

VISUAL AND MOTION CUES  
IN HELICOPTER FLIGHT

by

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ABSTRACT

This paper investigates the relative importance of motion and visual cues on the ability of experienced pilots and non-flying subjects to control a hovering helicopter. It examines the interaction of these different forms of input information and the methods by which they are utilized by these two classes of subjects. The method by which control of such a high-order system as a helicopter is effected is discussed and a theory on this is advanced. A simple visual display system which provides a unique description of position and attitude with respect to a defined axis system and utilizes relatively inexpensive and available analog equipment is presented.

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SYMBOLS

For coordinate system defined:

x - longitudinal displacement

y - lateral displacement

z - vertical displacement

p - angular rate about x axis

q - angular rate about y axis

r - angular rate about z axis

L - moment about x axis

M - moment about y axis

N - moment about z axis

$\phi$  - roll angle

$\theta$  - pitch angle

$\psi$  - yaw angle

Specified by subscripts:

F - force

V - velocity

W - angular rate

I - moment of inertia

J - product of inertia

K - constant

## Miscellaneous:

$\delta$  - control stick deflection

$\delta_c$  - collective stick deflection

$\delta_a$  - lateral deflection of cyclic stick

$\delta_e$  - longitudinal deflection of cyclic stick

$\delta_r$  - rudder pedal deflection

$\alpha$  - angle of attack of rotor blades

$\omega$  - oscillatory frequency

$\tau$  - oscillatory period

## CHAPTER 1

### INTRODUCTION

During the spring of 1965 observations were made by the author of pilots performing the various tasks associated with flying a helicopter with the aim of determining the type of input information required by the pilot to effect his task. Primarily qualitative, these studies were made both visually and photographically, and covered all phases of flight.

The most interesting, from the point of view of input data required, and the most difficult, from the point of view of the pilot's ability to control the aircraft, is hover. During this phase, heading (that is the direction in which the nose is pointing) is maintained by rudder control, altitude by collective pitch control, and horizontal position by cyclic control. Once a heading has been established, relatively few corrections need be made by use of the rudder pedals. Having maintained an equilibrium altitude, the collective pitch control stick, located to the left of the pilot, is held fixed in position, either by a friction lock, or, often, by the pilot's left knee pressing against it. Position in the horizontal plane is strongly affected by multiple external influences, and requires

constant attention and manipulation of the cyclic control stick. The pilot's control movements are rapid and of small magnitude.

In maintaining hover the pilot watches, primarily, the horizon, or objects some distance away, rather than those in the immediate vicinity of the craft. Corrections to lateral and angular displacements are made considerably before they become visually evident. Thus, although gross determination of position and attitude is made visually by the pilot, it appears that fine corrections in maintaining these variables are primarily responses to motion cues.

Having observed these characteristics in actual flight, it was decided to attempt to determine more accurately, by means of a flight simulator, the importance and interaction of these visual and motion cues. Determination as to whether or not training and experience were strong factors in the ability of subjects to utilize the various forms of input information was also attempted.

Working with a flight simulator, the investigation entailed providing the subject with various combinations of input information. Always given a visual determination of his position, he was provided successively with no attitude information, with visual attitude cues, with both visual and motion cues for attitude, or only motion cues. The pilot's ability to control his position accurately in each of these modes was measured and compared. Both experienced helicopter pilots and subjects with no flight experience were used.

## CHAPTER 2

### DERIVATION OF CONTROL EQUATIONS

The control equations used for this investigation are the uncompensated stability equations for the Boeing CH-46 tandem rotor helicopter as presented in TRECOM TR-64-50 (10). The values of the stability derivatives used in these equations are updated versions of those presented in the report.

The CH-46 uses three separate stabilizing controls. The collective control stick travels through 12 inches of arc on an 18.19 inch radius arm, and full deflection of this stick corresponds to a  $16^\circ$  change in collective rotor pitch. Thus  $2.36^\circ$  of control deflection correspond to  $1^\circ$  rotor travel. The rudder pedals travel through  $\pm 2.30$  inches of arc at a 14.00 inch radius. The cyclic control stick travels through  $\pm 6.00$  in. at a 24.75 inch arm in the longitudinal direction, and  $\pm 3.60$  in. at 24.42 inch arm in the lateral direction. These allow the maximum deflections of controls indicated in table 2.1. All stability derivatives were converted into lbs. or ft.-lbs. / degree to allow their application to the simulator controls. The stability derivatives for hover are listed in table 2.2.

The linearized stability equations, as used here, are:

$$m (\dot{V}_x + V_z W_y) = F_x = V_{v_x} V_x + X_q W_y + X_{v_z} V_z + X_{\delta_e} \delta_e + X_{\delta_z} \delta_z - (m g \cos E_0) \Delta E \quad (2.1)$$

$$m (\dot{V}_y + V_x W_z - V_z W_x) = F_y = Y_p W_x + Y_r W_z + Y_{v_y} V_y + Y_{\delta_r} \delta_r + Y_{\delta_a} \delta_a + (m g \sin E_0) \phi \quad (2.2)$$

$$m (\dot{V}_z - V_x W_y) = F_z = Z_{v_x} V_x + Z_q W_y + Z_{v_z} V_z + Z_{\delta_e} \delta_e + Z_{\delta_z} \delta_z - (m g \sin E_0) \Delta E \quad (2.3)$$

$$I_x \dot{W}_x - J_{z_x} \dot{W}_z = L = L_p W_x + L_r W_z + L_{v_y} V_y + L_{\delta_r} \delta_r + L_{\delta_a} \delta_a \quad (2.4)$$

$$I_y \dot{W}_y = M = M_{v_x} V_x + M_q W_y + M_{v_z} V_z + M_{\delta_e} \delta_e + M_{\delta_z} \delta_z \quad (2.5)$$

$$I_z \dot{W}_z - J_{z_x} \dot{W}_x = N = N_p W_x + N_r W_z + N_{v_y} V_y + N_{\delta_r} \delta_r + N_{\delta_a} \delta_a \quad (2.6)$$

Maximum values of the variables, in keeping with the small angle approximations utilized in the development of the display system, were chosen for a helicopter at or near hover.

$$W = .5 \text{ rad/sec}$$

$$V = 20 \text{ ft/sec}$$

$$\Delta E = 5.73 \text{ deg} = .1 \text{ rad}$$

$$\phi = 5.73 \text{ deg} = .1 \text{ rad}$$

Combined with values for the stability derivatives, these reduced the above equations to:

$$\dot{V}_x = .323 \delta_z - 3.22 \phi \quad (2.7)$$

$$\dot{V}_y = -1.33 W_x + 3.22 \phi \quad (2.8)$$

$$\dot{V}_z = -.284 V_z - 1.91 \delta_z \quad (2.9)$$

$$\dot{W}_x = -.87 W_x + .211 \delta_a + .029 \delta_r \quad (2.10)$$

$$\dot{W}_y = -.633 W_y + .151 \delta_e - .012 \delta_z \quad (2.11)$$

$$\dot{W}_z = -.064 W_z + .039 \delta_r + .008 \delta_a \quad (2.12)$$

Integration and combination of these equations allowed determination of position and attitude of the aircraft with respect to inertial space. These equations were programmed for the TR-48 analog computer, and the output used as command input for the moving-base simulator and input variables for the display. The program for these equations is shown in figure 2.1.

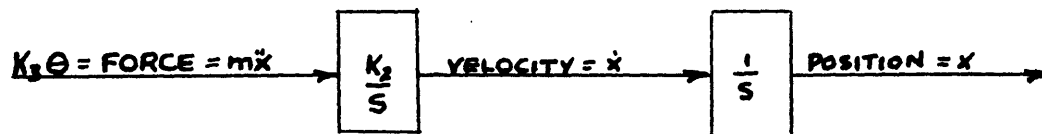
CHAPTER 3

CONTROL REQUIREMENTS

In a helicopter the pilot's cyclic control stick governs the angular accelerations of the aircraft. Without compensation of any form, a change in stick position causes a change in the angle of attack,  $\alpha$ , of the rotor blades. This, in turn, results in a moment about the center of mass of the vehicle. Thus, the process between stick deflection,  $\delta$ , and rotation of the helicopter to a new orientation,  $\Theta$ , is of the form



Since the thrust of the helicopter is proportional to the angle at which it is tipped, the relation between the angle of attack of the vehicle,  $\Theta$ , and an inertial position,  $x$ , is of the form



Thus, the relationship between control stick deflection and the position of the aircraft is a fourth-order function in both the  $x$  and  $y$  directions. The system is essentially second order in the  $z$  direction. In order

to hover, therefore, a pilot of an unaugmented helicopter must control two fourth-order systems in order to maintain his horizontal position.

The uncompensated control system described above is for a theoretical helicopter control system in which the pilot's stick output is proportional to the angle of attack of the rotor blades. In practice such a system has been found to be too difficult to control, and modifications have been introduced to ease the control task.

In the simplest of helicopters a mechanical feedback linkage is utilized such that the pilot's stick output is proportional to the angular rate of rotation of his craft. For larger, more complicated helicopters, more sophisticated systems involving higher-order non-mechanical feedback loops allow the pilot control stick deflection to be proportional to the aircraft attitude. The M. I. T. Instrumentation Laboratory is, in fact, working on a system in which the control stick deflection is proportional to the helicopter velocity with respect to a ground-based inertial frame (10).

This experiment, though, deals only with the pure, uncompensated control form to investigate the basic dynamics of vehicle control rather than the modified forms used in flying aircraft.

In the initial construction of this experiment an attempt was made to control the helicopter, allowing six degrees of freedom, by means of a fixed-base simulator. The subject was given an integrated display indicating position and orientation in a hovering condition and

was instructed to maintain hover, holding the altitude, longitudinal, and lateral position of the vehicle constant. Despite large amounts of practice, this position could not be held for more than a few seconds. There was no indication that inclusion of motion cues would alleviate the situation.

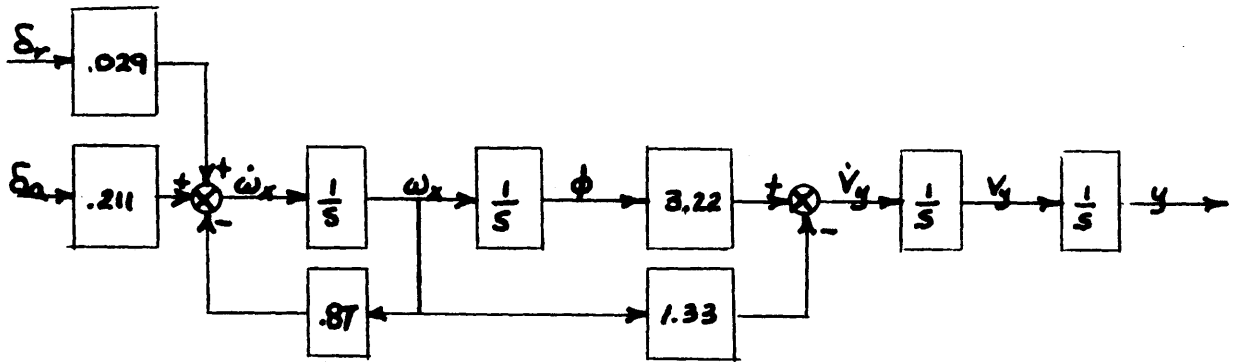
In order to simplify the task, the system was altered such that altitude was maintained automatically, allowing the pilot to concentrate on maintaining horizontal position only. No improvement in control was evident, however it was noted that loss of control occurred almost exclusively in the longitudinal mode.

Accordingly, the lateral mode was automatically stabilized, allowing the pilot to concentrate wholly on control of one fourth-order system. Still no improvement was noted. Indications were that lack of display detail in the pitch mode did not allow the subject to locate and utilize pertinent cues until after the controllable stability limits had been surpassed.

In the roll mode, however, these cues were available and provided sufficient feedback to make lateral control possible. Emphasis, therefore, was placed upon a more thorough investigation of the relative importance and interaction of visual and motion cues in lateral control. Altitude and longitudinal position were fixed, and coupling with all other modes was eliminated.

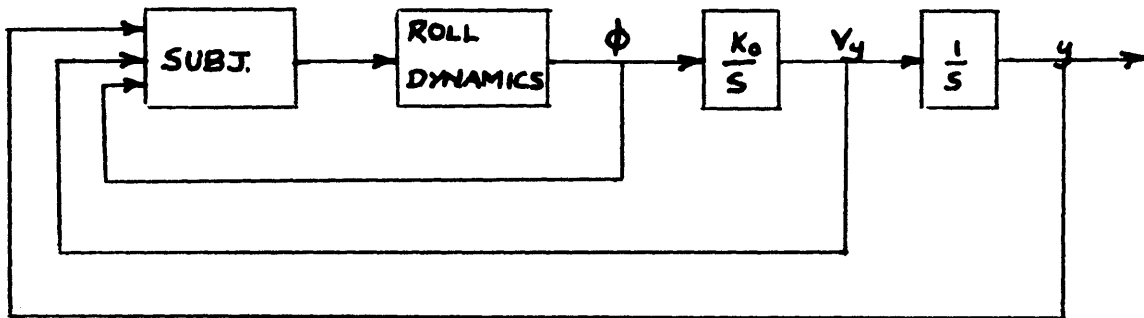
In the roll mode the system transfer function, from stick deflection,

$\delta_r$ , to lateral position,  $y$ , is



Since the effect of the  $\delta_r$  input turned out to be negligible upon the overall control of the craft, this branch was deleted from the final system, making the final control input only the lateral displacement of a single stick.

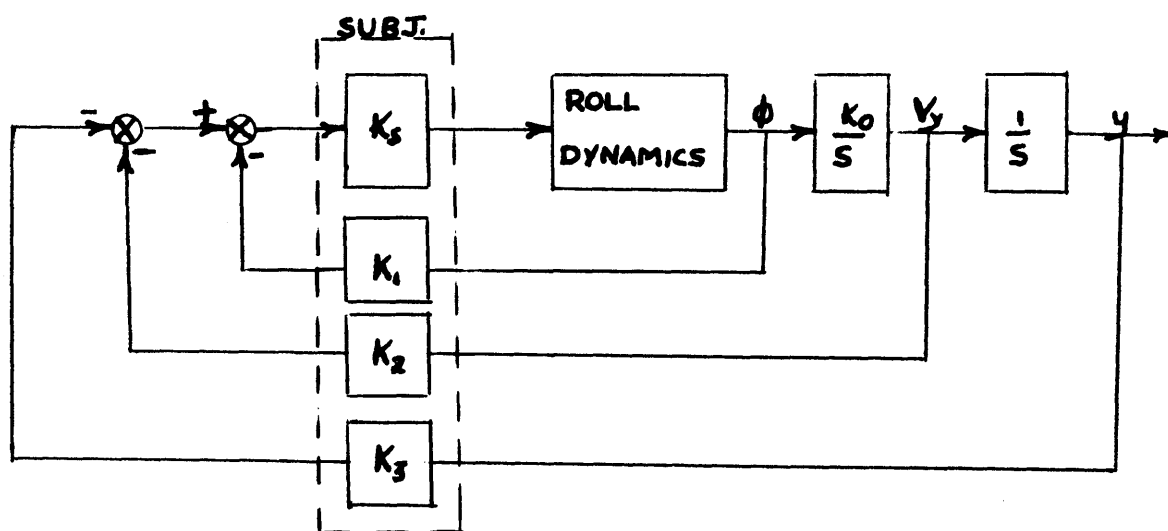
In an attempt to determine at least the basic form of the dynamics of the system with which the subject must contend and the type of response which would be demanded of the subject, the following form was assumed



in which the quantities presented for any given run in the form of visual or motion cues were taken to be simple feedback loops to the operator. If a particular variable were not indicated to the subject, that feedback

loop would be eliminated in the analysis.

There was, at the outset, no evidence to indicate whether the subject applied the same transfer function to all variables fed back or to indicate even the amount of attention which he gave to each of his cues. Thus, if the system is taken to be of the form

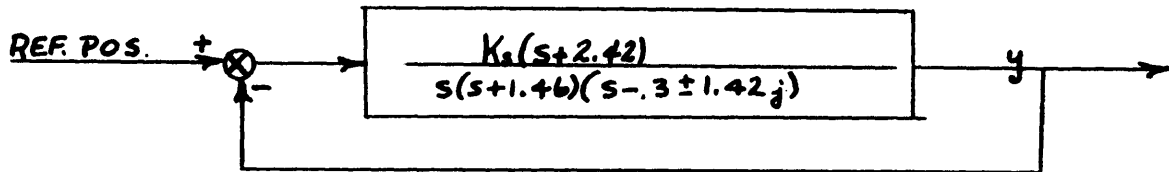


the gains  $K_1$ ,  $K_2$ , and  $K_3$  determine the importance of each cue to the subject. Since there were initially no indications as to the relative magnitude of these gains, they were, for the sake of analytical simplicity, assumed to be unity.

The analysis was, of course, done with the actual lateral control transfer form rather than the simplified schematic shown above. The root-locus was plotted, allowing the subject forward-loop gain,  $K_S$ , to vary. This is equivalent to saying that the subject utilizes the various feedback variables equally at all times. From this a more adequate determination of the mathematical form of a transfer function to replace

$K_S$  and possible values for the feedback constants may be determined.

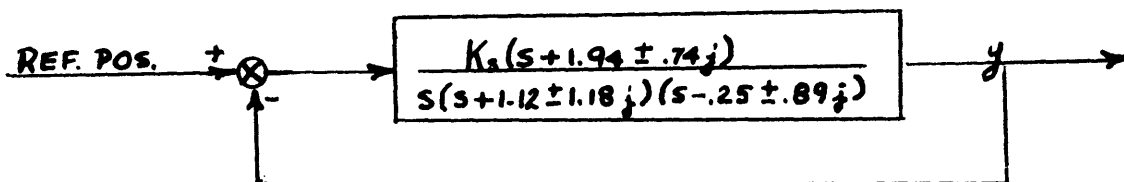
If only visual display of position, and therefore, implicitly, velocity, but not roll, is used, the system transfer function appears as



It is this fourth-order system, a root-locus plot of which is shown in figure 3.1, to which the operator must add his dynamics in order to stabilize the system. As is seen from the plot, two complex zeroes and a sufficiently high gain to maintain closed-loop poles to the left of the imaginary axis are required on the part of the subject in order to stabilize the system.

Both McRuer and Ashkenas (11) and Muckler and Obermayer (13) indicate evidence that second-order leads can be produced. This system requires one more pole.

If a visual indication of roll (or, for that matter, a motion roll cue) is added to the system, the transfer function becomes a more complex



as is plotted in figure 3.2. In this case the second-order feedback allows the two zeroes, still required of the subject for system stability, to be more easily created. That is, the second-order cue given by the roll indication gives the subject the information he needs in order to create a second-order lead. It is to be noted, also, that the branch of the root-locus plot comprising the negative real axis may be attributed to the last order of integration - that is, the integration of velocity to determine position.

The addition of one more second-order cue, such that the subject is presented with both visual and motion cues in roll, may be represented by two parallel unity feedback loops from roll to the subject. The system then changes to



which is very similar to the single-cue roll feedback case except that the stable complex loop has become more of a dipole and the unstable open-loop complex poles have moved farther from the imaginary axis. As shown in figure 3.3, the dynamics of the system remain essentially the same and the subject's task also has not changed.

If the subject maintains a very small gain in the position feedback loop, he can stabilize the position loop and may then concentrate on controlling a system one order lower. The open-loop characteristics

of a system in which velocity is the output variable are shown in figure 3.4, and it is apparent that for any positive gain the closed-loop system is stable.

Thus the mathematical complexity of the system to be controlled by the subject, and therefore his capability to adequately maintain a hovering position, is not necessarily determined by the form of the visual or motion cues in themselves, but rather by the subject's ability to detect and utilize the information contained therein.

Throughout this discussion the dynamics of the simulator itself have been ignored. A frequency-response analysis of the visual and motion simulation equipment used here indicated that at the range of frequencies of concern the lag was well below the human detection threshold, and did not in any way alter the fidelity of the cues supplied to the subject.

## CHAPTER 4

### EQUIPMENT AND PROCEDURE

Motion simulation was accomplished by means of the M. I. T. Man-Vehicle Control Laboratory NE-2 motion simulator, developed by the NASA Ames Research Center, which allows two angular degrees of freedom. In this experiment the pitch and roll modes were used, and only the latter was used for the results discussed herein. The NE-2 motion simulator is essentially the sawed-off cab of a military jet fighter mounted on gimbals and driven by servos. A more complete discussion of the NE-2 simulator is given by Meiry (12).

The subject effected control through a centered floor-mounted stick with very low spring force - only enough to indicate a centered position. The output of the stick, which acted as the cyclic control, became the input for the stability equations, which were programmed on a EAI TR-48 analog computer (7). The output of the stability equations - position and attitude - became the input for the display equations (see next chapter), also programmed on the TR-48. The visual display was projected on the face of a Waterman S-11-A oscilloscope mounted in the simulator cab approximately two feet in front of the subject. An

auxiliary oscilloscope at the computer acted as a monitor for the experimenter.

The stick position input signal and the computer output of roll angle, lateral velocity, and lateral position were recorded on two Brush Mark 280 pen and ink strip recorders. It was possible to disconnect either the motion servos or the display roll indication while still recording their commanded value. A block diagram of the simulation system is shown in figure 4.1.

The integrated absolute value of the lateral deviation from the required hovering point over the entire run was taken as an error indication and was recorded for each run. Although, in theory, a pilot who stabilized his craft some distance from the required hover point would thus rapidly run up his indicated error, while one who performed wide, rapid gyrations passing through the required hover could possibly attain a lower error score, even though his control was not as good, in practice this was not found to be the case. A pilot who managed successfully to stabilize the craft at some point usually managed to ease it to the required point, whereas one who oscillated rapidly generally lost all control shortly.

The visual display contained a horizon line with a red reference marker to indicate a level position, and four dots, which were the corners of a square, 50 feet on a side, seen in perspective from 1000 feet away and an altitude of 200 feet. An excursion of 125 feet laterally to either side of the required hover position was allowed. If the subject exceeded

that limit the run was terminated. Each run was initiated with the aircraft in equilibrium at the required hover point. The noise of the system itself was sufficient to generate the initial disturbances requiring the pilot to take corrective action.

Care was taken to ensure that error scores were truly indicative of control ability. For short time periods error was primarily a function of input noise and possibly a few initial corrective motions, and therefore a minimum time period was required. Control was generally lost after a number of excursions to the extreme permissible limits, thereby running up a rather large error score not indicative of previous control ability. Due to external influences such as fatigue some subjects were bound to lose control if the run were extended too long. A maximum time period was thus required. Therefore all runs which retained control until one minute had passed were terminated at that point, and only error scores for this time period were compared. This provided sufficient time to overcome initial disturbances and damp out original control movements, thereby giving a reasonably correct estimate of ability to control the system, and yet not so much time as to exceed the abilities of some of the subjects.

It was attempted to even out the psychological variables in the experiment - that is, to present the same information to each of the subjects in the same way so as to reduce the possible disparities in motivation and knowledge of the specific equipment involved. Each subject was

impressed by the experimenter with the difficulty of controlling the system, and told that only a few people were capable of doing so at all. Hopefully this motivated the subjects to "show" the experimenter that they certainly were capable of doing so. Many were also attempting to perform better than all the other subjects, although none was told whether he was performing better or worse than the others. Each was, however, encouraged and told when an individual run was better than his own average to that point.

Initially the problem and the display were explained to each subject. The experimenter then demonstrated, by means of an external stick and the monitor scope, the effects of various control movements. He also operated the system for as long as the subject desired, pointing out the importance of the various cues, i. e., that roll angle gives an indication of acceleration.

Then a period of acquaintance or training was provided, during which the subject, in the cab, was allowed to get the "feel" of the stick and the resulting visual and motion responses to his control movements. The subject was then given the full visual display and attempted to control it until lateral displacement exceeded the prescribed limits. This process was repeated until the subject attained a "plateau," or a point at which control ability was not improving significantly with successive runs. A similar process was then initiated including motion cues. After the subject had become thoroughly acquainted with the equipment and

system, the recorded runs were initiated. In no case was the subject told what was being measured.

The first set of runs consisted of visual control only (fixed base) until a sufficient number of one-minute runs had been accomplished such that the scatter of error scores had centered on a single region. The motion cue was then added, and the process repeated. Next, visual roll was not displayed, but the motion cue was provided. Then the motion cue was eliminated, so that there was no indication of roll angle, visual or motion. Finally, visual and motion cues were added again. If, at any time, there was any indication of a significant learning process taking place, any earlier runs which might have been affected by this were repeated and the second set of data used.

Although the effects of fatigue could not be completely eliminated, they were reduced where possible. If possible, data was taken on successive days, and, where this was not possible, rest and coffee breaks were instituted. If a period of more than one day separated successive tests, the training period was reinstated at the second test and a check was made for learning effects.

## CHAPTER 5

### VISUAL DISPLAY SYSTEM

The display designed for this study is of the inside-out type, and was chosen so as to provide the pilot with a unique description of the outside world as seen from his helicopter. There is no ambiguity as to his position in all three dimensions, and motions in all six degrees of freedom are clearly represented and easily distinguishable. Limitations are placed upon the detail and complexity of the representation of the outside world by the equipment available. The entire display is operated by a EAI TR-48 analog computer, one sine wave generator, and a very light single beam oscilloscope. The advantage of this display system is the large quantity of information it presents with rather simple, light, and comparatively inexpensive equipment. This type of display is therefore available for use by investigators who do not have the complicated and heavy analog-digital equipment required for the more sophisticated displays such as that proposed by Connelly and Fedoroff ( 6 ).

The input to the visual display system is the location and attitude of the aircraft with respect to a fixed coordinate system. Calculation of this information for this experiment is discussed in Chapter 2 of this

report. Once the location of a discrete set of points in inertial space is known, their position with respect to the aircraft body-axis system is determined, and their apparent visual position on a screen or window placed in front of the pilot is calculated. These points are then displayed at these corresponding positions on the face of the oscilloscope, which then acts as a window for the pilot, indicating to him in perspective the apparent position of points on the ground as they would be seen from his flying helicopter.

In this case a pattern of four points defining a rectangle on the ground and a line representing the horizon were chosen. Centered, these appear on the screen as drawn in figure 5.1. Translation of the helicopter to the right and left (+y and -y respectively), up and down (-z and +z respectively) and forward and backward (+x and -x respectively) cause the points to move on the screen as shown in figure 5.2. Similarly, positive roll, pitch, and yaw are depicted in figure 5.3. It is clear from these drawings that each position and attitude, and each combination of positions and attitudes, has a unique and unambiguous representation.

Figure 5.4 indicates the relation of the inertial and body coordinates and the pilot's screen for zero roll, pitch, and yaw when the aircraft body axis is located at the pilot's eye and at some position  $-x$ ,  $-y$ ,  $-z$  with respect to the inertial origin. The vertical position of the apparent location of this inertial origin as seen on the pilot's screen is designated by  $\bar{z}_0$ , and the horizontal position is  $\bar{y}_0$ . The coordinate  $\bar{x}_0$  is the distance from the pilot's eye to the center of the screen, at which

point  $\bar{y}_o$  and  $\bar{z}_o$  are zero.

As seen in the x, z plane, this appears as shown in figure 5.5.

Clearly, then,

$$\frac{\bar{x}_o}{-x} = \frac{\bar{z}_o}{-z}$$
$$\bar{x}_o = \frac{\bar{z}_o}{x} z$$

Thus, if the aircraft gains altitude, the point moves down on the screen, and if the aircraft moves forward, the point moves down on the screen, as depicted previously in figure 5.2. Similarly, in the x, y plane (figure 5.6)

$$\frac{\bar{x}_o}{-x} = \frac{\bar{y}_o}{-y}$$
$$\bar{y}_o = \frac{\bar{x}_o}{x} y$$

Therefore, if the aircraft translates to the right (y becomes smaller), the point moves to the left, and if the aircraft moves forward, a non-centered point moves farther from the center, again agreeing with the display drawings of figure 5.2. This is the entire set of equations required for a complete three-dimensional representation of translational motion.

It is to be noted that in the y, z plane the equation is

$$\frac{\bar{x}_o}{-z} = \frac{\bar{y}_o}{-y}$$

but

$$\frac{\bar{x}_o}{-z} = \frac{\bar{z}_o}{-x}$$

so

$$\bar{y}_o = \frac{\bar{z}_o}{x} y$$

which is identical to the equation developed above.

For the body axis used the positive attitude convention is shown in figure 5.7. This corresponds to positive nose up pitch, clockwise (right wing down) roll, and nose right yaw. The transformation matrices from inertial to body axes are then

$$\text{yaw: } \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\text{pitch: } \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}$$

$$\text{roll: } \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix}$$

The two-degree-of-freedom moving-base simulator used pitches about the roll axis. The transformation equation thus becomes

$$\begin{bmatrix} \bar{x}_1 \\ \bar{y}_1 \\ \bar{z}_1 \end{bmatrix} = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & \sin \phi \\ 0 & -\sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} \bar{x}_0 \\ \bar{y}_0 \\ \bar{z}_0 \end{bmatrix}$$

Expanding and using small angle approximations

$$\begin{bmatrix} \bar{x}_1 \\ \bar{y}_1 \\ \bar{z}_1 \end{bmatrix} = \begin{bmatrix} 1 & \theta\phi + \psi & -\theta + \psi\phi \\ -\psi & 1 & \phi \\ \theta & -\phi & 1 \end{bmatrix} \begin{bmatrix} \bar{x}_0 \\ \bar{y}_0 \\ \bar{z}_0 \end{bmatrix}$$

and the equations for the display screen become

$$\bar{y} = \frac{\bar{z}}{\bar{x}} (\psi \bar{x} + y + z \phi)$$

$$\bar{z} = \frac{\bar{z}}{\bar{x}} (\theta \bar{x} - y \phi + z)$$

It was found that for ease in programming, the form

$$\bar{y} = \bar{x} \left( \psi + \frac{y}{\bar{x}} + \frac{z}{\bar{x}} \phi \right)$$

$$\bar{z} = \bar{x} \left( \theta - \frac{y}{\bar{x}} \phi + \frac{z}{\bar{x}} \right)$$

is more convenient, since the terms  $y/x$  and  $z/x$  can be determined once and used in both equations. Reducing these equations for the horizon by letting  $x$  approach infinity gives

$$\bar{y} = \bar{x} \psi$$

$$\bar{z} = \bar{x} \theta$$

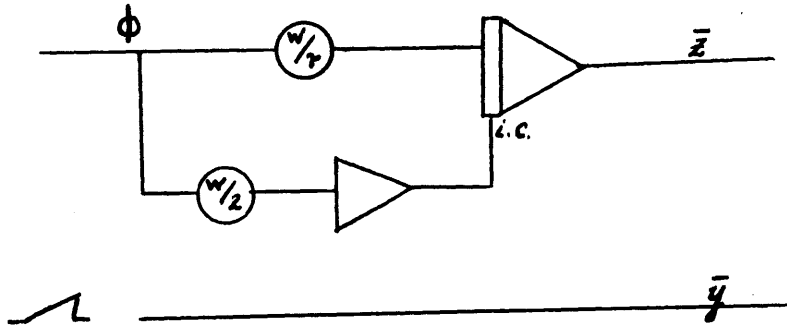
where the roll equation must still be added. It is

$$\bar{z} = \bar{y} \phi$$

In order to draw the horizon line completely across the screen, it must be driven horizontally by a sawtooth. If the screen is of width  $w$  and the sawtooth of frequency  $1/\tau$ , the vertical drive must be

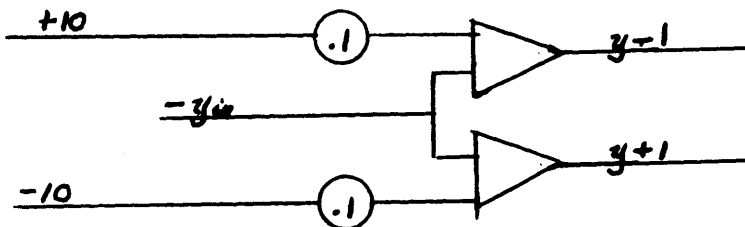
$$\begin{aligned}
 x &= w \phi \left( \frac{t}{\tau} - \frac{1}{2} \right) \\
 &= -\frac{w}{2} \phi + \frac{w}{\tau} \phi \int_0^{\tau} dt
 \end{aligned}$$

Programmed for the analog computer, this is



The integrator is operated repetitively in phase with the sawtooth which is drawn from the computer rep. op. timing.

The four points defining the rectangle are obtained by adding and subtracting 1 volt from the input value of  $y$  as follows



These two values are then chosen alternately as inputs to the calculations, and define the right and left sides of the rectangle. A square wave is added to the  $x$  value to provide the vertical definition of the rectangle.

This square wave also operates the y value relay, and alternates at a rate of 10 cps. The square wave is also an output of the computer rep. op. timing.

Two essentially separate sets of calculations are made: one to determine the four corners of the rectangle and the subsequent movements of these points, and a second to draw the horizon. These can be left separate on a dual beam oscilloscope, but for a single beam must be displayed alternately. This is accomplished with a final relay operating at 15 cps. The total computer diagram for the display system is shown in figure 5.8.

Variations in yaw angles are more clearly shown if the "sides" of the rectangle are indicated by solid lines. These could, for instance, indicate the edges of a runway or perhaps a nominal flight path. The mechanism for including these lines in the display is discussed in the paper by Vuorikari (18), with whom much of the work on this display system was done.

## CHAPTER 6

### EXPERIMENTAL SUBJECTS

Seven subjects were used in the experiment. All were in good health, had good vision, were athletic, and appeared to have reasonably good coordination. Five of the seven subjects were college students between the ages of 20 and 24. None of these had any flight experience whatsoever, although one was experienced with the simulator in other experiments.

Subject number 1 was tested over a large number of successive days and indicated a slow learning curve over this time. Having the greatest amount of training on this equipment of all subjects, the results shown for this subject were taken primarily on the last two days of testing. Unfortunately, due to mechanical difficulties, little data could be taken for the motion-roll-only mode for this subject.

Subjects number 2, 3, 5, and 7 received a medium amount of training. Subject number 7 had been used in previous experiments in this simulator, but not for the same system. This subject also had some fixed-base experience with this system in its initial phases.

Subject number 4 was a helicopter pilot with 500 hours of fixed-

wing time and 6400 hours of helicopter time logged. He was most anxious to prove himself competent in the use of the system. Subject number 6 was a younger pilot than subject 4. He had 220 hours in fixed-wing craft and 3000 hours in helicopters logged. He had faster reactions than subject 4 and was more precise in controlling the magnitude of his stick input signals.

Significant opinions and comments of the subjects were recorded and contributed to the interpretation of the results presented.

## CHAPTER 7

### RESULTS AND DISCUSSION

Early in the experimentation, while the pitch mode was being investigated with fixed-base simulation, the extreme importance of the second-order cue (roll or pitch angle) in the control of the system was recognized. As was noted previously, longitudinal control could not be maintained to any significant degree because the particular display system used did not clearly indicate the very small pitch angles which provided the control cues necessary for longitudinal control. Thus the ability of the subject to recognize and utilize this particular cue determined his ability to control the system. This result was verified in the final experiment. In the lateral mode, when both motion and visual roll cues were eliminated, none of the subjects was able to effect any significant degree of control over the system.

Subject number 4, one of the helicopter pilots, was most frustrated by his inability to even begin to control this system, and stated that he thought he would be able to control the system with sufficient practice. The experimenter found no evidence to support this proposition. Figure 7.1 gives a short portion of the record of stick position

and roll angle on two runs for subject 4. In figure 7.1 A, during which run the subject had both visual and motion roll cues, the stick position fairly accurately follows roll angle. The subject is thus controlling on the basis of the second-order cue, since the sign of the stick position follows the sign of the roll angle. When the subject had no second-order feedback - that is, no roll cues - the record for subject 4 appeared as in figure 7.1 B. There is, in this case, a large lag in the relation of stick sign to roll angle sign. The subject was, in fact, controlling on the basis of velocity, the third-order cue. This resulted in termination of the run approximately nine seconds after initiation.

It appears, then, that a person is capable of controlling a fourth-order system of this type by introducing, as was shown to be required, a second-order lead. Subjects were, however, not able to generate this term themselves, even if given the position and velocity cues, but required a second-order cue, the roll, which they could then follow.

It must be noted, however, that not all subjects were able to control the system even with second-order feedback cues. In spite of intensive training over a period of days, subjects number 2 and 3 were never able to maintain a significant amount of control over the system, and no data taken on these subjects could be used in the final analysis. These subjects were apparently not able to distinguish the significant cues, even when pointed out to them by the experimenter, and take the appropriate corrective action. They stated that they were overwhelmed

by the task and saturated by the amount of input information which they had to digest and evaluate in order to maintain control of the system.

Two runs by subject 3 shown in figure 7.2 indicate this tendency. Both cases are for fixed-base simulation with a visual roll indication. In figure 7.2A the subject makes a few initial correct movements to establish the proper lead, but then gets diverted in trying to control the velocity and allows the roll angle to build up to such a large value as to totally eliminate any chance of ever regaining control of his craft. Figure 7.2 B shows the very next run. In this case the subject manages nicely to maintain a low roll angle, but allows the velocity to build up. In both cases the subject used very large control stick deflections, and, despite the experimenter's repeated admonitions, never ceased to over-control.

A typical successful normal run with full visual simulation but no motion cues is shown in figure 7.3 for subject 5. He successfully uses small control stick deflections to maintain a small roll angle and manages to utilize the roll cue effectively to maintain the velocity and position of his vehicle within the prescribed bounds. Throughout, he reverses the roll angle to prevent a large velocity from building up, and moves the craft toward center by allowing a small roll angle to give a small velocity in the correct direction and then immediately reducing the roll angle to prevent greater acceleration. As the helicopter approaches a centered position the subject initiates a roll angle opposite

that of the velocity vector. This type of control requires attention to all three variables simultaneously - position, velocity, and acceleration.

There is evidence to indicate that the successful subject utilizes a hierarchy of control techniques. That is, although keeping track of the values of all variables, he tends to stabilize each in order. The first order of the hierarchy is to maintain low roll angles. Once the angular variation has been stabilized, the subject attempts to reduce his velocity to near zero. Once he has stabilized himself at some position away from the center, he attempts to move closer to the required hover point. Of course, while stabilizing roll he cannot allow large positional deviations, but once each order has been stabilized, maintaining stability becomes more of a simple gain task than a lead task. Thus the complexity of the control task has been reduced by the simple expedient of stabilizing each loop successively from inside out.

The less-stabilized situation required a first or second-order lead on the part of the subject, and elicited a bang-bang type of control. This result is similar to the evidence found by Young and Meiry (19) in their investigation of control in higher-order systems. As successive loops became stabilized and the requirement switched increasingly toward a gain, the control stick movements tended away from bang-bang control toward simple tracking. This is illustrated in figure 7.4, which shows a stick-deflection record for subject 6 with both visual and motion roll cues.

A compilation of the average integrated error scores for all the subjects except numbers 2 and 3 is presented in table 7.1. A number of interesting relationships are evident from this chart.

Although all these subjects were capable of controlling the craft with both visual and motion cues, subjects 5 and 7 actually had higher error scores for the combined input cues than for the visual cue alone. Thus it was more difficult for them to control the system when there was a motion cue than it was when just this cue was eliminated. This is surprising, since one would think that additional cues would make the control task easier. Previous investigations such as those of Belsley (3) and Rathert et al (16) also indicated that motion cues aided control. In most experiments, however, experienced pilots were used. Both these subjects had no previous flying experience, and for them, apparently, motion was not a valid cue, but was interpreted, rather, as a disturbance.

This unexpected result does, however, have a valid explanation. In order to retain control over velocity and position it is necessary to initiate small roll angles. For a subject used to being upright, not tilted, these angles give an "uncomfortable" feeling, and there is a strong tendency for the subject to interpret them as errors and try to correct them. Thus the subject did not make use of this additional cue as an extra aid in control, but rather had to learn to overcome the disturbing

effects of this sensation.

Subject number 5 was able to do so, even to the extent that he was later able to control the system with motion cues alone. It required, however, considerable roll angles to elicit the correct response from the subject, and large lags tended to develop in the control performance. Overcorrections were the rule, and the subject was, at best, only able to maintain a comparatively large amplitude oscillatory system.

Subject number 7 had previous experience in this motion simulator during which a roll angle was, indeed, an error. He showed serious signs of retroactive inhibition, and, although with much effort he was able to overcome the disturbing influence of the motion cue and concentrate on the visual, when the visual cue was eliminated, and only motion presented, he was totally unable to effect any significant control.

Subject number 1, on the other hand, although he had no flight experience, was able to reduce his score when the motion cue was added. This subject, as noted above, had the greatest amount of training with the system, and it is this factor, apparently, which produced this result. Records of early runs by subject 1 were similar to those for subjects 5 and 7 in that the motion cue did appear to be a disturbing influence rather than an aid. As the subject became more acquainted with the system he learned to accept, and finally, to use the motion cue as added information for control. It is unfortunate that equipment malfunctions prevented testing of this subject at an advanced stage with only motion cues. That

might have dramatically illustrated this effect.

Equally surprising was the fact that subjects 4 and 6, the helicopter pilots, were unable to control the fixed-base system at all, but were immediately able to effect control when the motion cue was added. For subject number 4, in fact, there was no appreciable change in error score when visual roll was eliminated. Both pilots stated that they felt equally at ease controlling without the visual cue as with it.

Tracking records for these two subjects in the fixed-base mode indicate some indecision as to the direction in which to move the stick and a resulting lag greater than any found with motion cues. Brown, et al (4) found a similar confusion and lack of decision to exist in pilots deprived of motion cues. There was, upon occasion, a tendency for these subjects to interpret the fixed-base display as an error, rather than an inside-out display. The resulting confusion caused incorrect control stick deflections. When, however, they were given the motion cue, they were able to psychologically reorient themselves and both "see" and feel the craft moving left and right. The visual display then became more realistic to them.

As was noted during observations of pilots in actual flight, for an experienced subject it is the motion cue rather than the visual cue which allows the pilot to control the stability of his craft. He becomes so attuned to using this cue, that when deprived of it and offered a substitute, he is no longer able to effect adequate control.

Both these effects - the disturbing influence of motion cues on inexperienced subjects and the complete reliance upon motion cues by experienced pilots - are unexpected but not illogical. They both seem to have rational and easily explained bases.

## CHAPTER 8

### CONCLUSIONS AND RECOMMENDATIONS

A fourth-order system can be controlled if derivative feedback is provided. When the second-order is fed back, the subject is capable of producing a second-order lead to allow the stabilization of this loop. He then concentrates on the third order, and finally on the fourth order, in order to maintain system stability. By establishing this hierarchy of functions - stabilizing a system successively, loop by loop, from the inside out - the operator manages to reduce the complexity of the required control task.

The details of the method by which this is accomplished have not been determined. The exact degree of feedback required, the allowable complexity of a system which can be controlled, and the range over which this method is successful is still open to investigation. The change in the operator's control form and transfer function as each loop is stabilized and the variation in methods between different operators can be looked into. Why two subject were not able to control the system was not explained. All these are avenues of possible investigation which still must be pursued.

Ability to utilize motion cues where the motion constitutes a de-

parture from normal equilibrium is a function of experience with the system. For inexperienced subjects the motion cue is effectively a disturbance which must be overcome, and a visual cue only allows more effective control responses. The experienced operator, however, depends strongly upon the motion cue even to the extent that he is unable to effect control without it. The visual cue is, to him, of little value.

Whether this is a general rule or only applies specifically to this situation - the comparison between experienced pilots and non-flying subjects for the helicopter is questionable. The extent to which it is necessary for the motion cue to be a departure from equilibrium and the learning curves involved in adapting to this situation have also not been determined. These, also, suggest multiple new experimental projects.

TABLE 2.1

MAXIMUM STICK DEFLECTIONS

DIRECTION	ANGLE
$\delta_a$	37.8°
$\delta_r$	9.4°
$\delta_e$	13.9°
$\delta_z$	8.45°

TABLE 2.2

STABILITY DERIVATIVES

$X_{\delta_e}$	50.4 lbs. /deg.
$Z_{\delta_e}$	34 lbs. /deg.
$M_{\delta_e}$	15,900 ft. -lbs. /deg.
$Y_{\delta_a}$	248 lbs. /deg.
$Y_{\delta_r}$	17.6 lbs. /deg.
$L_{\delta_a}$	2,840 ft. -lbs. /deg.
$L_{\delta_r}$	395 ft. -lbs. /deg.
$N_{\delta_a}$	843 ft. -lbs. /deg.
$N_{\delta_r}$	3,880 ft. -lbs. /deg.
$X_{\delta_z}$	188 lbs. /deg.
$Z_{\delta_z}$	-1,100 lbs. /deg.
$M_{\delta_z}$	-1,270 ft. -lbs. /deg.

TABLE 7.1

INTEGRATED ABSOLUTE ERROR

SUBJECT	FIXED BASE	MOTION & VISUAL ROLL CUES	MOTION ROLL CUE ONLY
1	3.80	2.58	no data
4 *	X	3.64	3.79
5	2.34	3.63	5.59
6 *	X	1.99	3.74
7	3.65	5.71	X

\* experienced helicopter pilots

X subject unable to effect control in this mode

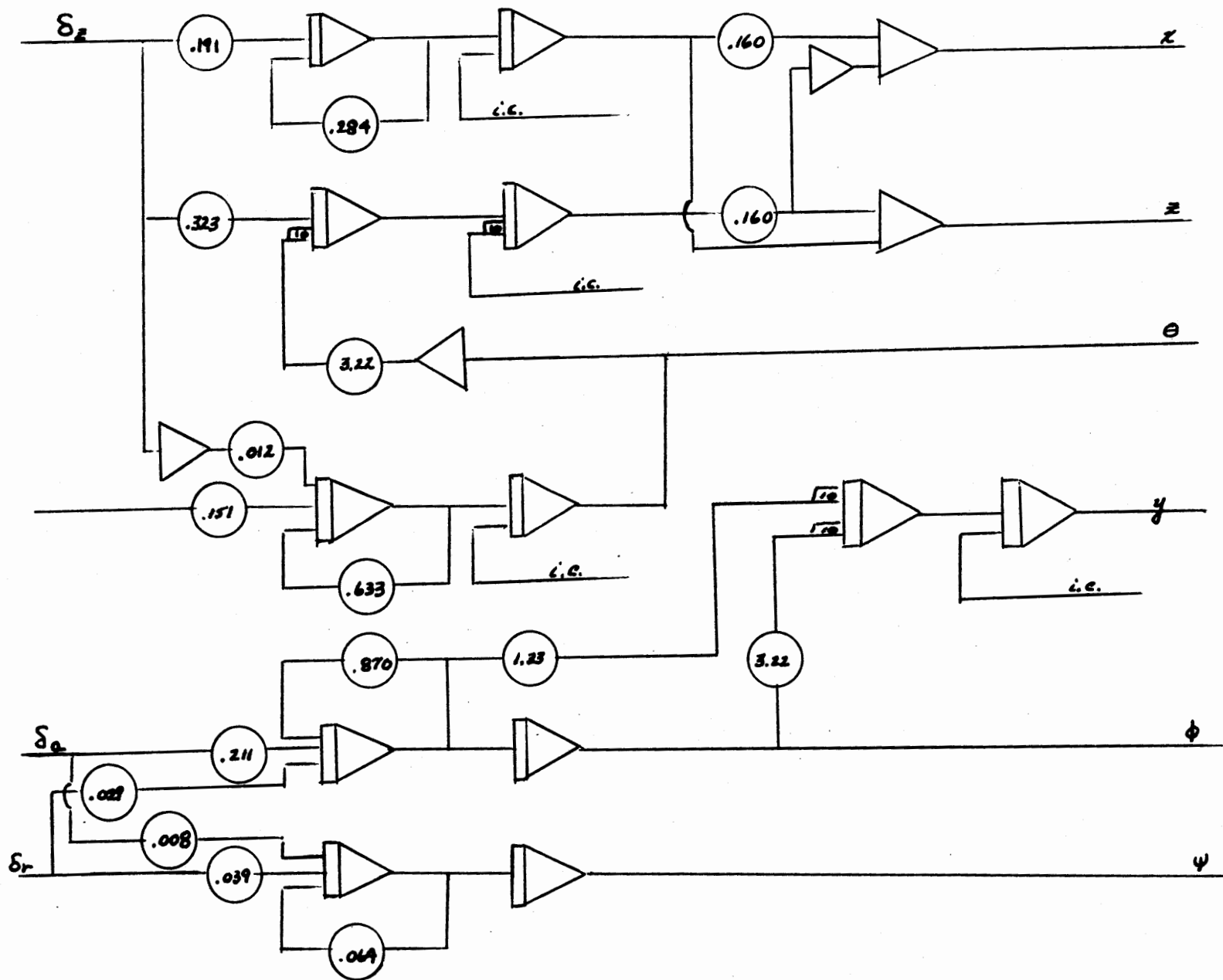


Figure 2.1 Analog computer program for full dynamics of CH-46 tandem-rotor helicopter

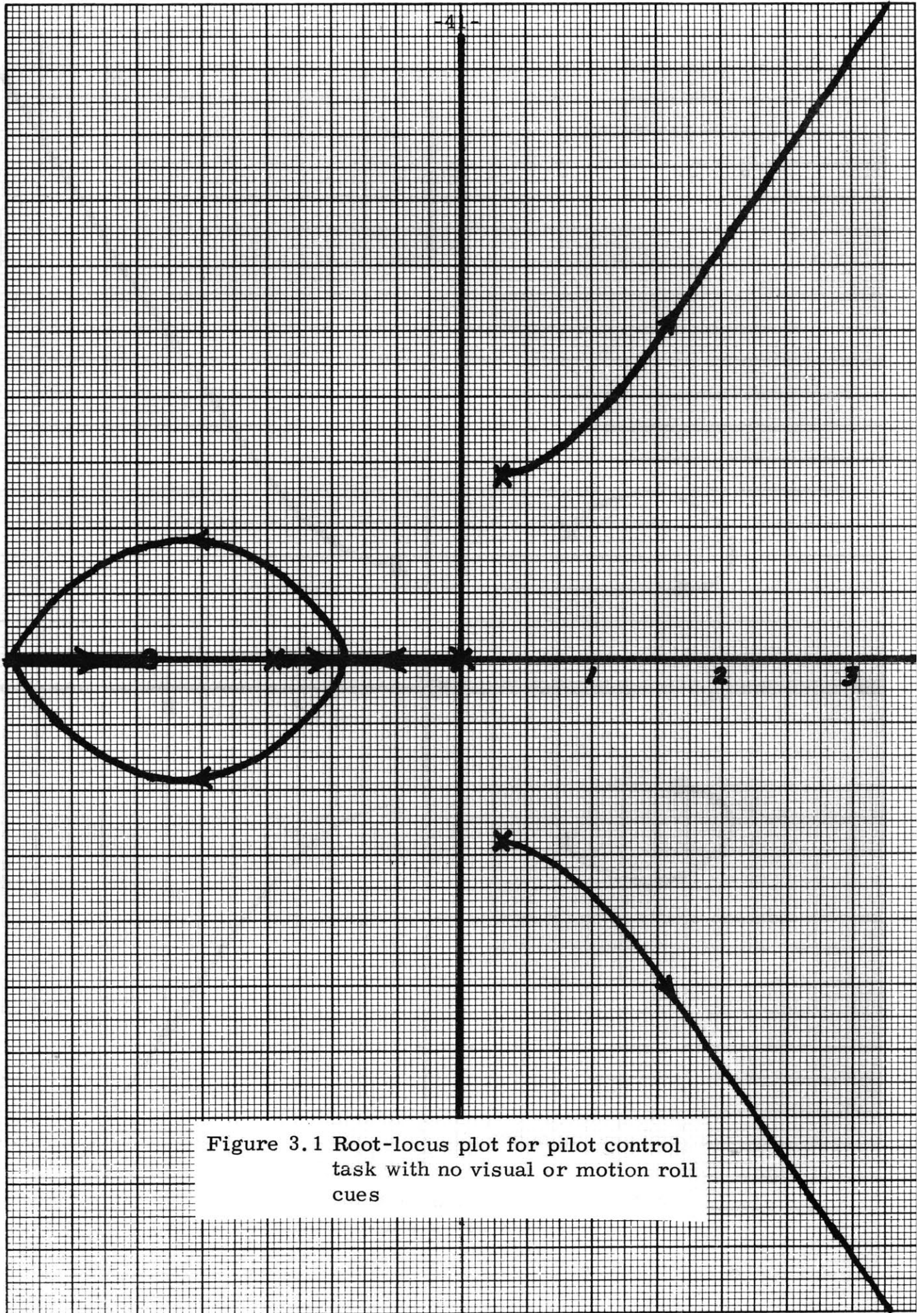


Figure 3.1 Root-locus plot for pilot control task with no visual or motion roll cues

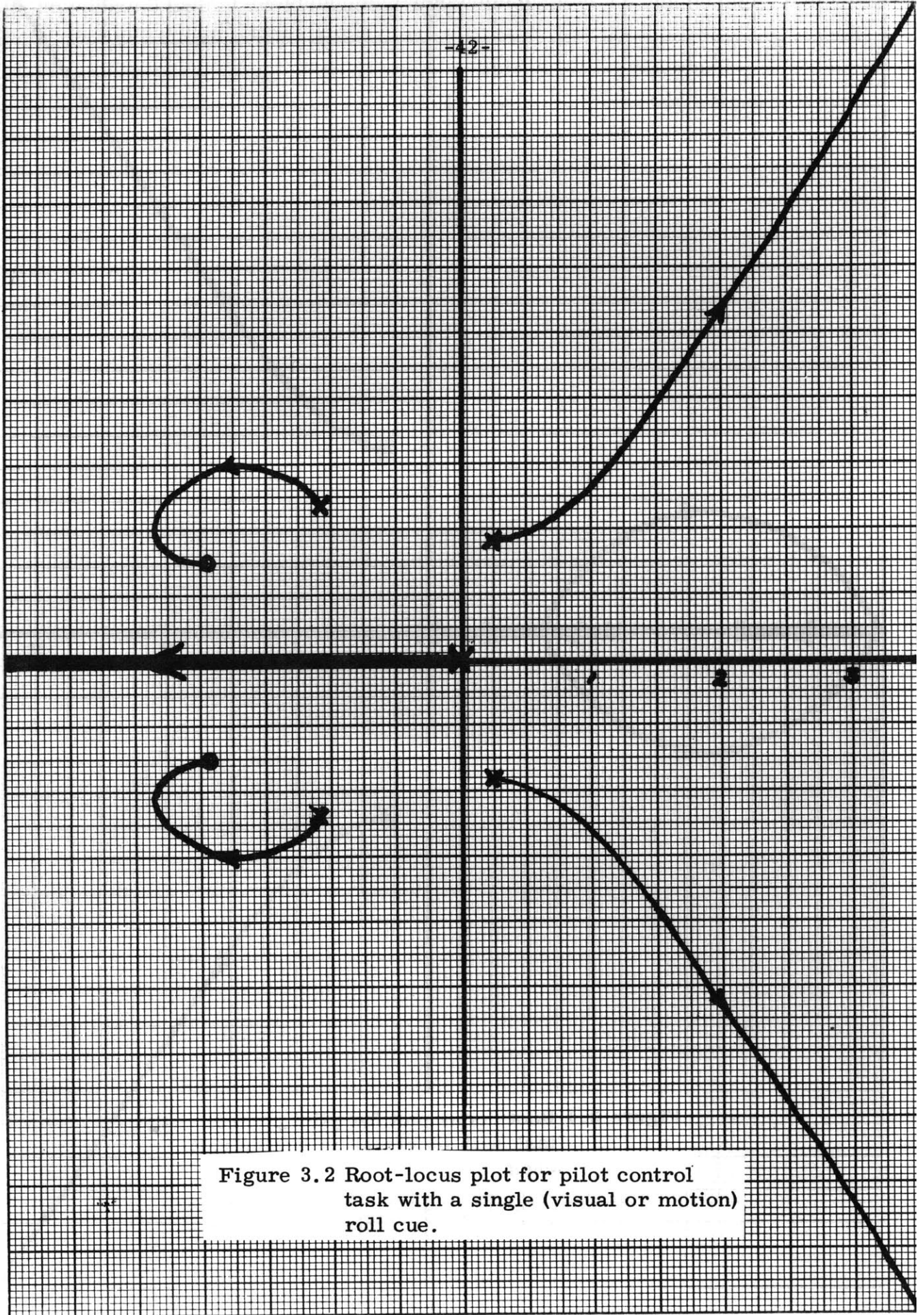


Figure 3.2 Root-locus plot for pilot control task with a single (visual or motion) roll cue.

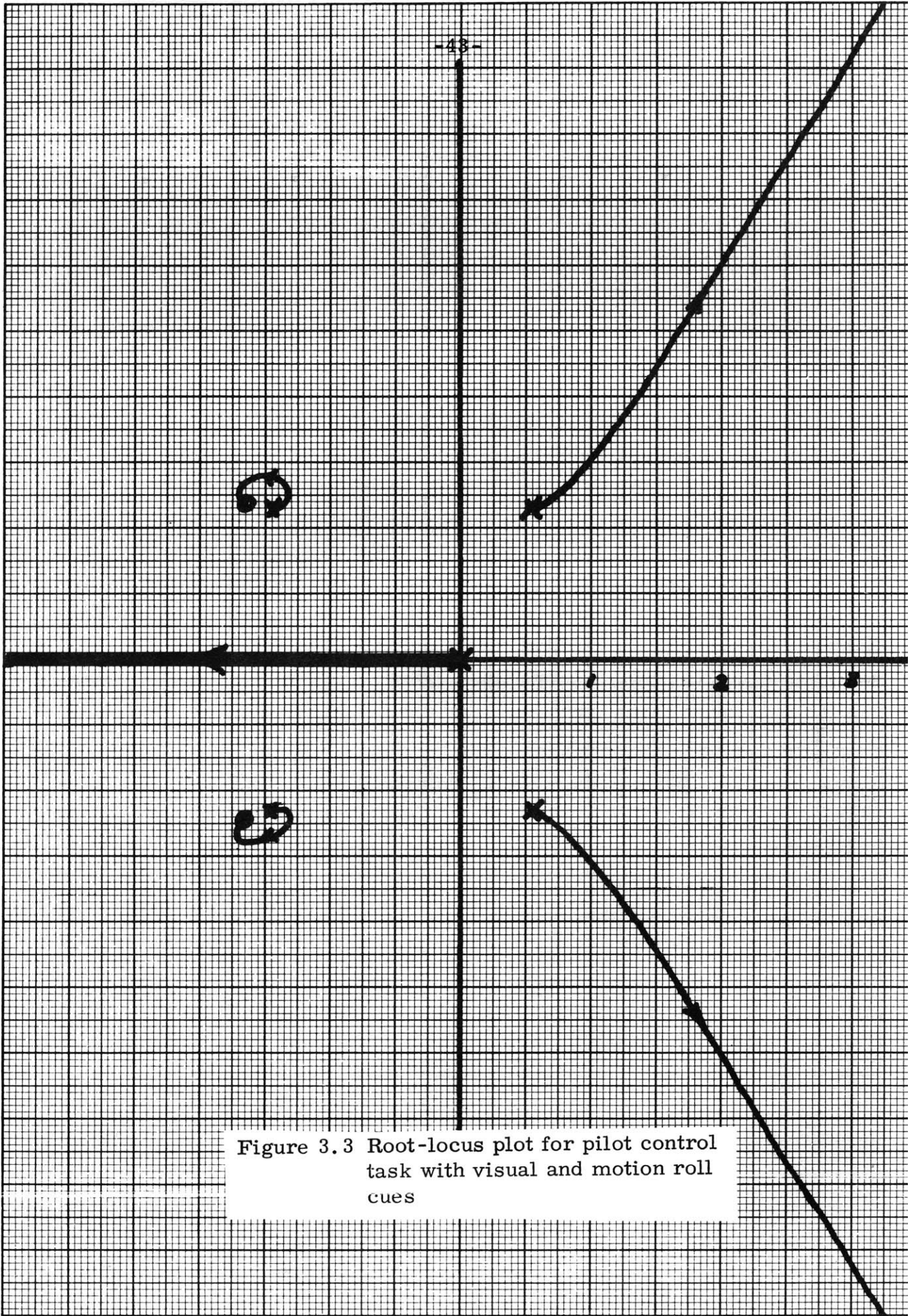


Figure 3.3 Root-locus plot for pilot control task with visual and motion roll cues

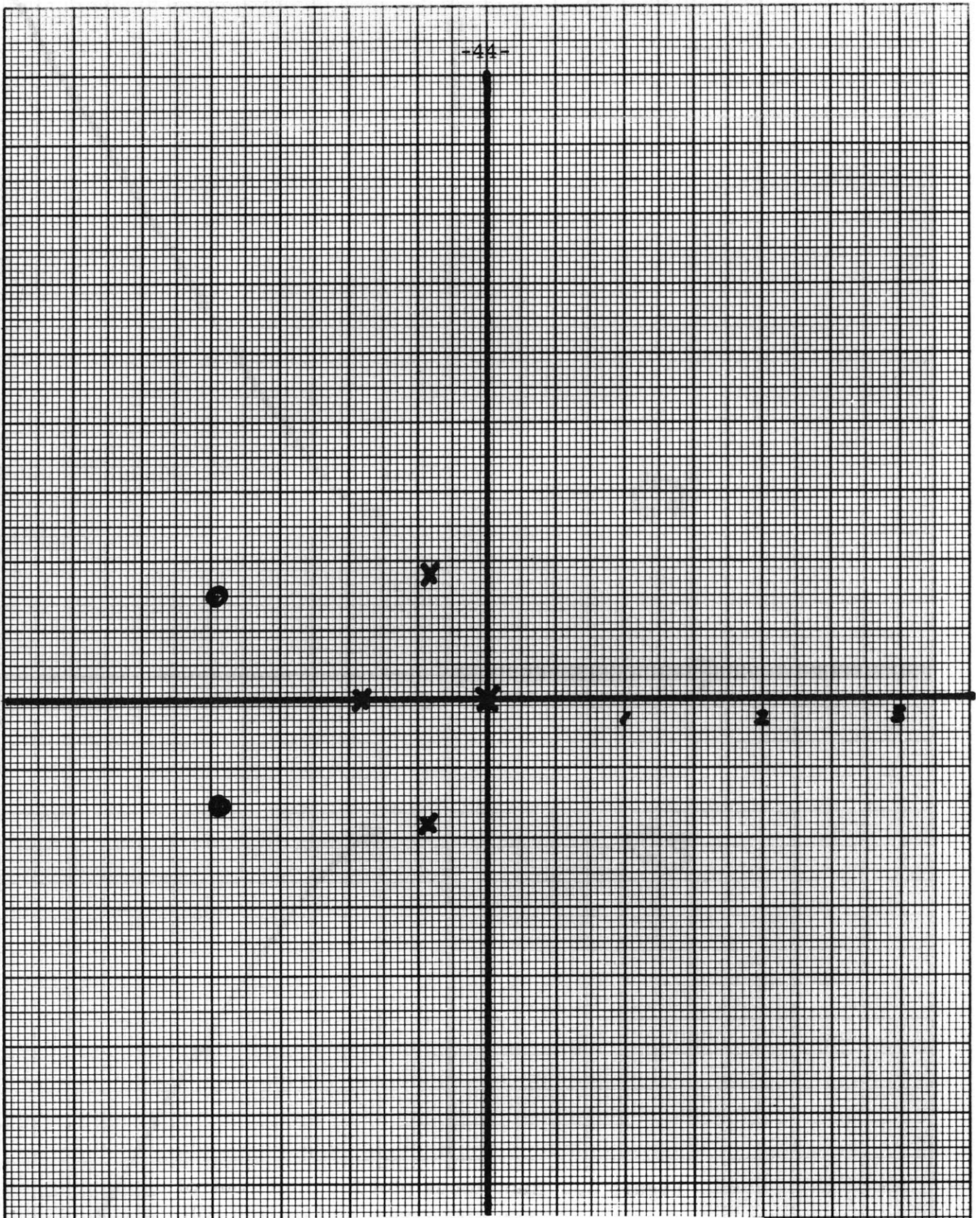


Figure 3.4 Open-loop root-locus plot for pilot velocity-control output task with visual and motion roll cues

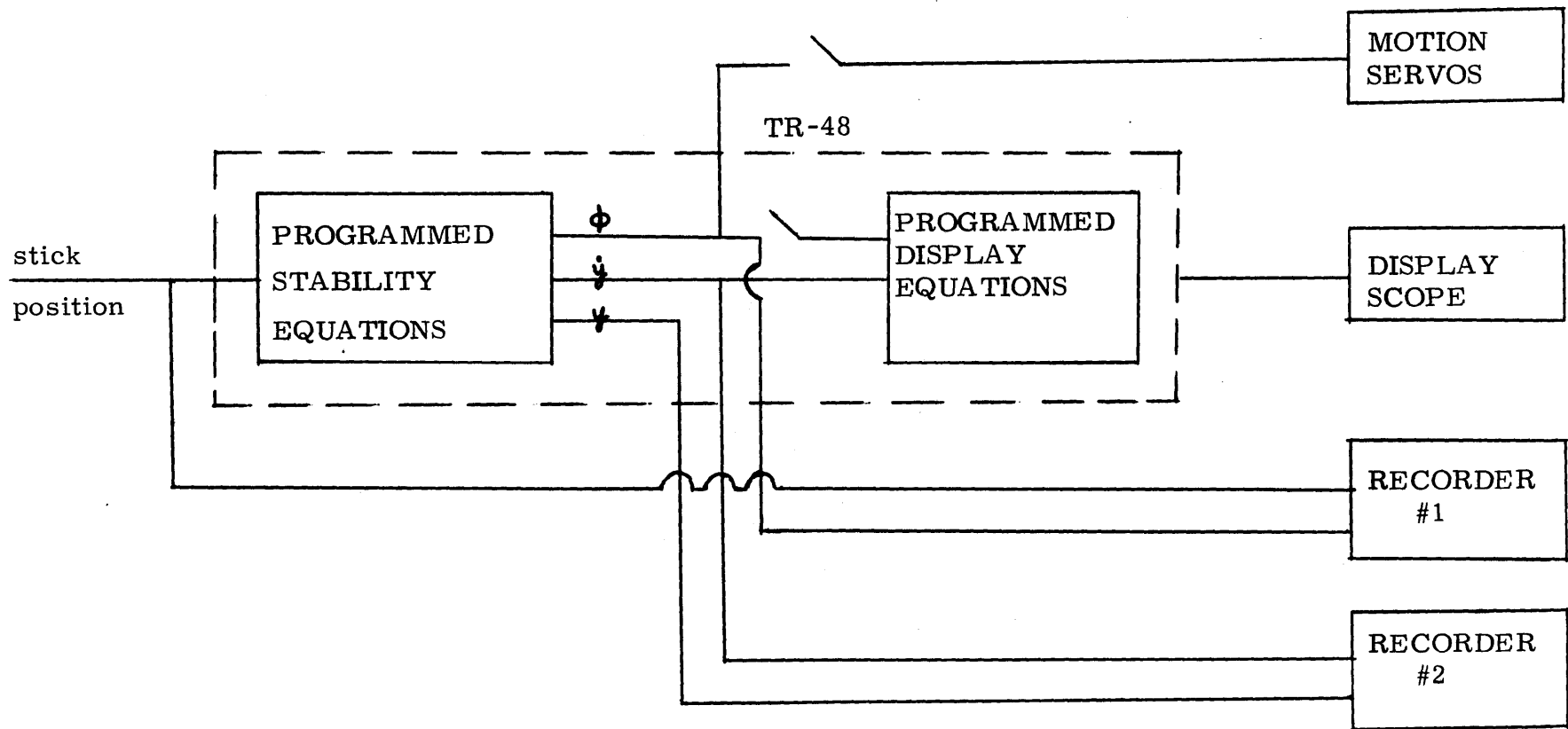


Figure 4.1 Block diagram of experimental system used to simulate flight and record results

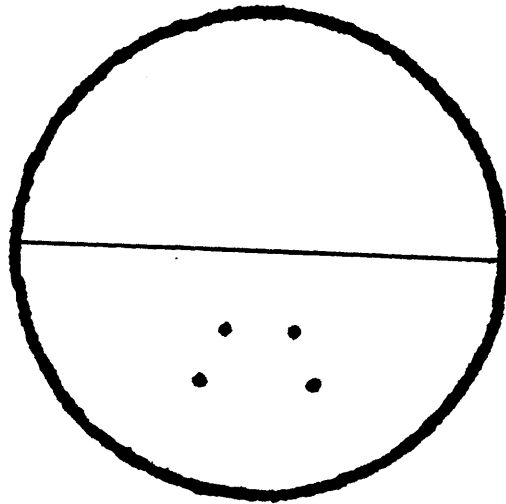


Figure 5.1 Appearance of visual display when subject is maintaining correct position and attitude. The horizontal line represents the horizon and the four dots indicate the corners of a rectangle on the ground, seen in perspective

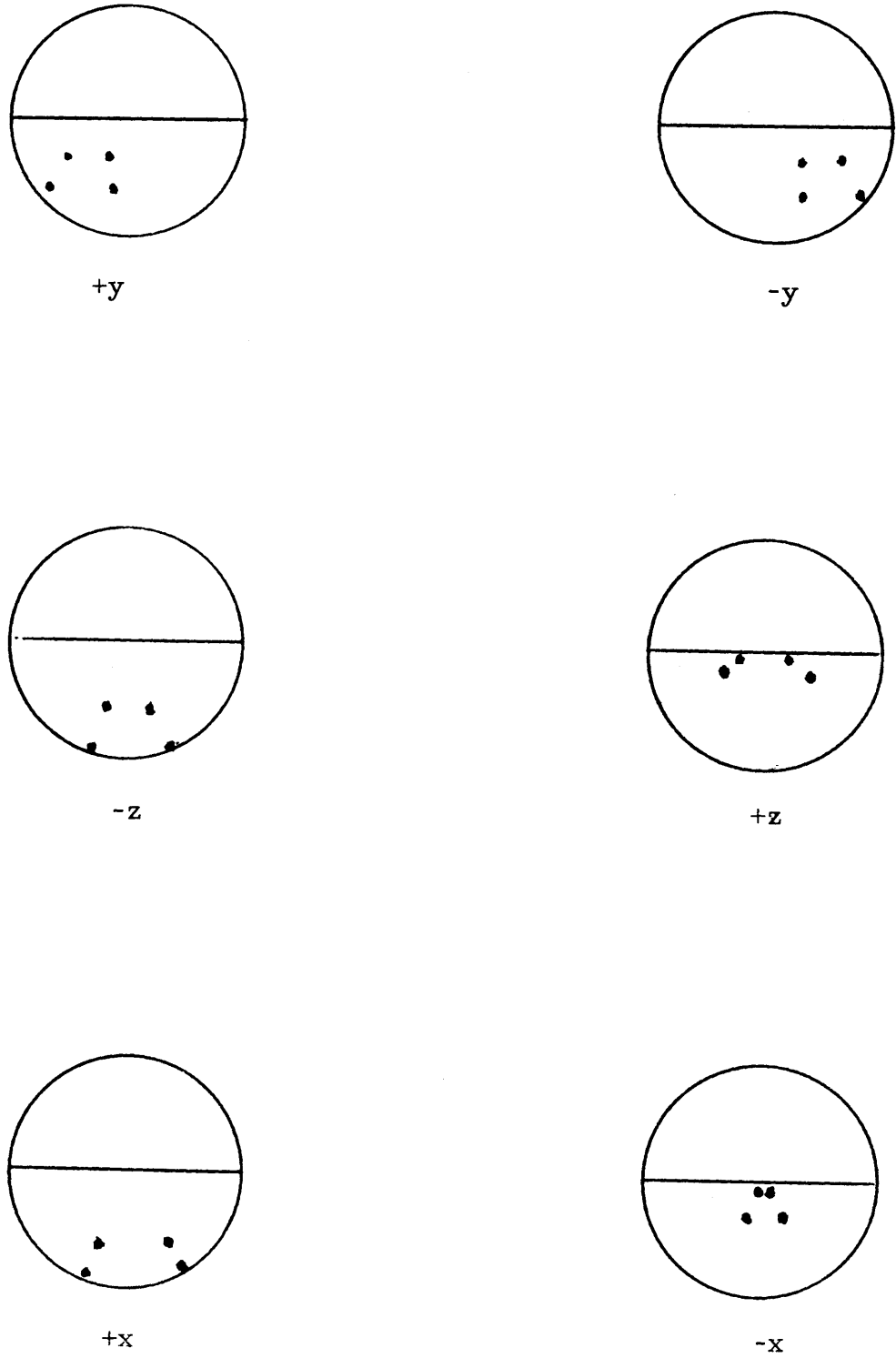
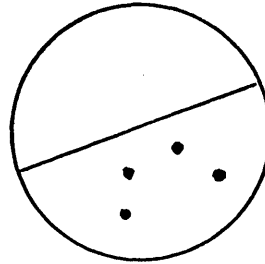
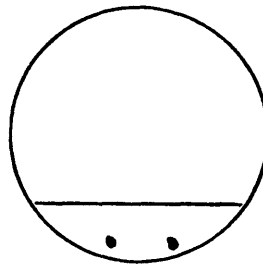


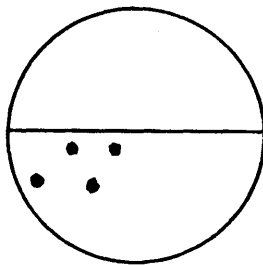
Figure 5.2 Appearance of the visual display after translation of the helicopter along each of three axes



roll



pitch



yaw

Figure 5.3 Appearance of the visual display after positive rotation of the helicopter about three axes

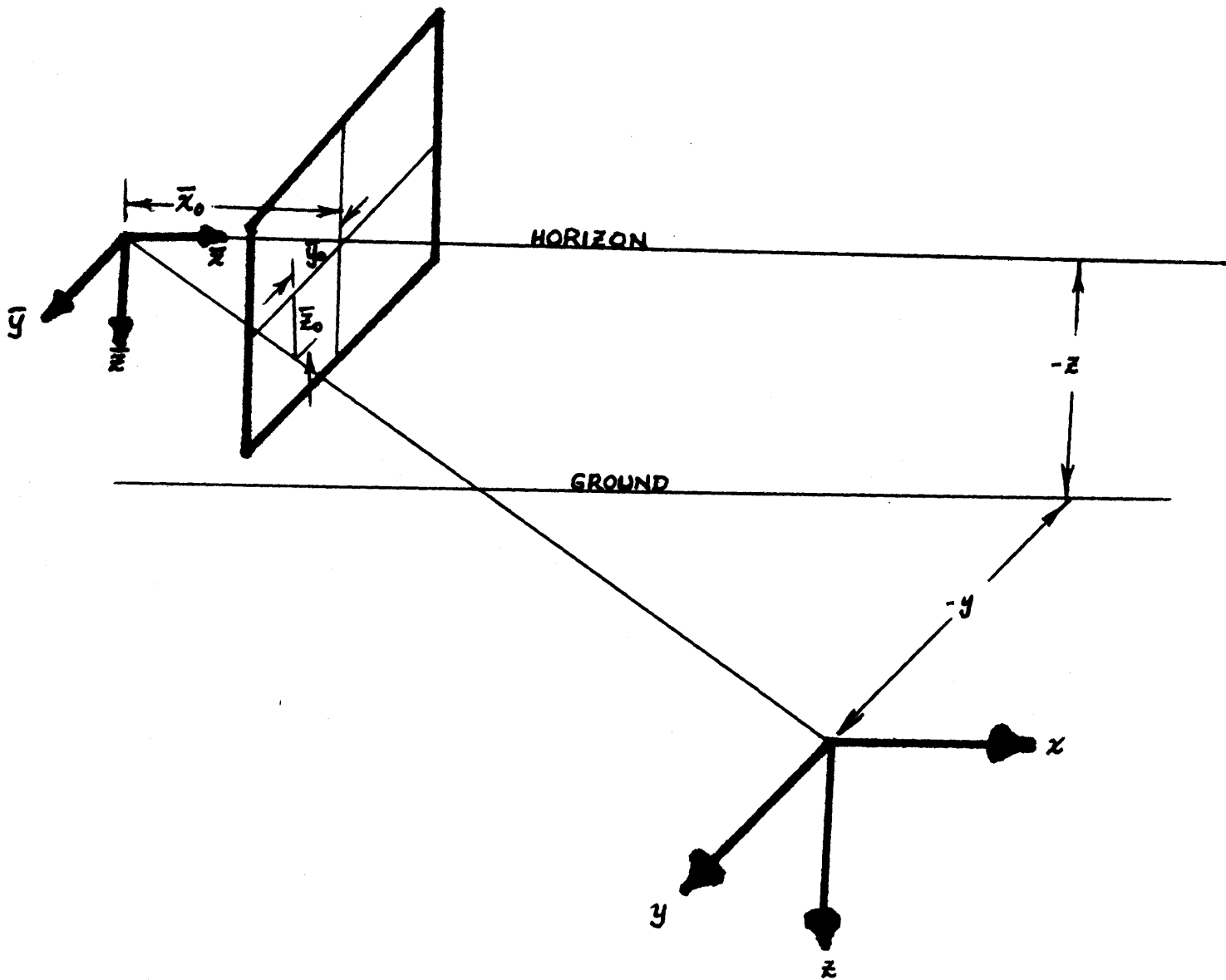


Figure 5.4 Relation of inertial and body coordinates showing the apparent position of a point on the ground as seen on the visual display screen

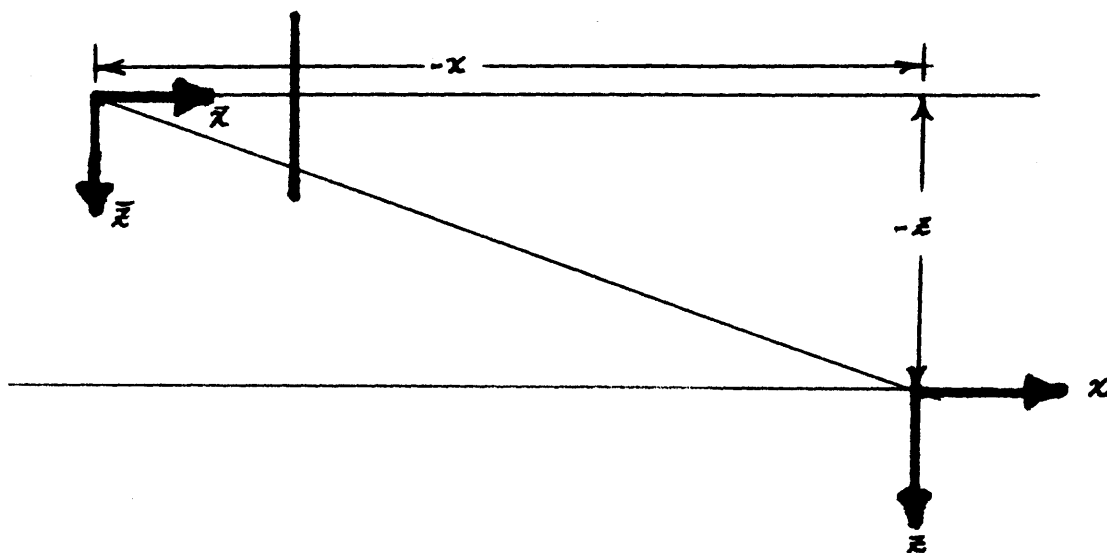


Figure 5.5 Projection of coordinate systems and display screen in  $x, z$  plane

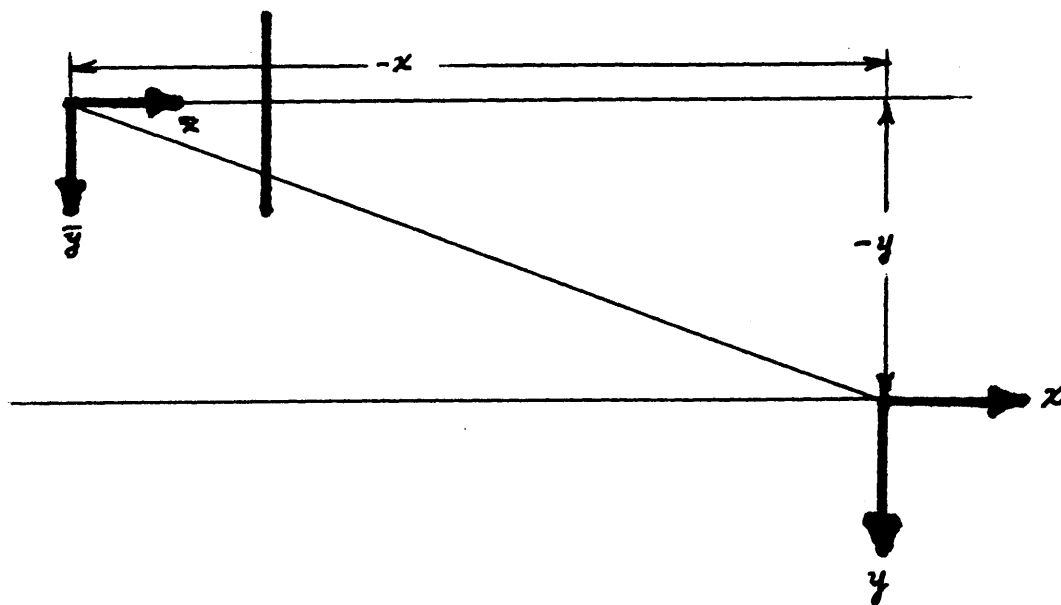


Figure 5.6 Projection of coordinate systems and display screen in  $x, y$  plane

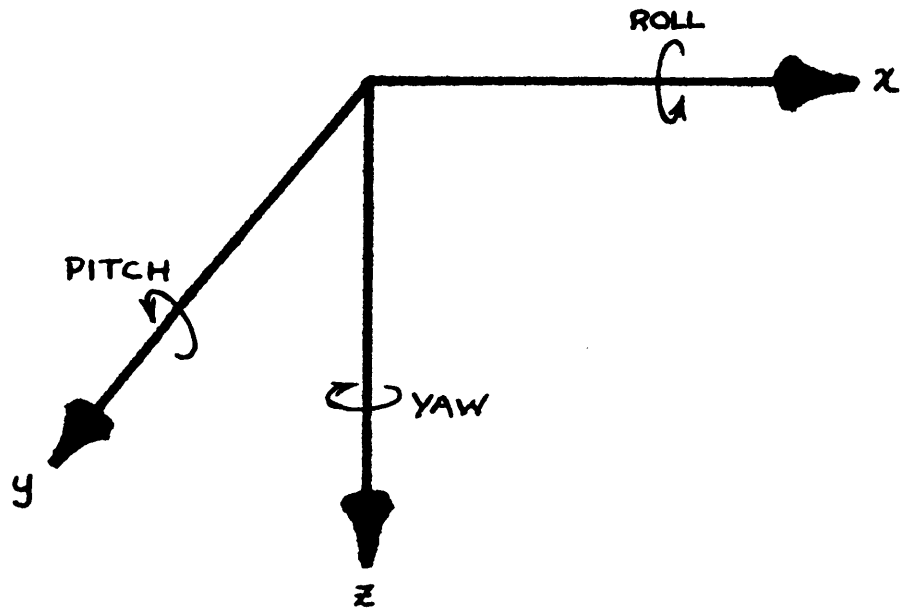


Figure 5.7 Positive attitude convention

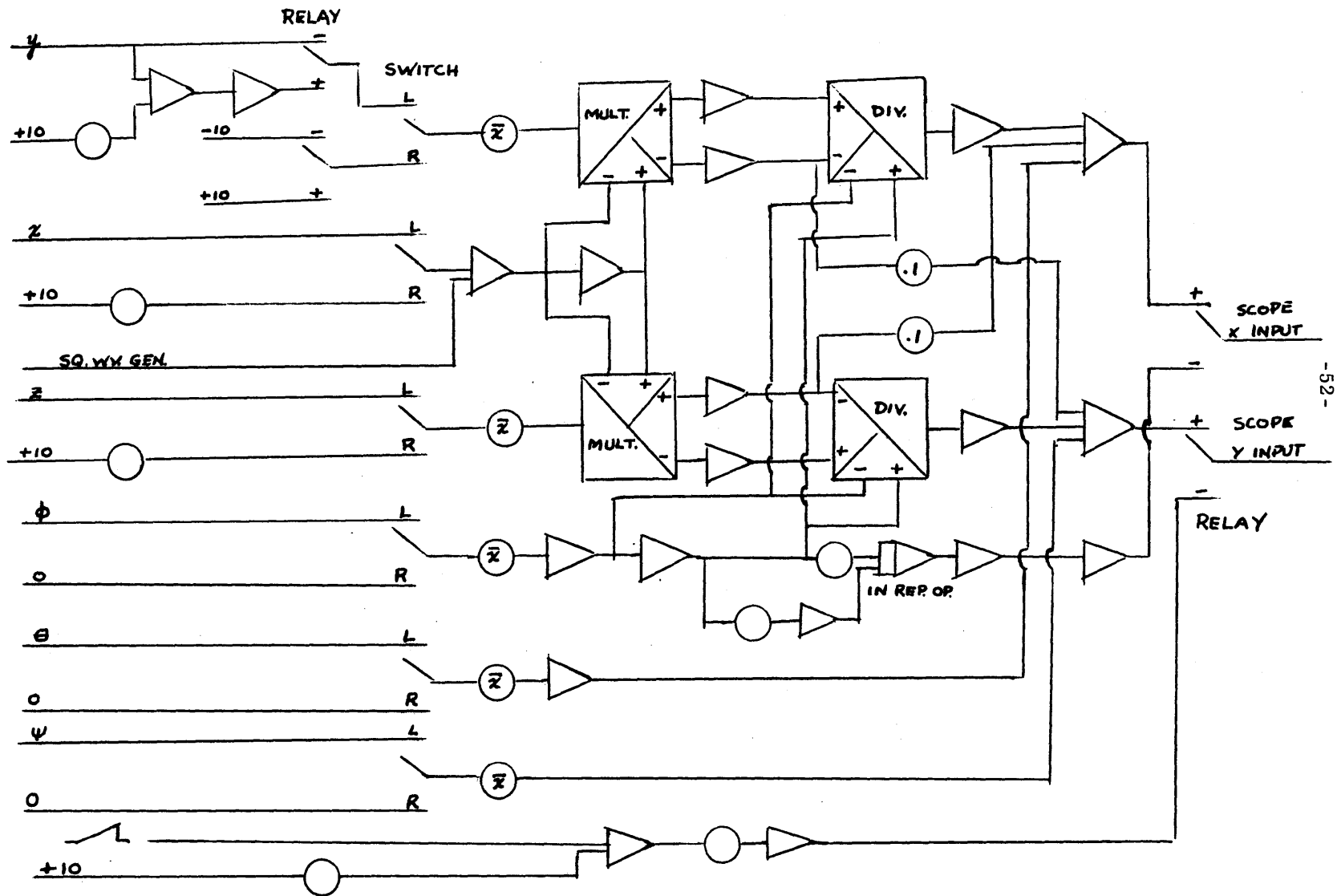


Figure 5.8 Analog computer program for visual display system. Input is position of craft in inertial space. Output feeds into oscilloscope x and y inputs. Left position of switches connects to external determination of inertial position. Right position of switches allows internal stabilization of specific modes.

stick

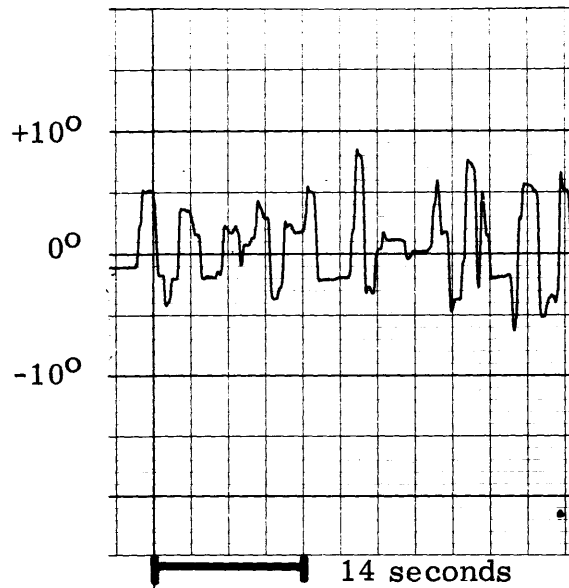
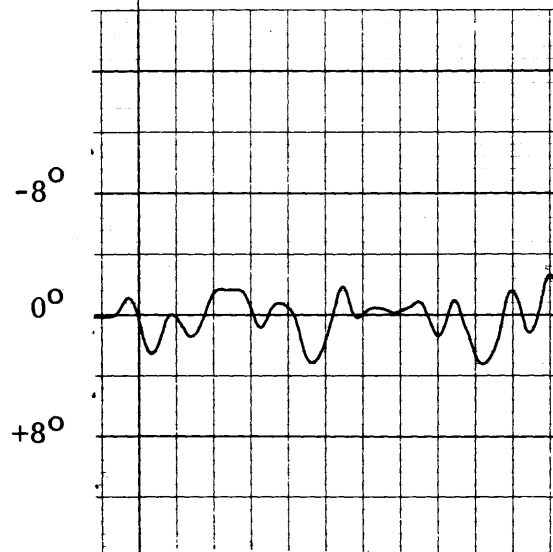


Figure 7.1 A  
Roll cues

roll



stick

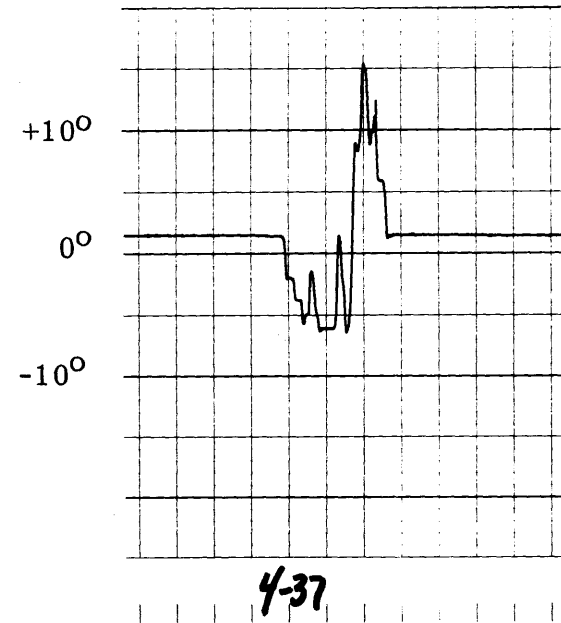


Figure 7.1 B  
No roll cues

roll

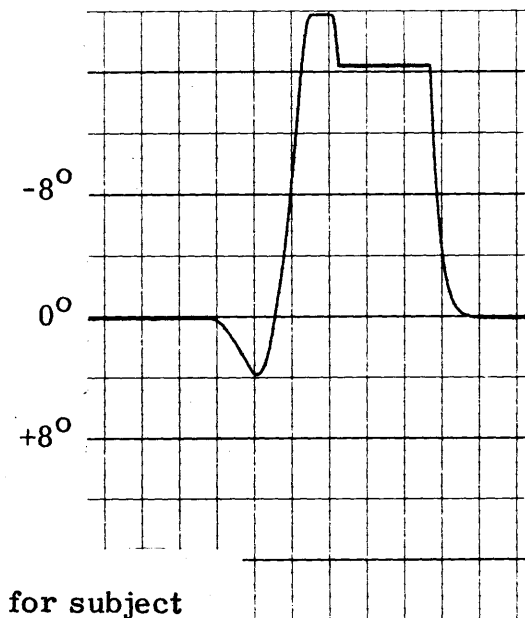


Figure 7.1 Record of stick position and roll angle for subject number 4 a) with roll cues presented b) with no roll

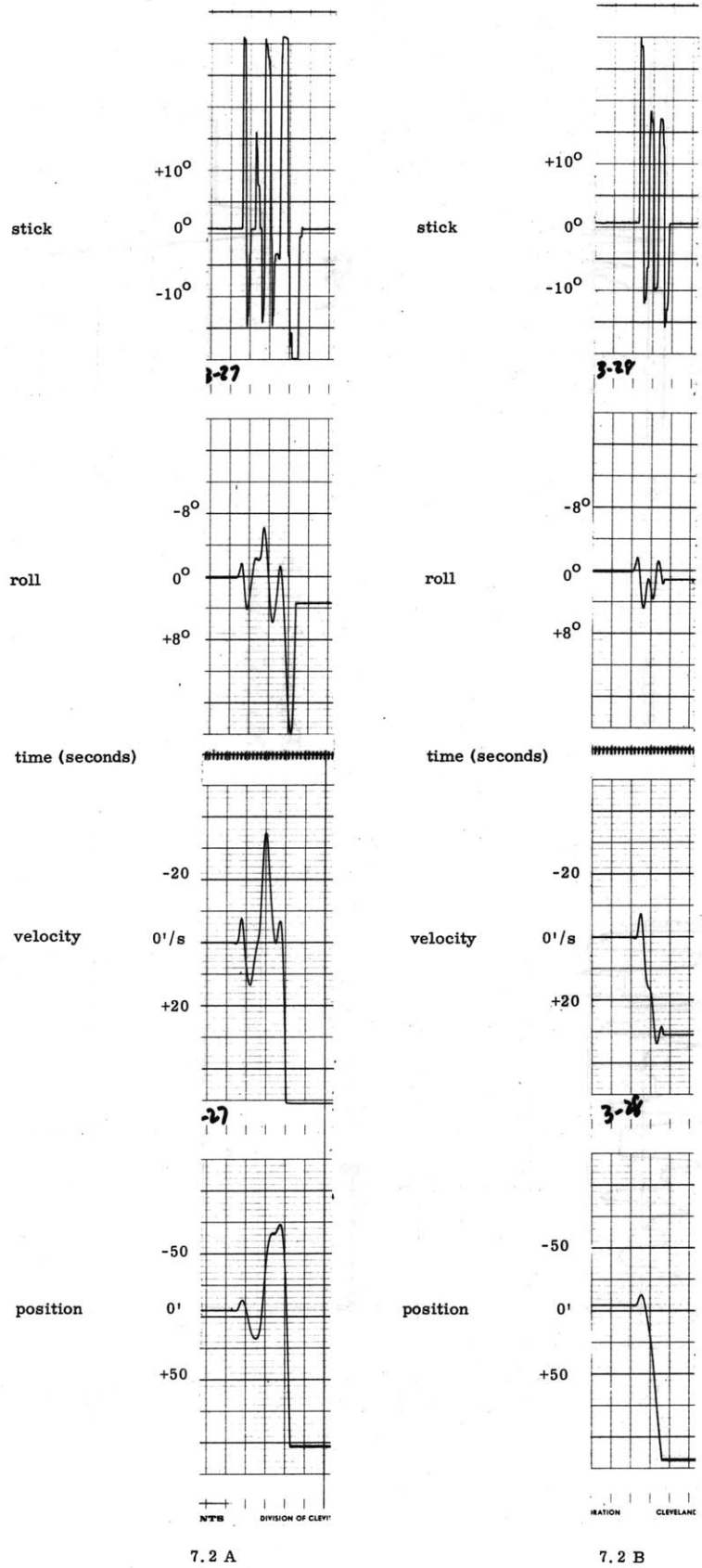


Figure 7.2 Record of two successive runs by subject number 3 showing loss of control due to a) build-up of excessively large roll angle b) build-up of excessively large velocity

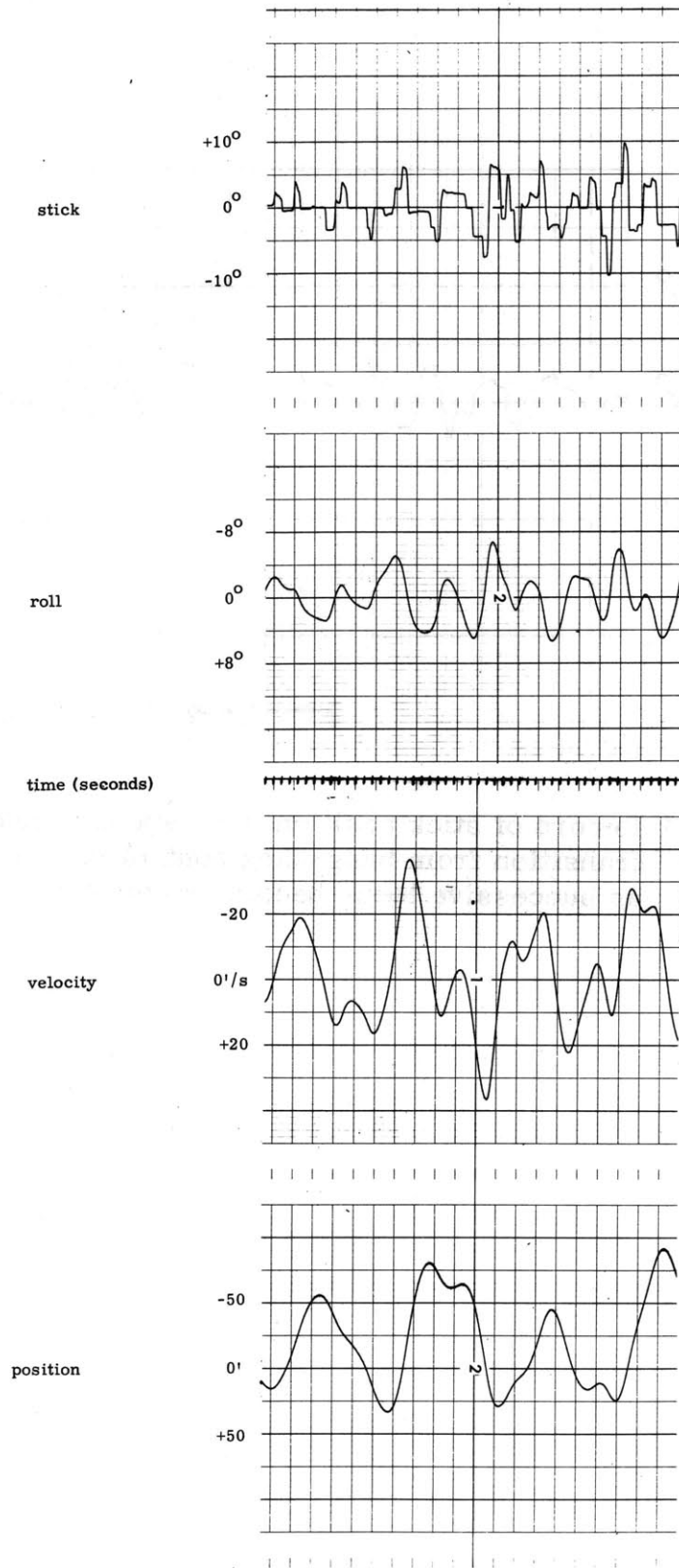


Figure 7.3 Record of typical successful run with full visual simulation but no motion cues

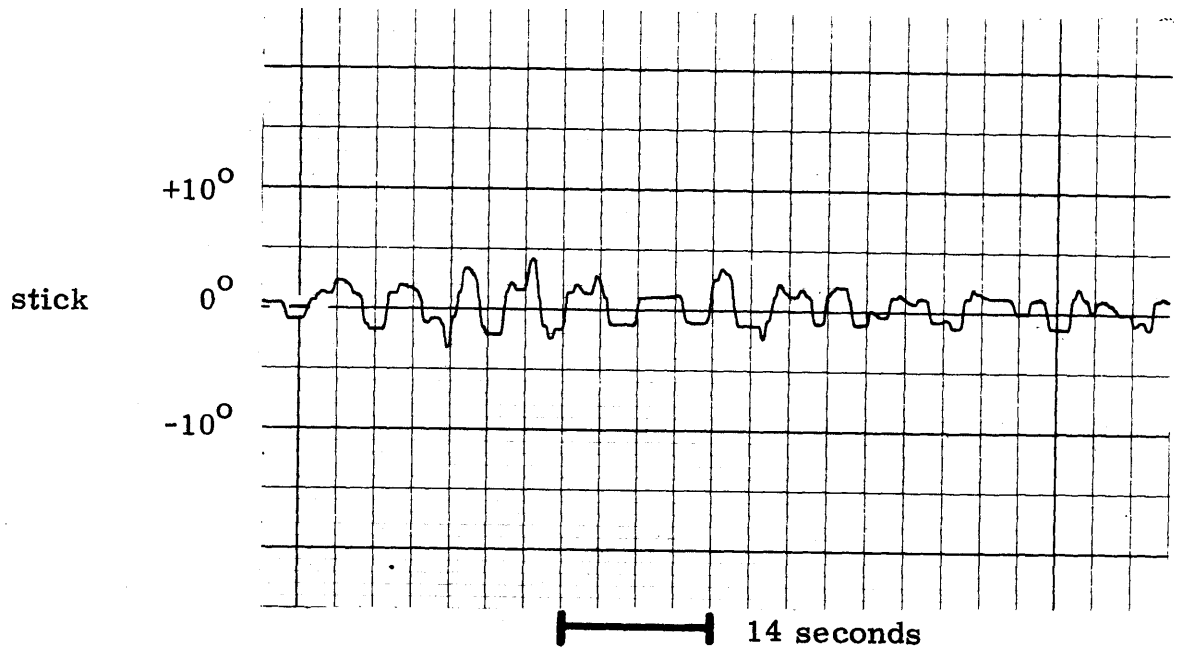


Figure 7.4 Record of stick position for subject number 6 showing transition from bang-bang control toward simple tracking as successive loops become stabilized

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