
8	Acceleration Recording of Dynamic Simulation	14
9	Block Diagram of Computer Programming Requirements	16
10	Mean Integrated Absolute Error Performance in Pitch and Roll during Static and Dynamic Conditions	21
11	Mean Integrated Absolute Error Performance in Pitch and Roll during the First and Second Trial Series	22
12	Mean Number of Control Stick Reversals per Pilot	25
13	Average Number of Stick Reversals for 9 Pilots - First Trial Series	28
14	Average Number of Stick Reversals for 9 Pilots - Second Trial Series	29
15	Mean Integrated Absolute Error Scores in Pitch for 5 Volunteer Subjects	32
16	Individual Percentage Change Scores for Volunteer Subjects	33
17	Mean Integrated Absolute Error Scores in Roll for 5 Volunteer Subjects	35

LIST OF FIGURES

Figure	Title	Page
18	Individual Percentage Change Scores for Volunteer Subjects	36
19	Example of Control Stick Movements	37

LIST OF TABLES

Table	Title	Page
I	Summary of Analysis of Variance of Integrated Absolute Error Scores in Pitch	19
II	Summary of Analysis of Variance of Integrated Absolute Error Scores in Roll	20
III	Results of Chi Square Analysis of Control Stick Reversals	26

INTRODUCTION

On February 12, 1963 a Northwest Airlines jet transport encountered severe turbulence in a thunderstorm shortly after takeoff from Miami, Florida, and crashed a few minutes later. Subsequently other jet commercial carriers have experienced difficulty in severe air turbulence, usually associated with thunderstorms, and have crashed or gone into steep, perilous dives from which a recovery has been made after frightening losses of altitude and at least one instance of severe structural damage to the aircraft. The most recent incident from which a recovery was made occurred on 12 July 1963 over O'Neill, Nebraska, when a United Airlines Boeing 720-B, Flight 746, flying at FL375 encountered severe turbulence in the cirrus portion of a thunderstorm. The crew had just initiated a climb to an intended FL410 to top the clouds. Instead control was lost and Flight 746 entered a steep dive that was terminated at approximately 12,000 feet, an unanticipated loss of some 25,000 feet altitude. This and other similar incidents during the past year have created great concern in the airline industry and to the Federal Aviation Agency (FAA). In an attempt to solve the problem and to learn ways by which it may be avoided in the future the Aviation Medical Acceleration Laboratory (AMAL) of the U.S. Naval Air Development Center was approached by representatives of the airline industry and the FAA to determine if there was any way in which a simulation could be made using the laboratory's human centrifuge that might add to the knowledge already obtained in studies of previous incidents and crashes. The record of the events occurring in the UAL's Flight 746 taken from its onboard Fairchild 1127 Flight Recorder was made available (see Figure 1) to the AMAL and the vertical accelerations taken from this record were programmed on the computer that is used to run the centrifuge. An initial study was agreed to in which it would be determined whether or not a satisfactory simulation could be reproduced physically on the centrifuge, and if so to determine any effects that these physical forces might have upon the flight crew that would possibly explain the course of events leading to loss of control and altitude.

In 1959 the AMAL had attempted to perform a turbulence simulation in connection with a low level weapons delivery study (1). In that case there were large acceleration forces in the transverse or G_x axis as well as the desired G_z and the simulation was not considered by the pilots riding the program to be very realistic. The present study clearly demanded rapidly changing vertical accelerations in the G_z axis from +2.5 G_z to -2 G_z at an average frequency of at least 1 cps in almost random bursts. The vertical alterations were accomplished by moving the seat as far off center in the gondola as possible and then rotating the gondola on its inner gimbal at the desired frequency while the outer gimbal was rotated to give the desired

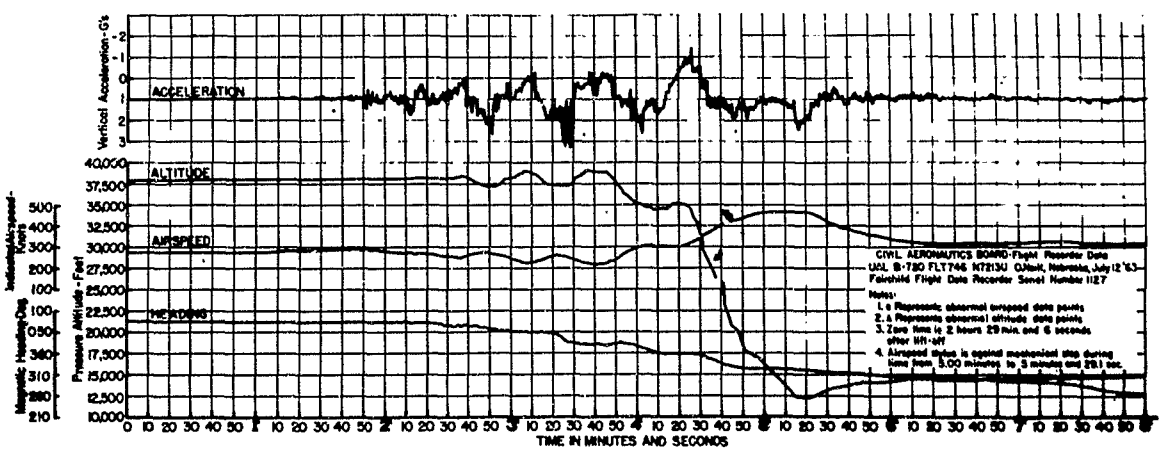

Figure 1. Flight Recorder Data UAL B-720 Flight 746 N7213U.

G vector as the entire arm rotated at a speed designed to produce the desired magnitude of G. The precise means by which this was accomplished is discussed under Materials and Methods below.

In order to assess the realism of the simulation thus obtained, the two pilots who had actually experienced the encounter in UAL Flight 746 were brought to the AMAL where they rode the centrifuge version. It was their opinion that the simulation was excellent, based on their memory of the actual event. Subsequently six other experienced airline pilots were brought to the AMAL to ride the simulation and they agreed that the sensations experienced were realistic although none had experienced turbulence of such magnitude in actual flight. Two FAA test pilots also flew the simulation. Thus, 10 pilots served in Phase I.

In addition, five volunteer AMAL subjects participated in a second phase of this experiment, Phase II. Four of these subjects made eight dynamic-static pairs of runs, and one made six dynamic-static pairs. The purpose of this phase was to evaluate the effects of repeated trials on a group of naive subjects.

In addition to demonstrating a subjectively realistic simulation of UAL Flight 746's turbulence encounter, the following questions were answered: 1. Whether or not there were any significant differences in error performance between pilots. 2. Whether or not there were differences in error performance during static and dynamic runs. 3. Whether or not there were significant differences between trials, i.e., practice effects, and 4, the presence or absence of interaction effects among the subjects. 5. Whether or not control stick reversals occurred during transitional G states (Kinesthetic Illusion). 6. Whether or not turbulence affected visual capability of the pilot. 7. And finally, whether or not there were any significant physiologic changes induced by turbulence.

MATERIALS AND METHODS

Eight experienced airline pilots and two FAA test pilots were used as subjects on the human centrifuge. They were placed in an aluminum suit and secured by a standard U.S. Navy lap belt and shoulder harness. The pilots were permitted to adjust the shoulder harness to suit their comfort. The control column from a DC-8 aircraft was positioned at an average distance with respect to the pilot's seat.

The instrumentation consisted of an artificial horizon Lear 3" (4003 G Type MM-3) and a Navy standard 3-pointer altimeter. The artificial

horizon was located approximately 30 inches from the pilot's eye. The relative positions of the seat, the pilot, the control column, artificial horizon, and the altimeter are shown in Figure 2. These dimensions represented an average of those designed for a DC-8 cockpit. The control forces were adjusted to 40 pounds.

Each pilot was given two pairs of runs lasting six minutes each and consisting of a static simulation during which he attempted to control the artificial horizon while the centrifuge remained stationary, followed by a dynamic run during which the same control task was presented on the artificial horizon as the centrifuge simulated the turbulence.

For Phase II of the experiment, five non-pilot volunteer AMAL subjects were selected to study learning effects. Four of these received eight dynamic-static pairs of runs, and one received five dynamic-static pairs. Finally, two pilots were tested in a phase in which the visual task was disconnected.

Before each run, a briefing session was held with each pilot. The pilot was told that the task was to keep the plane straight and level by using the artificial horizon. Following each testing phase, a debriefing session was held with each pilot, in which a wide variety of subjective comments and evaluations were recorded. These are discussed in the Results section.

The human centrifuge (Figure 3) consists of an enclosed gondola mounted in a controllable two gimbal system at the end of the 50 ft. long main arm. The gondola is an oblate spheroid described by rotating a 10 ft. x 6 ft. ellipse about its minor axis. This gimbal system is a unique feature of the human centrifuge and is normally used to control the direction of the resultant acceleration vector with respect to a subject located at the center of the gondola. It is possible, for example, through the use of an analog computer (Figure 4) in the centrifuge control system, to continuously compute the gimbal positions and the centrifuge angular velocity which are required to maintain the direction of a desired G profile along the spinal axis of a subject seated in the gondola. This effect is obtained by storing the G profile on a curve follower whose output, when operating, is a dc voltage proportional to the G. This dc voltage is fed into the analog computer which is programmed with the following coordinate conversion equations:

(1) $G_z = R/g \sqrt{\omega^4 + \dot{\omega}^2 + (g/R)^2}$; $G_x = 0$; $G_y = 0$

(2) $\tan A = R/g\, \omega^2$

(3) $\tan B = \dot{\omega}/\sqrt{\omega^4 + (g/R)^2}$

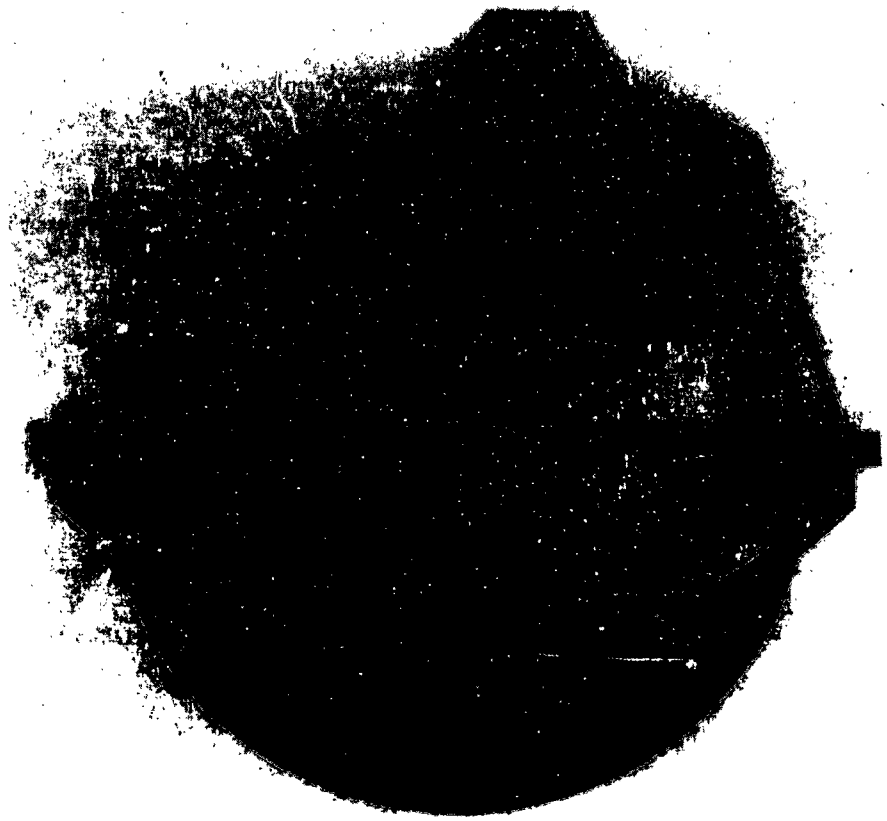

Figure 2. Cutaway view of centrifuge gondola showing pilot seated 4 ft. back of center of rotation.

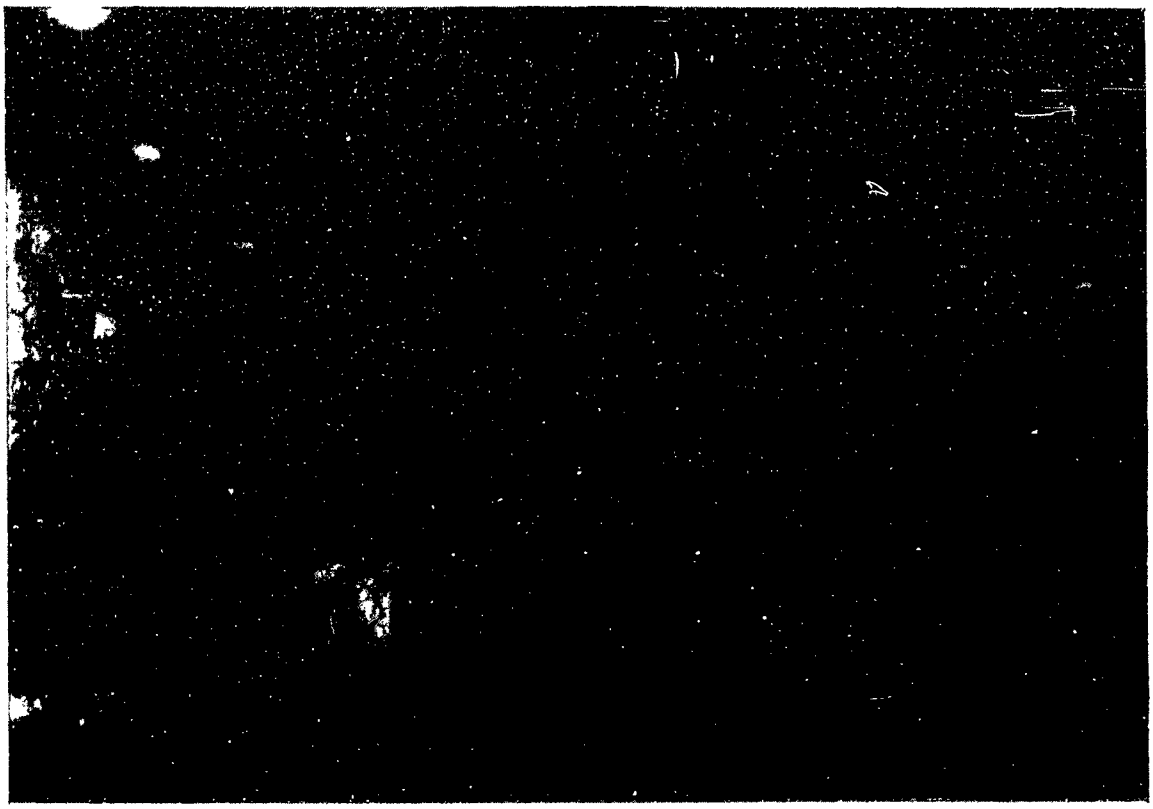

Figure 3. Human Centrifuge at Aviation Medical Acceleration Laboratory.

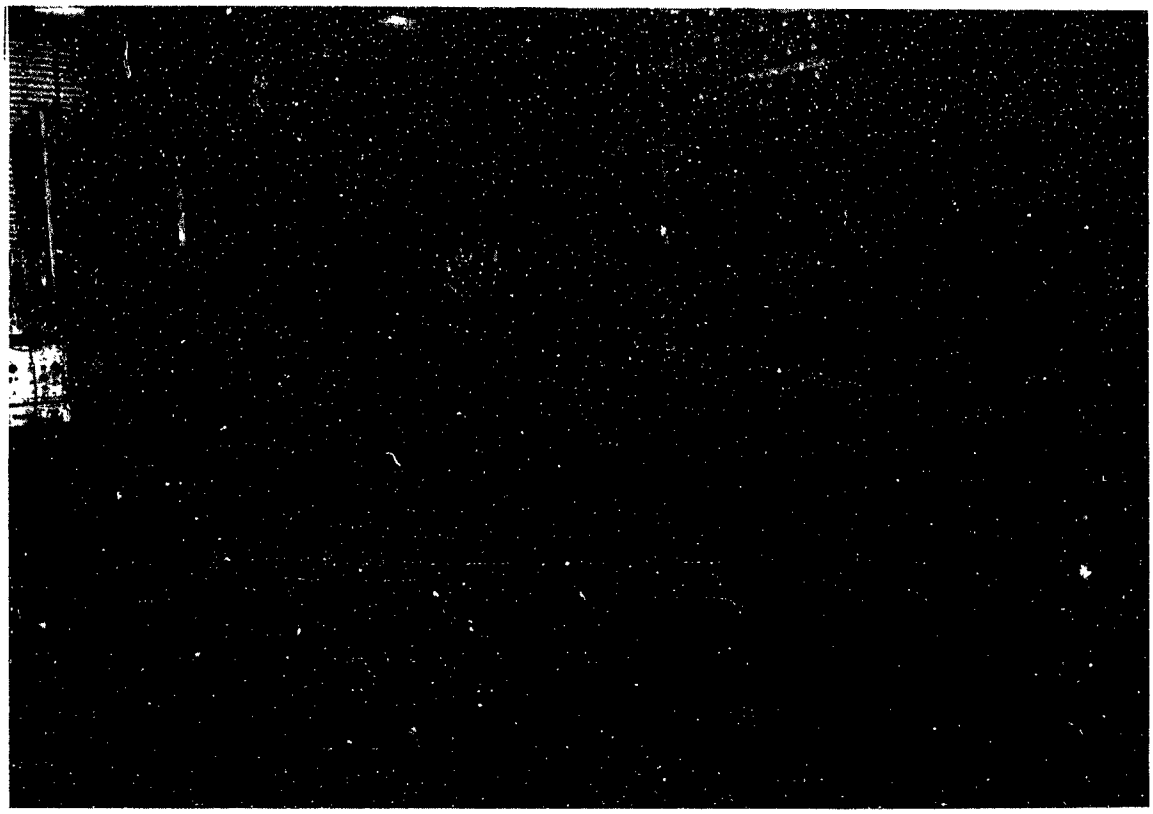

Figure 4. Main centrifuge control center showing the analog computer facility in the foreground.

where

ω = angular velocity of centrifuge arm (rad/sec)
$\dot{\omega}$ = angular acceleration of centrifuge arm (rad/sec^2)
A = angular position of outer gimbal (roll axis)
B = angular position of inner gimbal (pitch axis)
R = length of centrifuge arm (50 ft.)
g = acceleration of gravity (32.16 ft/sec^2)
G_z = subject longitudinal acceleration component (G-units) (eyeballs down)
G_x = subject transverse acceleration component (G-units) (eyeballs back)
G_y = subject lateral acceleration component (G-units) (eyeballs left)

These equations have been programmed successfully for a large number of computer-controlled centrifuge studies. Limits exist, however, on the frequency with which an oscillating G profile could satisfactorily be generated in this manner. In particular, for an amplitude varying from 1 G to 2 G, the power available in the centrifuge and gimbal drive motors would limit the maximum frequency attainable to approximately 0.5 cps. Even if more power were available in the drive motors, the angular accelerations required of the gimbal systems would introduce such undesirable effects on the subject that little validity could be placed on centrifuge simulation studies beyond this frequency.

The basic information available for defining the G requirements of this simulation study was the flight record shown in Figure 1. Since the vertical G accelerometer was the only one recorded, and that presumedly at the c.g. of the aircraft, it was not known whether the other two components of the acceleration vector remained zero during the entire turbulent situation and whether the acceleration at the pilot location was sufficiently different from that recorded. Available for evaluating the simulation beyond any comparison of accelerometer tracings, however, were the pilot and copilot who had flown the actual flight.

Careful examination of the G profile revealed a relatively high frequency component which varied randomly between 1 cps and 4 cps superimposed upon a lower frequency component which varied between 0.1 cps and 0.2 cps. Also, the amplitude of the high frequency component varied randomly between +1 G and -1 G and that of the lower frequency component between +2.5 G and -2 G. In view of the previous discussion, the high frequency variation in the G profile could not be accomplished in the conventional manner. Also, the equations as described could not accommodate a G requirement of less than 1 G resultant. If this simulation was to be performed on the centrifuge, therefore, a unique approach was required.

Consider the effect that can be achieved by placing the pilot and his cockpit equipment approximately 4 ft. back of the center of the gondola, as shown in Figure 2. If the inner gimbal is now driven with sharp pulses of small angular displacement in either direction, positive and negative accelerations of short duration can be imparted to the pilot. These accelerations are due to the angular accelerations of the gimbal and are defined by the following equation:

$$(4) \quad G_i = r/g \, \ddot{B}_i$$

where

r = radius of pilot rotation (4 ft)
$\ddot{B}_i$ = angular acceleration of inner gimbal (max = 10 rad/sec^2)
G_i = acceleration on subject in G-units (max = 1.2 G)

By limiting the angular displacements to ±5 degrees in order to prevent excessive fore and aft acceleration effects to the pilot, and by pulsing these motions in a random manner with a programmed amplitude control, the gondola itself was found to be capable of functioning as a dynamic simulator of the high frequency portion of the desired G-profile (Figures 5 and 6).

The random pulses were obtained by differentiating the sum of three square wave function generators which were set at the approximate frequencies of 0.2, 0.4, and 0.6 cps. To achieve the desired effect these pulses were filtered through a 0.2 sec resistance-capacitance network. The amplitude envelope of these pulses was controlled by multiplying their dc voltages by the output of a variable diode function generator which had been programmed to vary according to the dotted lines shown in Figures 5 and 6.

The mean G ($\overline{G}_z$) or low frequency portion of the flight profile is shown in Figure 7 with the high frequency portion removed. The simulation of this G profile, with the exception of that portion below 1 G which will be discussed shortly, was accomplished in the conventional manner as described previously using a curve follower, upon which the mean G profile was stored, and an analog computer programmed with the coordinate conversion equations (1), (2), and (3).

That portion of the mean G curve less than 1 G (cross patched on Figure 7) cannot be simulated dynamically by any earth bound simulator due to the ever present acceleration of gravity.

It was decided, therefore, to compromise this requirement by using the following guidlines:

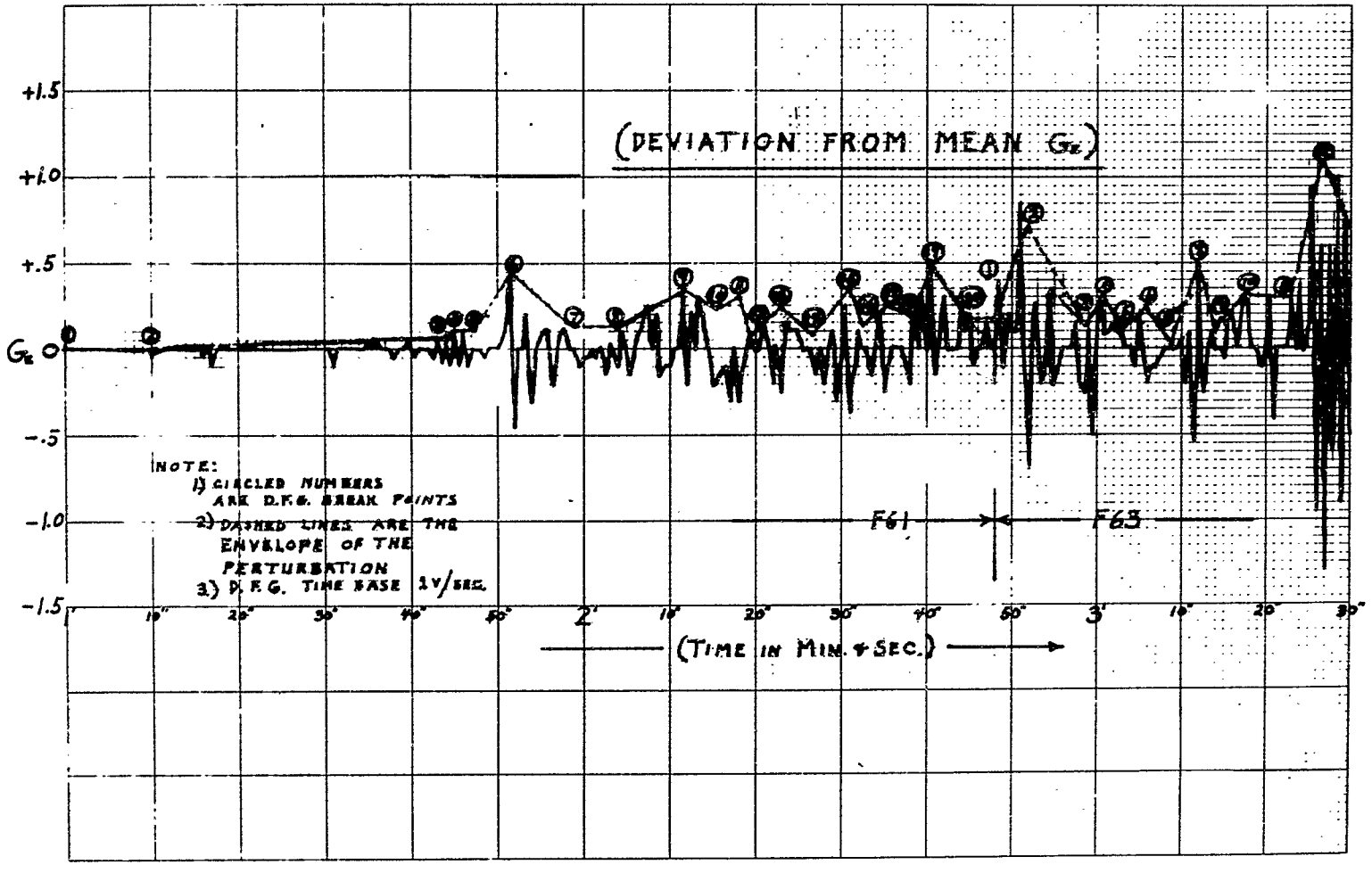

Figure 5. High frequency portion of desired G-profile.

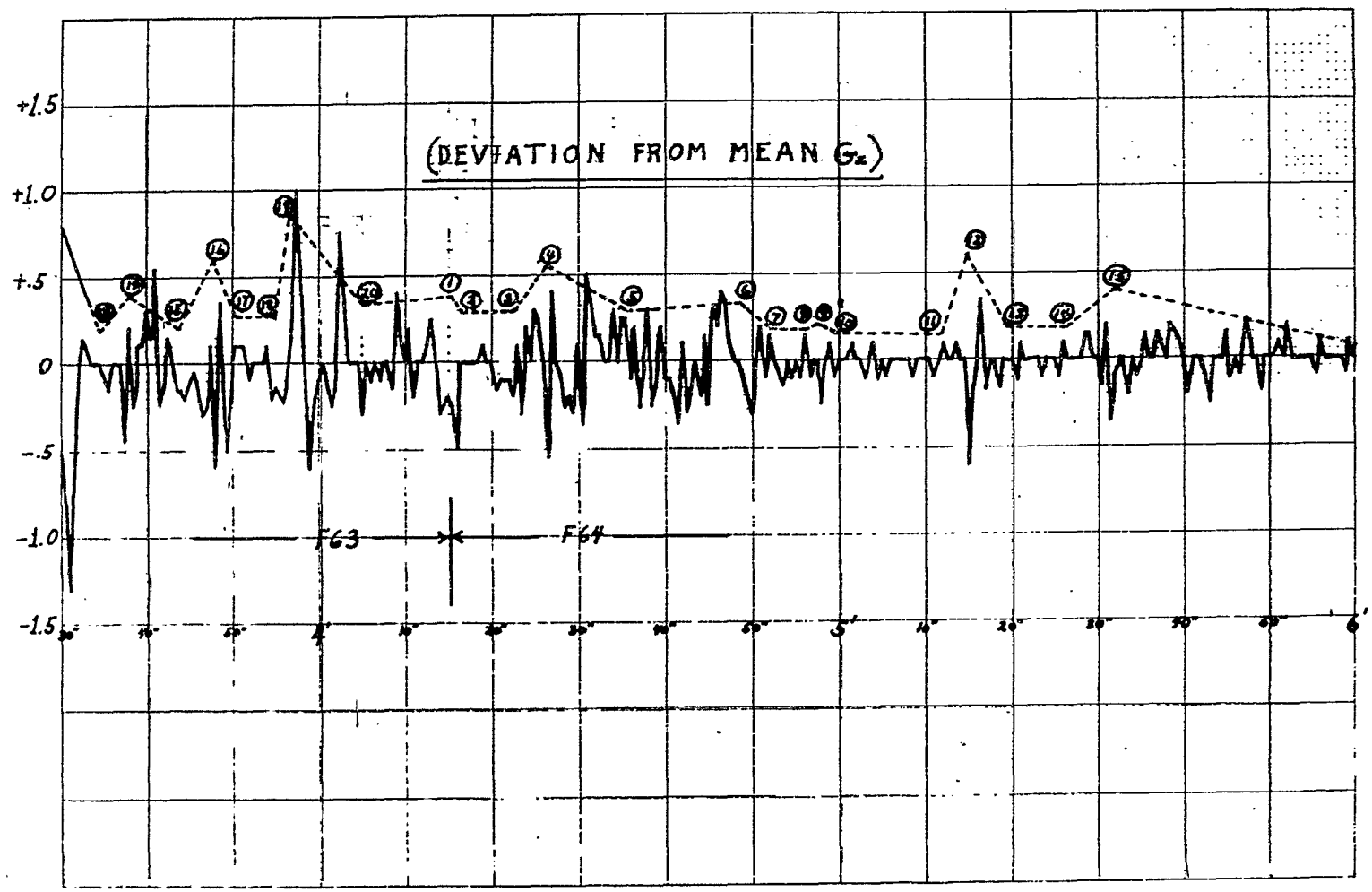

Figure 6. High frequency portion of desired G-profile.

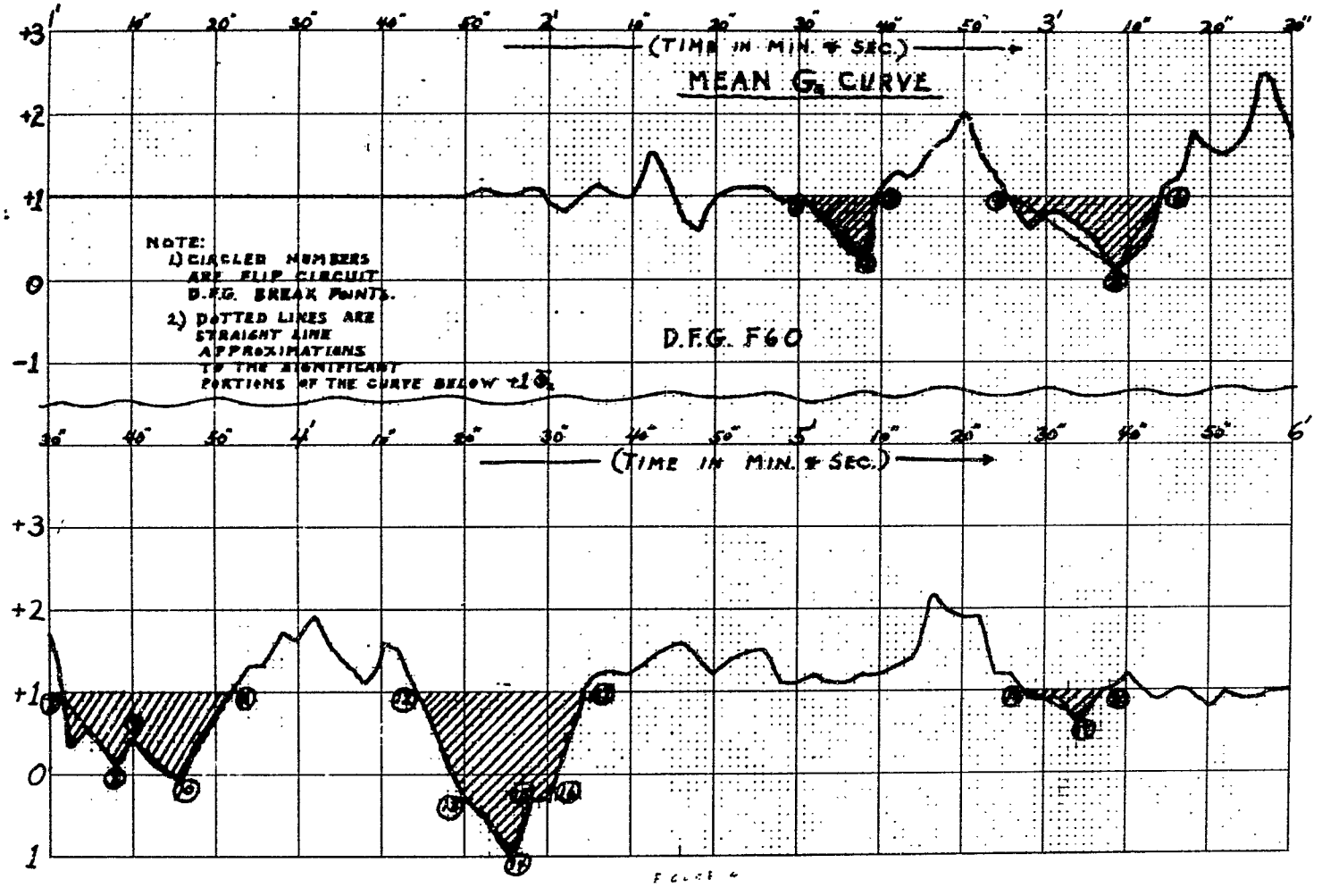

Figure 7. Mean G or low frequency portion of desired G-profile.

$$(5)\quad \left.\begin{array}{l}\overline{G}_z \text{ (simulated)} = \overline{G}_z \\ \overline{G}_y \text{ (simulated)} = 0\end{array}\right\} \quad \text{For entire profile}$$

$$(6)\quad \overline{G}_x \text{ (simulated)} = 0 \qquad G_z > 1\ G$$

$$(7)\quad \overline{G}_x \text{ (simulated)} = -\sqrt{1 - \overline{G}_z^2}\ ;\ G_z \leq 1\ G$$

These guidlines dictate that for portions of the mean G pr[illegible]e less than 1 G, the $\overline{G}_z$ simulated will satisfy the flight record, but $\overline{G}_x$ w[illegible] no longer be zero. It will, in fact, reach as high as -1 G when $\overline{G}_z$ becomes zero. The negative G was selected because the flight record indicated that the pilot was normally flying an outside loop when the G profile became less than 1 G. Equation (7) was accomplished by programming another variable diode function generator with an inner gimbal command which would be superimposed upon the two additional commands previously described which provide the random pulses and the coordinate conversion requirement. This additional command actually flips the pilot up and over in order to obtain $\overline{G}_z$ values less than 1 G. The displacement requirement for this flip is defined by the following relationship which is equivalent to equation (7):

$$(8)\quad B_f = -\operatorname{Cos}^{-1}(\overline{G}_z)\ ;\ \overline{G}_z \leq 1\ G$$

A portion of the actual accelerometer recording taken between the third and fourth minute of the dynamic simulation is shown in Figure 8. G_z pulses of frequencies up to 5 cps at amplitudes of ± 1 G are easily discernible superimposed upon the lower frequency $\overline{G}_z$ which varied between ± 1.5 G.

Since the main purpose of this study was to evaluate the dynamic simulation capability of the centrifuge for turbulence conditions, it was decided that the G profile would be pre-programme[illegible] and that it should not be affected by any control from the pilot other than his voluntary termination of a run. This stipulation required that any instrumentation display that is controlled by the pilot could have no direct relationship to the dynamic situation as simulated by the centrifuge. It was anticipated that, if the simulation capability was demonstrated satisfactorily, this study would be followed by a more sophisticated one. This second study would have the pilot, the atmos[illegible]heric turbulence inputs, and the aircraft aerodynamics in the control loop in such a manner that the pilot would be given the actual problem of flying the dynamically-simulated aircraft through the turbulence conditions.

In order to make some evaluation of the pilot's ability to control the aircraft during turbulence conditions, it was decided in this first study to give him a control problem on the pitch and roll attitude indicators. The problem required the pilot to maintain a zero reading on these indicators, each of which was being driven off center continuously by a random oscillating signal. This oscillating signal was derived by summing the outputs of three

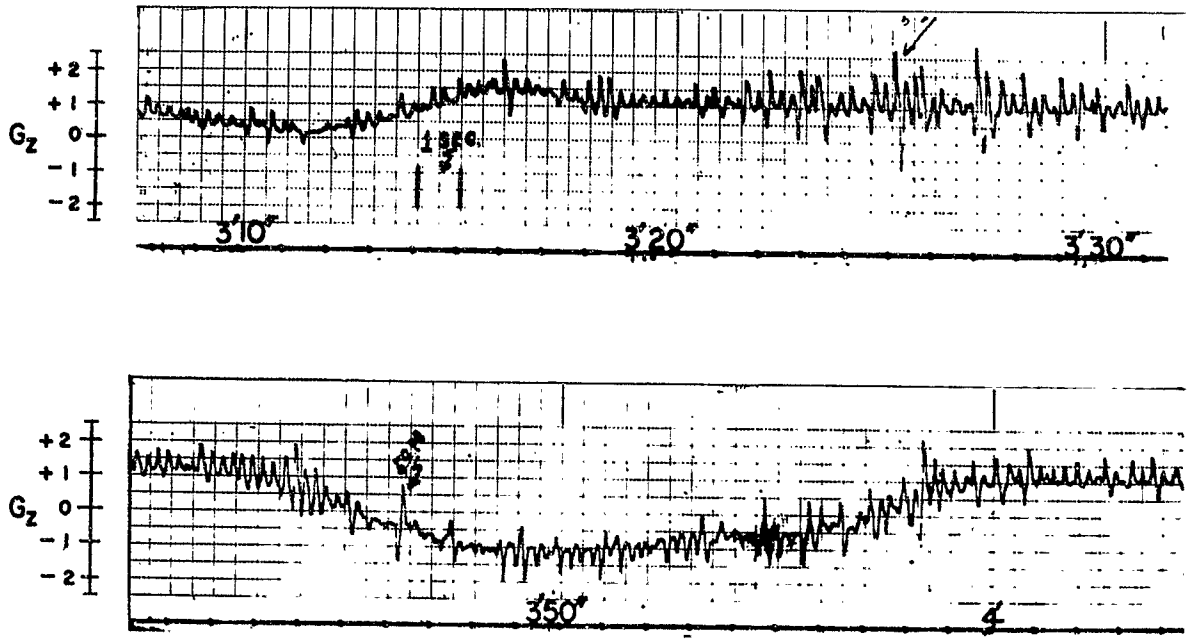

Figure 8. Acceleration recording of dynamic simulation.

sinusoidal function generators which were obtained simultaneously from the same three function generators which produced the square waves in the inner gimbal pulse generating circuit. The wheel and yoke signals which the pilot used to control the attitude indicators were fed through the aerodynamics of the 720 B aircraft in order to maintain a degree of control familiarity for the pilot. A block diagram of the total computational setup including the centrifuge control and pilot task are shown in Figure 9.

RESULTS

The results of this experiment are based on nine sources of data. Some of the data were quantitative, having been directly recorded and/or calculated in terms of specific measurable units. The other data were qualitative and subjective, based on observations which were made by the pilots themselves and the scientific personnel who conducted the experiment. The quantitative data were subjected to graphic and statistical analysis, whereas the qualitative data could only be reported in terms of verbal descriptions, summaries or examples. The general approach in this paper is to report all data, with the expectation that the quantitative data may be useful for deriving specific conclusions from this experiment, and the qualitative data may be useful for planning other experiments to investigate problems for which no final conclusions could be derived at this time.

The data available for analysis in this experiment were as follows:

1. Integrated absolute error scores in pitch and in roll tracking performance for each pilot during each run.

2. On-line paper-chart and magnetic tape recordings of the pitch and roll excursions of the target, the pilot's control stick movements in pitch and roll, and the acceleration environment to which the pilot was being exposed.

3. Comments made by the pilots during centrifuge runs, or immediately following the completion of centrifuge runs, while the pilot was still in the cockpit.

4. Observations made by the medical officer, project officer, or performance monitor, during runs, based on the television monitoring, performance recordings, or answers made by the pilot to specific questions.

5. Results of medical examinations and/or observations usually conducted before or after centrifuge runs.

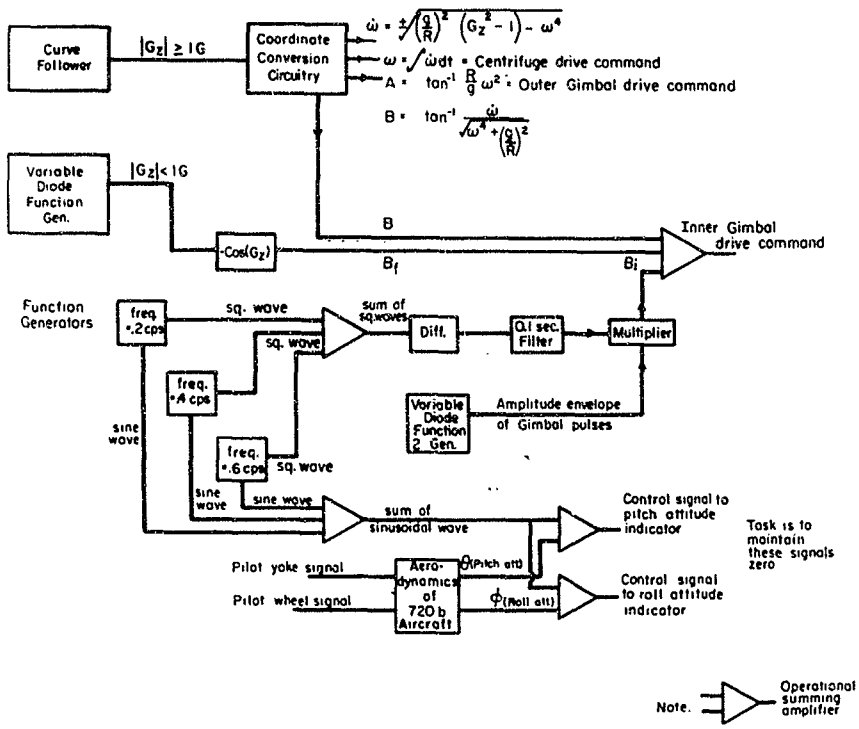

Figure 9. Block diagram of the computer programing requirements for the total control problem.

6. Recorded debriefings, in which the pilot was interviewed by the research staff following a series of runs. These consisted of voluntary comments by the pilot regarding himself and his condition, as well as the pilot's answers to specific questions asked by the scientific staff.

7. Moving pictures of the pilot in his cockpit, showing his position, his face, a portion of the reverse side of his task, and some of his performance.

8. Results of two additional special runs in which the pilot performed his task without visual display cues.

9. Results of tests conducted on nine volunteer non-pilots, whose data could not be considered as a portion of the findings, but which could provide additional information.

The results of the analysis of the integrated absolute error scores are presented first, as an indication of over-all pilot performance during the dynamic and static runs. Then, the more detailed analysis of specific portions of the runs are presented.

Integrated Absolute Error in Pitch and in Roll Performance. During each six-minute run, the integrated absolute error obtained by the pilot in his pitch performance and in his roll performance was computed by the 231R computer system as the run proceeded, and recorded on the Performance Monitor's recorder. At the end of each run, the amounts of integrated absolute error in pitch and roll were printed out as general scores in an attempt to reflect the over-all performance proficiency along the pitch and roll axis of the task. Using this procedure, the integrated absolute error scores for 10 pilots were obtained, and made available for statistical analysis. Preliminary inspection of these scores had indicated that there were large individual differences among the pilots, and that some pilots appeared to undergo more performance decrement than others during centrifuge runs. Also, there were suggestions that some of the pilots enjoyed major improvement in their second dynamic run as compared with their first dynamic run, whereas little or no practice effect appeared to be present for other pilots. These data were subjected to an analysis of variance to determine:

1. whether there were any significant differences in error performance between pilots

2. whether there were significant differences in error performance during static and dynamic runs

3. whether there were significant differences between trials (test series)

4. whether there were significant interaction effects among subjects.

Two analyses of variance were conducted on the integrated absolute error scores, one on the pitch scores, and one on the roll scores. A two-factor analysis of variance was used in which the first factor (the presence or absence of acceleration) was fixed with the second factor (trial series) treated as a random factor. All ten of the pilot subjects were treated as a single group with repeated measures across both factors.

The results of the analysis of variance for the pitch scores are shown in Table I. This summary table shows that there was a significant difference between pilots ($F = 4.00$, $p < .05$). However, there were no significant acceleration effects; there were no statistically significant differences between the scores which were obtained during static and dynamic runs. Similarly, there were no significant test trial series effects; there were no statistically significant differences between scores obtained between Trial Series 1 and Trial Series 2. However, there was a significant interaction effect ($F = 11.04$, $p < .01$) between the pilot variable and the acceleration variable. Some pilots accumulated significantly more error than others during exposure to the acceleration conditions.

Similar results were obtained in the analysis of the integrated absolute errors for roll. A summary of this analysis is shown in Table II. The pilot variable is highly significant ($F = 24.16$, $p < .01$). However, this analysis shows no significant acceleration effects, nor any significant effects due to trial series. However, as in the pitch score analysis, there was a highly significant interaction effect ($F = 7.73$, $p < .01$) between the pilot variable and the acceleration variable, showing that some pilots accumulated significantly more roll error than other pilots during exposure to the acceleration conditions on the centrifuge. None of the other interaction conditions are significant.

Figure 10 presents the mean integrated absolute error scores for the performance in pitch, and for performance in roll under both static and dynamic conditions. As has already been indicated in the statistical analysis, there are no significant differences between the pitch means for static ($\overline{X} = 21.52$) and dynamic ($\overline{X} = 21.49$) conditions. Similarly, for roll, the means between static ($\overline{X} = 29.30$) and dynamic ($\overline{X} = 30.54$) are not statistically different. Similarly, Figure 11 presents the mean integrated absolute error performance in pitch and in roll for the first trial series

TABLE I

Summary of Analysis of Variance of
Integrated Absolute Error Scores in Pitch

Source	df	MS	F
Between Pilots	9	60.045	4.00*
Within Pilots			
Acceleration (A)	1	.008	-
Trial Series (B)	1	61.034	4.07
A x B	1	.363	-
A x P	9	28.470	11.04**
B x P	9	15.004	
A x B x P	9	2.578	

* $p < .05$

** $p < .01$

TABLE II

Summary of Analysis of Variance of
Integrated Absolute Error Scores in Roll

Source	df	MS	F
Between Pilots	9	386.179	24.16**
Within Pilots			
Acceleration (A)	1	15.398	-
Trial Series (B)	1	.787	-
A x B	1	28.265	1.41
A x P	9	155.240	7.73**
B x P	9	15.981	
A x B x P	9	20.076	

** $p < .01$

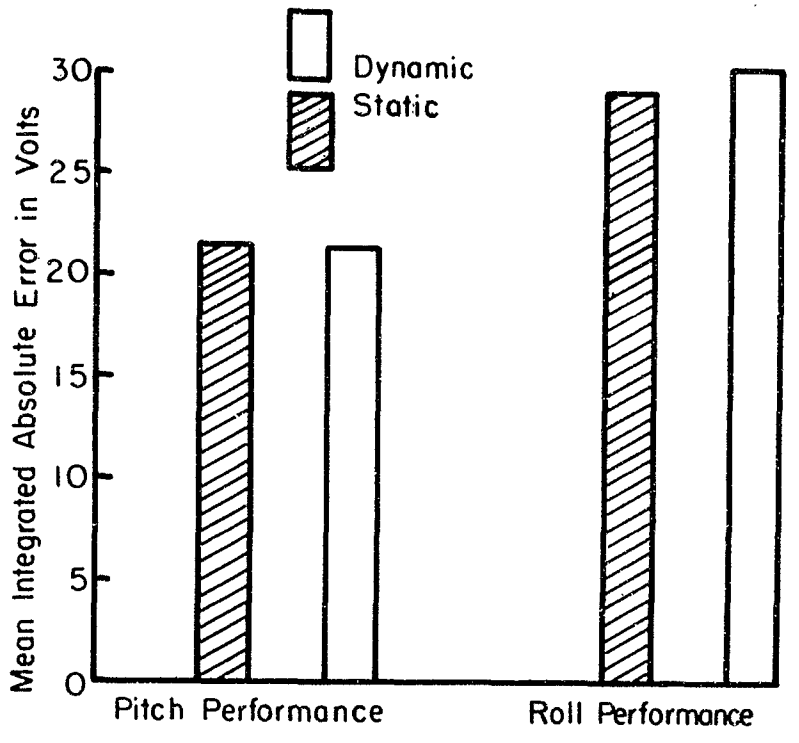

Figure 10. Mean integrated absolute error performance in pitch and roll during static and dynamic conditions.

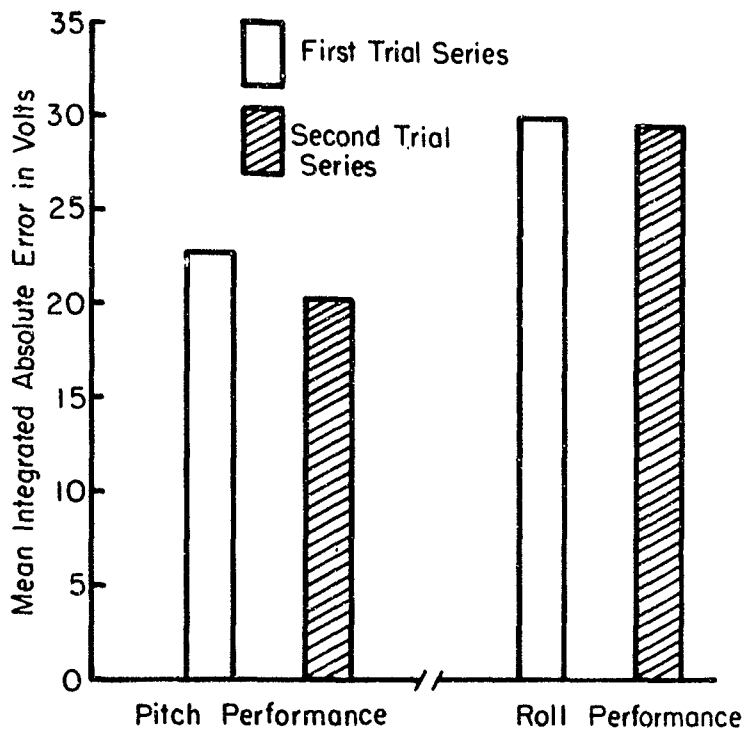

Figure 11. Mean integrated absolute error performance in pitch and roll during the first and second trial series.

and the second trial series. As was indicated in the analysis of variance, the pitch score means between the first trial series ($\overline{X}$ = 22.74) and the second trial series ($\overline{X}$ = 20.27) are not statistically different. Similarly, the roll score means between the first trial series ($\overline{X}$ = 30.06) and the second trial series ($\overline{X}$ = 29.78) are not statistically different. Thus, these analyses show that overall performances in pitch and in roll were unaffected by exposure to acceleration on the centrifuge. Similarly, there were no observable practice effects. The analysis showed that the only statistically significant variations were those involving individual differences, and reactions to the acceleration conditions which were produced on the centrifuge. The same conclusion holds for both pitch and for roll.

The above findings were somewhat startling in view of the marked amount of subjective comment which the pilots had made regarding the effects of the centrifuge accelerations on their performance. Subjectively, major differences existed between the static and dynamic centrifuge conditions. Similarly, some pilots were subjectively aware of major practice effects. However, the integrated error scores used in this study were not sensitive enough to measure these effects. This conclusion is supported by (1) the subjective reports of the pilots, (2) the subjective impressions of the scientific observers, (3) the spectral density analysis of selected magnetic tape recordings, and (4) an analysis of the control movements of the pilots made under static and dynamic conditions. Therefore, it is concluded that the total integrated error method of analysis was inappropriate as a measure of performance proficiency in this experimental design.

Control Stick Reversals. During the dynamic runs and also during the debriefing sessions, some of the pilots made reference to control stick reversals which they believed they had performed. Sometimes, the pilots reported that there was a tendency to experience a kind of kinesthetic illusion during which they made inappropriate pitch control movements in the opposite direction from those required. These were reported to be especially prominent when negative G_z was encountered for the first time. Some pilots reported that an initial movement of the yoke in the wrong direction was the rule rather than the exception. Also, some stick movements which were believed to be involuntary were not considered of major hazard in normal aircraft control, whereas others were considered to be of major hazard potential. It was suggested, for example, that by responding to a strong kinesthetic illusion of climb or dive, after correcting from an unusual nose up or nose down attitude, pilots may create ever increasing deviations from normal flight pitch attitude in both directions alternately, somewhat analogous to pilot induced oscillations, until the aircraft stalls or falls off into a steep dive.

Sometimes, during the runs, the pilots called out specific times when they were aware that they had made incorrect control stick reversals in pitch. These were then marked on the performance recorder by the performance monitor. However, due to the difficulties in speaking during extreme turbulence (the pilots were generally advised by the medical officer not to speak during severe turbulence because of the possibility of mouth or tongue injury), pilots sometimes attempted to identify these movements at a later time, either immediately after the end of the severe portion of the run, or during the later debriefing interview. However, for the most part, it was not possible for the performance monitor to specifically recognize these inadvertent control stick reversals during the runs.

Consequently, it was decided to obtain a frequency count of the number of stick reversals just prior to a turbulence period in which there was a major acceleration change, during the period of stress, and immediately following this period. There were four maximum stress periods during which control stick reversals were most likely to occur. These were as follows: between the 120th and 150th second of each run; between the 150th and 169th second of each run; between the 180th and 217th second of each run; and between the 217th and 271st second of each run. Thus, it was decided that a simple count of the number of stick reversals which occurred during periods of turbulence and acceleration stress would, if compared with stick reversals made at identical times during the static control runs, indicate whether there was a measurable tendency for the pilots to make stick reversals as a function of these maximum stress conditions. Since there was some difficulty in determining whether the stick reversals tended to occur just prior to, during or following these periods of maximum turbulence and acceleration change, it was decided to include a time period immediately before and following each condition which was equal in length to the duration of the test condition. In this way, all stick reversals made both before, during, and following maximum stress would be counted in the dynamic runs, and they could be compared with identical time periods during the 1 G static runs.

Figure 12 summarizes the results of this analysis. The figure shows the mean number of control stick reversals per pilot for each of the four turbulence-acceleration conditions. The figure clearly shows that for each of the four conditions, there were more stick reversals during the dynamic testing phase than during the static testing phase.

To evaluate whether significant differences occurred among the frequency of control stick reversals made by the pilots under the dynamic and the static conditions, a series of chi square (X^2) analyses were conducted. The results of these analyses are shown in Table III. The table presents the number of

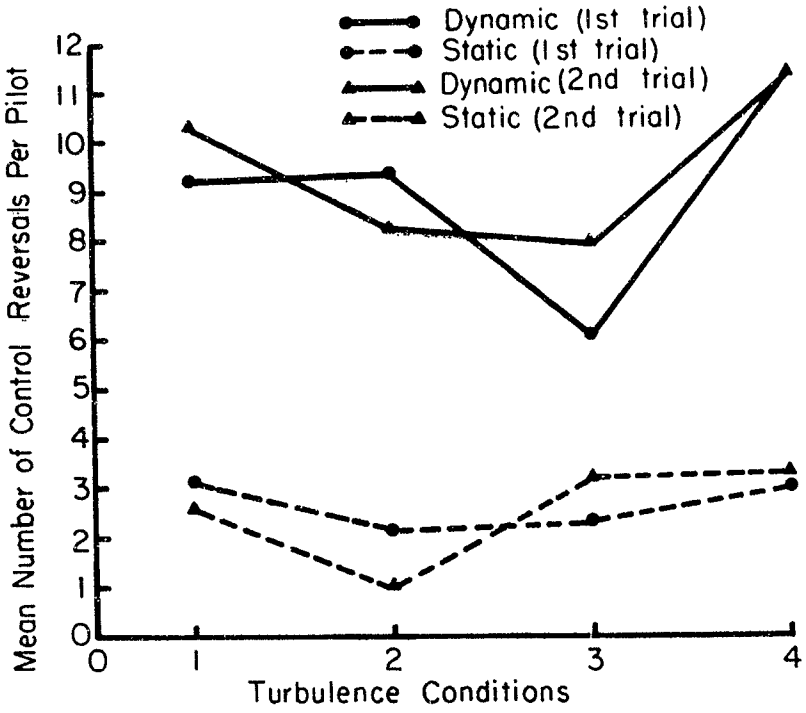

Figure 12. Mean number of control stick reversals per pilot during dynamic and static testing for each of the four turbulence conditions.

TABLE III

Results of Chi Square Analysis of Frequency of Control Stick Reversals during Static and Dynamic Centrifuge Tests Within Each Turbulance-Acceleration Condition

Condition	Centrifuge	Trial Series	Control Reversals	X^2	p
1	static	1	28	27.26	<.01
1	dynamic	1	83		
2	static	1	19	40.24	<.01
2	dynamic	1	84		
3	static	1	21	14.78	<.01
3	dynamic	1	54		
4	static	1	27	43.77	<.01
4	dynamic	1	102		
1	static	2	23	41.47	<.01
1	dynamic	2	92		
2	static	2	9	50.90	<.01
2	dynamic	2	74		
3	static	2	29	23.68	<.01
3	dynamic	2	80		
4	static	2	30	30	<.01
4	dynamic	2	90		

stick reversals made under each condition during static testing and during dynamic testing. This is shown for the conditions during the first trial series, and also for the conditions during the second trial series. All of the X^2 values are highly significant, indicating that for each of the turbulence conditions during the first trial series, there were significantly more control reversals during dynamic testing than during static testing. Similarly, during the second trial series, there were significantly more control reversals for each condition during the dynamic testing than during the static testing.

A more detailed analysis of the control stick reversal data is shown in Figure 13. Here, the control stick reversal data are presented in terms of the average number of stick reversals immediately before the onset of each severe turbulence condition, the average number of stick reversals during each turbulence condition, and the average number of stick reversals following each turbulence condition. Inspection of this figure indicates that the number of control stick reversals was not generally greater during the period of severe turbulence than they were shortly before the onset of severe turbulence, or shortly following the cessation of severe turbulence and acceleration change. There was no consistent pattern. There were differences, however, between dynamic and static conditions during each of the time intervals, but there is no consistent pattern with respect to conditions before, during or after. Hence, this figure tends to confirm the hypothesis that there were major differences in number of control stick reversals performed under conditions of static and dynamic testing. However, this figure shows no tendency for any consistent pattern with respect to number of control stick reversals before, during, or following conditions of severe turbulence and acceleration change. No pattern is shown for either the dynamic conditions, or for the static conditions. Figure 14 is presented to illustrate that the same general findings occurred during the second trial series, e.g., that the number of control stick reversals during the second series was essentially the same as the one during the first trial series.

It had been reported by some of the pilots that after completion of their first trial series (during which they gained some experience regarding the effects of turbulence and acceleration change), they made fewer control stick reversals during the second trial series. Inspection of Figures 12, 13, and 14 indicates that there was no observable improvement during the second trial series as compared with the first trial series. Careful inspection of these figures in terms of comparisons of first and second trials suggests that there were no noticeable differences as a function of practice, either before, during, or after the conditions of severe turbulence and acceleration. The number of control stick reversals did not show any consistent tendency for change.

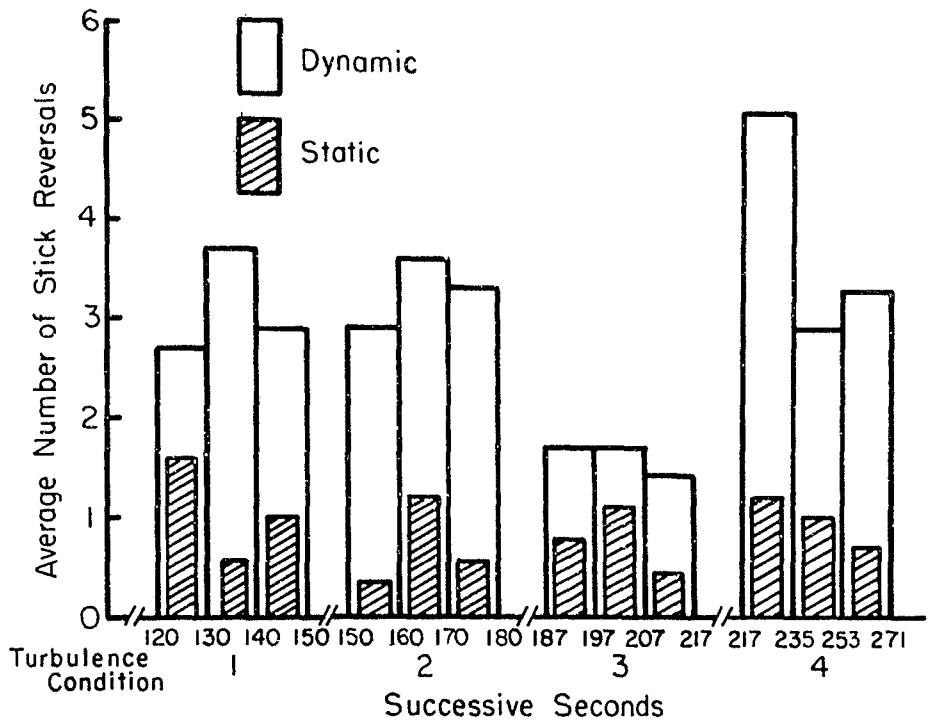

Figure 13. Average number of stick reversals for 9 pilots during each of four turbulence-acceleration conditions during static and dynamic centrifuge runs during the first trial series.

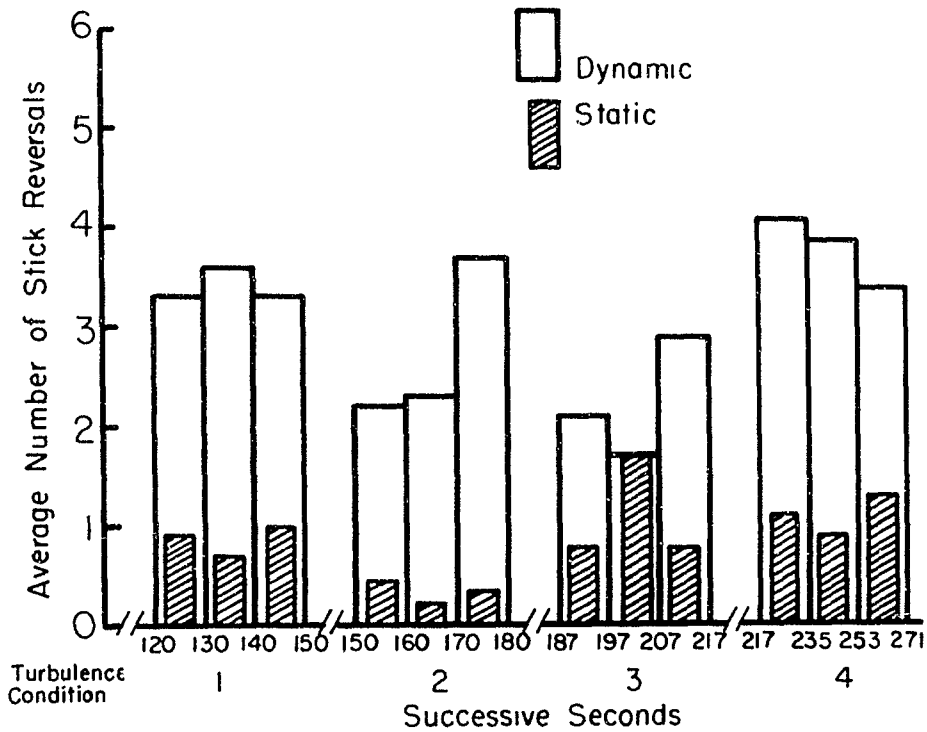

Figure 14. Average number of stick reversals for 9 pilots during each of four turbulence-acceleration conditions during static and dynamic centrifuge runs during the second trial series.

It should be noted, however, that in this analysis, only the frequency of control stick reversals was evaluated. There was no way in this particular experiment to use the paper-chart recordings so as to evaluate the control stick reversals in terms of their magnitudes of reversal. The recordings which were made on the magnetic tape, however, are presently being analyzed in terms of the magnitude of control stick responses. This analysis, when completed, will present a spectrum of the number of control stick responses of varying amplitudes. It will then be possible to evaluate the effects of each of the four turbulence-acceleration conditions on the amplitude of control stick reversals, as well as on all control stick movements per se. In addition, these data are being subjected to an autocorrelational analysis which will indicate for any given pilot the degree of relationship which existed between his control stick performance at any given instant and his performance at any other instant. Consequently, it will be possible to describe the performance of each pilot in terms of the spectral density of his control stick movements, and the relationship which existed among his control movements, during any of the turbulence-acceleration conditions and/or control non-turbulence-acceleration conditions, or during any of the static conditions. At the time of the writing of this report, the results of this phase of the data analysis are not finished.

It is important to note that the pilots were able, subjectively, to indicate when they made incorrect control responses, or control reversals which, in their opinion, would result in major difficulties in controlling their airplane, or which might even result in their losing control. It was not possible, however, to specify exactly which specific control motions were subjectively observable by the pilots as being of major significance insofar as their flying performance was concerned. The determination of "critical" control reversals, as compared with control reversals of minor consequence, is an important, but difficult, determination to make. It is expected that a method will be developed for making these determinations in a subsequent study. Since the piloting task was randomized (e.g., not specifically related to the turbulence and accelerations being imposed on the pilot), and since there was no specific knowledge at that time as to what to look for as these particular runs were being conducted, it was not possible at a later time to make these determinations as the runs proceeded, and it was not possible to identify specifically which control movements were critical and which were not.

Effects of Practice. In this investigation, it was not possible to test the pilots a sufficient number of times to obtain much information on the effects of practice. It was possible to test each pilot only for two static-dynamic pairs of runs lasting six minutes each. This was not a sufficient number of trials to obtain a learning curve. Consequently, five volunteer

AMAL subjects were selected and these men received repeated practice on static-dynamic pairs of runs in which the exact same time scale and acceleration profile was provided. The task, however, was the same randomized task which had been used for testing the pilots in the earlier phase of the experiment. An attempt was made to maintain exactly the same conditions in this special training phase as had been used in the earlier pilot testing phase. Under these conditions, four of the volunteer subjects received eight static-dynamic pairs of centrifuge runs, and one additional subject received five static-dynamic pairs. (This particular subject was required to go on a TDY trip and could remain at the AMAL only long enough to complete five of the eight pairs of runs.)

Figure 15 presents the mean integrated absolute error scores in pitch for this sample of subjects through the eight static and the eight dynamic runs. The figure suggests that by the end of the third trial, the mean integrated absolute error in pitch had reached its maximum degree of proficiency. Similarly, the figure suggests that for the static runs, the mean integrated absolute error in pitch had reached its maximum level of proficiency by the fifth run. Further, the differences between static and dynamic runs were most striking during the first pair of runs.

A detailed analysis of the scores which were used in Figure 15 showed, however, that there were major individual differences among the subjects, and that their relative proficiency on static and dynamic testing runs was not consistent. Consequently, each subject's static score was used as his own base line, and was used as the denominator for expressing the percentage change which occurred between each pair of static-dynamic runs. The results of this analysis are shown in Figure 16. A large amount of variability is shown. A further check into the nature of the performance task indicated that there had probably been some changes in the task itself, so that at least some of the large fluctuation is due to the task as well as to the subject's performance. Consequently, it is difficult to reach any specific conclusion from an inspection of this figure, except that the figure does show the results of the scores which were obtained. Another study would be necessary to determine a learning curve. Whereas there is no specific data to suggest that learning did or did not occur, it seems inconceivable that some learning did not. All of the subjects reported that they believed they had learned (a) how to sustain the turbulence and acceleration effects of the centrifuge runs, and (b) how to perform their task under these conditions. However, most of the subjects did report that the task itself appeared to change in difficulty level during different runs.

An attempt was made also to find if there were any learning curves for roll performance as a function of practice. The integrated absolute error scores in roll were averaged for the static runs and for the dynamic runs,

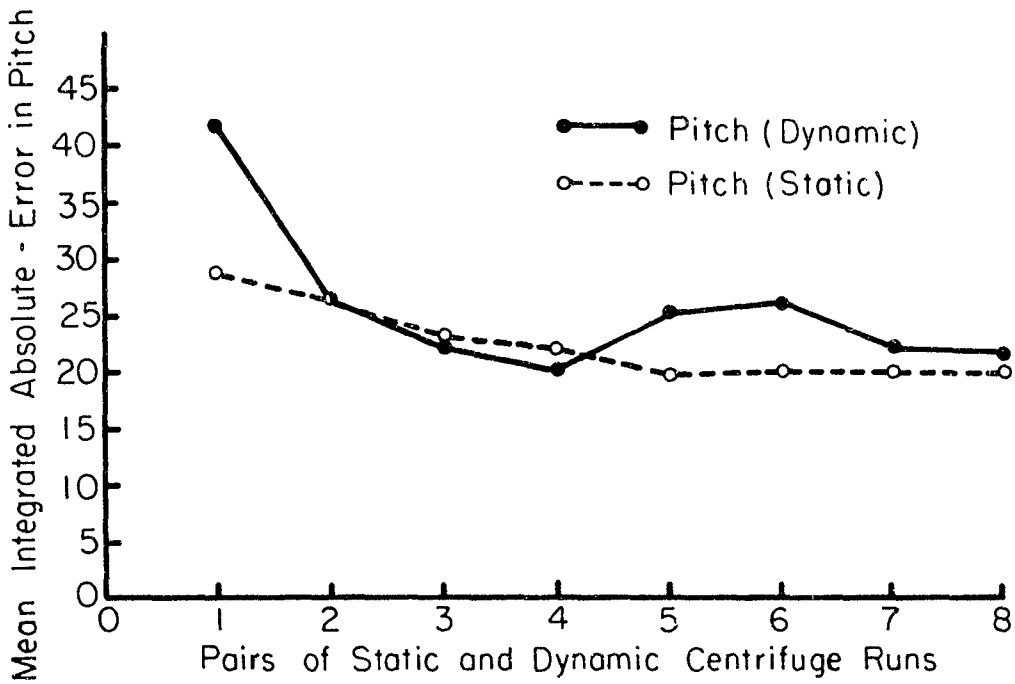

Figure 15. Mean integrated absolute error scores in pitch for 5 volunteer subjects who practiced the tracking task during successive pairs of static and dynamic centrifuge runs.

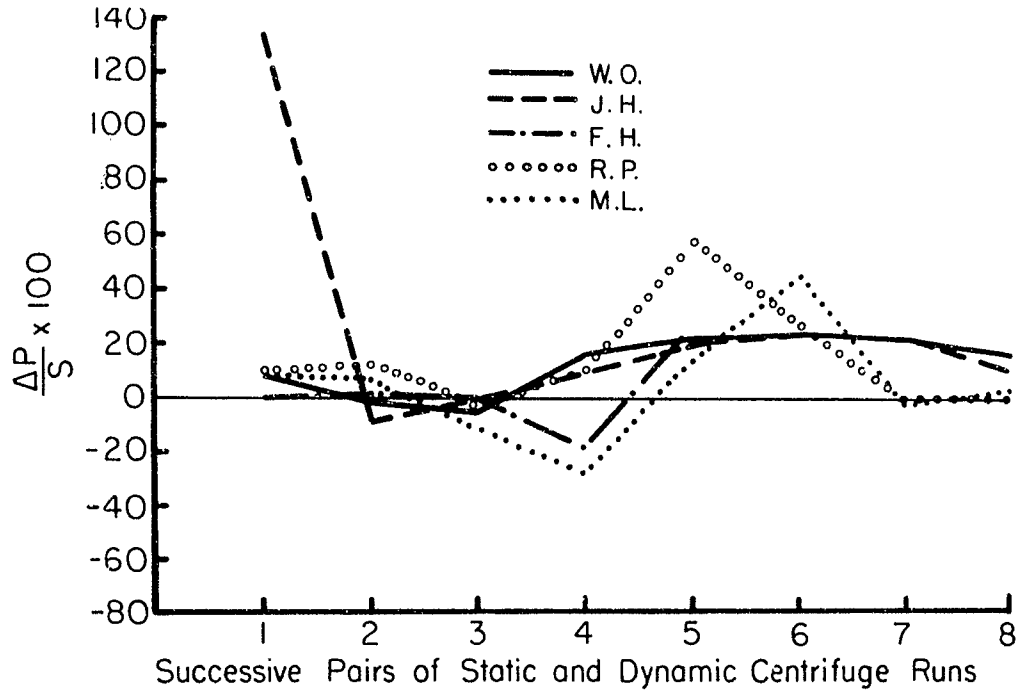

Figure 16. Individual percentage change scores for volunteer subjects who completed successive static-dynamic pairs of runs.

and these are plotted as a function of successive trials in Figure 17. This figure could possibly be interpreted as suggesting a small amount of learning in roll performance, especially during the static runs. However, individual variation was too great to permit any specific conclusions regarding learning. This is illustrated in Figure 18 in which the subject's score is plotted for each run in terms of percentage change over his own baseline performance. No consistency is observable, and no conclusions regarding possible learning effects during exposure to the dynamic centrifuge runs can be derived. The same limitations discussed earlier regarding integrated absolute error analysis undoubtedly apply to these data. A review of the subjective impressions indicated that even though the subjects believed they were improving as a function of repeated trials, they commented that the task difficulty level appeared to change. Learning curve data must await another centrifuge investigation. Further detailed analysis of the pitch and roll performance data resulting from these particular runs does not appear to be justified, since it appears that both our independent variables (the centrifuge as well as the task) as well as our dependent variables (the subject's responses in pitch and roll) varied from run to run. A series of spectral density analyses is currently being conducted on the magnetic tape recordings of the pitch and roll stick movements of the subjects, the task excursions which were presented to the subject, and the centrifuge turbulence and accelerations which were presented in this phase of the experiment.

Pilot's Control Motions When Visual References Were Not Available. Throughout the experimental phase involving the pilots, there had been a major interest in the possibility that there may be some kinesthetic illusions which may cause the pilot to make control reversals when the acceleration field changed. A brief series of tests was conducted in a preliminary attempt to measure some possible aspects of this illusion and/or the effects it may have on pilot performance. Two pilots were tested under conditions in which the visual task was disconnected, and in which the pilot was required to continue to perform the control task with the control stick motions which appeared to him to maintain a proper flight attitude. Thus, he was asked to perform strictly from his kinesthetic cues (e.g., "seat of the pants" sensations). The stick responses were recorded on the performance monitor's paper chart recorder, and also on the magnetic tape recorder.

During these runs, there were some conspicuously large stick reversals which appeared at times which would be very critical, and these stick motions appeared to be related to the type of acceleration which was induced on the subject by the centrifuge. (See examples in Figure 19.)

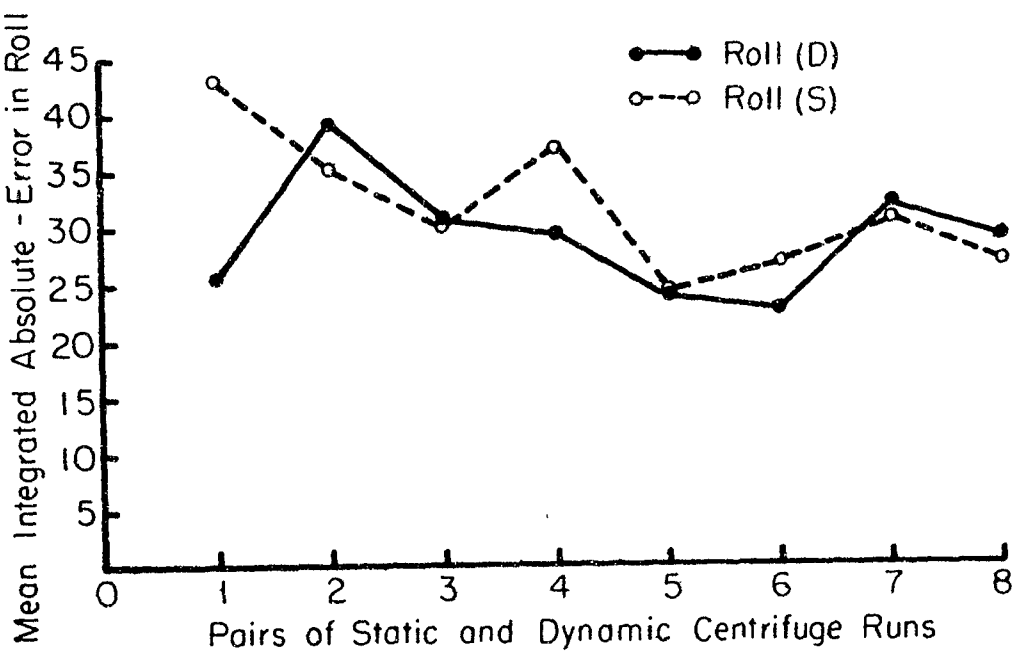

Figure 17. Mean integrated absolute error scores in roll for 5 volunteer subjects who practiced the tracking task during successive pairs of static and dynamic centrifuge runs.

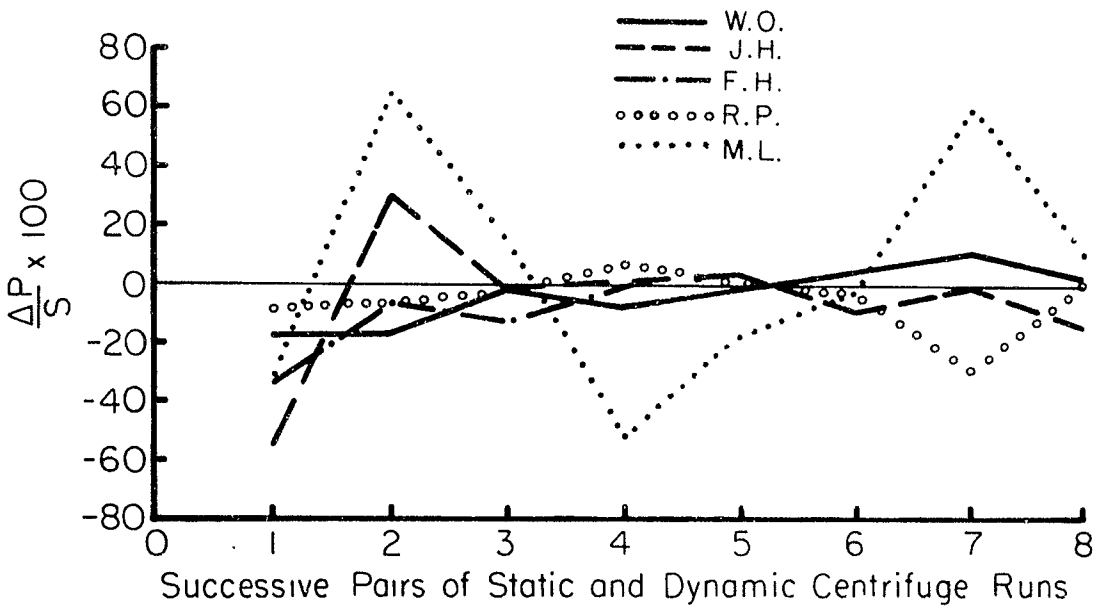

Figure 18. Individual percentage change scores for volunteer subjects who completed successive static-dynamic pairs of runs.

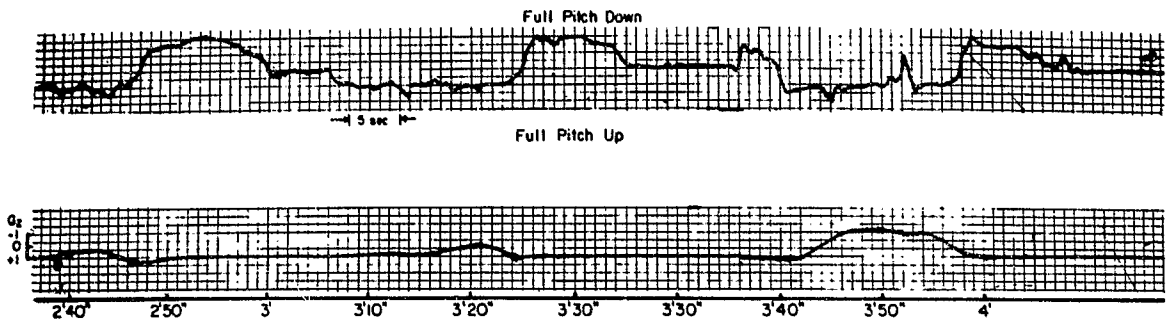

Figure 19. Example of control stick movements made when the visual reference for the tracking task was inactivated and the pilot was attempting to perform by using his kinesthetic cues.

However, it is also possible that these motions may be appropriate, so far as the subject is concerned, since they may be merely responses to the angular velocities and the directional components of the inner gimbal of the centrifuge, as it produced the programmed acceleration profiles. It is not possible to determine whether these particular control reversals are actually misinterpretations of the acceleration profiles which were being simulated by the centrifuge, or whether they are correct interpretations brought about by the inner gimbal actions (which in this case would be artifacts) which were required in order for the centrifuge to produce the required acceleration profile changes which were being programmed by the computer.

The solution to this problem must await a further experiment on the centrifuge. The two pilots made comments which suggested that the pilots did get sufficient physical kinesthetic cues upon which to base their control stick inputs in order to maintain the flight attitudes which they thought were required, even without the visual flight indicator references. However, in their opinion, they were not able to perform effectively for they had no way of knowing the results of their control movements. The pilots reported that the acceleration forces induced some changes in stick positions in both pitch and roll attitudes. However, the pilots were quite certain that they did not make any involuntary control motions, although they were of the opinion that they made some wrong responses. In order to determine exactly what types of control movements occurred during specific types of acceleration conditions, it will be necessary to examine the magnetic tape recordings of the specific control inputs.

Effects on Vision. Most of the pilots in the main experiment reported that during the periods of major turbulence and acceleration stimulation, their vision was blurred. There was some blurring of the instruments, and sometimes the pilots reported difficulty in maintaining focus on the artificial horizon. All pilots concentrated on the artificial horizon, and very few scanned the altimeter or any other objects during dynamic runs. The pilots reported that they could concentrate on one instrument fairly well, but it would have been difficult to have concentrated on two or more instruments because visual scanning is difficult under conditions of turbulence. The most difficult period was during negative G turbulence. During this period, pilots lost the artificial horizon most frequently, and were required to refocus most often. They reported some distraction because of this, and also they reported that it takes a little longer to interpret their instruments during this type of exposure. All pilots felt that the Lear 3-inch face model 4003G artificial horizon used in this simulation was easier to interpret than the type of instrument employed in their commercial jet aircraft, and most of them had suggestions to make regarding

possible improvement of their instruments in their commercial cockpits. However, in the centrifuge simulation, there was a shadow of the aircraft in the horizon, due to reflection resulting from the lighting arrangement, which gave the appearance of another line. This caused some visual distraction. Visual distraction was also produced by the camera (when operating), and, during the negative G portion, views of the centrifuge chamber.

The debriefing sessions revealed that most pilots attributed any difficulties they had in maintaining proper flight attitude to visual disturbances, such as blurring, visual distraction, problems in focusing, interpretation and/or reading the artificial horizon. If the pilot concentrated on the artificial horizon, he could maintain his orientation with regard to that instrument, but was of the opinion that he would have been unable to maintain a useful panel scan had there been more flight instruments.

Pilots' Evaluation of Their Own Performances. During the debriefing sessions, the pilots made tape recordings of their own impressions and evaluations of their piloting performance. Also, specific questions were asked by the scientific staff which attempted to obtain additional evaluative and descriptive comments by the pilots. All of the pilots reported that some decrement occurred in their performance during the first dynamic run, and that this was due to the turbulence and to the accelerations to which they were exposed. They were aware of some involuntary control inputs, some errors of interpretation, and some distractions in performing their tracking task, which could be attributed to the pnysical forces to which they were being exposed. All pilots felt that maintaining their aircraft attitude indicator in proper position was more difficult during dynamic conditions than during the static control conditions. The majority of these problems were not believed to be of major significance, however, because the pilots were able to maintain satisfactory control of their flight task, and most of the errors which they made were small in amplitude and of short duration, and not considered a hazard to normal control.

The most important result, in the pilots' opinion, was the tendency, during the onset of negative G, to move the control column in the opposite direction from that required for maximum control of the aircraft. When negative G_z was encountered for the first time, an initial movement of the yoke column in the wrong direction was the rule rather than the exception. This tendency was reported by all pilots, either during the run itself, or during the debriefing session which followed. Some pilots believed that this response was due to a misinterpretation as to the kind of response which should have been made in order to perform the proper flight attitude maneuver. Others believed that this response was due to some kind of kinesthetic illusion which was usually accompanied by an involuntary

control input in the wrong direction. Other pilots were of the opinion that this incorrect movement of the control column was due to a combination of several factors: (a) a misinterpretation of the flight task requirements within the negative G environment, (b) a misinterpretation of (and possible confusion about) the sensations and cues which occurred during this particular turbulence, and (c) inadvertent unintentional responses due to the turbulence conditions and the changes which were occurring in the acceleration environment. There was agreement among the pilots concerning the occurrence of the incorrect control movements, but there was not necessarily agreement as to what may have caused them. Questioning also indicated that the period of transition of G, or change to and from G, was probably more important in causing these inadvertent control movements than was the period of negative G itself.

There appears to be a consistent tendency for the pilots to experience a kind of kinesthetic illusion when G forces are terminated, or when G forces are applied in the opposite direction, from those experienced by the pilots just a few seconds sooner. For example, it appears that if a pilot has been under positive G, and this G is suddenly stopped, the pilot pulls on the yoke as if he were in negative G. The release from positive G leads to an assumption of negative G. This is sometimes accompanied by a control motion in the wrong direction so far as the aircraft simulation is concerned. This tendency for a false perception, or illusion, and its associated tendency for incorrect response, has been described by Armstrong (2, p. 228-229) and discussed by Chambers and Fried (3, p. 193) and Chambers (4, p. 280). It results from the change in pressure sensation on the body against the seat and straps, and the stimulation of the proprioceptive and vestibular systems. Return to level flight, following reduction of G from a pitch or climb, creates false sensations. Similarly, the reduction in G following a catapult launch, may produce a false sensation in pitch, and the pilot may make the wrong control movement. Thus, in this experiment, the pilots reported that they put in the wrong pitch control movement to correct their flight attitude when their acceleration environment changed to negative G. The simulated aircraft feels as if it is going into a climb, in nose up attitude, and as the G reduces, the pilot pulls back on the control column when he should be pushing forward. The release from positive G leads to a false impression of negative G.

There was some indication that the pilots may delay making any response at all until he is sure he is making the correct motion, and then it is the wrong one. Sometimes he may delay too long, and then he is not certain just what he should do to attain correct vehicle attitude. Closed-loop centrifuge operations would have been helpful in further validating this impression.

Sometimes, the centrifuge pitches up and the pilot puts forward pressure to start it down, and then the nose (of the simulated aircraft) comes back down through the horizon and by the time the pilot has interpreted this and decided that he should get back up again, the nose is going down, and he is still holding forward pressure with it. Thus, there seems to be some suggestion that by responding to a kinesthetic illusion after correcting from an unusual nose up or nose down attitude, pilots create ever-increasing deviations from normal flight pitch attitude in both directions alternately. This is somewhat analogous to pilot-induced oscillations.

There was a marked influence of the changing load factor. When the load factor was reduced below the normal 1 G, some pilots tended to pull. When the load factor was increased, the tendency was to push. The pilots indicated that during these transition phases from positive to negative G, performance was the most difficult. There were occasional disagreements between visual and kinesthetic cues in this particular experiment, and there is some suggestion that the kinesthetic illusion tendency was associated with temporary confusion at times regarding the pilot's position and task requirements. It is interesting that the non-pilots did not seem to be concerned about this aspect. They did not have long associations built up regarding what an aircraft should be doing when associated with certain motion perceptions and pressure sensations. The pilots appeared to fly a simulated aircraft, taking into account the entire vehicle and the piloting task, as indicated both by their sensations and the flight task. The non-pilots appeared to fly the task strictly as a tracking task, without concern of the simulated vehicle and its flight characteristics. Some of the pilots indicated that "involuntary control movements" which they made were largely the result of what they had been taught in transport flying training and experience.

More research is needed to measure and evaluate the performance of pilots during these transitional G states, and to determine their normal tendency for responding. Also, measurement of the amount of agreement among kinesthetic, visual, proprioceptive, and vestibular stimulation, is needed. Also, research to determine the effects of prior practice is needed. In this investigation, all of the pilots seemed to feel that two centrifuge runs provided them with major benefit in improving their performance.

Pilot ability to concentrate on his performance task, or his ability to avoid being distracted by the turbulence and acceleration stresses, was considered to be a very important factor in maintaining performance proficiency. The pilots reported that they paid little or no attention to the altimeter because a brief glance at that instrument, or at any other item,

could be sufficient to cause loss of control of their simulated aircraft. For the pilots, included in the described pilot concentration requirements, were the requirements for maintaining focus, readiness to scan the instrument panel or other objects, and to constantly interpret and evaluate the flight task display. During the negative G period, the pilots reported that it was more difficult to interpret their flight task.

In this experiment, disorientation was not a prominent feature, and motion sickness did not occur in the jet pilot population. However, "light-headedness" did occur several times in both the pilot population and in the group of other volunteer subjects. Some tendency for nausea was also reported, especially in the non-pilot group. Some pilots described the negative G portion as "a weird sensation". If the pilot concentrated upon the artificial horizon, he could maintain his orientation with regard to that instrument, but, in his judgment, was unable to maintain a useful panel scan. Some pilots were bothered by their tendency to misinterpret control movement requirements, and some reported a conflict between visual and acceleration cues. No vertigo was reported. One pilot reported that during the first severe pitch movements in the centrifuge, he found himself becoming disoriented, and that hanging by his seat belt added greatly to the confusion. Although several pilots indicated slight disorientation, none was prolonged, and no pilot felt that the tests on the centrifuge produced any serious amount of disorientation. Whether longer test periods would have produced disorientation is unknown.

However, pilots were not always sure of their position within the cockpit with respect to their simulated flight position. For example, one pilot reported, "I felt at the point where you apparently had me upside down that first of all I wasn't aware that I was upside down. I felt the negative G, but I had no real conscious impression that I wasn't sitting right side up. I suppose that I could have interpreted this as being upside down in the airplane in negative G, but I didn't in this case. I believe I felt at the time as if it were a pushover", (not a colloquialism).

All of the pilots reported that they experienced improvement in their performance as a function of repeated trials. After the first trial, they believed that they did better on the second. And after the second trial some pilots felt that they had benefited sufficiently so that no further trials were needed. Among the non-pilot group, the consensus of opinion was that performance improved steadily until the fourth dynamic run, and others felt that they continued to improve beyond the fourth. Thus, subjectively, the dynamic runs on the centrifuge were of major training value. This was especially true in the four conditions of extreme turbulence and acceleration change. The pilots felt that experiencing the turbulence

conditions was a major factor in building their confidence. This was especially true as a result of the first run. During the second run, all pilots were more relaxed, they did less over-controlling, and they were of the opinion that their performance improved as a result of their first dynamic centrifuge exposure. The pilots believed that one of the major benefits from a training point of view was that of becoming familiar with the sensations produced by negative G and turbulence. Other benefits were "learning how to concentrate on the piloting task" and avoid distractions during exposure to the turbulence stress, "learning how to compensate for the effects of G", and "learning how to recognize errors", and "learning how to correct for incorrect control movements".

During the debriefing, some questions were asked regarding fatigue. The answers to those questions indicated that in these particular centrifuge runs, the onset of fatigue was much faster than in normal instrument flying under turbulence conditions. Also, the fatigue was experienced during dynamic runs, not during static runs. All of the pilots could have gone through more trials, but they were tired and were not eager to do so. The fatigue seemed to be of a general over-all body nature, largely muscular. Some pilots reported fatigue in the legs, arms, neck muscles, and eyes.

During the debriefing sessions, the pilots emphasized the importance of proper restraints to help protect the pilot against the effects of turbulence and negative acceleration. The pilots felt that they would have made more involuntary control inputs had they not had a shoulder harness and lap belt. Performance proficiency appeared to be influenced by the effectiveness of the restraints used. During the rough air turbulence simulations, the pilots had their feet placed firmly against the floor (this would have been difficult to do in a real aircraft with rudder pedals); and during the negative acceleration portion, the pilots had their feet braced underneath the instep bar. On several runs, the pilots reported that with no support for the elbows, there was a tendency for inadvertent force movements to be made on the control column as a result of the effects of acceleration and severe turbulence on the arms. The pilots indicated that they could avoid this by concentrating on the effects and compensating for them, but that it was a major distraction from the piloting task. During severe turbulence and acceleration, the experiment clearly demonstrated the importance of tightly fastened seat belts and shoulder straps.

Adequacy of the Centrifuge Simulation. Throughout the debriefing sessions, and at other times during the program, frequent questions were asked in an attempt to find whether the pilots felt the centrifuge actually simulated the physical events encountered in severe turbulence in commercial jet aircraft. The vertical accelerations were taken from United Airlines

Flight #746 on an onboard Fairchild 1127 Flight Recorder in a United Airlines Boeing 720B airplane, which encountered severe turbulence and acceleration changes. Only G_z accelerations had been available for describing the acceleration environment encountered at the various altitudes and velocity conditions. Similarly, only a small portion of a jet aircraft (the DC8 yoke) was available, and the seat, instrumentation, and flight attitude indicator were substituted from other types of aircraft. Consequently, there was major interest in the degree to which the pilots felt the turbulence conditions were realistically simulated in the centrifuge.

The two pilots who had actually experienced the UAL Flight #746 in the 720B (in the particular flight which was recorded) reported that the fidelity of these simulations was excellent, based on their memory of the actual flight. The other eight pilots who rode the centrifuge also indicated that the simulations were very realistic even though none of them had experienced turbulence of such magnitudes and accelerations in actual flight. In general, the simulations were much more realistic than the pilots had expected them to be. The turbulence motions, the accelerations, and the physical environment in general, appeared to be realistic. However, some of the other aspects of the simulation were critically evaluated. The flight indicator was not realistic for this specific type of jet aircraft, and its extent of change (especially in pitch) was greater than would have occurred in a commercial jet liner some pilots believed. In the commercial jet, the pilots reported, pitch indication does not change as abruptly as did the centrifuge task; however, roll in the jet aircraft can change even more abruptly than it did in the centrifuge task. Similarly, the noise level was not realistic. One of the questions had to do with control forces. Some pilots thought the control forces were realistic, and others felt they were not. Most pilots seemed to feel that more realistic control pressures would be highly desirable, although for this particular series of tests, it was not a serious distraction from the realism of the simulation. All pilots thought a stabilizer trim switch would have added to the realism. Similarly, the fact that there was no yaw control (no rudder pedals) detracted some from the simulation, especially during the more difficult maneuvers. The lighting was somewhat disconcerting at times (e.g., as when the camera was on), and also when the pilot was able to see through the door of the centrifuge during some maneuvers. Also, the appearance of a shadow on the horizon tended to confuse some pilots. The restraint system and the seat were not realistic, and the use of the hard hat and/or felt cap were not realistic. However, these aspects did not detract appreciably from the physical turbulence conditions which were being studied in this project. The negative G portion was especially realistic, the pilots thought, and the turbulence conditions seemed real.

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