MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEMI ANNUAL STATUS REPORT: INTEGRATION OF VISUAL AND MOTION CUES FOR SIMULATOR REQUIREMENTS AND RIDE QUALITY INVESTIGATION

NSG 22-009-701
May 1975 - November 1975

PRINCIPAL INVESTIGATOR

L.R. YOUNG

MAN-VEHICLE LABORATORY
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

(NASA-CR-145978) INTEGRATION OF VISUAL AND MOTION CUES FOR SIMULATOR REQUIREMENTS AND RIDE QUALITY INVESTIGATION Semiannual Status Report, May - Nov. 1975 (Massachusetts Inst. of Tech.) 40 p HC
N76-14790
Unclas
G3/53 07386

SEMI ANNUAL STATUS REPORT

NASA GRANT NGR 22-009-701

INTEGRATION OF VISUAL AND MOTION CUES FOR SIMULATOR REQUIREMENTS AND RIDE QUALITY INVESTIGATION

MAY 1975 - NOVEMBER 1975

Professor L.R. YOUNG, Principal Investigator

INTRODUCTION

During this reporting period, work has continued on the use of the Ormsby model for predicting vestibular response, specifically in a coordinated turn; on the use of visual cues in landing, including a pilot experiment using the video tapes made at Langley; a comprehensive review of present day computer state-of-the-art was made and a decision concerning the best system for the Man Vehicle Laboratory; and finally, several papers have been published concerning the work performed under this grant.

This report contains detailed progress reports on each of these categories and has appended copies of the papers published during this period.

VISUAL CUES IN LANDING

The aim of this effort is to investigate the pilot's visual perception of aircraft position and flight path during landing approaches with the ultimate objective of determining the relative importance of various visual cues. Two different methods are currently being investigated:

1. Presenting the subject with computer generated runway images and measuring the effects of deliberate distortions on the subject's visual perceptions.
2. Presenting the subject with recorded television images of different approaches and measuring his magnitude estimates of deviation from a nominal flight path.

Computer Generated Images

To display an accurate runway image requires proper three dimensional perspective. The ADAGE AGT-30 graphics computer used in this project has no built-in perspective capability in either hardware or software, so development of a program for creating perspective is required. An important requirement of this program is that it be fast enough to avoid unacceptable flicker in the display.

Our efforts in this area will take advantage of programming being performed for another grant by modifying existing programs which currently have a suitable image of the High Intensity Runway Lighting system. We also plan to modify the electronics of the Amphicon video projector to project images generated by the ADAGE graphics computer.

Magnitude Estimates from Video Tapes

Video tapes of landing approaches were made under the supervision of Dr. Quiejo with the Langley Landing Terrain Scene Generator. The approaches were made with random variations in distance, glideslope, and flight path angle to be appropriate for psychophysical testing. Approximately 10 seconds of each approach at each distance was shown. The tapes start with a set of 21 scaling runs to help the subject calibrate his magnitude estimation scale for both glide slope and flight path at each of the three distances. Then follows 81 presentations of the factorial combinations of three glide slopes, three flight paths and three distances, with three replications each.

Preliminary measurements indicated that the Amphicon video projector can be adapted to the Boeing cockpit simulator to give an image with the proper scaling and field of view as seen form the pilot's window. The video projector was temporarily set up without the cockpit, though, to ascertain proper working order and to make a preliminary set of tests which are described below.

Ten subjects participated in the preliminary tests, viewing the 21 scaling runs and 81 approaches. These tests were designed to determine the appropriateness of the deviations of glideslope, flight path and distance, as well as to refine the scaling technique. To further verify the procedure, we have performed a data analysis on these responses to check the experimental design, even though the images are not the ones to be used in the final tests.

The following items are observations we have made from the preliminary experiments, and consideration is being given to modifying the video taping of the approaches to remedy these situations.

1. The exposure time of 10 seconds is too long for the short distance (the optical probe is on the runway before the run is over).
2. The closest distance should be shown first during the scaling runs, so that the nominal aim point is well defined.
3. To provide a global view of the scene, we suggest making a complete approach and then running it backwards to provide the subject with the appropriate set.

4. Because there are only three distances used, altitude cues could be obtained from the contents of the lower portion of the field of view, e.g. if a house was visible at a particular distance it meant that the flight path was lower than usual. This can be remedied by taking the nominal distance plus a small perturbation.
5. It would be advantageous to have less time between runs and have the run announced while the screen is blank.
6. One subject complained of the use of the ± 10 scale for magnitude estimates, and felt that the use of glide slope deviation in dots would be more apropos for the experienced airline pilot. However, there still remains the problem of assigning scale values to flight path deviations. (Preliminary results of our experiments indicate that this may not be a problem; the observers seem to respond to flight path <u>angle</u> deviation rather than <u>linear</u> displacement.)

The magnitude estimates of one subject were processed by an analysis of variance program which simultaneously generates the functional relation of the dependent variables (glide slope estimate and flight path estimate, in this case) as a function of the independent variables. The data for all three distances was pooled for this analysis and the results are shown in Figures 1 and 2.

It was determined that the magnitude estimate of the flight path angle deviation was significantly affected by distance and flight path only. The psychophysical function is shown in Figure 1 and indicates that the sensitivity of response is approximately the same for the 1000 and 3000 foot distances, but is significantly lower at the far distance (10,000 feet). We feel this is due to the very low angular velocity or weak streamer effects at these far distances, and the low sensitivity indicates that the pilot is not perceiving the same angular flight path error that he does at the nearer distance.

The magnitude estimate of the deviation of the glide slope estimate from normal is shown in Figures 2a and 2b. The main effect (Figure 2a) is due to the glide slope deviation itself; there was no interaction with glide slope deviation and other variables. However, there were strong and significant interactions between the distance and flight path, i.e. they strongly influenced the glide slope estimates. The analysis of variance model predicts the magnitude estimate to be the main effect shown in Figure 2a plus the perturbation effect due to flight path angle and distance shown in Figure 2b. Most of the perturbation effects shown in Figure 2b are due to the manner in which we initially chose to record the stimuli. If the next set of recordings can be made with the suggestions noted above, we expect that these artifactual effects will disappear.

The results of these preliminary tests are quite encouraging, and indicate that our technique for obtaining psychophysical functions of flight path and glide slope deviation will be successful and will add insight into the pilot's perception during visual approach.

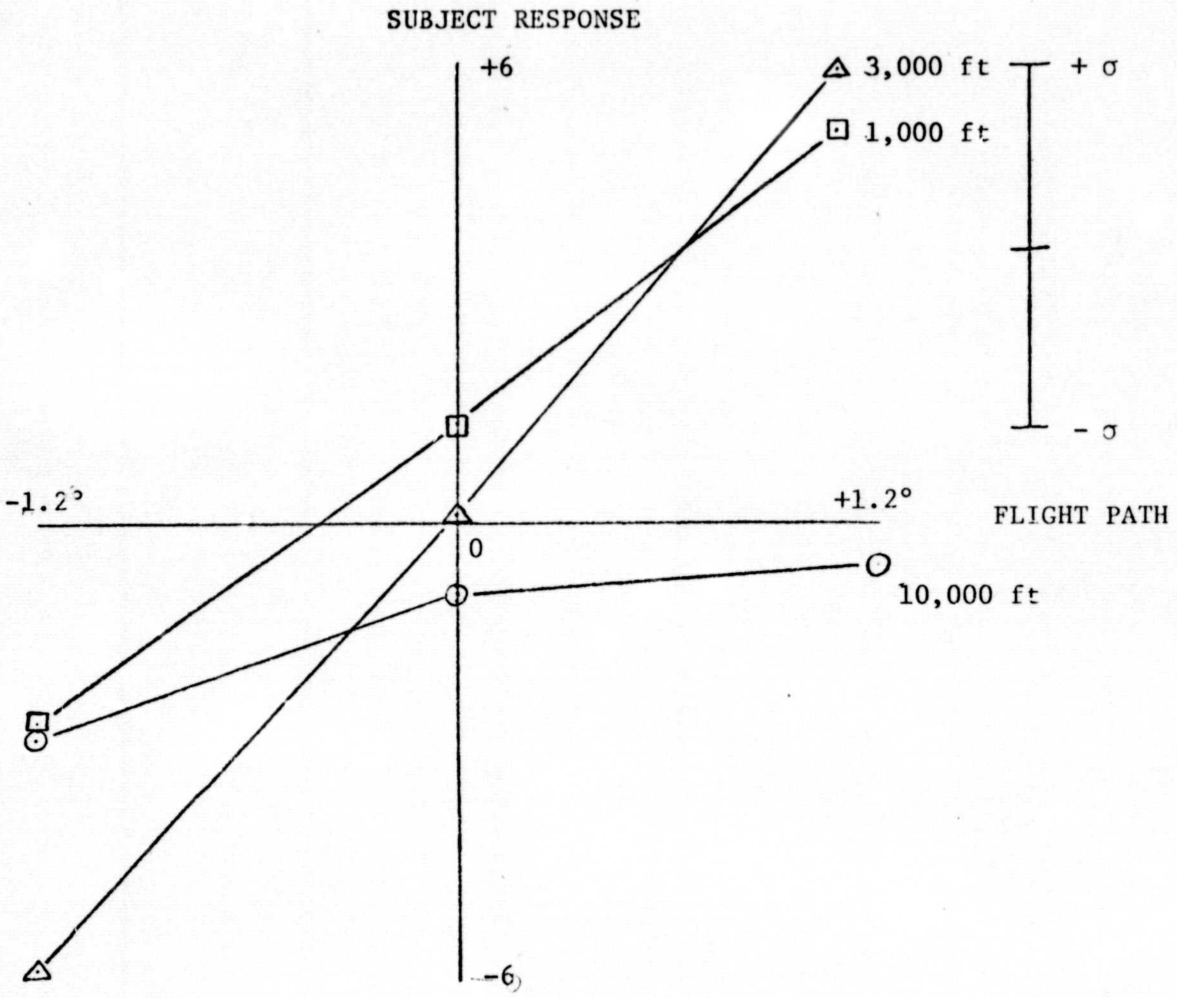


FIGURE 1. MAGNITUDE ESTIMATE OF FLIGHT PATH ANGLE DEVIATION

COORDINATED TURN SIMULATION

The Ormsby model of dynamic orientation has been used to predict non-visually induced sensations during coordinated aircraft turns. The results are shown in the the first four figures in this section for an idealized, 85 knot, 30° degree bank, turn. Notice in figures 3 and 4 that attitude and angular rate perceptions are not consistent. Furthermore, on a three degree of freedom simulator, it will be impossible to duplicate both simultaneously.

The Ormsby model was also used to investigate the problem of simulating this turn on a three degree of freedom standard LINK GAT-1 trainer. When a simple scheme is used to assign penalties for incorrect attitude and angular rate perceptions during a given simulation, it appears that an optimum simualtion should attempt to duplicate either attitude or rate perception. In other words, one extreme or the other. The choice between these two possibilities depends on the weighting factors assigned to the two perception penalties. Unless angular rate perception is weighted far more heavily than attitude, the scheme suggests that the optimum simulation should remain faithful to attitude perception.

A simulator motion profile which closely duplicates attitude perception in the original turn is shown in Figure 2.

An experiment will be run, probably using NASA's instrumented Cessna 172, to check model predictions for the real aircraft turn. Meanwhile, experiments are underway at MIT to check model predictions for the LINK simulation. These experiments also investigate the possibility of using a visual display, in combination with actual LINK motion, to create the contradictory angular rate perception discussed before. A byproduct of this work will be some basic information about the interaction of roll circularvection and true rolling motion. This type of study has never been done with rotation about a non-vertical axis.

The experiment itself is outlined below.

Vertical tracking and roll rate estimation experiment using the LINK trainer.

I. Purpose

A. To study the ability of subjects to dynamically track vertical in two axes (pitch and roll).
B. To study the ability of subjects to estimate roll rate dynamically and determine the psychophysical scaling law involved.
C. To test the Ormsby model predictions for coordinated turn simulation
D. To study the interaction of roll circularvection and actual rolling motion

II. Set-up

A. LINK GAT-1 cockpit:

1. Head rest
2. Black curtain covering instrument panel
3. Voltmeter mounted just slightly lower than eye level.
4. Hand grip indicator device (shown in Figures 5,6, and 7).

    a. Not shown in the diagram is a 12" pointer which can be mounted on top of the handle. When mounted, the pointer reaches just below eye level.
    b. The pitch and roll gimbal axes are outfitted with precision 5KΩ potentiometers (±1% indep. lin.)
    c. ±10 V is sent down from the analog computer through the LINK slip rings, and placed across the two potentiometers. The armature signals are run through the slip rings and back up to the analog where they are buffered with an analog amp (100 KΩ impedance), and scaled to yield a reading of gimbal angles.
    d. The roll armature can also be fed to the voltmeter, producing a meter deflection proportional to the hand grip roll angle.
    e. It should be noted that the potentiometer load ratio is 20:1, and should lead to no more than 0.75% load distortion.
    f. After scaling errors and such things are accounted for, read out can be considered accurate to at least ±5%. It is probably much more accurate.

5. Optics system

    a. The optics system is set up to project horizontal stripes on the opaque side windows of the cockpit. The stripes can move up on one window and down on the other creating a roll circularvection display.
    b. The film drive motor is built into a velocity servo so that film speed is proportional to system input voltage.

c. The arbitrary calibration scheme is

$$\frac{\text{stripe speed on window}}{\text{radius of cockpit}} = \text{angular velocity}$$

It is arbitrary because it is not clear that the stripes are resolved by the subject. The subject may visualize the stripes occuring some distance away from the cockpit. It is this apparent distance that actually determines the angular velocity of the roll cue.

B. LINK motion drives

1. The motion drives are set up to be run from an outside source, independently of the factory designed logic.
2. Using position potentiometer and tachometer feedback, and the analog computer, roll and pitch axes are set up as position servos.
3. Yaw is set up as a velocity or yaw rate servo.

C. Output

1. Feedback from roll and pitch position potentiometers, yaw tachometer, film tachometer, and the hand grip potentiometers are sampled every 0.2 seconds through the A/D converter.
2. These samples are stored in core, and at the end of each run (64 seconds) can be dumped onto data tape.
3. The data tape automatically keeps an index to tell the computer where the next available space is and to keep track of previous starting locations.
4. Hand grip output and two LINK feedbacks are also recorded during each run on a four channel stip chart.

III. Vertical tracking task

A. Procedure

1. Instructions to the subject

a. Keep gaze at top of pointer
b. Keep pointer aligned with what you perceive as vertical with respect to the room.

2. Stimuli (see Figures 8, 9, 10, and 11)

   a. Practice routines made up of rolls and pitches, between plus and minus 7°, at different constant rates. Pitch and roll stimuli given first separately, then simultaneously.
   b. Simulation of idealized, 30°, 85 knot, coordinated turn.

      1. Optimum simulation as predicted by Ormsby model.
      2. Film strip motion added (stripe motion mimics visual scene motion during actual turn).
      3. Turn simulation as done by the original LINK trainer motion logic.
      4. Film strip motion added (same as above).

B. Preliminary results

1. Subjects are able to indicate their true orientation to within about 2.5 degrees when the stimulus remains within 10 degrees of the vertical. Larger stimulus angles have not been tried.
2. So far, subjective indications of pitch orientation appear to be as accurate as roll indications. This is a little surprising since aligning the pointer in pitch requires the subject to rely heavily on depth perception. The pointer is in front of the subject, and too high for the subject to look down on.
3. Dynamically, there is from 0.5 to 1.5 seconds lag in the subjective response.
4. When the cockpit orientation passes through zero, subject response often seems to lag at zero and then jump ahead. A satisfactory explanation of this has not yet been found.
5. During the simulation based on the Ormsby model (Figure 10), the onset of roll in and roll out is almost always detected quickly (lag of 0.5 to 1.5 seconds). The washout back to zero roll angle, however, is often detected very slowly or not at all. This can be seen in Figure 13. The phenomenon is not predicted by the Ormsby model, and its explanation is not too clear at the present time. It should be noted that the roll rate (2 deg/sec) and the roll angle (2 deg) involved, are both above the accepted thresholds of

0.8 deg/sec and 0.3 deg respectively.

6. Subjects consistently detect the simulated elevator illusion (pitch back of about 4° during the Ormsby model simulation.
7. During the simulation using standard LINK logic (Figure 11), subjects consistently detect their true orientation to within about 2.5° (see Figure 14).

IV Roll rate magnitude estimation task

A. Procedure

1. Instructions to subjects

   a. Keep gaze on the meter
   b. During the first roll you feel, your maximum sensation of roll <u>rate</u> should correspond to 5 on the meter. This is the modulus. Subsequent motions should be rated proportionately (e.g. a roll rate that feels twice as fast should be a 10 on the meter).
   c. The first run will be practice
   d. During subsequent runs you will often be told when you are feeling the modulus.
   e. Attempt to continuously track your roll rate with the meter needle.

2. Stimuli

   a. Modulus - 5 deg/sec roll from 7° left to 7° right roll and vice versa.
   b. Calibration routine - same as the practice routines used for the vertical tracking task, but using only the roll axis.
   c. Film motion added to the calibration routines.

      1. Film maintains a constant speed during the entire run
      2. Film moves only during actual rolling of the LINK. The direction is sometimes consistent and sometimes contradictory to the actual cockpit motion. Film speed is always the same.

   d. Turn simulations with and without film motion - same as described for vertical tracking task.

B. Preliminary Results

1. Preliminary results suggest that the psychophysical law in operation is $\psi = K_1 \log\phi + K_2$,

where Ψ is subjective magnitude, ϕ is the physical magnitude, and K_1 and K_2 are constants.

2. The variance is too great to make these results very convincing or useful (Figure 16).
3. Subjects have been consistent at detecting a 1 deg/sec stimulus, which is just above threshold.
4. Subjects may be responding more to a vibration characteristic of the drive system than to the intended vestibular stimulus.

C. Possible modifications

1. Make LINK motion smoother - eliminate jerk and vibrations.
2. Superimpose low amplitude random noise on the LINK motion so that drive system characteristic cannot be used for cues.

Idealized Coordinated
Turn Profile

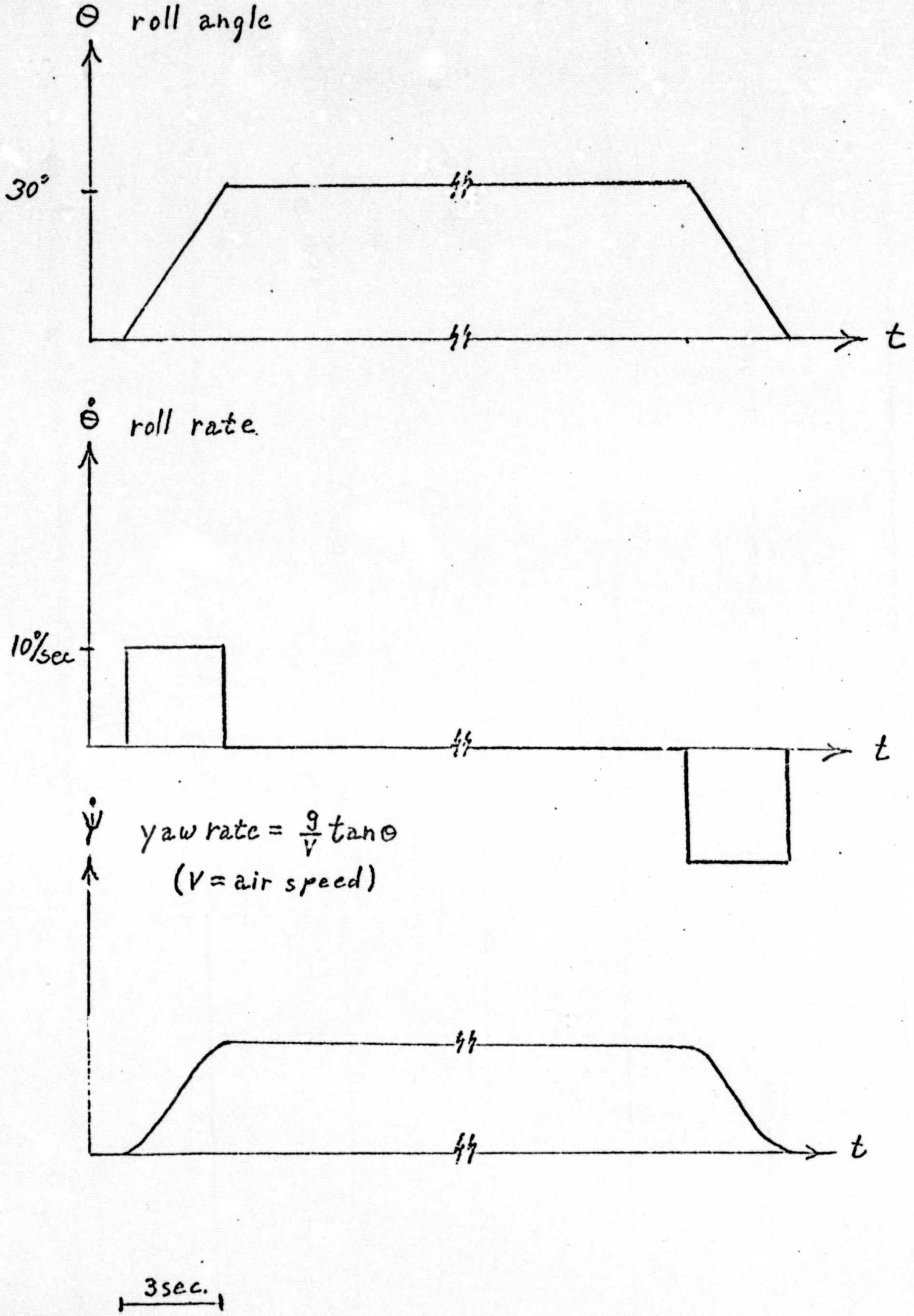
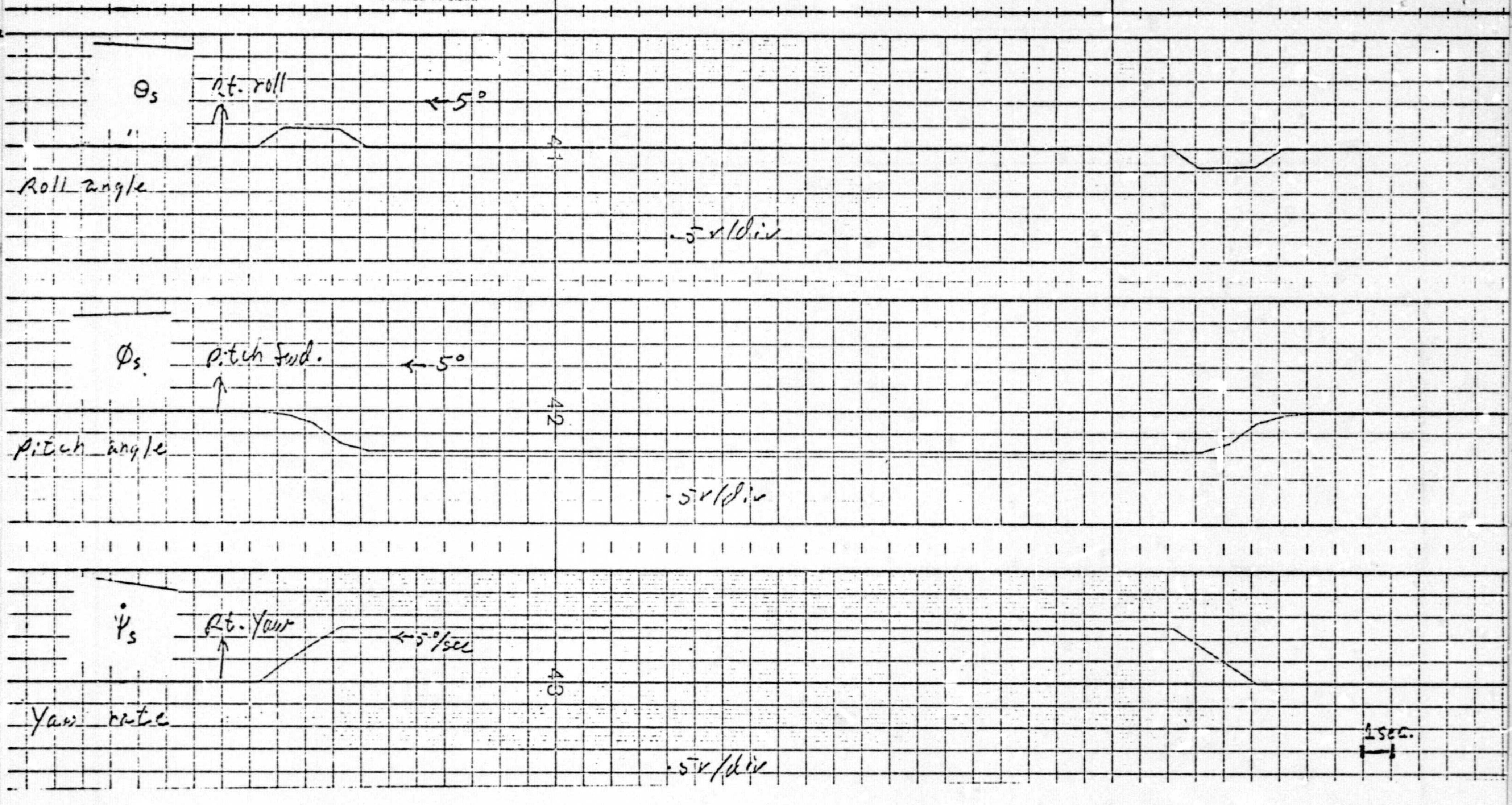


FIGURE 3.

Link Simulation of 30° Bank, 85 Knot, Coordinated Turn (Based on Ormsby Model)



$\dot{\psi}_s = \dot{\psi}\left(\frac{\cos\Theta}{\cos\Theta_s}\right)$ where Θ = roll angle in fig. 1 ; $\dot{\psi}$ = yaw rate in fig. 1

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

FIGURE 4.

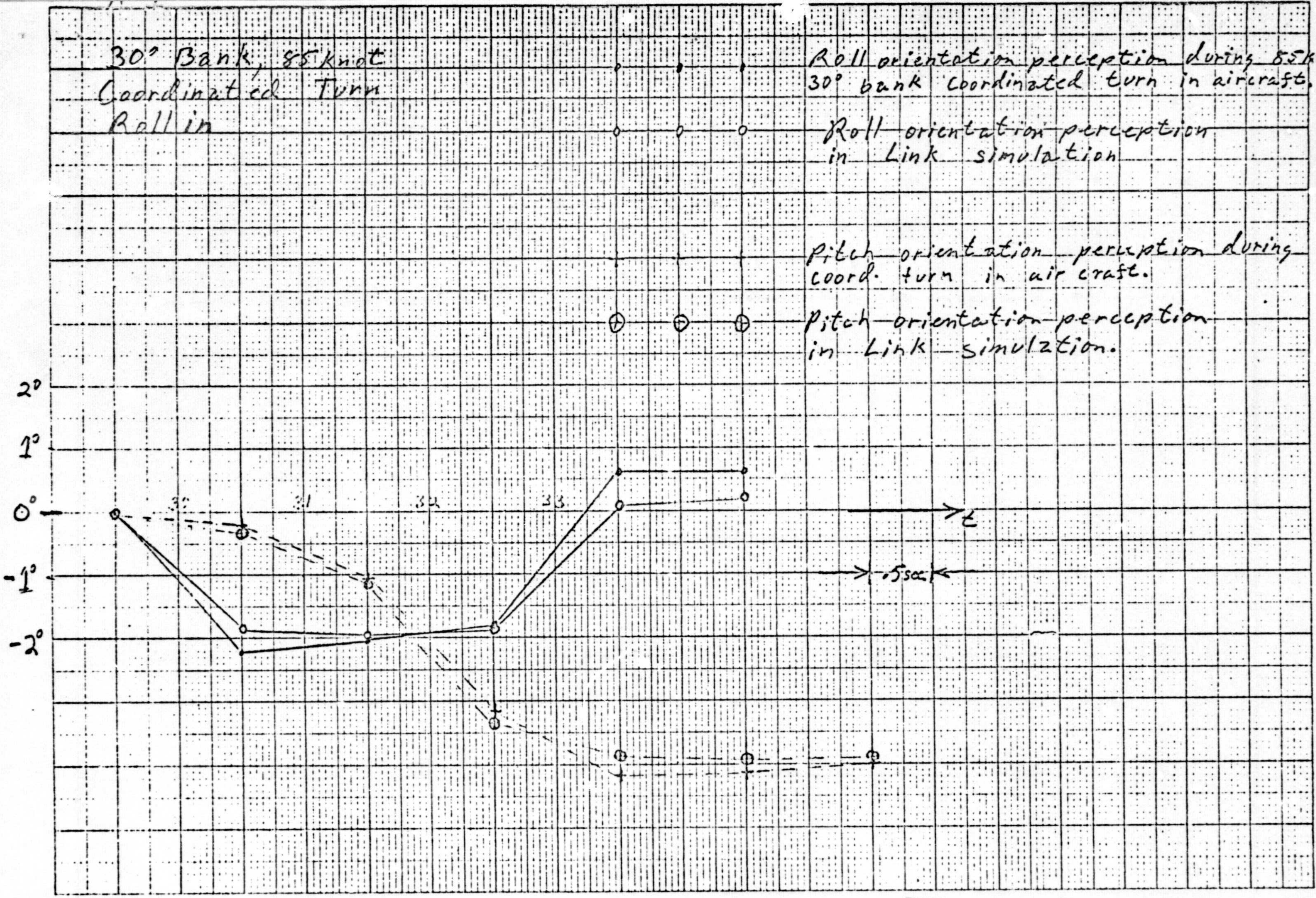

30° Bank, 85 knot
Coordinated Turn
Roll in
Roll orientation perception during 85 k
30° bank coordinated turn in aircraft.
Roll orientation perception
in Link simulation
Pitch orientation perception during
coord. turn in air craft.
Pitch orientation perception
in Link simulztion.
2°
1°
0°
-1°
-2°
30
31
32
33
t
.5 sec

FIGURE 5.

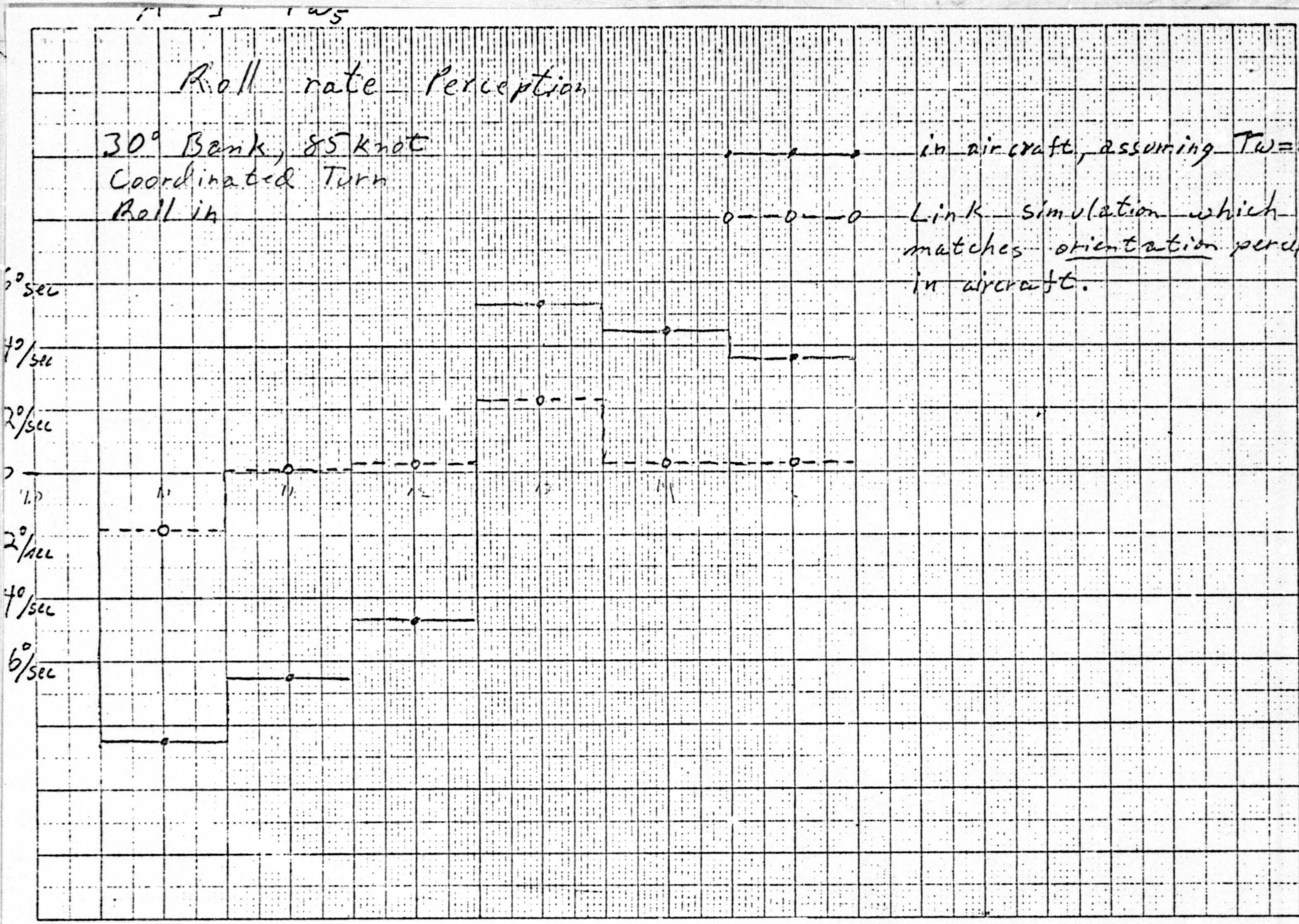
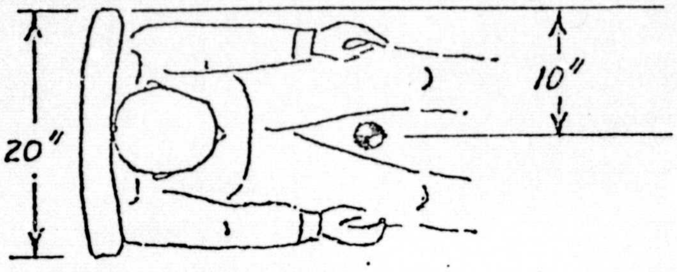
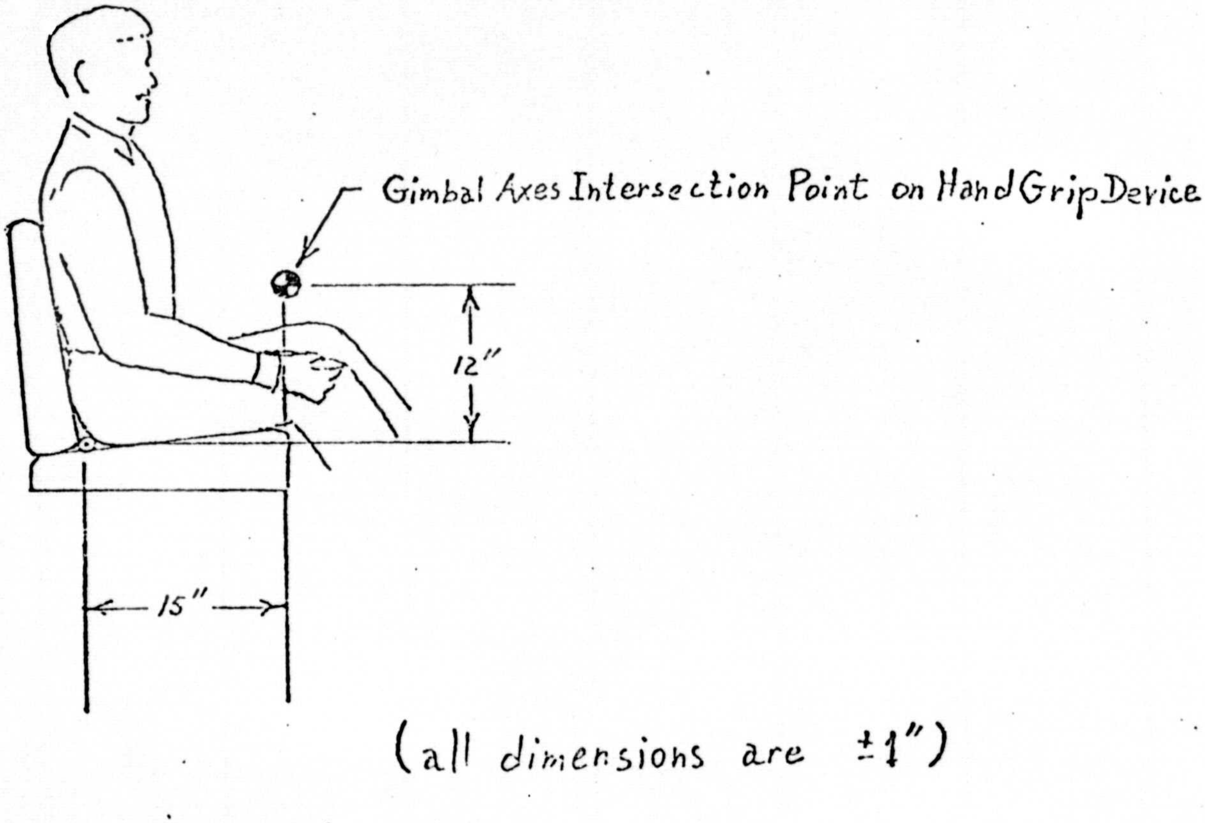

Roll rate Perception
30° Bank, 85 knot
Coordinated Turn
Roll in
in aircraft, assuming Tw=5sec.
Link simulation which matches orientation perception in aircraft.
6°/sec
4°/sec
2°/sec
0
2°/sec
4°/sec
6°/sec

FIGURE 6.

Position of Hand Grip Indicator Device as Installed in Link Trainer





(all dimensions are ±1")

FIGURE 7.

Side View of Hand Grip Indicator Device

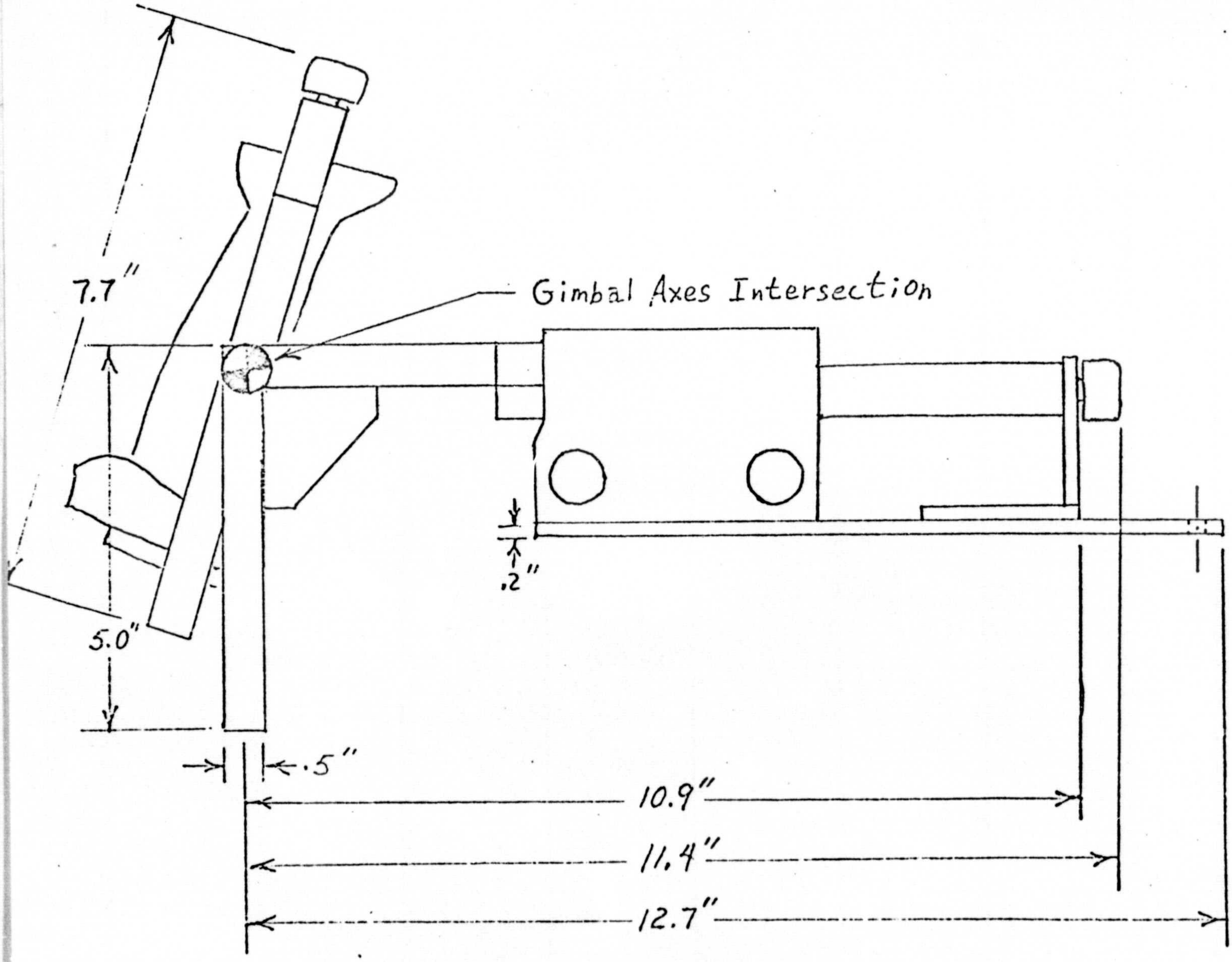


FIGURE 8.

Top View of Hand Grip Indicator Device

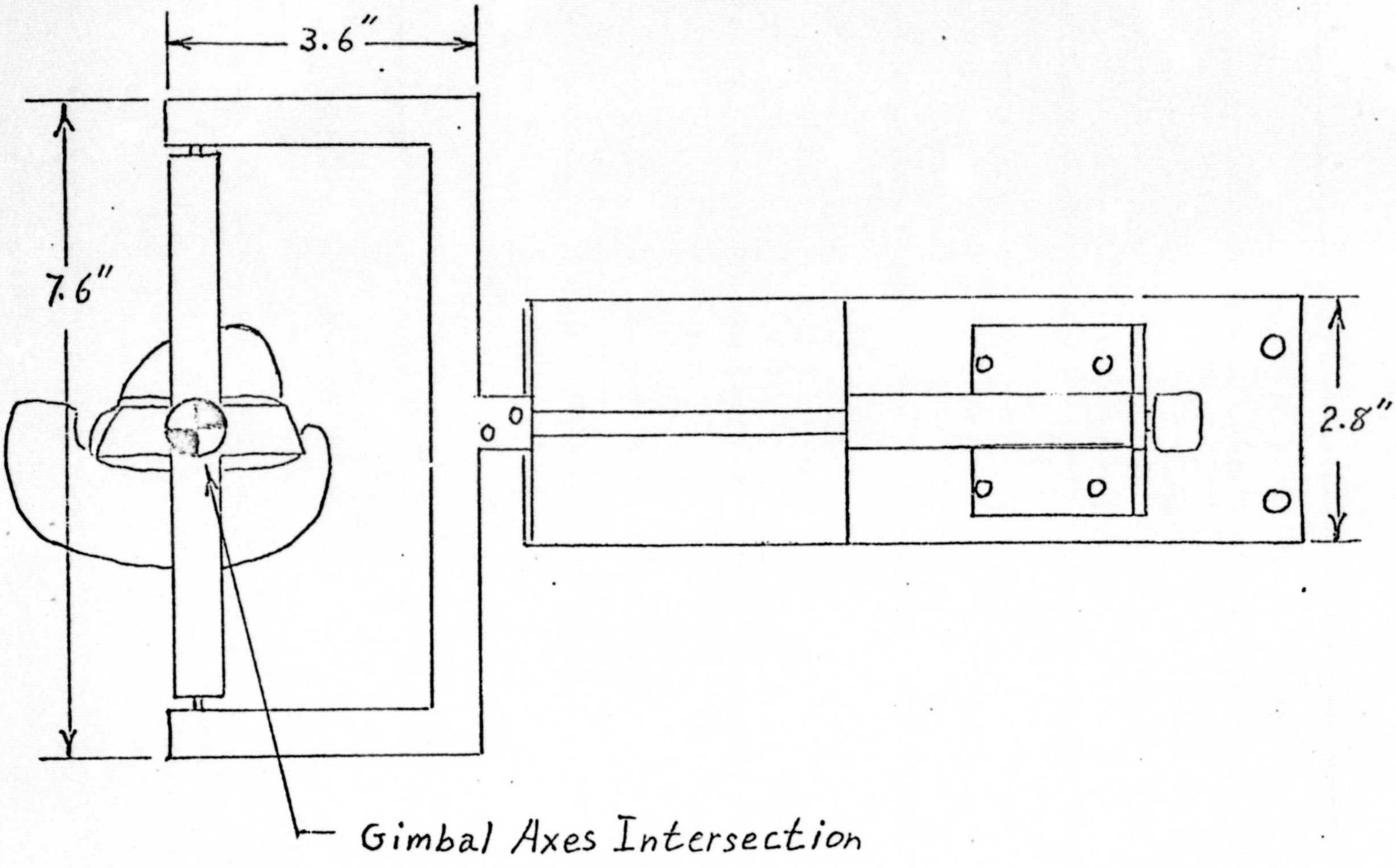
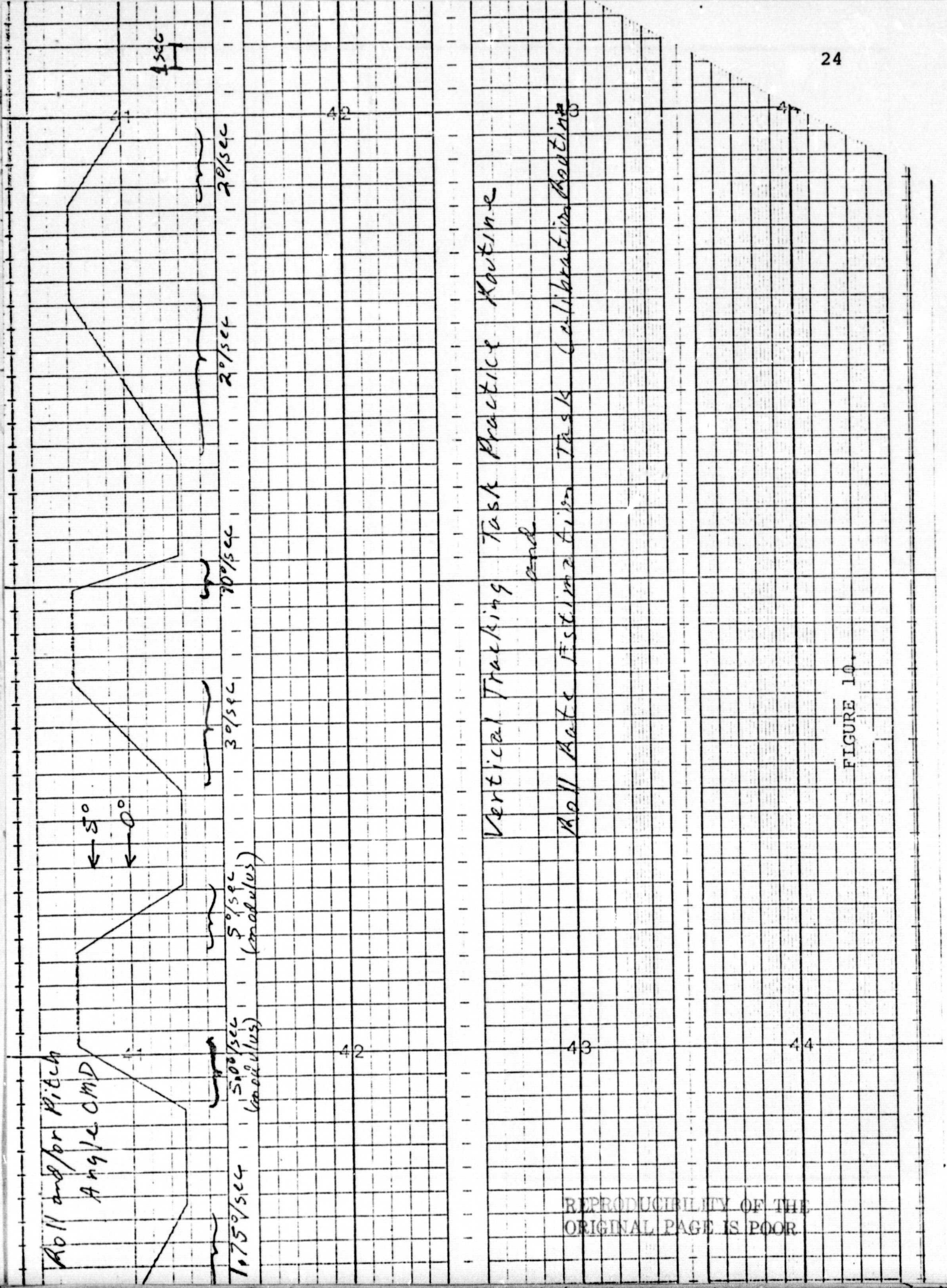
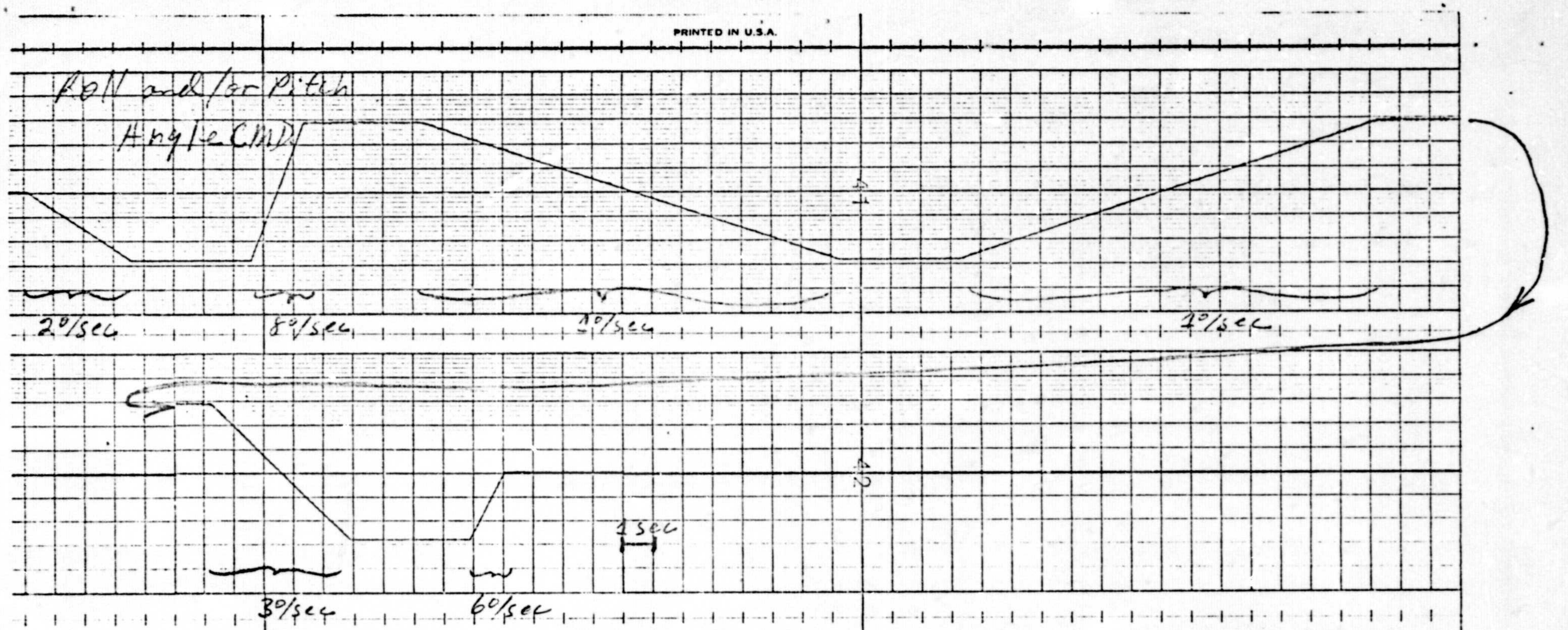


FIGURE 9.



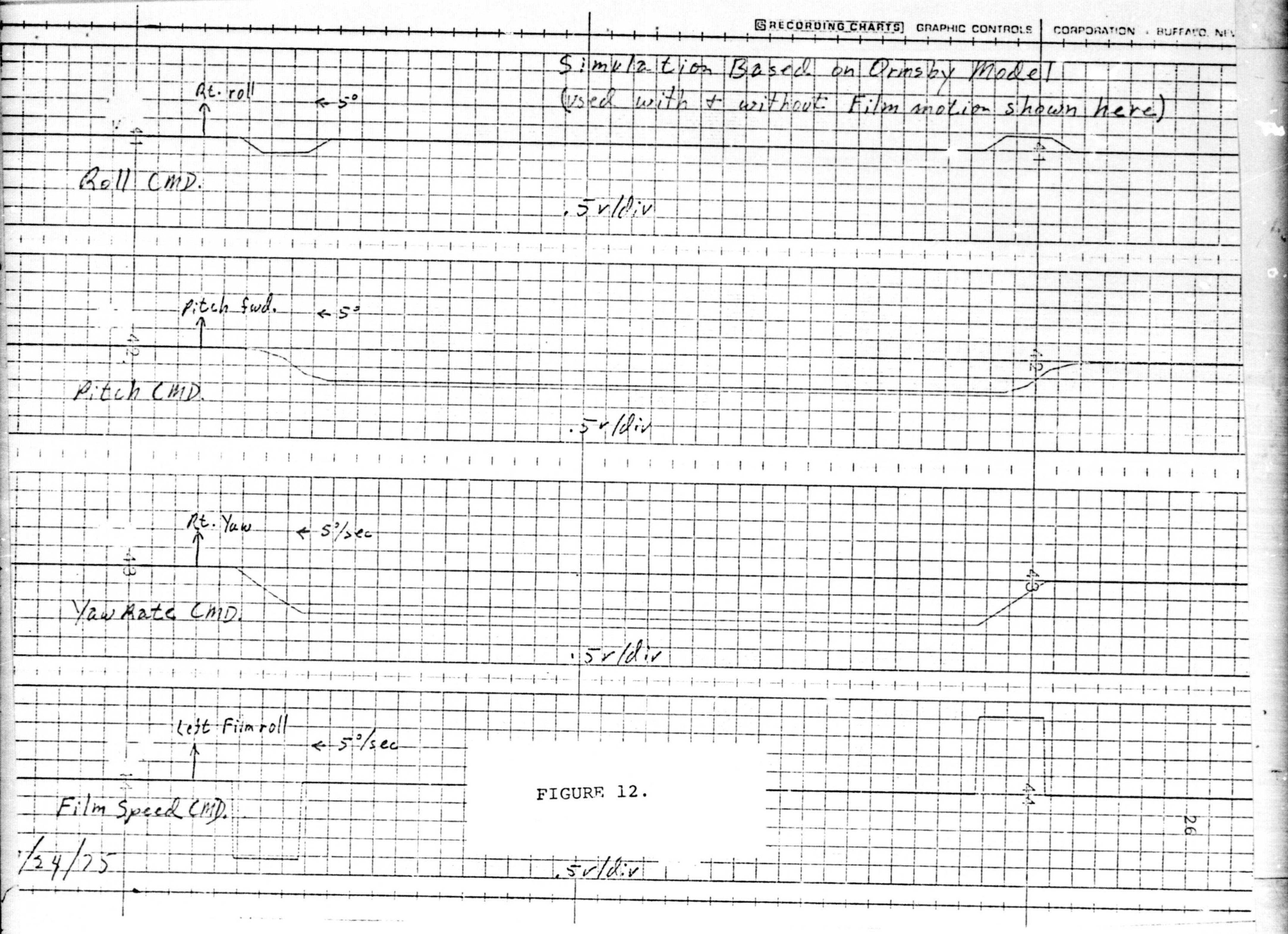
Vertical Tracking Task Practice Routine and Roll Rate Estimation Task Calibration Routine

FIGURE 10.



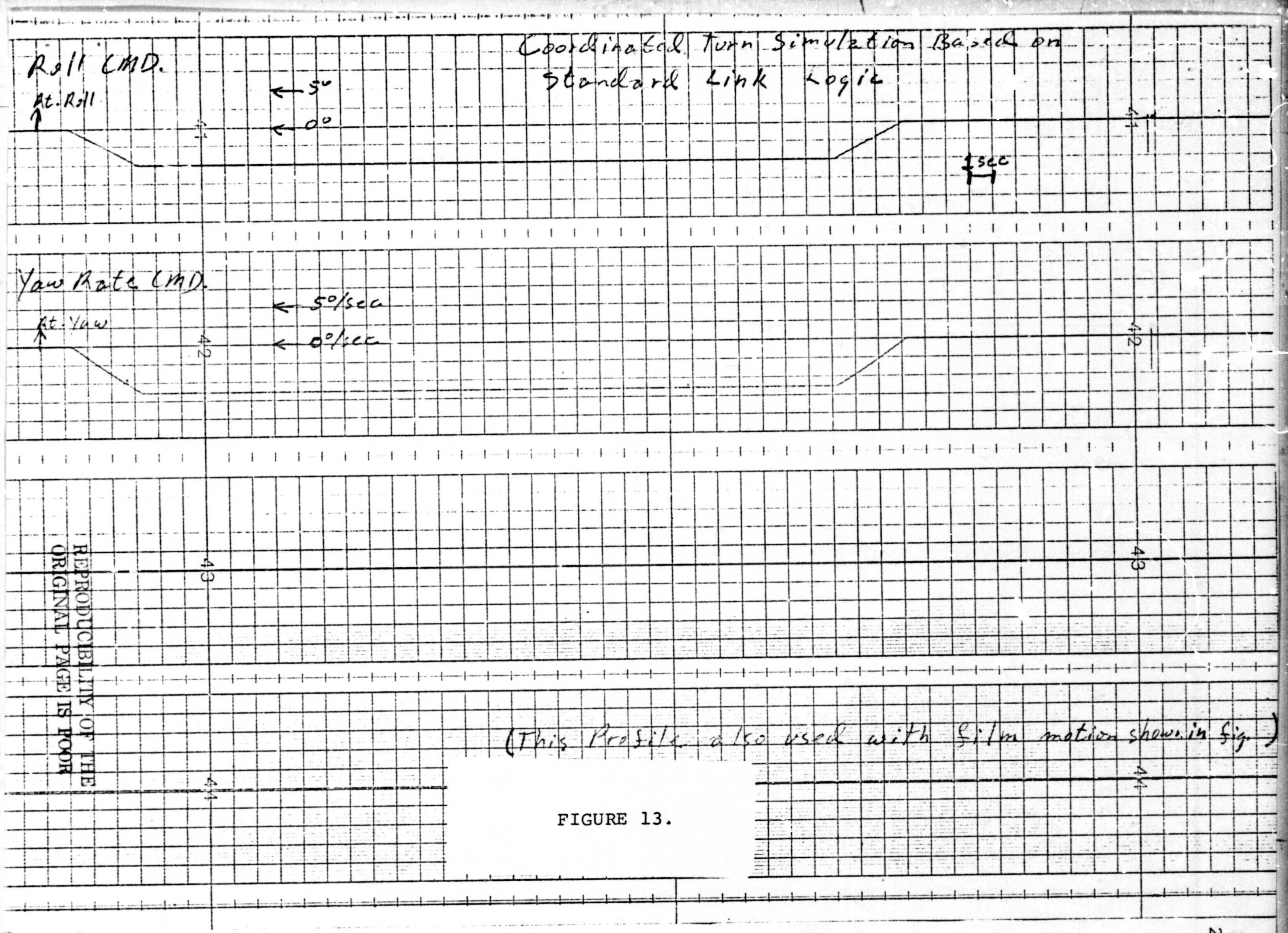
Vertical Tracking Task Practice Routine
and
Roll Rate Estimation Task Calibration Routine

FIGURE 11.



Simulation Based on Ormsby Model
(used with + without Film motion shown here)

FIGURE 12.



Coordinated turn Simulation Based on Standard Link Logic

(This Profile also used with film motion shown in fig.)

FIGURE 13.

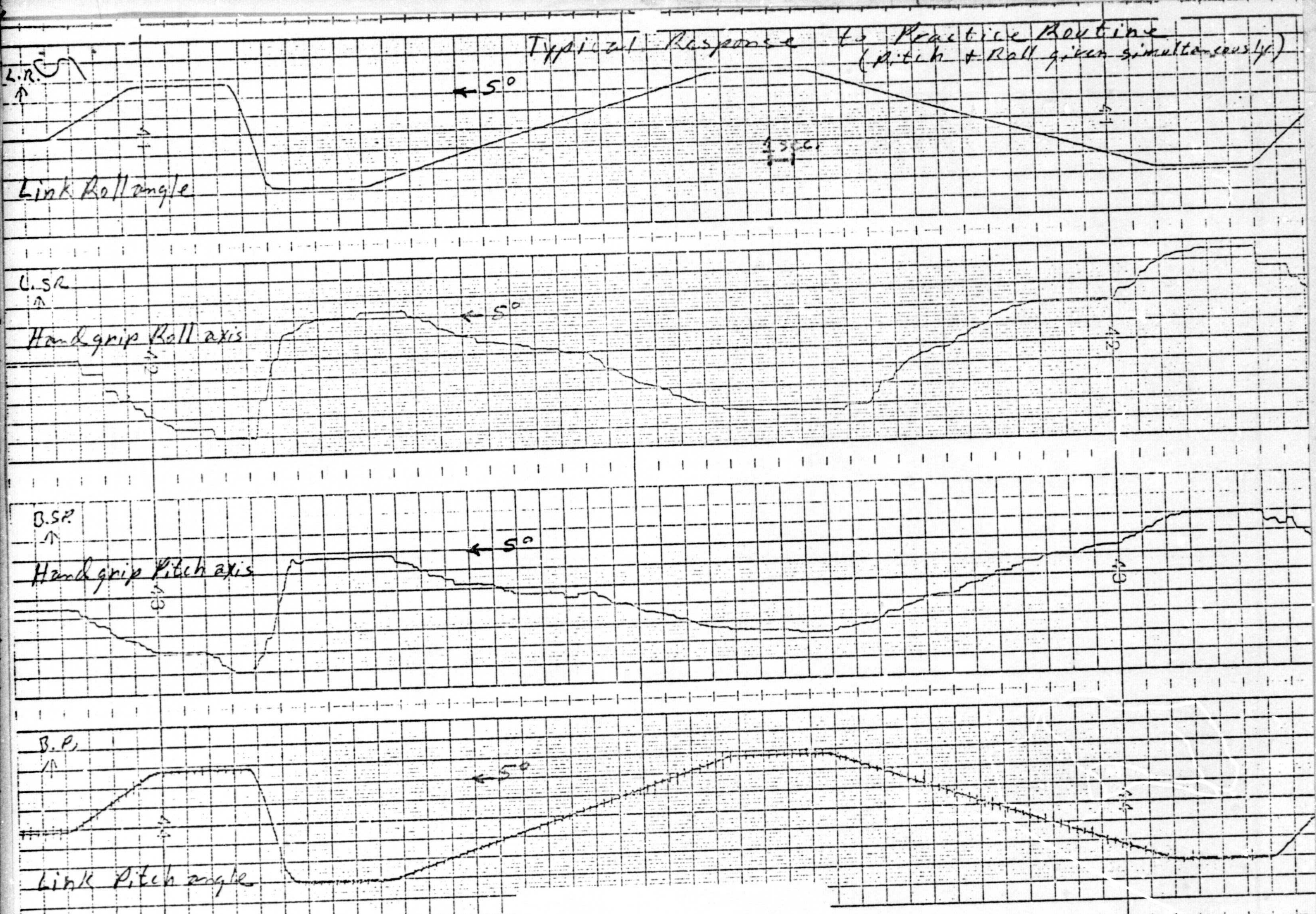
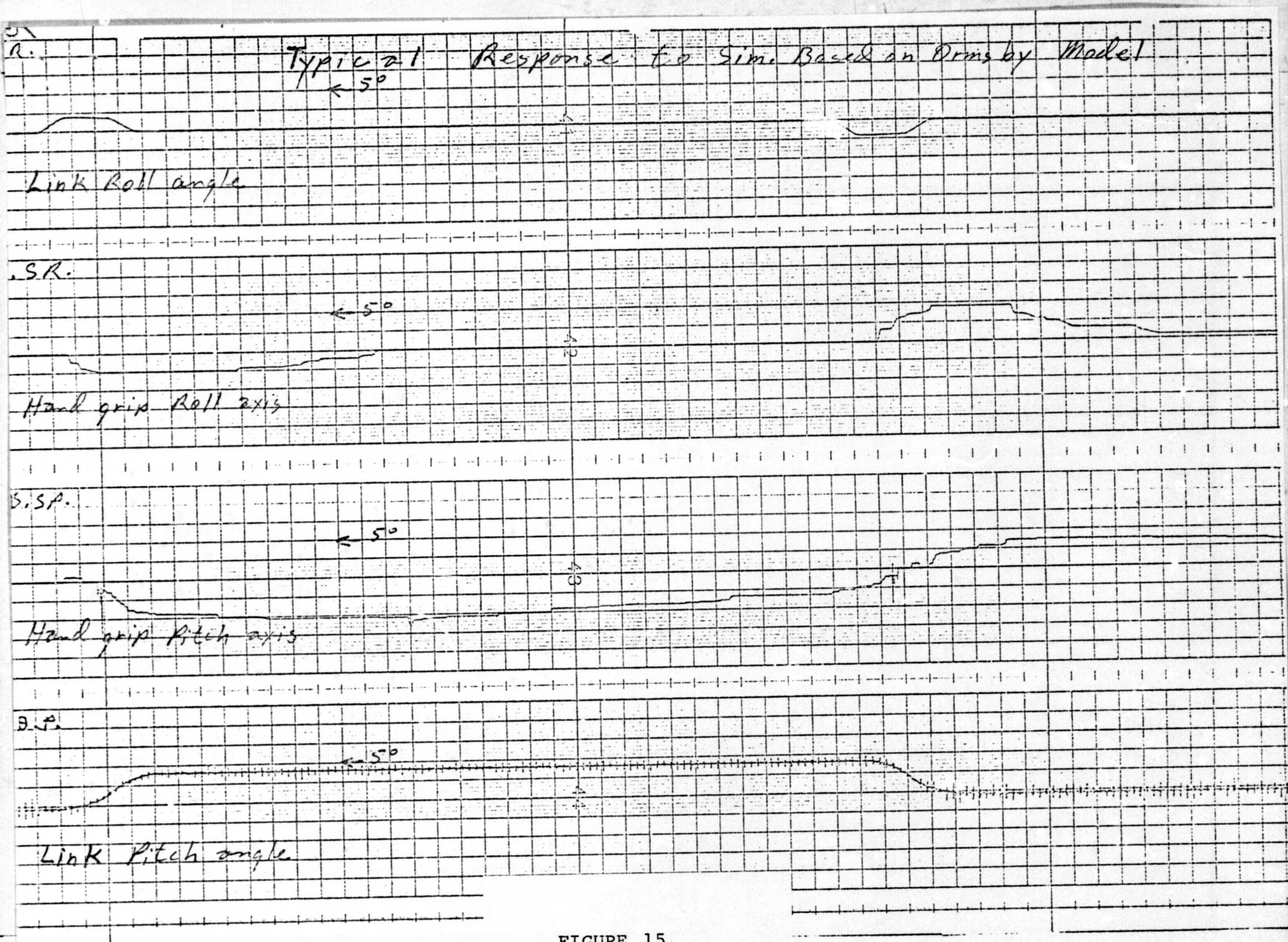

Typical Response to Practice Routine
(Pitch + Roll given simultaneously.)
L.R.
Link Roll angle
← 5°
1 sec.
41
L.S.R.
Handgrip Roll axis
← 5°
42
B.S.P.
Handgrip Pitch axis
← 5°
43
B.P.
Link Pitch angle
← 5°
44

FIGURE 14.



Typical Response to Sim. Based on Orms by Model

FIGURE 15.

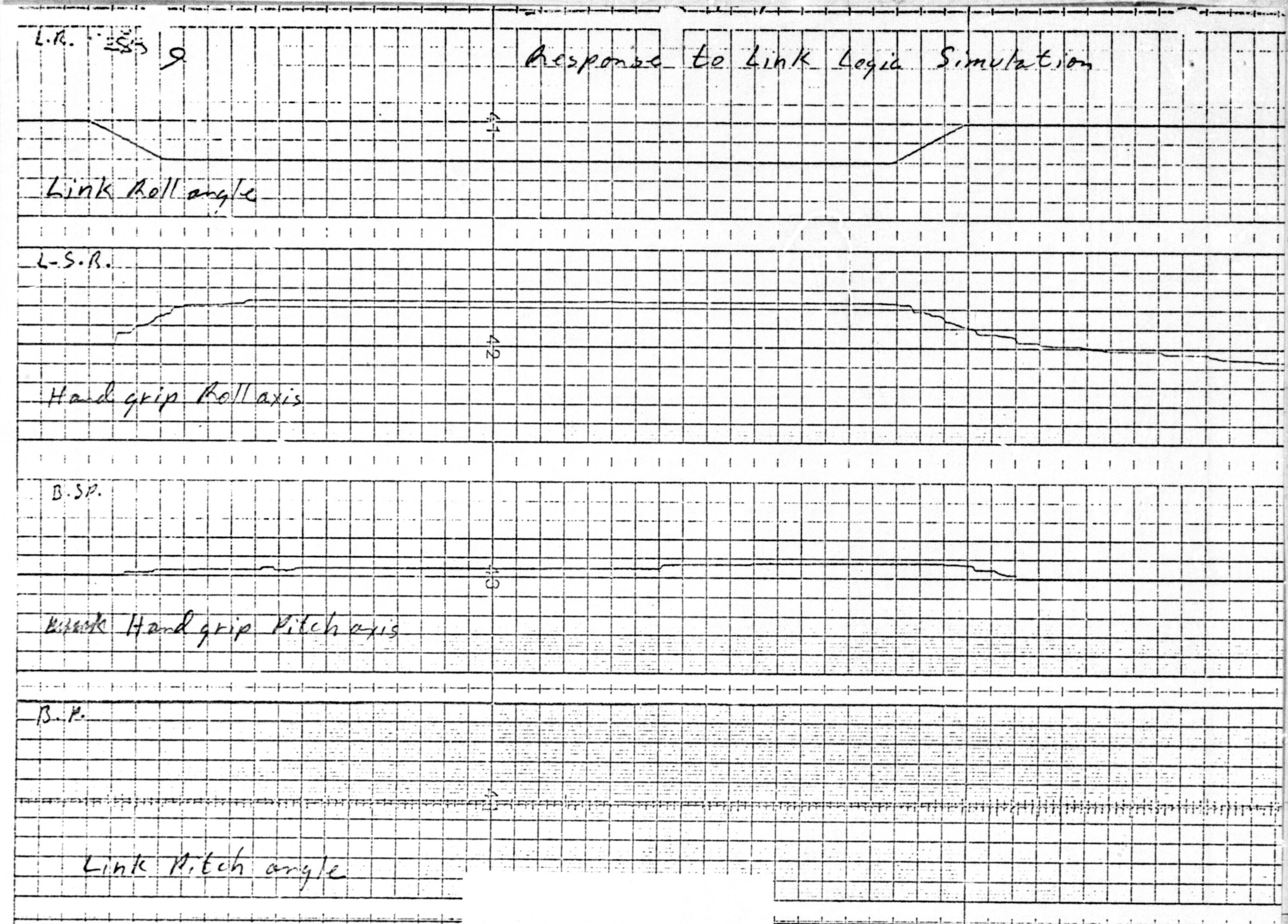

L.R.
9
Response to Link Logic Simulation
41
Link Roll angle
L.S.R.
42
Handgrip Roll axis
B.SP.
43
Handgrip Pitch axis
B.P.
Link Pitch angle

FIGURE 16.

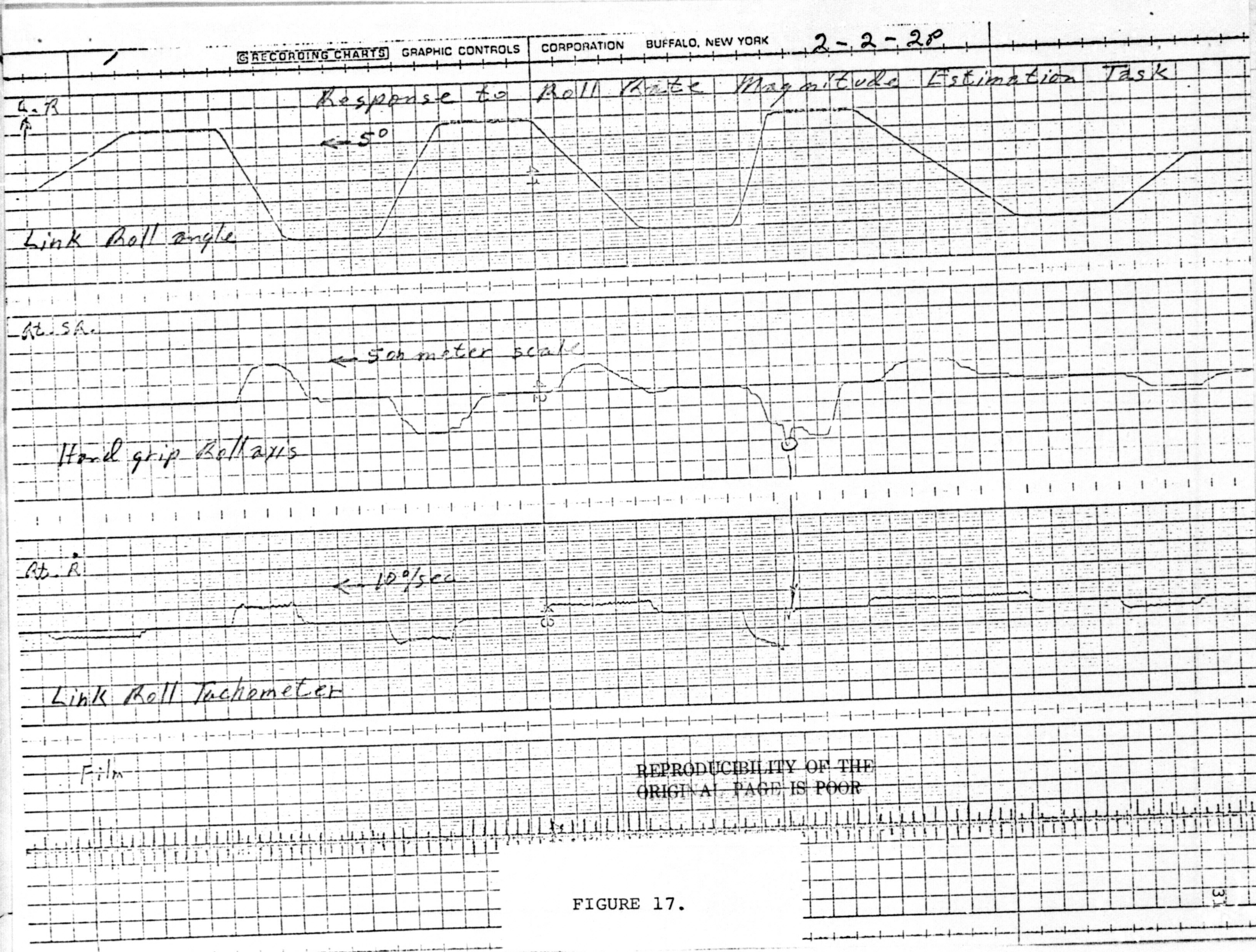

1
RECORDING CHARTS GRAPHIC CONTROLS CORPORATION BUFFALO, NEW YORK
2-2-28
Response to Roll Rate Magnitude Estimation Task
L.R
←5°
Link Roll angle
Rt. SR.
←50 meter scale
Hand grip Roll axis
Rt. Ṙ
←10°/sec
Link Roll Tachometer
Film

FIGURE 17.

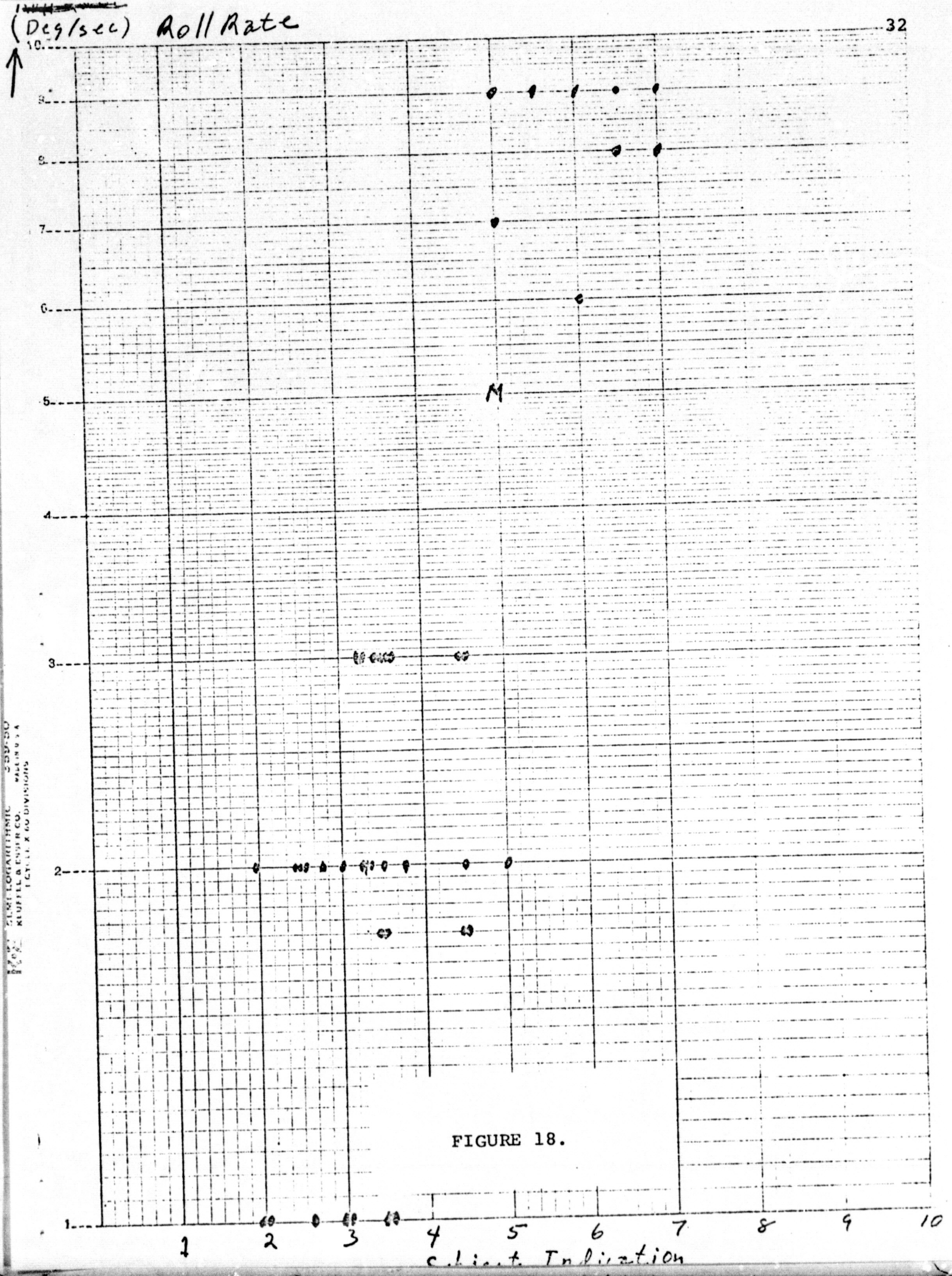

(Deg/sec) Roll Rate
10
9
8
7
6
5
4
3
2
1
M
1
2
3
4
5
6
7
8
9
10
Subject Indication
SEMI-LOGARITHMIC 359-50
KEUFFEL & ESSER CO. MADE IN U.S.A.
1 CYCLE X 60 DIVISIONS

FIGURE 18.

PUBLICATIONS

Several papers have been prepared and submitted for publication during the reporting period; several others have been presented at meetings. Abstracts of these papers are presented below.

A paper written by Professor Young, Drs. Berthoz and Pavard is in press in the Journal of Experimental Brain Research.

PERCEPTION OF LINEAR HORIZONTAL SELF-MOTION INDUCED BY PERIPHERAL VISION (LINEARVECTION)

A. BERTHOZ, B. PAVARD, and L.R. YOUNG

SUMMARY

The basic characteristics of linear horizontal motion have been studied. Objective linear motion was induced by means of a moving cart. Visually induced linear motion perception (linearvection) was obtained by projection of moving images at the periphery of the visual field. Image velocity and luminance thresholds for the appearance of linearvection have been measured and are in the range of those for image motion detection (without sensation of self motion) by the visual system. Latencies of onset are around 1 second and short term adaptation has been shown. The dynamic range of the visual analyser as judged by frequency analysis is lower than for the vestibular analyser. Conflicting situations in which visual cues contradict vestibular and other proprioceptive cues show, in the case of linearvection, a dominance of vision which supports the idea of an essential although not independent role of vision in self motion perception.

Two papers prepared by Professor Young and Dr. Charles Ormsby are in press; the first in Aerospace and Environmental Medicine and the second in the Journal of Mathematical Biosciences. The papers are abstracted here.

PERCEPTION OF STATIC ORIENTATION IN A CONSTANT GRAVITOINERTIAL ENVIRONMENT

C.C. ORMSBY and L.R. YOUNG

ABSTRACT

Human perception of the direction of the gravitational vertical, in the absence of visual cues, is based principally on vestibular information. This paper examines the setting of the apparent vertical (subjective indication of the earth vertical) under quasi-static conditions, in which the effects of body angular accelerations are assumed to have decayed to a negligible level. The variety of existing data is shown to be consistent with a simple vector transformation which could be associated with differences in the treatment of signals arising from stimuli in and stimuli perpendicular to the "utricle plane". The dynamic aspects of interactions between semicircular canal and otolith system information are discussed in a separate paper.

This paper attempts to unify the results observed and relate them to vestibular function by:

1. demonstrating that a relatively simple categorization of the stimulus enables one to predict qualitatively the deviations of the perceived vertical from the true direction of specific force;

2. constructing a model consistent with both the physical structure of the otolith sensors and with the above categorization of stimuli which predicts with reasonable accuracy the perceptions of orientation resulting from arbitrary constant specific force stimuli.

INTEGRATION OF SEMICIRCULAR CANAL AND OTOLITH INFORMATION FOR MULTISENSORY STIMULI

C.C. ORMSBY and L.R. YOUNG

ABSTRACT

In this paper the subjective responses to multisensory stimuli (those stimuli which simultaneously excite the semicircular canals and the otoliths) are modelled and the predictions of this model compared to the appropriate experimental data. Previous quantitative models have dealt almost exclusively with the response to noninteracting stimuli (those stimuli which excite either the otoliths or the semicircular canals, but not both). When the stimulus class is generalized to include any combination of rotational acceleration in three axes a number of significant problems arise. After these problems are discussed, a mathematical model is developed of the perception of dynamic orientation which results from the combined effect of arbitrary angular and translational accelerations. To illustrate the usefulness of the model for the conceptual understanding of responses to multisensory stimuli, three examples of the qualitative applications of the model are given. The paper concludes by presenting the quantitative predictions of the model along with frequency response of the model for small pitch and roll oscillations.

Professor Young made two presentations during the reporting period; one at the Ninth Center for Visual Science Symposium and the other at the Neurosciences Meeting. These papers are abstracted below.

INFLUENCE OF MOVING VISUAL STIMULI ON VESTIBULAR NUCLEUS NEURONS

V.S. HENN and L.R. YOUNG

ABSTRACT

This paper reviews some of the influences of moving visual fields on vestibular units in the brain stem of alert monkeys located in the medial vestibular nucleus. Only those units not directly linked to eye movements are considered. The neurons are identified by their characteristic response to horizontal angular acceleration seen during velocity steps and sinusoids in the dark. Visual influence on activity was demonstrated first by the activation or inhibition associated with movement of the whole visual field. Further investigation of visual-vestibular interaction in these units with rotation in the light and with combined oscillation of the animal and independent rotation of the visual field demonstrates the interaction between these inputs. Recordings of attempted head movements by measurement of torque on the head restraint show that, although this torque was frequently associated with vestibular or optokinetic nystagmus and unit activity, it was neither necessary nor sufficient for such activation.

Without any implication that these second order vestibular units code self motion, some of the parallels with the human circularvection data discussed by Held, Dichgans, and Young should be borne in mind. First, the time course of development of circularvection, its steady state during

constant visual field velocity, and its rebound following the stopping of the field is paralleled by the unit activity. Second, the interaction with vestibular stimuli, showing transient vestibular and steady state visual dominance of self motion is seen in the unit activity. Finally, the weaker correlation of unit activity with head torque is parallel to the human postural responses resulting from reaction to visually induced motion as measured on the posture platform.

PURSUIT EYE MOVEMENTS GENERATED DURING APPARENT MOTION

L.R. YOUNG and W. CHU

It has often been noted that smooth pursuit eye movements can be generated in the absence of any retinal slip velocity, as in the case of tracking an after-image, and aided by tracking one's own hand. The perceptual feedback hypothesis was advanced to account for such behavior on the basis that smooth eye movements were generated by vestibular inputs, efferent copy during after-image viewing, or even by an imagined target driven by active hand movement. In the current experiments, we examined the relationship between apparent motion of a series of horizontally spaced dots (phi phenomenon) and the following eye movements. Although it is known that the phi phenomenon does not require eye movement, and that smooth pursuit can be generated by discrete target steps, it remained undetermined whether the stimulus conditions which produced continuous apparent motion would also generate pursuit tracking.

The stimulus consisted of eight spots on a CRT covering a visual angle of 12 degrees, which were illuminated sequentially with various periods and duty cycles. For each of 7 subjects, a given "velocity", between 6 and 12 deg/sec was chosen, and the duty cycle was varied to present more or less phi. For conditions which did not produce phi, 50% more saccades per sweep were generated on the average then when phi was present. Similarly, for duty cycles which produced phi occasionally, the eye tracking showed more pursuit and fewer saccades during times when phi was reported.

These results support the perceptual feedback hypothesis by showing the tendency for pursuit eye movements to follow apparent smooth motion in the absence of continual retinal slip.

Finally, William H.N. Chu has completed his SM Thesis with support from this grant. The complete thesis (except the final appendix) is enclosed and the abstract is presented below.

DYNAMIC RESPONSE OF HUMAN LINEARVECTION

W.H.N. CHU

S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, January 1976.

ABSTRACT

The function of human visually induced sensation of linear motion (linearvection) was examined. The experiments performed were mainly designed to investigate the frequency response of the human linearvection mechanism. It was shown that both the gain and phase exhibited steady decrease for increasing frequency. Asymmetry in the response was also studied. It was shown that visually induced downward moving sensation is stronger than the sensation of upward motion. There also seemed to be a stronger backward moving sensation than the forward one. The break frequency was found to be approximately 0.1 Hz.