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EFFECTS OF GUST-INDUCED AND MANEUVERING ACCELERATION STRESS ON PILOT-VEHICLE PERFORMANCE

By

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Advanced manned missions occasionally will introduce new problem areas where the human pilot must perform a demanding control task in an environment which approaches some limit of his physiological tolerance. Spacecraft attitude control by the human pilot under the linear acceleration stress produced by reentry is a recent well-known example. In these cases successful understanding requires a joint effort by systems engineers, stress physiologists, and flight surgeons (see for example references 1 and 2). Often the motion simulation device used by the systems engineer to match the vehicle and systems dynamics to the pilot can be a useful source of information for those interested in the medical aspects of the problem, particularly since it usually is available early in the time schedule.

It appears at this time that missions requiring low-level terrain following in turbulent air for extended periods of time may present just such a new problem area. In the spirit of the foregoing remarks this paper will describe for this audience a piloted motion simulator study undertaken to assess the effects of gust-induced and maneuvering acceleration stress on pilot performance in a low-level penetration attack mission.

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In particular, the objectives of this study were to determine changes in terrain-following performance (i.e., a measure of the ability of the pilot to maintain a relatively constant small ground clearance while flying over terrain) as affected by the following independent variables.

a. Moving cockpit vs fixed cockpit simulation.

b. Subsonic vs supersonic simulated aircraft velocities.

c. Calm air vs turbulent air conditions.

d. The addition of a requirement for secondary task performance.

e. The introduction of a bending mode frequency near the visceral resonance frequency.

f. The failure of an automatic terrain-following system monitored by the pilot.

It was believed that a reasonable assessment of the effects of these variables could be obtained by utilizing a simulator that was capable of reproducing, to a large extent, the anticipated normal acceleration (acceleration forces perpendicular to a plane through the aircraft fuselage and wings) environment of an aircraft cockpit during low-level high-speed flight. Hence, the Ames Height Control Apparatus (HICONTA), a moving cockpit simulator capable of $\pm$ 50 feet of vertical motion and $\pm$ 50 feet per second^2 of perturbed vertical acceleration, was selected for this study. Figure 1 is a photograph of this simulator and support structure.

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Another requirement for this study was a situational display depicing aircraft attitude and terrain below and ahead so as to enable the pilot to perform the terrain-following task. This need was satisfied by using a terrain-following display evolved at the Ames Research Center and described in reference 3. It has been noted that a somewhat similar display independently evolved by Roscoe and Besco, reference 4, has been used with success in simulated terrain-following.

The remaining requirements for the simulation were straight forward and are described in the next section.

METHOD

In general, the technique employed was to expose the subject-pilots to pre-established combinations of the independent variables while they were engaged in the terrain-following task. At the culmination of the task, pen records of the flight path of the aircraft with respect to the terrain, acceleration forces induced, etc., were analyzed to evaluate per ormance.

Subjects.- Three pilots were used in this study. Two were NASA test pilots who had considerable prior experience with different aircraft types and simulation devices. The third subject was the author, rated as a commercial pilot with a moderate amount of experience in simulation devices. The three pilots are referred to as Pilots A, B and C, respectively.

Simulation.- An electronic analog computer, figure 2, was used to solve the equations of motion in six-degrees-of-freedom (three force and three moment equations about the aircraft axes) of an assumed variable-sweep wing fighter aircraft. Two aircraft velocities at flight near sea-level were simulated: one subsonic and one supersonic. Inputs to the equations of motion were from conventional cockpit controls located in the simulator cockpit and from simulated turbulent air, described in a later paragraph.

The cockpit of the Ames HICONTA, figure 3, was fitted with a seat including conventional lap and shoulder harness restraints, conventional fighter aircraft controls with longitudinal stick forces of six pounds per g at the supersonic velocity and four pounds per g at the subsonic velocity and a panel with aircraft type instruments, figure 4. In the center of the panel was located the terrain-following situational display (cathode ray tube) depicting aircraft attitude, bank angle and height relative to the terrain below and to the terrain at two points - five and ten seconds ahead. This display is shown in detail in figure 5.

A light canvas cover was used to completely cover the HICONTA cockpit, restricting the pilots' view to the cockpit interior and allowing a subdued lighting of the instrument panel, figure 6.

In addition to the simulated spatial orientation of the aircraft with respect to the earth's surface at sea-level provided by the usual aircraft panel instruments, simulation was made of terrain features and moderate turbulence for each of the two aircraft velocities considered. The terrain cross-section generated by filtering and squaring

Gaussian noise was somewhat comparable to that of coastal California. Since this terrain as generated was two-dimensional, i. e., height vs time, as the aircraft velocity was reduced to the subsonic region, the apparent motion of the terrain beneath the aircraft was slowed down correspondingly.

The turbulent air at each velocity was simulated by passing the output of a Gassian noise generator through a first order filter having the appropriate constants to result in a reproduction of sea-level gust spectra as described in reference 5 with an amplitude of 10 feet per second, RMS. This turbulence was allowed to excite the aircraft dynamics through the appropriate parameters, resulting in responses in aircraft angle-of-attack and normal acceleration. The normal acceleration forces at the pilot's station resulting from this wind gust simulation was approximately 0.2 g, RMS, with infrequent peaks of about 2 g and 0 g. Though the RMS g force was about the same for both velocities simulated, the frequency content at the subsonic velocity was lower and caused more pitching and more sustained up and down motion of the simulated aircraft.

Figure 7 is a block diagram of the simulation. In this figure an additional element, a 6 cps bending mode vibration, is included with dashed lines to indicate that it was used only for that portion of this study where attention was directed toward the effect of vibration near the visceral resonance frequency. The effect of bending mode vibration was accomplished by adding a 6 cps sine wave to the input to the HICONTA cab drive system and adjusting the amplitude until the cockpit accelerometer indicated 0.4 g peak to peak.

Test Procedure.- Prior to any test runs the pilots were allowed to practice the terrain-following task at the various test conditions until they became reasonably proficient. In all cases the instruction was to fly the simulated aircraft as closely as possible to a 250 foot clearance height above the terrain without ground contact. The following paragraphs describe the procedures used for each of the test conditions.

The test plan to determine the effects of moving vs fixed cockpit, calm air vs turbulent air and supersonic aircraft velocity vs subsonic velocity was established so as to nullify the effects of pilot differences, learning, fatigue and boredom. In this plan the two NASA test pilots (referred to as Pilot A and Pilot B in the table) were subjected to the sequence of test runs shown in Table 1. The test runs for each pilot were spaced from several hours to several days apart.

The presumption in this plan was that there would be no interaction among the pilots and the test conditions and that the effect of each condition could be assessed by summing the performance measures of the two pilots.

To investigate the effects of increasing pilot workload by the addition of other tasks, Pilot C concurrently performed tasks involving recognition, thinking and reacting while performing at the terrain-following task. The aircraft simulation was at the supersonic velocity with the cockpit moving. The procedure was to present ten minutes of secondary task activity concurrent with level terrain and calm air where the pilot was to maintain a constant 500 foot altitude. This was followed by 40 minutes of secondary task activity concurrent with terrain variation and turbulence where the pilot was to maintain a 250' clearance height and ended with a ten minute period identical to the first ten minute period. The secondary workload consisted of light switching, altimeter reading and mental arithmetic. The computer operator was to select the tasks, i.e., light switching only, altimeter reading and arithmetic, at random and present them after random time intervals. Only one task at a time was presented. Evaluation was made of terrain-following performance and secondary task performance.

The effects of acceleration due to bending mode vibration were investigated by exposing two pilots to a moving cockpit simulation of this environment, one at the subsonic velocity and the other at the supersonic velocity, and evaluating terrain-following performance and subjective comments.

To examine the capability of a pilot in assuming control in case of an automatic terrain-following system failure when only a visual display was used to monitor system performance, a rough analog of an automatic terrain-following system was constructed that would fly the simulated aircraft at an average height of 250' over the terrain with maximum clearance height excursions (due to smoothing the terrain features) of plus and minus 100 feet. The simulation utilized was a moving cockpit at the supersonic velocity. The pilot was instructed to monitor the system by observing the terrain-following display and when he thought that the system had failed, he was to report this verbally while taking over control. Since the automatic system controlled only the vertical clearance height of the simulated aircraft, the pilot was required to keep his hand on the stick at all times to control the bank angle. The automatic system was failed at random and without warning by the computer operator by merely turning it off. There were no transient effects or other warning indications to warn the pilot of failure. Evaluation was made of terrain-following performance and pilot comments.

In an attempt to arrive at an objective rating of pilot terrain-following performance, a number of statistical measures were employed. The linear correlation between aircraft altitude and terrain altitude, designated by r, was used to assess the pilot's ability to place the aircraft in-phase with the terrain. A value of one for r would indicate a perfect phasing of aircraft altitude with the terrain; values less than one would indicate the presence of aircraft motion not phased or not associated with the terrain. Since the standard deviation of the aircraft altitude, S_A, would necessarily be related to the standard deviation of the terrain, S_T, the dimensionless ratio $\frac{S_A}{S_T}$, was used to represent the amplitude ratio of aircraft motion to terrain motion. If this ratio were greater than one in calm air, it would be implied that the aircraft was deviating about the desired flight path (a constant height above the terrain) or was flying high over the hills and low in the valleys. A value of this ratio less than one would suggest that the pilot was filtering the terrain to obtain a smoother ride. With the introduction of turbulence, a value somewhat higher than one would probably be concurrent with optimum performance. Another important measure related to terrain-following performance was the mean height above the terrain, $\overline{H}$. The standard deviation of height above terrain, S_H, was also included in the table for reference. Another way of examining terrain-following performance would be to count the number of occasions that the simulated aircraft was flown above or below some arbitrary heights above the terrain. For this purpose, 125 feet was selected as the lower limit and 500 feet as the upper limit. The number of occurrences above and below these heights were determined by examining the entire pen records and not just from the sample points used to compute the other statistics described here.

RESULTS AND DISCUSSION

Figure 8, selected from the pen records of Pilot A's performance, subsonic velocity, moving cockpit, with turbulence, was reproduced to illustrate how the HICONTA cockpit duplicated the accelerations commanded from the analog of the aircraft. In general, as the frequency of the commanded acceleration increased above eight radians per second, the amplitude was progressively attenuated by the servo drive dynamics; as the commanded acceleration frequency was reduced below one and one-half radians per second, the amplitude was also progressively attenuated by "washout circuitry." This circuitry was used to keep the cockpit excursions within plus and minus 40 feet of the track center (10 feet was allowed at each end for a safety factor). The effect of the washout circuitry is best illustrated in the following table comparing cockpit and aircraft analog acceleration data for Pilot A when experiencing cockpit motion.

Test Condition	Aircraft Analog at Pilot Position (RMS g)	HICONTA Cockpit (RMS g)
Supersonic, calm air	.20	.05
Supersonic, turbulence	.27	.17
Subsonic, calm air	.10	.04
Subsonic, turbulence	.27	.24

From this table it is evident that the RMS of low frequency cockpit perturbations in acceleration, resulting from pilot control inputs while terrain-following in calm air, were reduced to about 25-40 percent of the commanded acceleration; whereas, the higher acceleration frequencies encountered during the simulation of turbulent air were reproduced fairly accurately. When the cockpit acceleration data of this table were applied to figure 7, a plot of pilot tolerance, it was implied that the motion effects due to turbulence should be tolerable up to two and one-half hours for the supersonic simulation and up to one hour for the subsonic simulation.

Figures 10 and 11 are samples of terrain-following performance. These figures emphasize the apparent difference in terrain as seen by the pilot at the two velocities considered, i.e., the terrain features appeared about two and one-half times faster at the supersonic velocity. Prior to any of the data runs, the pilots were allowed to practice the terrain-following task until they felt proficient. Pilot A had four hours of practice distributed among five spaced sessions. Though these sessions for Pilot A were all at the supersonic velocity simulation (his first data runs were in the supersonic simulation). He received an additional one-half hour of practice prior to data runs at the subsonic velocity simulation. Pilot C, who had been the subject of a previous study involving the terrain-following display, had about ten hours of fixed cockpit practice at the terrain-following task prior to the beginning of this study. In addition, he received two more hours of practice at the various combinations of cockpit motion, simulation wind condition and aircraft velocity prior to any data runs.

<u>Cockpit Motion, Aircraft Velocity and Turbulence Effects</u>.- These effects were investigated according to the plan outlined in Table 1. The resulting data for the two pilots involved are presented in Tables 2 and 3. Though an investigation of pilot differences in performance was not an objective of this study, there were notable differences as summarized in the following table.

Pilot	N	S_A/S_T	r	$\overline{H}$ (Ft.)	S_H(ft.)	No. of Occurrences	
						$H < 125$ ft.	$H > 500$ ft.
A	320	1.08	.973	318	95	20	73
B	320	1.08	.960	310	104	59	93

Pilot B tended to fly slightly lower and less in-phase with the terrain, resulting in a higher incidence of excursions above 500 feet and below 125 feet. These differences in performance may have resulted from Pilot A having received more practice prior to data runs. Examination of the pen records of the pilots' terrain-following performance indicated that Pilot A tended to lead the terrain, i.e., as a hill approached the aircraft during the simulation, he would quickly fly to an altitude above the hill and then, as the hill passed below, begin his descent so as to maintain a fairly close proximity to the backside of the hill. Pilot B tended to lag the terrain, i.e., as a hill approached the aircraft, he would wait a bit too long before initiating his pull up, resulting in the aircraft passing too close to the front side of the hill and overshooting the top and backside of the hill.

In general, pilot performance was very good considering the difficulty of the task and the amount of practice that the pilots had. Of the entire five hours and twenty minutes of simulated terrain-following data runs for both pilots, there were only five occurrences where the simulated aircraft was below 50 feet (one was a collision) and five occurrences where the simulated aircraft was above 1,000 feet. As these incidences occurred during the data runs, the pilots were interrogated as to cause. Some of the replies were, "I was winding the clock," "I was attending to the angle-of-attack indicator," "I was day dreaming," "I was removing the earphones." These remarks along with the concurrent large deviations in height above the terrain pointed out the necessity of almost continuous attention to the terrain-following display during the data runs.

The following table summarized terrain-following performance for the fixed cockpit and moving cockpit data runs.

Cockpit	N	S_A/S_T	r	$\bar{H}$ (ft)	S_H (ft)	No. of Occurrences	
						H 125 ft	H 500 ft.
Fixed	320	1.11	.973	311	103	53	80
Moving	320	1.05	.963	316	96	26	86

The differences shown in this table are small. For the fixed cockpit data runs, there was a slightly better phasing of the aircraft flight path with respect to the terrain, a slightly higher standard deviation of aircraft altitude with respect to terrain altitude and a lower mean height above the terrain. These statistics suggest that for the fixed cockpit simulation, the pilots, not being subjected to acceleration forces, were inclined to overcontrol slightly while maintaining a slightly better phasing with the terrain. The slightly lower mean for height above the terrain along with the small increase in variability of this measure possibly accounts for the increase in the number of occurrences where the flight path of the aircraft was less than 125 feet above the terrain. It is emphasized that these differences are small and that the distributions of aircraft height above the terrain for the fixed cockpit and moving cockpit data runs, figures 12 and 13, appear very similar.

The greatest difference between the fixed cockpit and moving cockpit performance occurred during the practice sessions. When the pilots were first exposed to the terrain-following task, the simulation was fixed cockpit. At this time there was a tendency for the pilots to induce large acceleration forces by extreme overcontrolling; however, when the cockpit was set into motion, this tendency immediately disappeared. During subsequent fixed cockpit simulations interspersed among moving cockpit sessions, this tendency was apparent but in diminishing amounts. It seemed as though the pilots were being conditioned by the moving cockpit sessions to treat the control stick with

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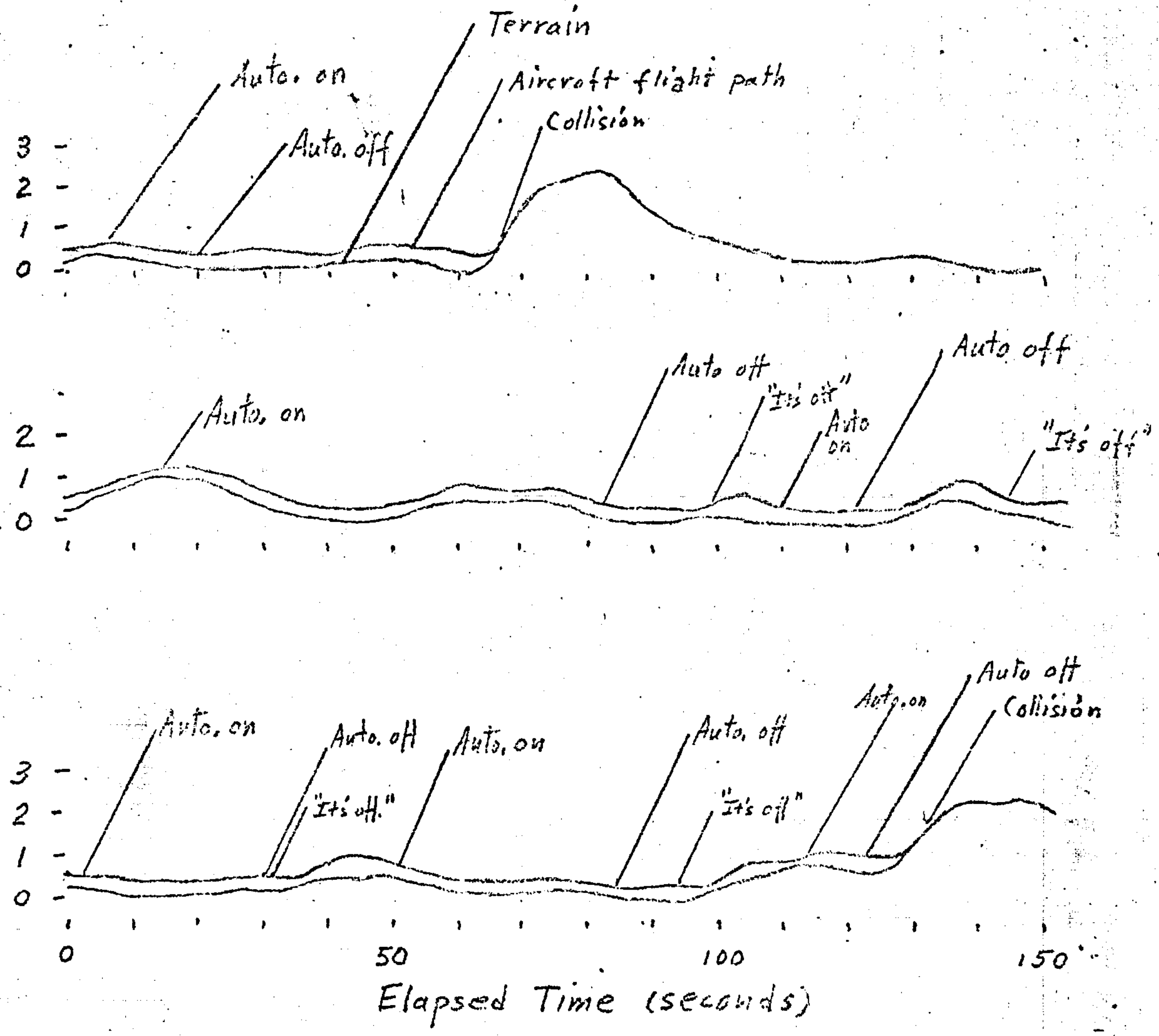


Figure 18: Simulated automatic terrain-following system failure. Pilot B, moving cockpit, supersonic with turbulence.

respect during the fixed cockpit sessions. Since there was no control group without moving cockpit experience, this hypothesis could not be substantiated.

When the data were examined to ascertain the effect on terrain-following performance resulting from wind condition, there was no apparent casual relation. The table below summarized these data.

Air	N	S_A/S_T	r	$\bar{H}$ (ft)	S_H(ft)	No. of Occurrences	
						H 125 ft	H 500 ft
Calm	320	1.08	.970	312	98	38	80
Turbulent	320	1.08	.964	315	101	41	86

The most striking difference in terrain-following performance at the two aircraft velocities simulated appeared in the mean height of the aircraft above the terrain, as shown in the table below.

Velocity	N	S_A/S_T	r	$\bar{H}$ (ft)	S_H(ft)	No. of Occurrences	
						H 125 ft	H 500 ft
Supersonic	320	1.06	.967	359	108	38	137
Subsonic	320	1.11	.969	268	90	41	29

The other differences shown in this table are small. At the subsonic velocity there was a slight increase in the standard deviation of aircraft altitude with respect to the standard deviation of terrain altitude. There was no difference in the correlation of aircraft altitude with terrain altitude. The lesser value of S_H for the subsonic condition in spite of the higher value of S_A/S_T for this flight condition was due to a lower value of the standard deviation of the terrain altitude at lower velocity. The small increase in the number of occurrences where the flight path was below 125 feet above the terrain and the large decrease in the occurrences above 500 feet reflect the joint effects of the differences in mean heights and standard deviations of height.

Secondary Task Effect - Prior to data runs to assess the effects of secondary task requirements on terrain-following performance, the pilot (Pilot C) was allowed approximately 20 minutes of practice of the secondary tasks concurrent with fixed and moving cockpit simulations of the supersonic velocity with the turbulence effect. During this practice period, he was given eight light switching problems, 13 altimeter reading problems and 16 arithmetic problems.

During the data run the computer operator became somewhat overzealous and often presented the pilot with a long sequence of arithmetic problems, spaced less than two seconds apart. Though it was recognized that this placed an additional burden on the pilot, only the results for the first problems of each sequence were used to evaluate performance at arithmetic throughout the data run. Similarily, there was some sequential repetition of the light switching problem; however, here the result was beneficial to the pilot since his finger was often still on the switch, and his resulting time to react was generally lower during the sequence. Here again, only the first problem of each sequence was used to evaluate performance at this task. The altimeter reading task was used only to burden the pilot and cause him to divert his eyes away from the terrain-following display and, consequently, performance at this task was not evaluated. Table 4 summarized the secondary task problems presented to the pilot during the data run.

Table 5 presents the results of performance at the two secondary tasks evaluated. Since there were no errors in the 58 first arithmetic problems of each sequence, only mean solution times are given (among the remaining 102 sequenced arithmetic problems, there were nine errors). The solution times for arithmetic include the problem reading time, which was fairly uniform throughout.

Table 5 indicates that there was no difference in secondary task performance when the pilot was doing the terrain-following task in turbulent air as compared to secondary task performance when he was flying level in calm air. The only change in performance indicated in this table was a progressive decrease in the time required to do mental arithmetic as the task was performed.

Table 6 presents the statistics relative to the terrain-following performance that was concurrent with the secondary tasks. With the exception of one occurrence when the pilot flew the simulated aircraft to a height of 50 feet above the ground, the closest approach to the terrain was 85 feet and the highest distance from the terrain was 640 feet. In general, the statistical data in Table 7 indicate that the performance was good and stable throughout the data run.

The following comments were made by the pilot just after the data run:

"At one point, after repeatedly pushing the wrong button to turn off the blue altimeter light after completing a response to an altitude problem, I looked at the throttle to see why the light didn't go out. In the process, the flight path came very close to the terrain, and when I noticed this, I made a sharp pull-up. I don't remember when

I got the light turned out."

"At another point when I was being given a fast sequence of arithmetic problems and the terrain was changing somewhat, during a pull-up I felt some confusion and dizziness, bording on vertigo."

The first incident quoted here occurred during the first ten minutes of terrain-following concurrent with the secondary tasks and was the incident resulting in the lowest approach to the terrain. The second incident cited occurred at the end of a rapid sequence of nineteen arithmetic problems; the last two problems were answered incorrectly.

These two cases are cited to point out that the pilot did become momentarily confused at times in spite of the good performance at the secondary tasks and the terrain-following. Apparently the pilot had, on occasion, very little reserve to meet an unexpected crisis in a logical manner. For example, why did he look at the throttle switches to determine why a light could not be turned off instead of trying the other switches. It is also pointed out that in spite of the momentary periods of confusion, recovery was rapid enough so as to not affect overall performance statistics.

Bending Mode Vibration Effect - In considering the type of aircraft that probably would be used for the mission considered in this study, it was assumed that the fuselage would be long and slender and somewhat flexible with the pilot's position located some distance from the center of gravity. It was also assumed that this structure would have a natural frequency somewhere about six cycles per second and that this bending mode vibration would be excited to some extent by turbulence. Since this frequency lies fairly near to what has been determined to be the visceral resonance frequency, see figure 17 extracted from reference 7 . It was decided to include a brief investigation of this structural vibration effect on terrain-following performance.

For this purpose, a six cycles per second signal was introduced directly into the HICONTA cockpit servo drive system, see figure 7 , and adjusted so as to cause the cockpit to move at 0.4 g, peak to peak. When Pilot A was subjected to a 90 second exposure of this motion added to the motion effect resulting from the terrain-following simulation at the subsonic velocity with turbulence, he stated that he could orient the aircraft fairly well by panel instruments but that terrain-following with the display provided was not possible. He further stated that should he actually encounter this kind of problem, he would fly the aircraft up to a higher altitude and wait until that patch of turbulence was behind the aircraft and then resume the terrain-following task. Pilots B and C made approximately the same comments after brief exposure to the same environment. At a later date, Pilot C made a serious attempt to do the terrain-following task while subjected to the bending mode vibration simulation along with the wind gust effect at the subsonic velocity and was able to perform over a five minute period apparently as well as he had done previously with turbulence but without the bending mode effect. Pilot B was recalled and asked if he would like to try the terrain-following task with the bending mode effect included in the supersonic simulation. He replied, "For ten seconds?" He was made aware that Pilot C had experienced this particular simulation at some length and encouraged to give it a try. Figure 14 is a sample of Pilot B's terrain-following performance over the same portion of terrain-following performance extracted from the five minutes that he performed at this condition. Figure 15 is a reproduction of his performance over the same portion of terrain in a data run made in a prior session. Figure 16 is a sample of the HICONTA cockpit acceleration during this simulation. Pilot B's comments made during the simulation were: "It's not so bad after you learn to relax;" "It seems to be about the same frequency as the vibration you get in a helicopter but with much more amplitude."

Apparently, the addition of the 6 cps, 0.4 g peak to peak, motion produced an effect that seemed worse than it actually was, particularly when performing the rather trying task of terrain-following with turbulence. Figure 17, a plot of subjective response to vibratory accelerations from reference 7, tends to confirm this observation since the curves of this figure show the bending mode vibration simulated in the current study as being somewhat less than mildly annoying when presented without any other motion effect. It is suspected that the current simulation would be rated as more than mildly annoying. In spite of the additional stress imposed by the simulation of a bending mode vibration, the pilots were able to adjust to the environment and perform the terrain-following task as well as before, at least for a short time period (five minutes).

The monitoring of an automatic terrain-following system. - The results of the investigation of the ability of a pilot to monitor an automatic terrain-following system by observing the terrain-following display are presented in Figure 18. This record indicates that the terrain-following display was of little value in determining that the automatic system had failed. Even though the pilot was anticipating a failure of the automatic system, he was unable to prevent collisions in the two cases where the system was failed while the aircraft was approaching a hill. The pilot commented that if this kind of a failure were a possibility, he would fly the aircraft manually. It is recognized that current concepts of automatic terrain-following systems, such as that described in reference 8, provide for warning the pilot of system failure and also incorporate fail-safe features such as an automatic pitch-up command if the system fails. The results of this investigation substantiate the need for warning devices.

SUMMARY

A simulator study was conducted to assess the effects of gust-induced and maneuvering acceleration stress on pilot-vehicle performance during extended periods of low-level, high-speed flight. NASA test pilots were subjected to this acceleration stress on the Ames Height Control Simulator, a device capable of realistically reproducing the vertical acceleration environment of this flight mode.

The primary piloting task consisted of "flying" as close as possible to a 250 foot clearance height above the terrain without ground contact by use of conventional aircraft controls while viewing aircraft instruments and a display depicting the terrain configuration ahead and below. Controlled variables were aircraft velocity, cockpit motion, gust intensity, additional secondary tasks, the presence of a bending mode vibration near the visceral resonance frequency and the requirement for monitoring an automatic terrain-following system.

SYMBOLS

N	Sample size
r	Correlation coefficient
S_A	Standard deviation of aircraft altitude (feet)
S_T	Standard deviation of terrain altitude (feet
S_H	Standard deviation of height of aircraft above the terrain (feet)
$\bar{H}$	Average height of aircraft above terrain (feet)
A_{ZP}	Normal acceleration of pilot's station in aircraft analog (g)
A_Z cockpit	Vertical acceleration of HICONTA cockpit (g)

REFERENCES

1. Creer, B.Y., Smedal, H.A., and Wingrove, R.C.: "Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance". NASA TN D-337, 1960.

2. Smedal, H.A., Captain, USN, MC, Rogers, Terence A., Ph.D., Duane, Thomas D., M.D., Ph.D., Holden, George R., and Smith, Joseph R. Jr.: "The Physiological Limitations of Performance During Acceleration", Aerospace Medicine, Vol. 34, No. 1, January 1963.

3. Wempe, T.: "Fixed-Base Simulator Evaluation of a Pilot's Terrain-Following Performance as Affected by Display Mode and Duration of Task," (unclassified) proposed Ames TN.

4. Roscoe, S. and Besco, R.: "An Experimental Evaluation of the Hughes Predictive Situational Display for Terrain-Following," Hughes reference number 2732.01/2, 1963.

5. Press, H., Meadows, M., and Hadlock, I.: "A Reevaluation of Data on Atmospheric Turbulence and Airplane Gust Loads for Application in Spectral Calculations," NACA report 1272, 1956.

6. Notess, C.: "The Effects of Atmospheric Turbulence upon Flight at Low Altitude and High Speed," Cornell Aeronautical Laboratory, Inc. FDM No. 325, 31 October 1961.

7. -----: "Human Reaction to Low Frequency Vibration," Technical Report D3-3512-1, Contract NONR 2994(00) Office of Naval Research.

8. Sherrerd, H. and Pelton, F., editors.: "Terrain-Avoidance," (based on the papers presented during the CAL Terrain-Avoidance Seminar, 17-19 October, 1961). Cornell Aeronautical Laboratory, Inc., Confidential Report 116, 1961. Title unclassified.

AIRCRAFT VELOCITY	TEST RUN	TIME	COCKPIT	AIR	TEST SEQUENCE Pilot A	TEST SEQUENCE Pilot B
Supersonic	I	40 min	Fixed	Calm	1 - 1st half	4 - 2nd half
				Turbu-lence	1 - 2nd half	4 - 1st half
	II	40 min	Moving	Calm	2 - 1st half	3 - 2nd half
				Turbu-lence	2 - 2nd half	3 - 1st half
Subsonic	III	40 min	Fixed	Calm	3 - 1st half	2 - 2nd half
				Turbu-lence	3 - 2nd half	2 - 1st half
	IV	40 min	Moving	Calm	4 - 1st half	1 - 2nd half
				Turbu-lence	4 - 2nd half	1 - 1st half

TABLE 1 - Experimental plan to determine the effects of aircraft velocity, cockpit motion and air condition on terrain-following performance.

Test Condition			Variables Data					No. of Occurrences		Height Excursion	
Velocity	Cockpit Motion	Air	r	$\frac{S_A (ft)}{S_T (ft)}$	$\bar{H}$ (ft)	S_H (ft)	AZP RMS(g)	H<125'	H>500'	Min.(ft)	Max.(ft)
Super-sonic	Fixed	Calm	.988	$\frac{543}{545}=1.00$	319	83	.09	1	12	112	1440
			.840	$\frac{328}{305}=1.08$	366	180	.30				
		Turb.	.987	$\frac{541}{475}=1.14$	345	106	.30	4	11	40	1150
			.961	$\frac{377}{322}=1.17$	389	112	.29				
	Moving	Calm	.988	$\frac{553}{531}=1.04$	355	86	.19	1	26	0	1100
			.977	$\frac{456}{414}=1.10$	451	102	.20				
		Turb.	.974	$\frac{542}{549}=0.99$	369	126	.26	0	14	—	860
			.960	$\frac{320}{328}=0.98$	356	92	.27				
Sub-sonic	Fixed	Calm	.993	$\frac{530}{502}=1.06$	282	68	.07	1	6	110	730
			.993	$\frac{478}{[illegible]}=1.11$	308	70	.17				
		Turb.	.961	$\frac{240}{208}=1.15$	235	70	.29	8	1	100	530
			.977	$\frac{261}{225}=1.16$	263	63	.29				
	Moving	Calm	.982	$\frac{561}{536}=1.05$	279	106	.09	4	2	90	520
			.966	$\frac{148}{147}=1.01$	239	38	.11				
		Turb.	.932	$\frac{173}{147}=1.16$	256	64	.21	1	1	80	510
			.973	$\frac{265}{234}=1.13$	[illegible]	66	.32				

Table 2. Pilot A, test results for velocity, motion and wind condition study. Statistics for each row summarize 20 data points representing 10 minutes of test. Data are in sequence that tests were conducted.

Test Condition			Variables Data					No. of Occurrences		Height Excursion	
Velocity	Cockpit Motion	Air	r	$\frac{S_a}{S_T}$	$\bar{H}$ (ft)	S_H (ft)	A_{ZP} RMS(g)	H<125'	H>500'	Min. (ft)	Max. (ft)
Sub-sonic	Moving	Turb.	.959	167/177 = 0.94	251	51		2	2	100	620
			.981	523/502 = 1.00	289	103					
		Calm	.962	460/43[illegible] = 1.05	261	125		7	3	50	780
			.925	215/199 = 1.08	246	82					
	Fixed	Turb.	.877	215/185 = 1.16	269	104		8	11	5	780
			.918	635/517 = 1.23	326	169					
		Calm	.95[illegible]	[illegible] = 1.02	240	75		10	3	70	620
			.965	288/212 = 1.36	269	100					
Super-sonic	Moving	Turb.	.[illegible]52	477/437 = 1.09	396	147		6	21	40	1430
			.[illegible]9	361/375 = 0.96	352	92					
		Calm	.[illegible]	[illegible] = 1.01	334	83		5	17	[illegible]0	730
			.813	363/311 = 1.17	348	102					
	Fixed	Turb.	.978	[illegible]/399 = 1.06	297	83		12	25	40	1070
			.975	426/[illegible] = 1.01	371	87					
		Calm	.[illegible]	3[illegible]/2[illegible] = 1.[illegible]	345	110		9	11	60	810
			.936	258/251 = 1.03	[illegible]	91					

Table 3, Pilot B, test results for velocity, motion and wind condition study. Statistics for each row summarize 20 data points representing 10 minutes of test. Data are in sequence that tests were conducted.

Control Task	Time Period	Number of Problems in Each Task				
		Light Switching Only		Altimeter Reading	Arithmetic	
		Total	1st in Sequence		Total	1st in Sequence
Level, 500 ft, calm air	10 min.	10	7	8	12	10
Terrain-following with turbulence	1st 20 min.	47	25	35	49	24
Terrain-following with turbulence	2nd 20 min.	10	9	11	60	9
Level, 500 ft, calm air	10 min.	4	4	17	39	15

TABLE 4 - Type and quantity of secondary task problems presented to the pilot during the data run to assess the effects of secondary task workload concurrent with the terrain-following task.

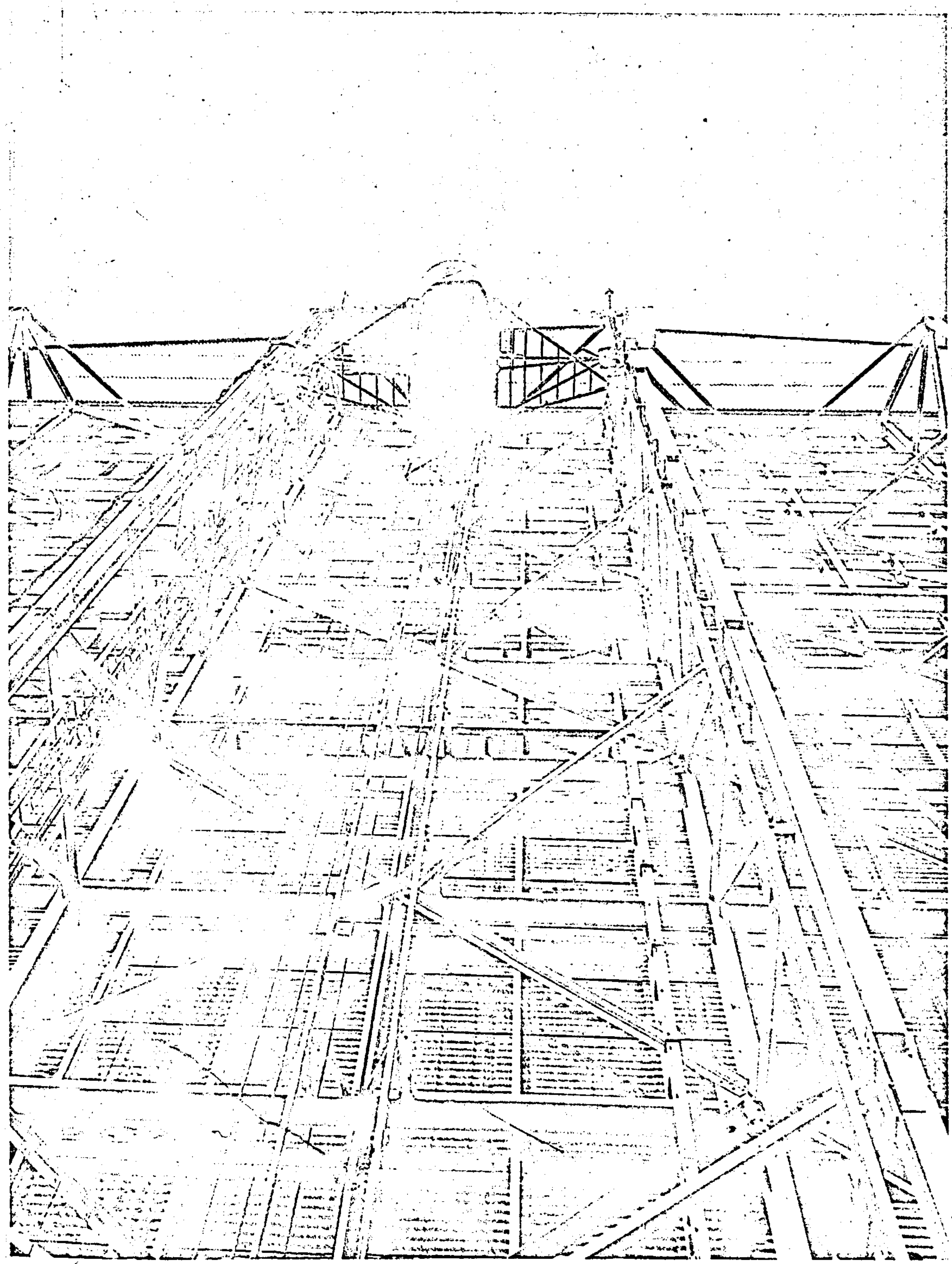
Control Task	Time Duration	First Problem of Each Sequence			
		Light Switching		Arithmetic	
		N	$\overline{T}$ (sec.)	N	$\overline{T}$ (sec.)
Level flight at 500 ft, calm air	10 min.	7	.78	10	4.98
Terrain-following with turbulence	1st 20 min.	25	.77	24	4.27
Terrain-following with turbulence	2nd 20 min.	9	.78	9	3.57
Level Flight at 500 ft. calm air	10 min.	4	.75	[illegible]	3.77

TABLE 5 - Results for secondary tasks performed concurrently with the terrain-following task.

Control Task	Time Period	N	S_A/S_T	r	$\bar{H}$ (ft)	S_H(ft)	No. of Occurrences	
							H< 125 ft	H>500 ft
Level 500 ft calm air	* 20 min.	44	-	-	514	48	-	-
Terrain-following with turb.	1st 10 min.	22	1.16	.986	288	70	2	0
Terrain-following with turb.	2nd 10 min.	21	1.05	.986	296	75	1	3
Terrain-following with turb.	3rd 10 min.	21	1.12	.985	283	91	3	-
Terrain-following with turb.	4th 10 min.	22	1.06	.989	278	69	1	2

*The first and last ten minutes of level flight at 500 feet were grouped since there were no significant differences between the data.

TABLE 6 - Results of terrain-following performed concurrently with secondary tasks.



A-32206

Figure 1. Ames Height Control Apparatus (HICONTA)

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A-32209

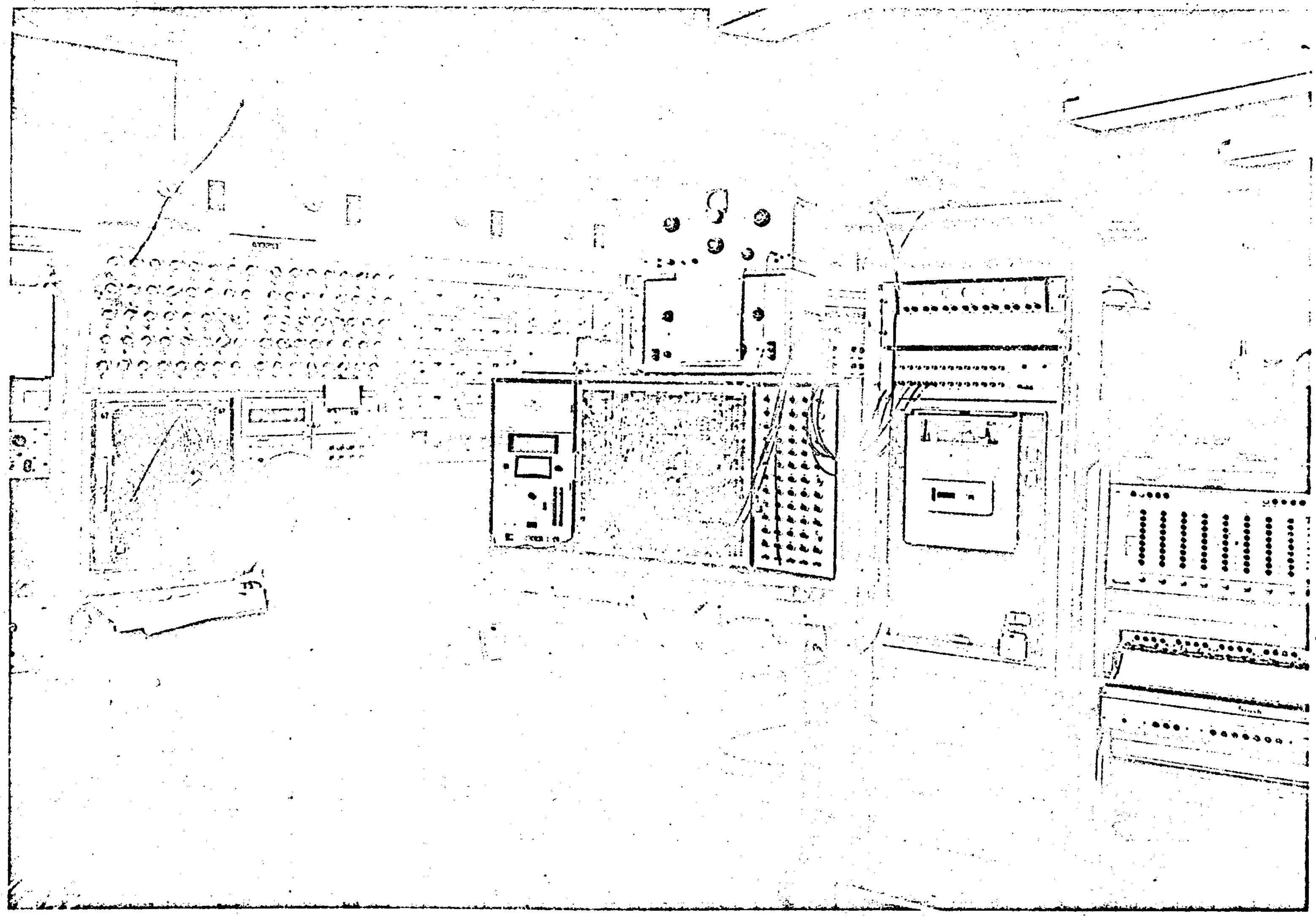

Figure 2. HICONTA electronic analog computer and other ancillary equipment

A-32207

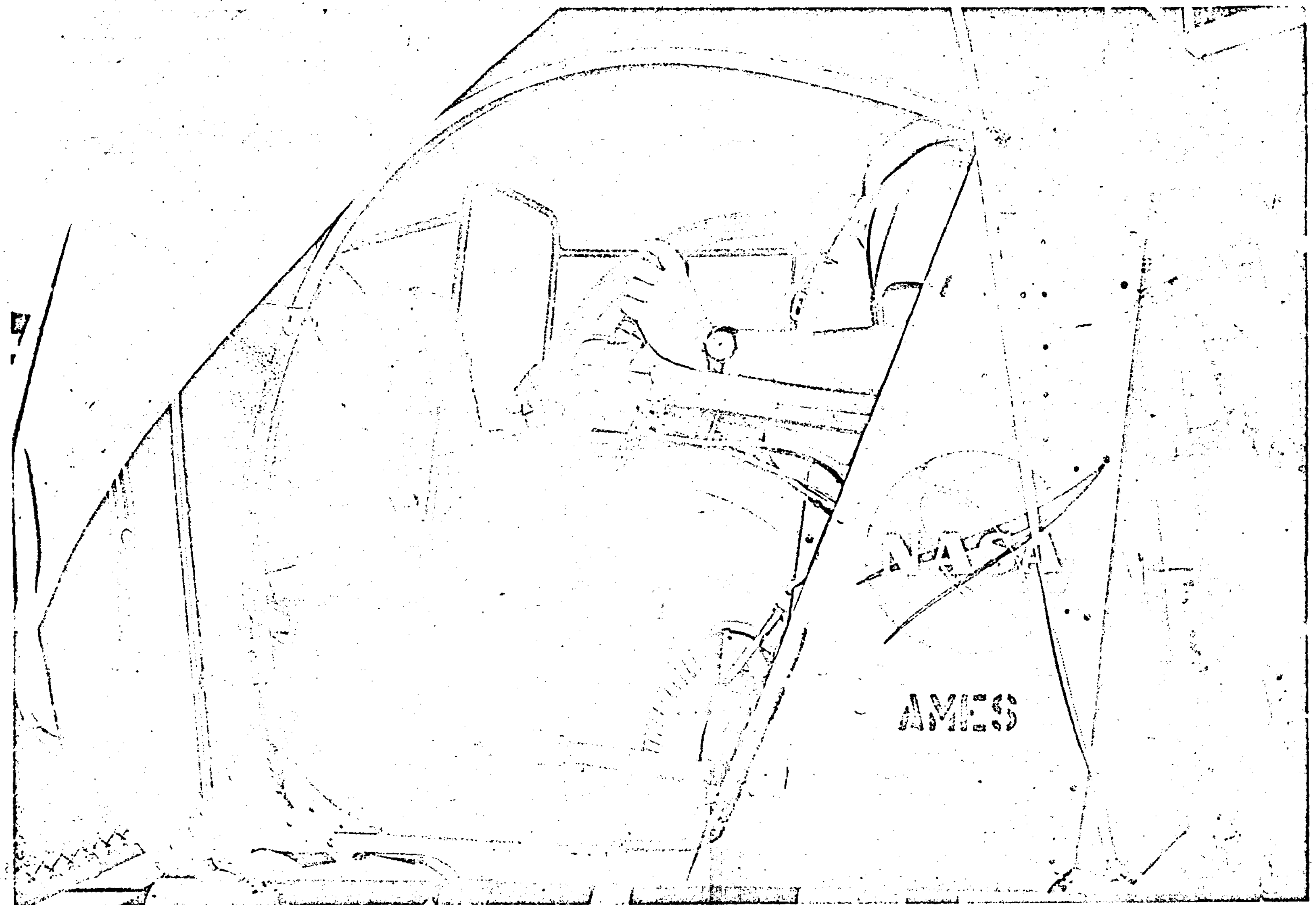

Figure 3. Pilot position in HICONTA cockpit.

A-32208

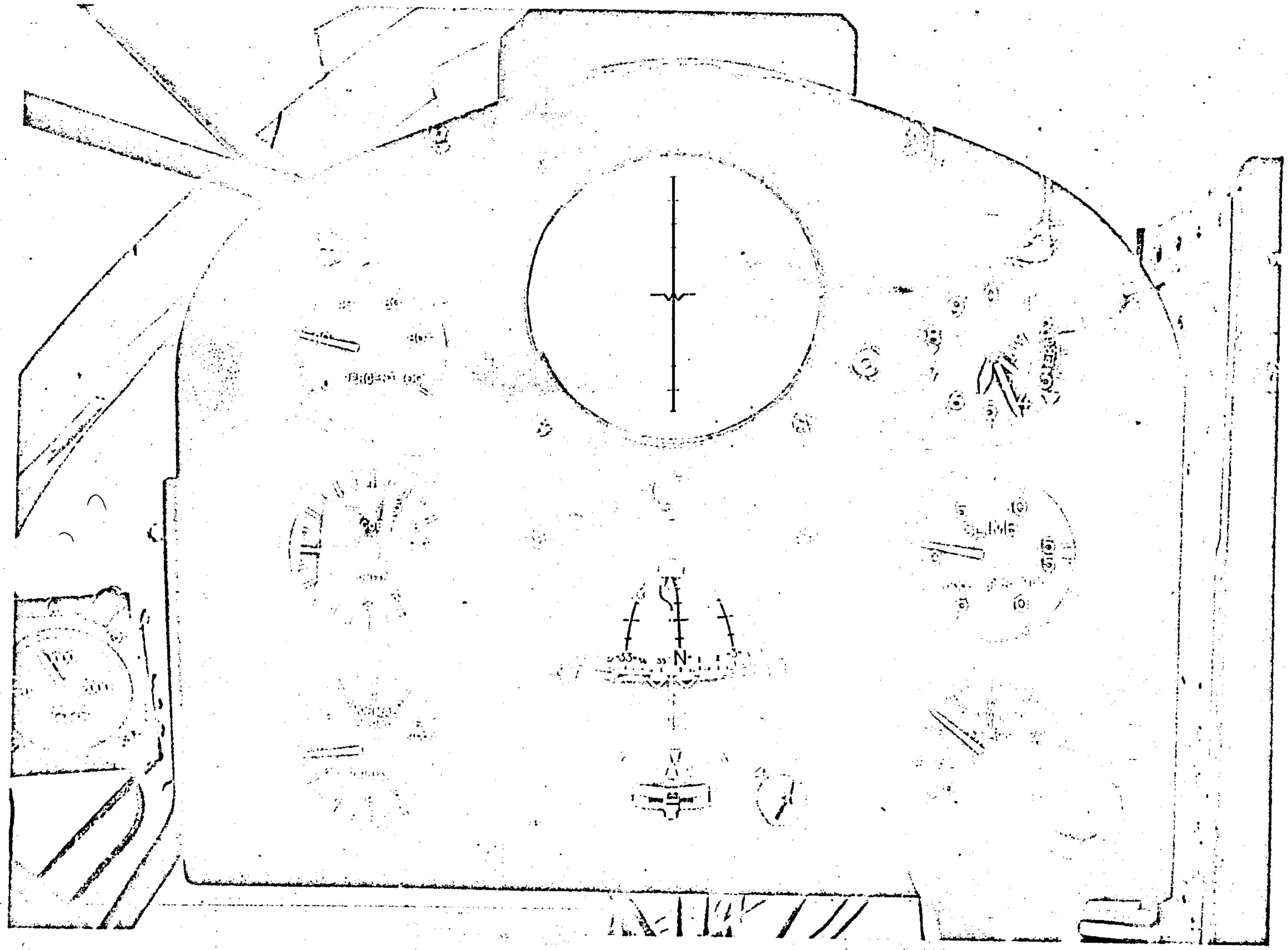

Figure 4. HICONTA instrument panel

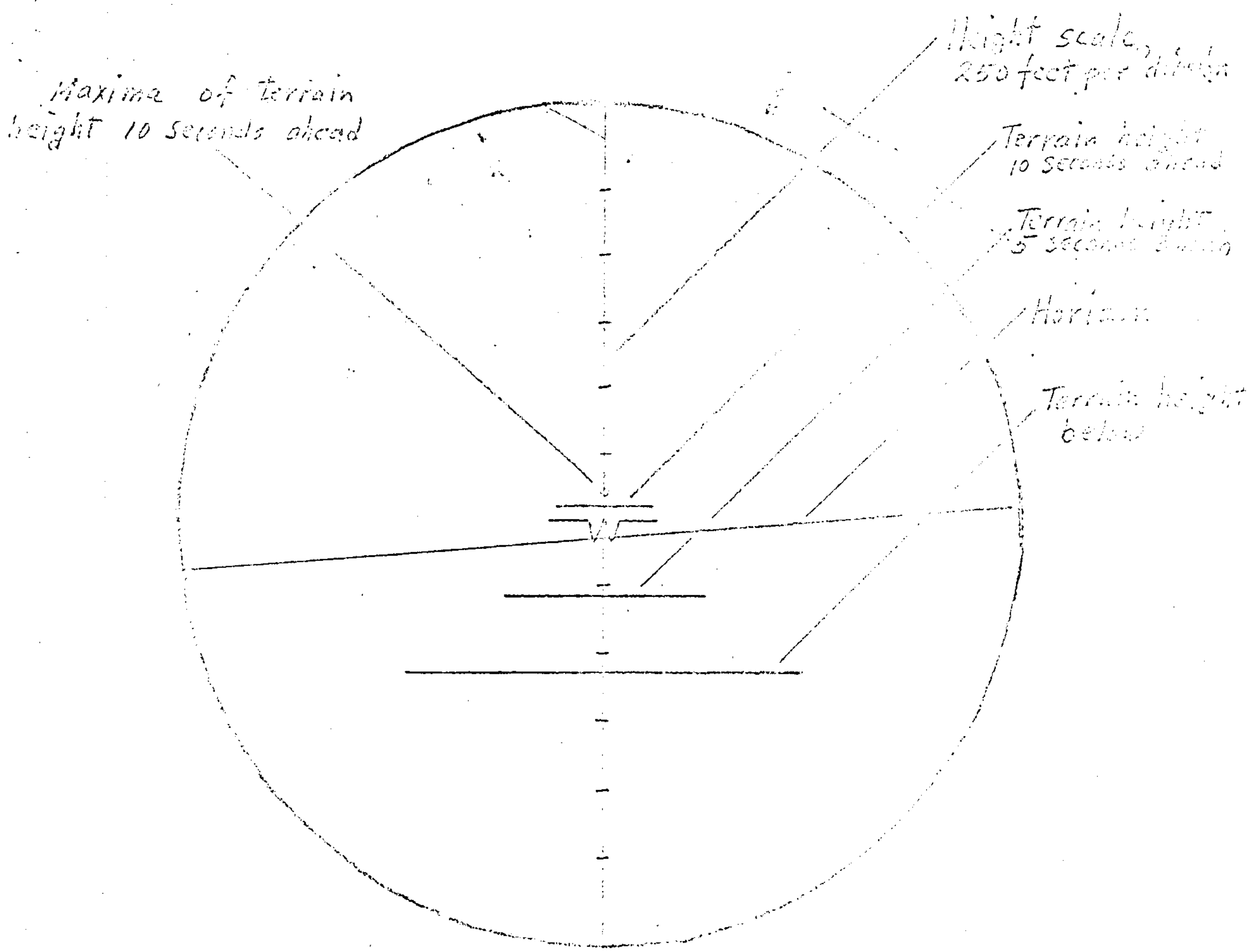

Figure 5. - Terrain-following situational display - full scale.

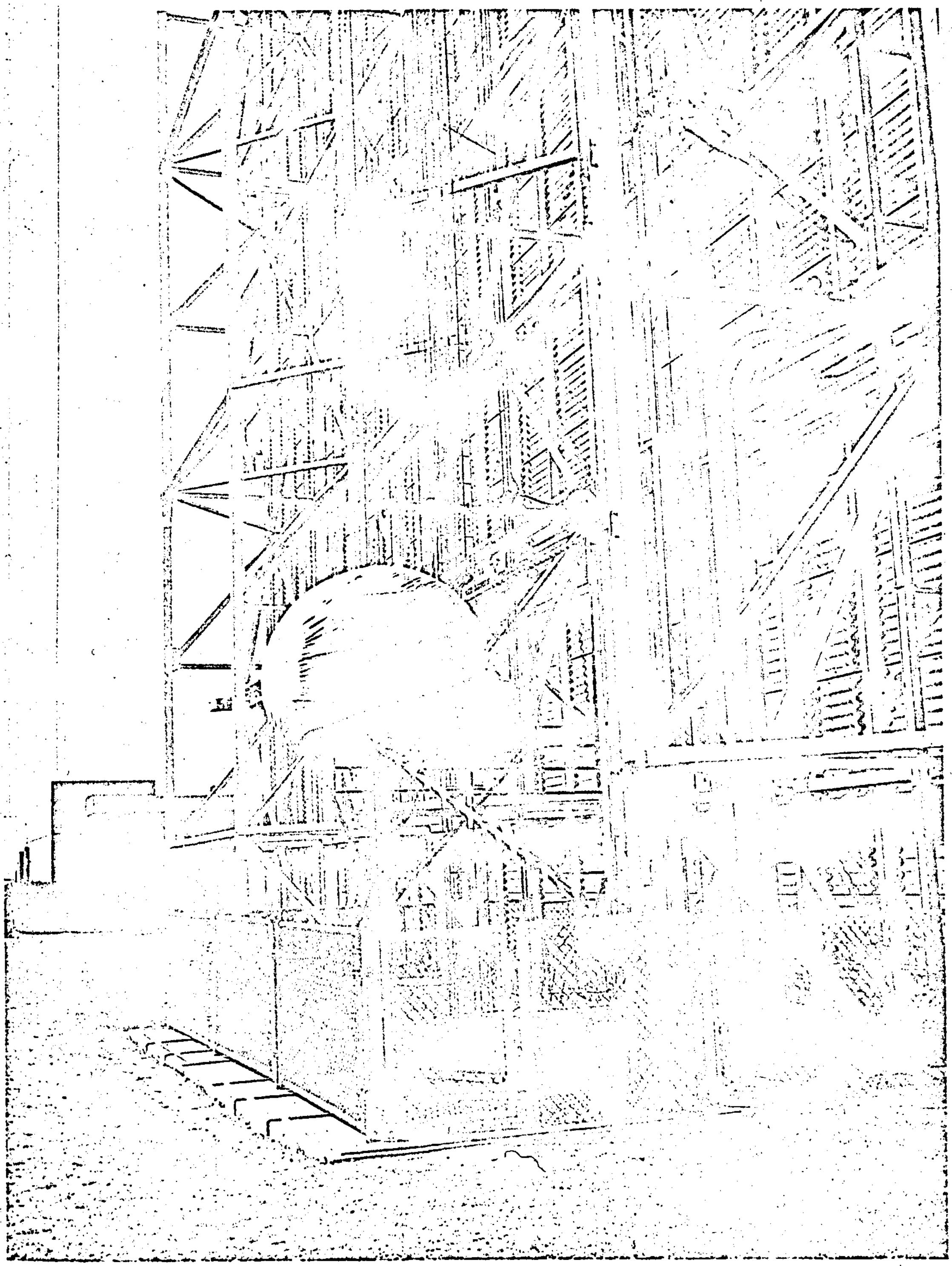

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Figure 6. HICONTA cockpit enclosure.

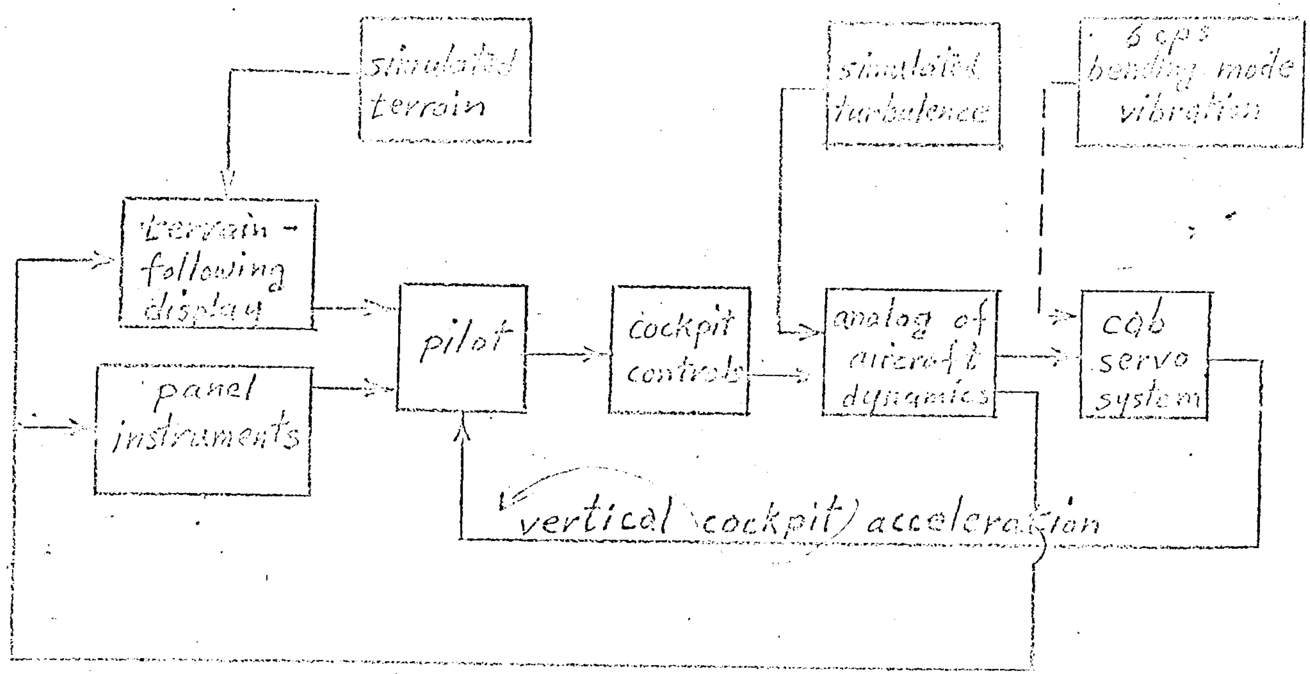

Figure 7. Block diagram of terrain-following flight simulation.

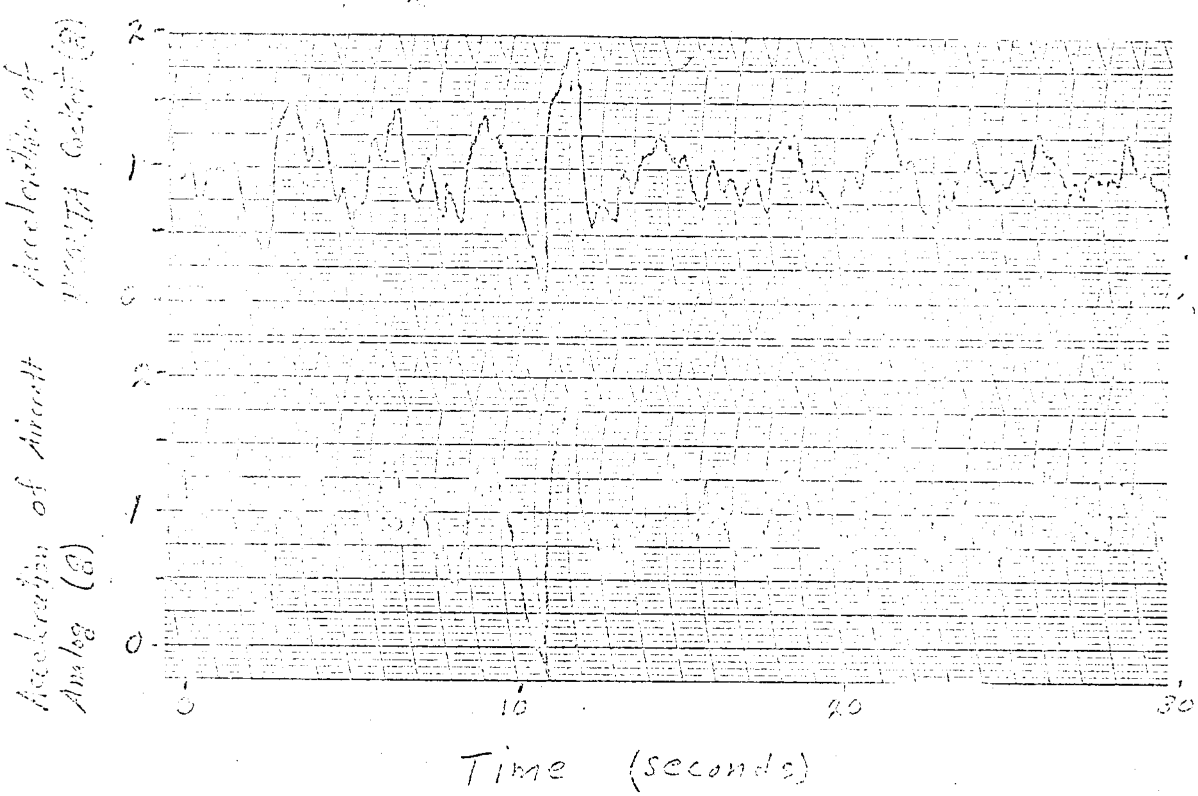

Figure 8. Sample of ~~aircraft and HIGONTA cockpit~~ acceleration records, extracted from test run for [illegible], subsonic, moving cockpit, [illegible] turbulence.

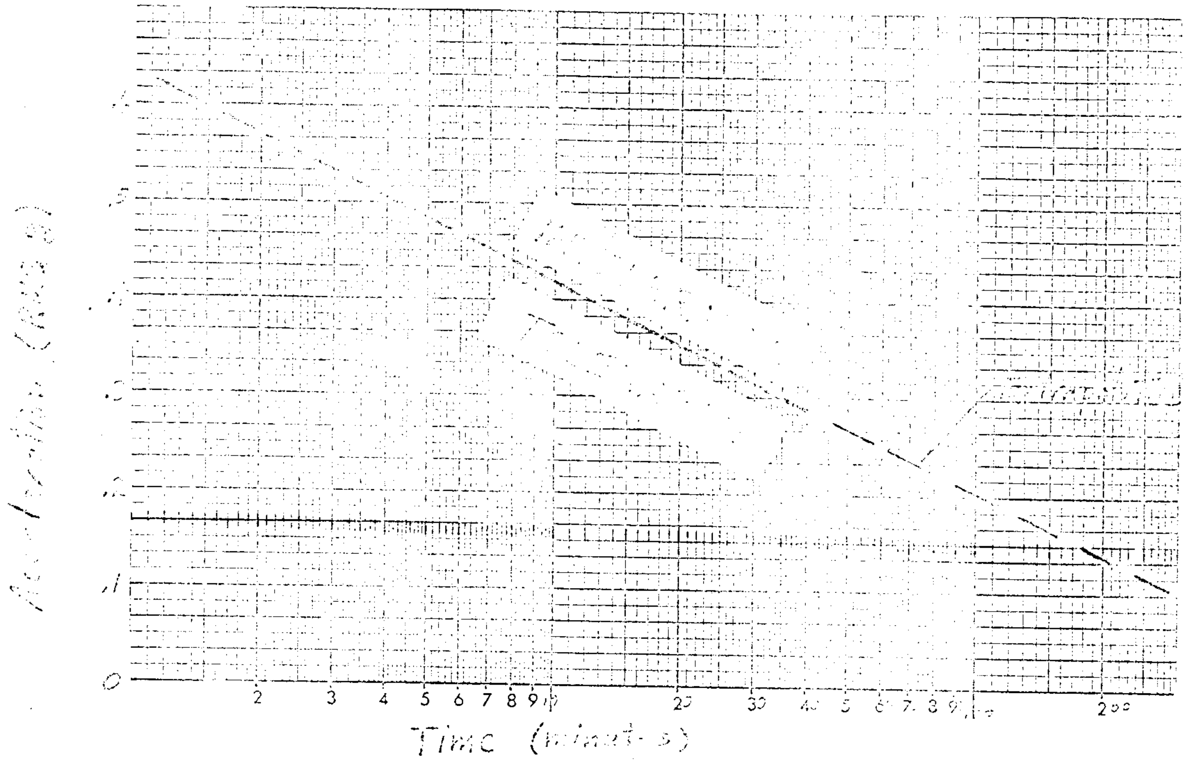

Figure 9. - Pilot tolerance to [illegible] [illegible] acceleration extracted from reference 4.

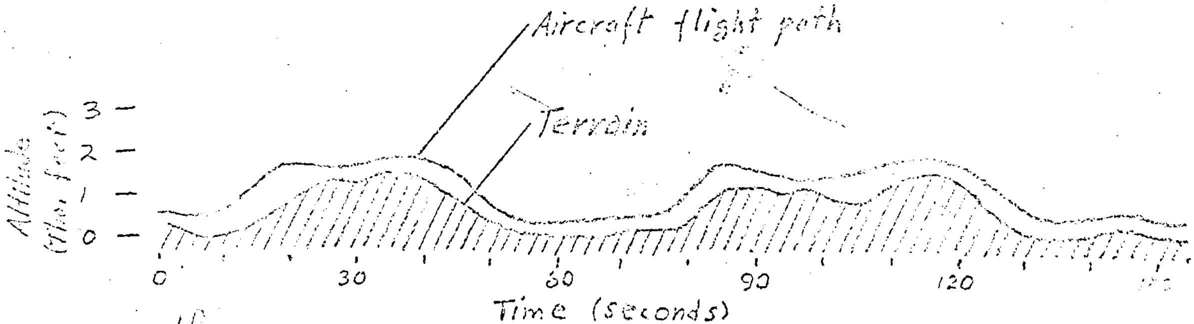

Figure 10. Sample of terrain-following. Pilot A, sonic, moving cockpit with turbulence.

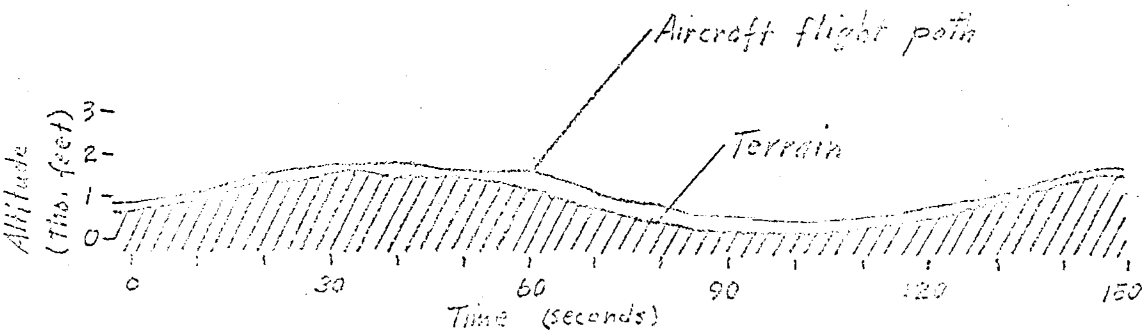

Figure 11. Sample of terrain-following. Pilot A, subsonic, moving cockpit with turbulence.

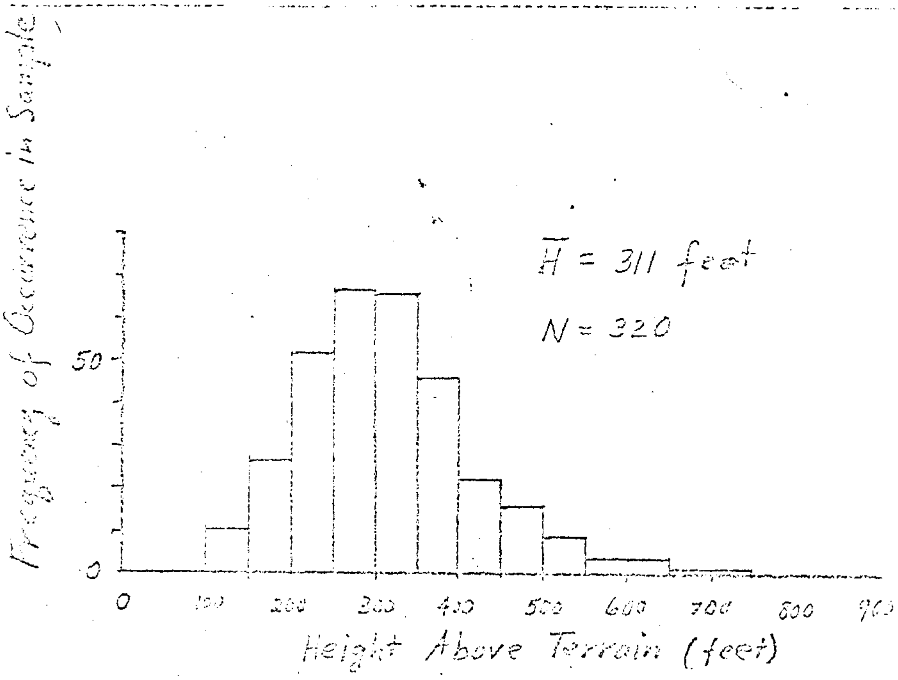

Figure 12. Histogram of height above terrain, all fixed cockpit data.

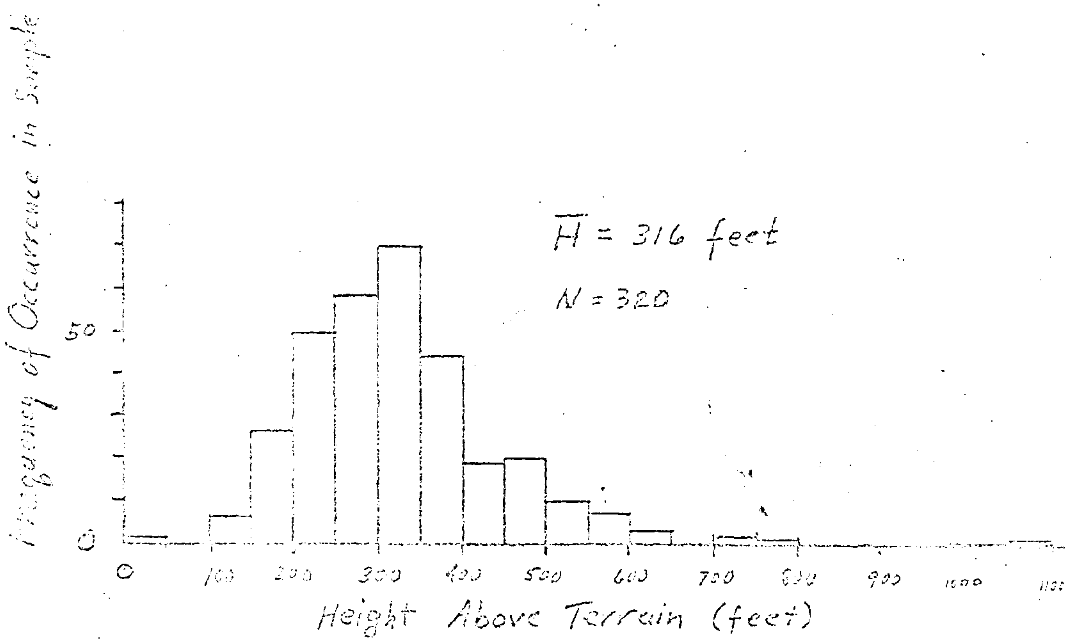

Figure 13. Histogram of height above terrain, a moving cockpit data.

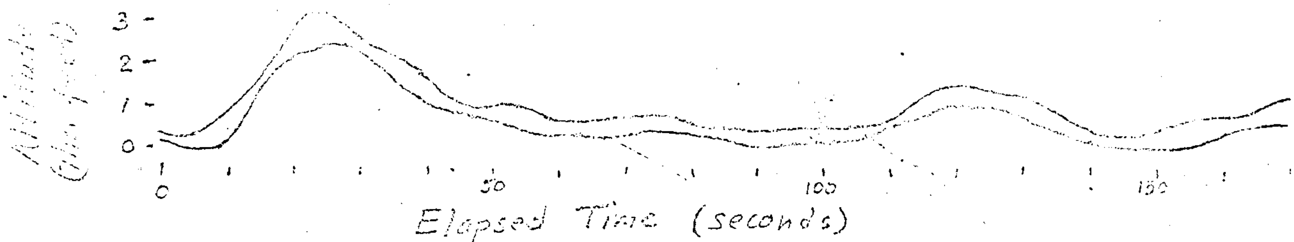

Figure 14. Sample of terrain-following with 6 cps, .4 g peak to peak acceleration added to wind gust effect. Pilot B moving cockpit, supersonic velocity.

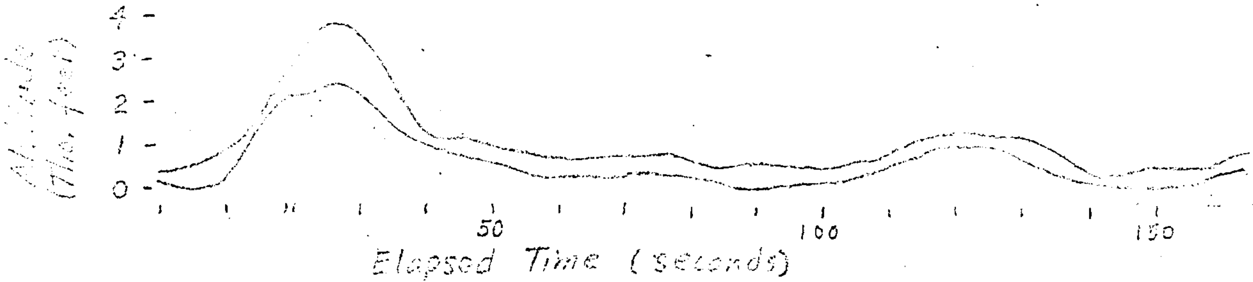

Figure 15 Sample of terrain-following with [illegible]
[illegible]

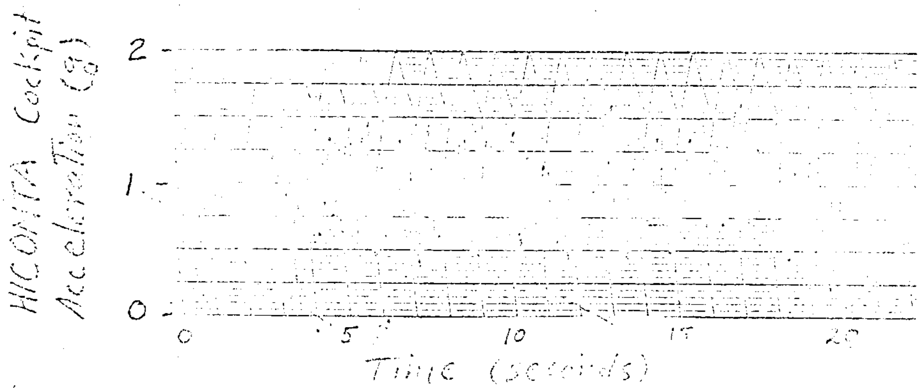

Figure 16, Sample of HICONTA cockpit acceleration record during data run of figure 14.

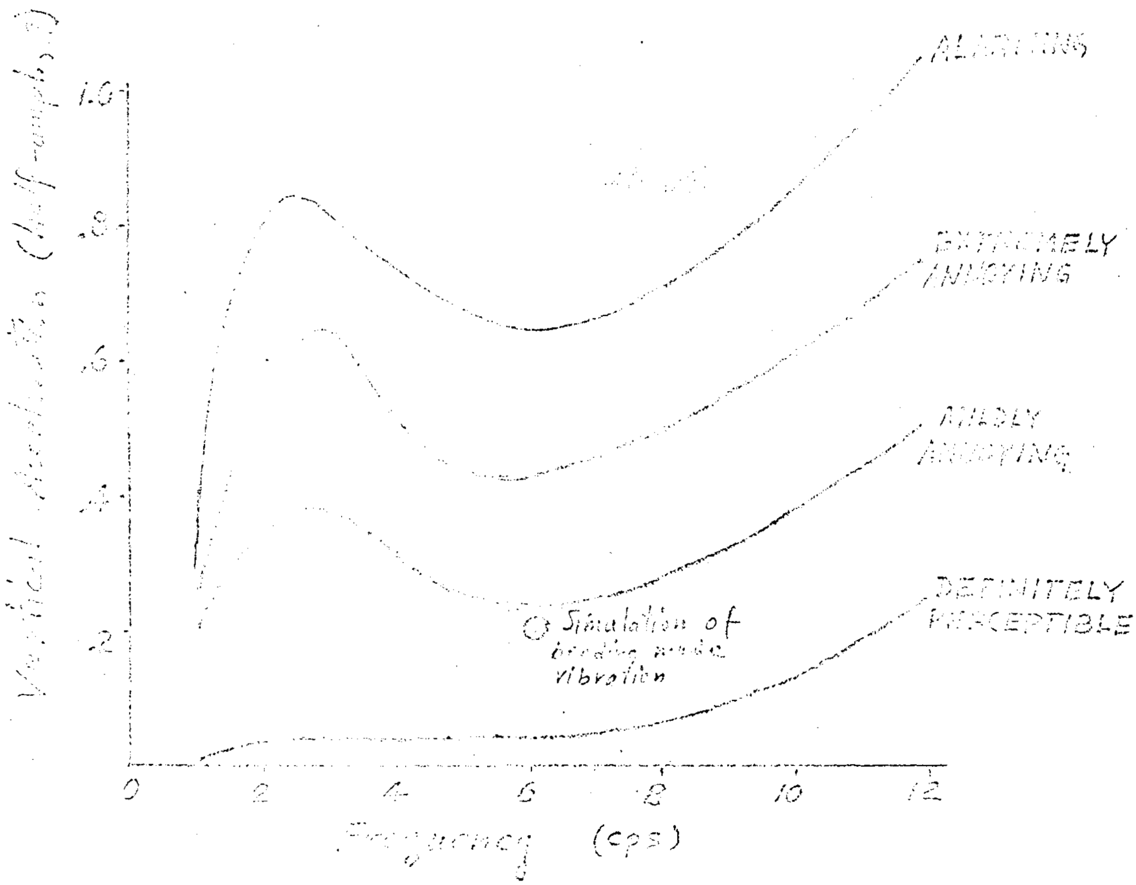

Figure 17 – Human subjective response to vibratory accelerations – from reference 5.