

NASA TECHNICAL NOTE



NASA TN D-8001 e.1

NASA TN D-8001

LOAN COPY: RETU  
AFWL TECHNICAL L  
KIRTLAND AFB, TX



FIXED-BASE SIMULATOR STUDY OF THE EFFECT  
OF TIME DELAYS IN VISUAL CUES ON  
PILOT TRACKING PERFORMANCE

*M. J. Queijo and Donald R. Riley*

*Langley Research Center*

*Hampton, Va. 23665*



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1975



0133901

1. Report No. NASA TN D-8001	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle FIXED-BASE SIMULATOR STUDY OF THE EFFECT OF TIME DELAYS IN VISUAL CUES ON PILOT TRACKING PERFORMANCE		5. Report Date October 1975	6. Performing Organization Code
		8. Performing Organization Report No. L-10152	10. Work Unit No. 504-09-41-03
7. Author(s) M. J. Queijo and Donald R. Riley		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Note	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23665		14. Sponsoring Agency Code	
		12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	
15. Supplementary Notes			
16. Abstract  An experimental study has been made to examine factors which determine the amount of time delay acceptable in the visual feedback loop in flight simulators. Acceptable time delays are defined as delays which significantly affect neither the results nor the manner in which the subject "flies" the simulator. The study was made using a fixed-base simulator with a closed-circuit television system. The subject tracked a target aircraft as it oscillated sinusoidally in a vertical plane only. The pursuing aircraft was permitted five degrees of freedom. Time delays of from 0.047 to 0.297 second were inserted in the visual feedback loop. A side task was employed to maintain the workload constant and to insure that the pilot was fully occupied during the experiment. Tracking results were obtained for 17 aircraft configurations having different longitudinal short-period characteristics. Results show a positive correlation between improved handling qualities and a longer acceptable time delay.			
17. Key Words (Suggested by Author(s)) Simulation Flying qualities Aircraft dynamics Time delay		18. Distribution Statement Unclassified - Unlimited  Subject Category 05	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 77	22. Price* \$4.75

# FIXED-BASE SIMULATOR STUDY OF THE EFFECT OF TIME DELAYS IN VISUAL CUES ON PILOT TRACKING PERFORMANCE

M. J. Queijo and Donald R. Riley  
Langley Research Center

## SUMMARY

An experimental study has been made to examine factors which determine the amount of time delay which is acceptable in the visual feedback loop in flight simulators. Acceptable time delays are defined as delays which significantly affect neither the results nor the manner in which the subject "flies" the simulator. The study was made using a fixed-base simulator in which a subject tracked a target airplane as it oscillated in a vertical plane only. The pursuing aircraft was permitted five degrees of freedom. Time delays of from 0.047 to 0.297 second were inserted in the visual feedback loop. Results from this study have indicated the following:

1. The acceptable time delay appears to be related to the frequency and damping of the short-period longitudinal mode of the simulated aircraft. In this study the aircraft lateral characteristics were held constant. In general, the acceptable time delay decreases as pilot rating increases (that is, as handling qualities become less desirable).

2. Even small time delays (in the order of 0.047 second) can have an adverse effect on pilot performance for some aircraft configurations. For the range of aircraft parameters of this study, the maximum time delay which could be tolerated (without affecting the subject's performance or operating procedure) was about 0.141 second.

3. Increasing task complexity or degrading the vehicle handling qualities reduces the acceptable level of visual-scene time delay.

## INTRODUCTION

Results obtained in a piloted simulator are valid and representative of the real vehicle if the subject is provided with the proper environment and cues, and if these conditions cause him to respond in the same manner as he would in the real vehicle. Most simulators are attached to the ground in some manner and therefore have very limited motion. In addition, out-of-the-window visual cues are usually generated by the use of models and closed-circuit television or by electronic image generators. Such visual cues do not provide good fidelity, for example, in the color, detail, and texture of the true visual scene.

Since the exact simulation of visual and motion cues is often prohibitively expensive or actually impossible, it becomes important to determine how great a departure from reality can be tolerated while still obtaining results that are valid with respect to the simulated vehicle and task. The acceptable departure might be tempered by many factors, such as the stability and control characteristics of the simulated vehicle or task. Acceptable departures may also depend on the factors involved. For example, greater realism might be required in visual cues than in motion cues.

The purpose of the present study is to examine the effects of time delay in the visual cues presented to the subject in a simulator. Time delays of this type can arise from such sources as the sampling rates in digital computing systems, the inertias of components of image-generating systems, or the computation time required to produce computer-generated images. This study was accomplished by first permitting the subject to fly the simulator with essentially zero time delay in the visual displays. This condition represented the "real" vehicle. Time delays were then put into the visual displays and their effects were evaluated. Since the rate of response expected in a visual scene is related to aircraft characteristics, some aircraft parameters were varied in this study.

## SYMBOLS

Values are given in both the International System of Units (SI) and in U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

A,B	constants in workload equation
a	acceleration caused by aerodynamic forces, $m/sec^2$ (ft/sec <sup>2</sup> )
c	average number of counts per minute for a single run
g	gravitational acceleration, $m/sec^2$ (ft/sec <sup>2</sup> )
I	moment of inertia, $kg\cdot m^2$ (slug-ft <sup>2</sup> )
L	lift force, N (lb)
$L_o$	$= \frac{\text{Trim lift}}{mV_{x,o}}$
$L_p$	$= \frac{1}{I_x} \frac{\partial l}{\partial p}$

$$L_r = \frac{1}{I_x} \frac{\partial \mathcal{L}}{\partial r}$$

$$L_\alpha = \frac{1}{mV_{x,0}} \frac{\partial \mathcal{L}}{\partial \alpha}$$

$$L_\beta = \frac{1}{I_x} \frac{\partial \mathcal{L}}{\partial \beta}$$

$$L_{\delta_a} = \frac{1}{I_x} \frac{\partial \mathcal{L}}{\partial \delta_a}$$

$\mathcal{L}$  rolling moment, N/m (ft-lb)

$\ell_j, m_j, n_j$  direction cosines ( $j = 1, 2, 3$ )

$M$  pitching moment, N/m (ft-lb)

$$M_q = \frac{1}{I_y} \frac{\partial M}{\partial q}$$

$$M_\alpha = \frac{1}{I_y} \frac{\partial M}{\partial \alpha}$$

$$M_{\delta_e} = \frac{1}{I_y} \frac{\partial M}{\partial \delta_e}$$

$m$  aircraft mass, kg (slugs)

$N$  yawing moment, N/m (ft-lb)

$$N_p = \frac{1}{I_z} \frac{\partial N}{\partial p}$$

$$N_r = \frac{1}{I_z} \frac{\partial N}{\partial r}$$

$$N_\beta = \frac{1}{I_z} \frac{\partial N}{\partial \beta}$$

$$N_{\delta_a} = \frac{1}{I_z} \frac{\partial N}{\partial \delta_a}$$

$$N_{\delta_r} = \frac{1}{I_z} \frac{\partial N}{\partial \delta_r}$$

PL	performance level
p	angular rate around aircraft longitudinal axis, rad/sec
q	angular rate around aircraft lateral axis, rad/sec
r	angular rate around aircraft normal axis, rad/sec
s	Laplace variable
u,v,w	aircraft velocities along the longitudinal, lateral, and normal axes, respectively, m/sec (ft/sec)
V	aircraft velocity, m/sec (ft/sec)
$V_{x,0}$	initial aircraft total velocity, m/sec (ft/sec)
WLI	work-level indicator
Y	side force, N (lb)
$Y_{\beta}$	$= \frac{1}{mV_{x,0}} \frac{\partial Y}{\partial \beta}$
$\alpha$	change in angle of attack from trim, rad
$\beta$	sideslip angle, rad
$\delta_a$	aileron deflection, rad or deg
$\delta_e$	elevator deflection, rad or deg
$\delta_r$	rudder deflection, rad
$\epsilon$	$= \epsilon_v + \epsilon_h$ , m (ft)
$\epsilon_h$	horizontal tracking error, m (ft)
$\epsilon_v$	vertical tracking error, m (ft)

$\zeta$	damping ratio of longitudinal short-period mode
$\tau$	units of time delay in visual-scene display (each unit equals 1/32 sec)
$\psi, \theta, \phi$	Euler angles, deg or rad
$\omega_n$	natural frequency of longitudinal short-period mode, rad/sec

Subscripts:

o	indicates initial condition
x,y,z	denote the aircraft or inertial x,y,z axes, respectively

A dot over a quantity indicates a derivative with respect to time. The rms ( ) indicates root-mean-square value of variable in parentheses for a single run. A bar over a symbol indicates the arithmetic mean of rms ( ) values for all runs having identical test conditions.

## DESCRIPTION OF APPARATUS

The tests were performed in the Langley Research Center Visual-Motion Simulator (VMS) shown in figure 1. For the present study, it was used as a fixed (nonmoving) base.

The subject's compartment is somewhat representative of a two-man cockpit (fig. 2). Although the panel instruments were illuminated, they were not operational and were not used by the subjects. Visual cues (target aircraft) were generated through the use of a small target model and closed-circuit television. The model was mounted in a three-gimbal support, and it rotated in response to the relative equations of motion of the two aircraft so that the subject would see the proper aspect of the target. The inertias of the model were very low, so that the rotations responded almost instantaneously. Elevation and azimuth changes of the target aircraft in the display were obtained by repositioning the television raster electronically. The repositioning was accomplished by using scaled voltages to represent angles of deflection in elevation and azimuth. This technique eliminated unwanted delays in visual-scene presentation; such delays occur when electromechanical systems (involving mirrors, gears, and electric motors) are used to obtain elevation and azimuth position. The image was displayed using a television screen with an infinity optics mirror.

The horizon also was projected on the screen. A reticle (crossed lines) was projected on the center of the screen to represent sights on the aircraft being flown by the subject. A photograph of a visual scene observed by the subject is presented in figure 3.

The subject maneuvered his aircraft through the use of a two-axis finger-tip pencil controller, which controlled rotations about the aircraft pitch-and-roll axes. Force characteristics of the controller are given in figure 4. The controller is shown in the photograph of figure 2. The equations of motion of the pursuing aircraft (appendix A) were solved by a digital computer.

## EXPERIMENT DESIGN

Permissible delays in visual presentations are those which do not affect the performance and technique of the subject. Evaluating and comparing techniques is difficult. Performance measurements can be obtained readily; however, interpretation of these measurements can be difficult because even in the face of a task of increasing difficulty the subject can maintain high performance by working harder. The strategy used in the present study was to provide a total task that would cause the subject to work at full capacity at all times. Time delays were then introduced into the visual display. If a time delay caused the task to become more difficult, there would be a corresponding reduction of performance. If the time delay caused no increase in task difficulty, then performance would remain at the level obtained with zero time delay, and it would be concluded that such time delays would be acceptable. The ability to make this judgment required that a method be devised for ascertaining that the subject was working at the same (full) capacity at all times. This method is discussed in detail in appendix B.

The subject was required to perform two unrelated tasks. One was essentially a tracking task and was designated as the primary task. The other was to increase the pilot workload so that he was fully occupied during the experiment.

### Primary Task

The primary task was to track a target aircraft which was performing a sinusoidal oscillation in altitude. The oscillation had an amplitude of  $\pm 30.48$  m ( $\pm 100$  ft) and a frequency of 0.21 radian per second (a period of 30 seconds). The pursuing aircraft was 182.88 m (600 ft) behind the target aircraft, and could maneuver in five degrees of freedom. Forward speeds of the target and pursuer aircraft were constant. The pursuing aircraft was controlled through the use of the two-axis finger-tip controller mentioned previously.

It should be noted that the frequency of oscillation of the target aircraft was 0.0335 hertz. At this low frequency the subjects should be applying no precognitive control associated with the sinusoidal nature of the target aircraft motion (ref. 1).



## Side Task

The side task was used to aid in defining the effort required in conducting the primary task. The side task was well suited for this purpose because of its self-pacing quality and because it did not interfere directly with the primary task. The task consisted of alternately tapping two metal strips which were inlaid on a wooden board as shown in figure 5. The board, 19.69 cm (7.75 in.) wide and 24.13 cm (9.50 in.) long, was mounted on the subject's left leg by means of a velcro strap. A metal stylus about the size of a pencil was used to tap the metal strips. When the stylus contacted a metal strip, an electrical circuit was closed. A strip chart recorder was included in the circuit, and it recorded each impact. The metal strips were about 1.27 cm (0.5 in.) wide and were placed 10.16 cm (4 in.) apart. A raised wooden strip, 1.91 cm (0.75 in.) wide and 0.635 cm (0.25 in.) high, was glued between the metal strips to prevent sliding of the stylus. The design of the side task used in this study is explained in detail in reference 2, and subsequently has been used in other investigations. (See ref. 3, for example.)

The subject held the stylus in his left hand and controlled the aircraft with his right hand. He was instructed to strike the metal strips alternately as rapidly as convenient, while keeping the target in view. In order to strike the metal strips, it was necessary to glance down at the side-task board. It was found that if the target was allowed to move away from the reticle by a distance equal to approximately the target wing span, the subjects would not take time to glance at the board, but would concentrate on control of the aircraft. Therefore, the rate of tapping would drop very rapidly until the target was reacquired close to the reticle.

## Test Hypothesis

It is well known that transmission-type time delays in visual cues are detrimental to task performance. (See refs. 4 and 5, for example.) Also the quantitative effects of time delay are related to task difficulty (ref. 5). It appears reasonable, therefore, that acceptable time delays in cues in a simulator (delays that would not alter a subject's response or performance) would be related to the handling characteristics of the vehicle, since task difficulty increases as handling qualities are degraded. Handling qualities are generally related to aircraft dynamic characteristics. One convenient measure of such characteristics is the frequency and damping of various modes of motion. For example, Cooper-Harper ratings of aircraft are sometimes related to natural frequency and damping of the longitudinal short-period mode (ref. 6). An example of rating criteria as a function of these parameters is shown in figure 6. It was anticipated that corresponding contours of permissible time delay in visual cues might be determined from the data.

The performance on the primary and side tasks was the basis used for determining the permissible time delay for each aircraft. The tracking performance and the performance on

the side task would be at some specific level for the "real airplane" case. This level would correspond to the simulator with no delays. As time delays were introduced, the primary task (tracking) and side task (tapping) were expected to vary as sketched in figure 7. As long as the performance in each task remained constant, the subject was believed to be performing in the same manner as when flying the real airplane. A departure from this level would indicate a change in operational procedure and that the subject was no longer flying the same airplane. This departure indicated the maximum time delay permissible for the particular aircraft characteristics.

### Scope of Experiments

In order to define the anticipated contours of permissible time delays, one basic set of aircraft parameters was selected (table I). Certain of these parameters ( $L_\alpha$ ,  $M_q$ , and  $M_\alpha$ ) were then varied to obtain a reasonable coverage of the frequency and damping of the short-period longitudinal mode. The values of  $L_\alpha$ ,  $M_q$ ,  $M_\alpha$ , and the corresponding values of  $\omega_n$  and  $\zeta$  are listed in table II. The relationship between  $L_\alpha$ ,  $M_q$ ,  $M_\alpha$ , and  $\omega_n$  and  $\zeta$  are detailed in appendix C.

Time delays in visual-cue presentation could be obtained conveniently in increments of 0.03125 second. After some initial experimentation, increments of 0, 1, 2, 3, 4, 5, and 8 were selected. A digital computer was used in solving the equations of motion of the simulated aircraft. The digital outputs were converted to analog signals to drive the visual displays. The digital computer used in this investigation updated at intervals of 0.03125 second. The Langley Research Center hardware for computer signal processing from analog to digital back to analog can be represented mathematically as a prefilter, computational delay, and zero-order hold. The prefilter attenuates the analog input-signal high-frequency components to suppress "aliasing" from occurring during the analog-to-digital conversion. The computational delay is that associated with the input, the processing, and the output of a signal through the computer. Finally, a zero hold adds one-half the computing interval caused by the sample-hold characteristics. This latter delay represents an average value for that portion of the equipment which includes the digital-to-analog converter, the scene-generation equipment for elevation and azimuth line-of-sight angles to the target, and the television display of the scene to the subject. For the prefilter setting of this study, the described hardware characteristics create an average time delay from input to output of 1.5 times the up-date interval (ref. 7). This delay has an average value of 0.047 second, which becomes part of the delay in the visual-scene presentation.

Performances in the primary and side tasks were measured for an interval of 2 minutes for each time delay. In order to obtain good statistical data, it would have been desirable to make many runs with each time delay, and to use a large sampling of subjects. However, this proved to be impractical, so a decision was made to use a reasonable number of

runs at each time delay (usually seven), but to use only two subjects. The subjects were research engineers, each with approximately 15 years of experience in flying various simulators.

## PRESENTATION OF RESULTS

### Basic Data

The basic data obtained in this study consist of the rms values of vertical and lateral displacements of the pursuing aircraft relative to the target, and the number of counts obtained on the side task for each 2-minute test. The latter was recorded as average counts per minute. In addition, the rms values of the control deflections  $\delta_e$  and  $\delta_a$  and their time derivatives were obtained. Samples were collected for the same test conditions, and computations were performed to obtain the arithmetic mean and standard deviation. These statistical data are listed in table III. A typical time history of control deflections and the vertical and lateral displacements are shown in figure 8 for illustrative purposes.

The values of  $\bar{\epsilon}_h$ ,  $\bar{\epsilon}_v$ ,  $\bar{\epsilon}_h + \bar{\epsilon}_v$ , and counts per minute  $\bar{c}$  are plotted as functions of visual-scene time delay for the various configurations in figures 9 and 10. It should be noted that the minimum time delay available was 1.5 units (0.047 sec) introduced by the digital computer.

### Measurement of Work Level

A basic requirement in interpreting the results of this study is that the subject be working at full capacity, regardless of the time delay in the visual scene. The subject's task involved manipulating the finger-tip controller and tapping the side-task board. A measure of the work level was assumed to be of the form

$$WLI = A(\bar{c}) + B(\bar{\delta}_a + \bar{\delta}_e) \quad (1)$$

where  $\bar{c}$ ,  $\bar{\delta}_a$ , and  $\bar{\delta}_e$  are the arithmetic mean of the rms values of the counts and control deflections for a given configuration. If work level was indeed independent of the time delay in the visual scene, then equation (1) should indicate a constant value of WLI for each configuration. The constants A and B were determined as shown in appendix B. As indicated there, test results and the use of equation (1) indicated that the subject's level of effort was independent of time delay.

### Task Performance

The measured quantities which were used in evaluating the level of task performance were the number of counts on the side task, and the vertical and lateral tracking errors.

The data of figures 9 and 10 indicate reasonably well the time delay at which each quantity shows the start of performance degradation. However, in order to try to define the time more accurately, the quantities were combined in an overall measure of performance. This measure was selected as

$$PL = \left( \frac{\bar{c}}{\bar{c}_{\tau=1.5}} \right) + \left( 1 - \frac{\bar{\epsilon}}{\bar{\epsilon}_{\tau=1.5}} \right) \quad (2)$$

where

$$\bar{\epsilon} = \bar{\epsilon}_h + \bar{\epsilon}_v$$

The level of performance is plotted against the time delay in figure 11 for each configuration. These figures were used to determine the time delay at which the level of performance begins to degrade. This point of degradation is judged to be the maximum time delay that produces simulator results and piloting techniques which are not contaminated by the effects of time delays.

## DISCUSSION OF RESULTS

### Basic Data

The basic data obtained in this study are given in table III and figures 9 and 10. The trends obtained with increasing time delays are approximately as were anticipated, with the tracking error generally increasing and the number of counts decreasing as time delay increased. The data also show that the total tracking error  $\bar{\epsilon}$  usually decreased; the number of counts increased when the natural frequency of the longitudinal short-period mode  $\omega_n$  was increased.

### Determination of Permissible Time Delay

The basic data were used with equation (2) to compute performance level (PL) to aid in defining the time delay at which performance level would start to deteriorate. That point is designated the maximum permissible time delay for the configuration involved. The performance level curves are shown in figure 11 as functions of the units of time delay. The start of performance level deterioration is clearly defined for some configurations (e.g., config. 4 shown in fig. 11(a) or config. 6 shown in fig. 11(b)). In some cases performance deterioration was apparent with just one added unit of time delay (config. 9, fig. 11(d)). In most cases, however, the data do not show such precise results, and some judgment had to be made in deciding when performance deterioration started.

### Contours of Permissible Time Delay

As mentioned in the section "Experiment Design," it was anticipated that the permissible time delays would be a function of aircraft dynamics, and thereby related to flying-qualities criteria. Therefore, permissible time delays as determined from figure 11 were plotted on a frequency-damping chart on which contours of a current pilot-rating criteria were drawn (fig. 12). The data indicate that the better the pilot rating of a configuration, the greater the time delay that can be tolerated in visual-scene presentation. If the frequency and damping characteristics are such that the pilot rating is about 6.0 or worse, even one additional unit of time delay (about 0.03125 sec) would have an undesirable influence on pilot performance or mode of operation.

The ranges of frequency and damping for the configurations shown in figure 12 were obtained by combinations of  $M_q$  and  $M_\alpha$  through the relationships of equations (B2) and (B3), holding  $L_\alpha$  constant at 2.0. Therefore, it was of interest to determine whether permissible time delays would be affected if frequency and damping values were obtained by using  $L_\alpha = 1.0$  and adjusting  $M_q$  and  $M_\alpha$ . Some results are shown in figure 13; they indicate that acceptable time delay is somewhat dependent on the individual parameters, rather than just on overall motion characteristics such as period and damping.

### Detection of Performance Degradation

Since the results of the study showed that very small time delays could affect performance and the mode of "flying" a simulator, it was of interest to determine whether the subject could detect a deterioration of his performance caused by the presence of time delays. The procedure used to resolve this question was to let the subject first perform the tracking task with the least possible time delay (0.047 sec). Next, several tests were made with time delays of various (constant) magnitudes. At the end of each 2-minute test, the subject was asked to indicate whether, based on his feeling of performance, he thought there was a time delay present. The results are shown in table IV. Interpretation of the results should be tempered by the fact that the subjects were aware that most of the tests would have time delays. In addition, since there were only two choices ("yes" and "no"), the subject could be expected to identify correctly the presence of time delays at least 50 percent of the time. The results shown in table IV indicate clearly that deterioration of performance caused by time delays above about 0.172 second was readily apparent to the subject. The effects of time delays less than 0.141 second were not readily detectable.

### Effect of Doubling Target Frequency

Most of the results of this study were obtained with the target oscillating with a period of 30 seconds. Reducing the period should make a tracking task more difficult.

It was important to determine if increasing the task difficulty (as well as changing aircraft dynamics) would have some bearing on the permissible time delay in visual presentations. Results for one aircraft configuration are shown in figure 14. The results indicated that while a visual time delay of up to 0.109 second was acceptable for a target period of 30 seconds, less than 0.047 second was permissible at a frequency of 15 seconds.

### CONCLUDING REMARKS

An experimental study has been made to examine factors affecting the acceptable time delay in the visual feedback loop in flight simulators. Acceptable time delays are defined as delays which will affect neither the results nor the manner in which the subject "flies" the simulator. The study was made using a fixed-base simulator in which a subject tracked a target airplane that oscillated in a vertical plane only. The pursuing aircraft was permitted five degrees of freedom. Additional time delays in increments of 0.03125 second were inserted in the visual feedback loop. Results from this study have indicated the following:

1. The acceptable time delay appears to be related to the frequency and damping of the short-period longitudinal mode of the simulated aircraft. In these tests the lateral aircraft characteristics were held constant. In general, the acceptable time delay decreases as pilot rating increases (i.e., as handling qualities become less desirable).
2. Even small time delays in the order of 0.047 second can have an adverse effect on pilot performance for some aircraft configurations. For the range of aircraft parameters of this study, the maximum time delay which could be tolerated (without affecting the subject's performance or operating procedure) was about 0.141 second.
3. Increasing the task complexity or degrading the vehicle handling qualities reduces the acceptable level of visual-scene time delay.

Langley Research Center  
National Aeronautics and Space Administration  
Hampton, Va. 23665  
June 17, 1975

## APPENDIX A

### EQUATIONS OF MOTION

The linearized equations used in this study for the pursuing aircraft are written about the aircraft body axes and are as follows:

$$a_x = 0 \tag{A1}$$

$$a_y = Y_{\beta\beta} V_{x,o} \tag{A2}$$

$$a_z = - \left( L_{\alpha\alpha} + L_o \right) V_{x,o} \tag{A3}$$

$$\dot{p} = L_p p + L_{\beta\beta} \beta + L_r r + L_{\delta_a} \delta_a \tag{A4}$$

$$\dot{q} = M_{\alpha\alpha} \alpha + M_q q + M_{\delta_e} \delta_e \tag{A5}$$

$$\dot{r} = N_r r + N_{\beta\beta} \beta + N_p p + N_{\delta_r} \delta_r \tag{A6}$$

In equations (A2) and (A3)

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$\beta = \sin^{-1} \frac{v}{V}$$

$$V = \left( V_x^2 + V_y^2 + V_z^2 \right)^{1/2}$$

and

$$u = \ell_1 V_x + \ell_2 V_y + \ell_3 V_z$$

$$v = m_1 V_x + m_2 V_y + m_3 V_z$$

$$w = n_1 V_x + n_2 V_y + n_3 V_z$$

Aircraft orientation and velocity relative to inertial space are required to generate the proper position of the target relative to the pursuer (for display purposes). The orientation of the pursuer in space is specified by Euler angles. These are determined from body angular rates by

## APPENDIX A

$$\dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta$$

$$\dot{\theta} = q \cos \phi - r \sin \phi$$

$$\dot{\psi} = (r \cos \phi + q \sin \phi) \frac{1}{\cos \theta}$$

Inertial accelerations are given by

$$\dot{V}_x = \ell_1 a_x + m_1 a_y + n_1 a_z$$

$$\dot{V}_y = \ell_2 a_x + m_2 a_y + n_2 a_z$$

$$\dot{V}_z = \ell_3 a_x + m_3 a_y + n_3 a_z + g$$

Direction cosines are defined as follows:

$$\ell_1 = \cos \psi \cos \theta$$

$$\ell_2 = \sin \psi \cos \theta$$

$$\ell_3 = -\sin \theta$$

$$m_1 = \cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi$$

$$m_2 = \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi$$

$$m_3 = \cos \theta \sin \phi$$

$$n_1 = \cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi$$

$$n_2 = \sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi$$

$$n_3 = \cos \theta \cos \phi$$

Initial conditions were  $V_{x,0} = 304.8$  m/sec (1000 ft/sec);  $V_{y,0} = V_{z,0} = 0$ ;  $\psi_0 = \theta_0 = \phi_0 = 0$ ; and  $p_0 = q_0 = r_0 = 0$ .



## APPENDIX B

### WORK-LEVEL INDICATOR

The purpose of this study was to examine the effects of time delay in the visual feedback loop on the performance of a subject flying an aircraft simulator, and to relate the maximum permissible time delay to aircraft dynamics. Maximum permissible time delay is defined herein as the largest time delay that has no effect on the subject's task scoring or mode of performance. With this delay or lower time delays, the subject presumably would be flying the simulator as if it had no time delays, and this situation would correspond to flying the "real aircraft." Increasing visual time delays beyond the maximum permissible value would generally cause the subject: (a) to work harder to maintain a high performance, if he was not already working at full capacity; or (b) to suffer a reduction in performance.

In the first situation the subject would be changing his mode of operation (by working harder). However, it is difficult to find a good means to determine if a subject's effort has indeed increased. It appeared that a better method of determining maximum permissible visual time delay would be increasing the pilot's task to his full capacity with zero time delays, then increasing the time delay to the point where his overall performance started to decline. The latter technique was used in this study. The purpose of the side task was to supplement the primary task so that the pilot was working at full capacity at all times.

It was necessary to find an indicator of pilot workload in order to ascertain that the overall effort remained constant at all time delays for any given configuration. It was also recognized that there would be variations in level of accomplishment of each of the two tasks, related to the aircraft dynamics and to pilot motivation. A measure of relative workload was developed on the assumptions that the subject's workload was a linear function of the number of counts per minute, and the sum of the rms values of the elevator and aileron control deflections. The work-level indicator was selected as

$$WLI = A\bar{c} + B(\bar{\delta}_a + \bar{\delta}_e) \quad (B1)$$

It was desirable to set arbitrarily the workload indicator equal to 1.0 for each case with no time delay, and then to observe whether the workload indicator changed as time delays were introduced in the visual scene. The procedure used in determining the constants A and B of equation (B1) was as follows:

1. Assume that the WLI would remain 1.0, independent of time delay.
2. Calculate A and B for each aircraft configuration, using all of the data for the configuration. The constants A and B were determined by obtaining the best fit of equation (B1) to the data in the least-square sense.

## APPENDIX B

When the constants were determined for each configuration, equation (B1) was used with the data for each individual time delay to see if WLI did remain constant (at a value of 1.0). The results given in table V show that the WLI did remain very close to 1.0 for all time delays of each configuration, thus lending some credence to the belief that the combination of primary and side tasks kept the subject working at a constant level.

## APPENDIX C

### FREQUENCY AND DAMPING OF THE SHORT-PERIOD LONGITUDINAL MODE

The longitudinal short-period mode characteristics of an aircraft can be easily obtained from the linearized equations of motion. The linearized equations written about body axes and using only the aerodynamic terms given in equations (A3) and (A5) are

$$\dot{w} + pv - qu \approx \dot{w} - qu = -(L_\alpha \alpha + L_0) V_{x,0} + g \quad (C1)$$

$$\dot{q} = M_\alpha \alpha + M_q q + M_{\delta_e} \delta_e \quad (C2)$$

By definition,

$$L_0 = \frac{\text{Trim lift}}{m V_{x,0}} = \frac{mg}{m V_{x,0}} = \frac{g}{V_{x,0}}$$

Equation (C1), therefore, becomes

$$\dot{w} - qu = -L_\alpha \alpha V_{x,0}$$

Assuming that  $u$  is approximately equal to  $V_{x,0}$ , and that  $\alpha = \frac{w}{V_{x,0}}$ , one obtains

$$\dot{\alpha} - q = -L_\alpha \alpha \quad (C3)$$

The Laplace transforms of equations (C3) and (C2) with  $\delta_e = 0$  are, respectively

$$s\alpha(s) - q(s) = -L_\alpha \alpha(s)$$

and

$$-M_\alpha \alpha(s) + (s - M_q)q(s) = 0$$

Therefore, the characteristic equation is

$$s^2 + (L_\alpha - M_q)s - (M_\alpha + L_\alpha M_q) = 0$$

## APPENDIX C

from which

$$\omega_n^2 = -(M_\alpha + L_\alpha M_q) \quad (C4)$$

$$2\zeta\omega_n = L_\alpha - M_q \quad (C5)$$

$$\zeta = \frac{L_\alpha - M_q}{2 \left[ -(M_\alpha + L_\alpha M_q) \right]^{1/2}} \quad (C6)$$

If  $\omega_n$ ,  $\zeta$ , and  $L_\alpha$  are specified, then corresponding values of  $M_q$  and  $M_\alpha$  can be determined readily from equations (C4) and (C5), and are

$$M_q = L_\alpha - 2\zeta\omega_n \quad (C7)$$

$$M_\alpha = -(\omega_n^2 + L_\alpha M_q) \quad (C8)$$

## REFERENCES

1. McRuer, Duane T.; and Krendel, Ezra S.: Mathematical Models of Human Pilot Behavior. AGARDograph AG-188, Jan. 1974.
2. Fitts, Paul M.: The Information Capacity of Human Motor System in Controlling the Amplitude of Movement. J. Exptl. Psychol., vol. 47, no. 6, June 1954, pp. 381-391.
3. Bergeron, Hugh P.; Adams, James J.; and Hurt, George J., Jr.: Analysis of Human Response in Combined Control Tasks. NASA TN D-4356, 1968.
4. Warrick, Melvin J.: Effect of Transmission-Type Control Lags on Tracking Accuracy. Tech. Rep. No. 5916, U.S. Air Force, Sept. 1949. (Available from DDC as AD 66 089.)
5. Leslie, John McLean: Effects of Time Delay in the Visual Feedback Loop of a Man-Machine System. NASA CR-560, 1966.
6. O'Hara, F.: Handling Criteria. J. Roy. Aeronaut. Soc., vol. LXXI, no. 676, Apr. 1967, pp. 271-287.
7. Muira, Takeo; and Iwata, Junzo: Effects of Digital Execution Time in a Hybrid Computer. AFIPS Conference Proceedings, Volume 24, 1963 Fall Joint Computer Conference, Spartan Books, Inc., 1963, pp. 251-265.

TABLE I.— PARAMETERS OF PURSUING AIRCRAFT

Parameter	Value
$L_{\alpha}$	Variable
$L_o$	0.0322
$M_{\alpha}$	Variable
$M_q$	Variable
$M_{\delta_e}$	-10.0
$L_{\beta}$	-42.14
$L_p$	-2.74
$L_r$	2.058
$N_{\beta}$	5.544
$N_p$	.0148
$N_r$	-.2782
$Y_{\beta}$	-.1589
$L_{\delta_a}$	-10.0
$N_{\delta_a}$	0

TABLE II.— COMBINATIONS OF NATURAL FREQUENCY  $\omega_n$ , DAMPING RATIO  $\zeta$ , AND CORRESPONDING VALUES OF  $M_\alpha$ ,  $M_q$ , AND  $L_\alpha$  USED IN THIS STUDY

Configuration	$\omega_n$	$\zeta$	$M_\alpha$	$M_q$	$L_\alpha$	
1	1.5	0.3	-4.45	1.10	2.0	
2	1.5	1.0	-.25	-1.00	↓	
3	2.0	.7	-2.40	-.80		
4	2.5	.2	-8.25	1.00		
5	3.0	.3	-9.40	.20		
6	3.0	.7	-4.50	-2.20		
7	3.0	1.0	-1.00	-4.00		
8	2.83	1.59	6.00	-7.00		
9	3.0	2.0	11.00	-10.00		
10	4.0	.3	-15.20	-.40		
11	4.0	1.5	4.00	-10.00		
12	4.5	.4	-17.1	-1.60		
13	4.5	.7	-11.65	-4.3		
14	4.5	1.5	2.7	-11.5		
15	5.5	1.0	-12.25	-9.0		
16	3.0	.7	-5.8	-3.2		1.0
17	2.82	1.59	0	-8.0		1.0

TABLE III.— SUMMARY OF DATA

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 1; Subject 1;  $\omega_n = 1.5$ ;  $\zeta = 0.30$ ;  $L_\alpha = 2$ ;  $M_\alpha = -4.45$ ;  $M_q = 1.10$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	6	2		1
Vertical error	6.2030	7.1198	6.7687	7.2966	9.3961	11.3005		13.4478
	1.1902	2.8090	1.1552	.7276	1.6557	5.2179		--
Horizontal error	3.9956	5.8863	4.8545	4.5525	6.0990	14.2098		15.3589
	2.1754	5.1429	1.7438	.7635	2.0056	13.4099		--
Total error	10.1989	13.0061	11.6232	11.8488	15.4951	25.5102		28.8066
	3.3357	7.7761	2.6393	1.0744	3.0699	18.6279		--
Counts per minute	21.0	17.1	13.7	13.9	10.2	9.3		7.0
	3.07	2.42	3.36	1.69	3.14	1.77		--
$\bar{\delta}_a$	.025986	.032294	.038506	.035996	.038886	.042960		.042540
	.008287	.005846	.009669	.006289	.007905	.009970		--
$\bar{\delta}_e$	.008048	.009365	.010613	.010447	.011498	.012045		.010360
	.001354	.001274	.001447	.001612	.001247	.001520		--
$\dot{\bar{\delta}}_a$	.083420	.100699	.113740	.102366	.102953	.115520		.109500
	.031500	.020920	.035000	.021450	.019540	.026130		--
$\dot{\bar{\delta}}_e$	.035931	.039556	.041772	.039480	.040820	.040510		.033030
	.004914	.005224	.006659	.005314	.003762	.002475		--



TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 2; Subject 1;  $\omega_n = 1.5$ ;  $\zeta = 1.0$ ;  $L_\alpha = 2$ ;  $M_\alpha = -0.25$ ;  $M_q = -1.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	4	6	6	6	5	6		4
Vertical error	4.8610	4.6345	5.1548	5.8253	6.4465	6.6864		8.6136
	.3316	.3264	.3594	.4974	.9860	.8943		1.4539
Horizontal error	2.7014	3.1983	2.8139	3.7618	5.7040	4.9393		8.5984
	.4587	.9827	.9427	1.4646	2.9450	2.0089		2.9364
Total error	7.5621	7.8328	7.9684	9.5875	12.1505	11.6257		17.2121
	.7803	1.2411	1.0281	1.6505	3.7606	2.8706		4.0526
Counts per minute	28.3	29.3	26.3	22.8	20.0	19.7		13.9
	2.10	1.86	2.30	3.84	1.46	4.43		1.44
$\delta_a$	.028475	.026447	.032472	.035868	.039800	.040155		.047393
	.003286	.004310	.006410	.006064	.005236	.005126		.003521
$\delta_e$	.007800	.007813	.009265	.009133	.009874	.010722		.012090
	.001393	.001020	.001746	.001108	.000492	.000646		.001245
$\sigma_{ri} \cdot a$	.097105	.091560	.104402	.106900	.117850	.117672		.131910
	.015309	.019157	.015815	.020316	.011607	.019650		.017454
$\sigma_{ri} \cdot e$	.033155	.032615	.035275	.032893	.036562	.036405		.035895
	.007956	.004790	.006993	.002721	.002653	.002446		.001655

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 3; Subject 1;  $\omega_n = 2.0$ ;  $\zeta = 0.70$ ;  $L_\alpha = 2$ ;  $M_\alpha = -2.4$ ;  $M_q = -0.80$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7	7	7
Vertical error	4.5781	4.4367	4.7893	5.3675	5.0502	5.3383		6.3694
	.2505	.5441	.5758	.4932	.7205	.6843		.8367
Horizontal error	2.3652	2.7420	3.4430	3.3214	2.9669	3.6381		7.0208
	.7401	.7422	2.1860	.8934	.5398	.9373		1.9245
Total error	6.9433	7.1783	8.2317	8.6889	8.0172	8.9764		13.3902
	.8458	1.0659	2.7200	1.2744	1.1713	1.2799		2.5567
Counts per minute	35.2	34.8	32.1	28.6	30.1	28.4		19.6
	3.22	4.05	4.92	3.58	3.71	3.38		3.33
$\bar{\delta}_a$	.027004	.030980	.034551	.036783	.035941	.038340		.048523
	.006824	.006847	.012633	.009272	.007767	.007418		.007519
$\bar{\delta}_e$	.007296	.007871	.008144	.009371	.008973	.009236		.010751
	.002051	.001677	.001715	.001996	.001759	.001642		.001602
$\dot{\bar{\delta}}_a$	.089890	.096559	.103587	.109733	.113919	.118333		.138990
	.021453	.026791	.034854	.028812	.026963	.027195		.025145
$\dot{\bar{\delta}}_e$	.029412	.031059	.031106	.034743	.033010	.033800		.036094
	.008783	.007283	.007455	.008722	.007373	.006441		.007152

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 4; Subject 1;  $\omega_n = 2.5$ ;  $\zeta = 0.20$ ;  $L_\alpha = 2$ ;  $M_\alpha = -8.25$ ;  $M_q = 1.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	5	5	5	4	5	4	4	
Vertical error	4.2227	4.3099	4.4074	4.9728	5.0737	5.6495	5.7449	
	.4666	.2597	.5594	.3450	.9918	.3520	.8998	
Horizontal error	3.0571	2.5780	3.0401	3.2105	4.0282	5.6687	5.7257	
	.8598	.8787	.9266	.6940	2.0918	4.4050	1.7084	
Total error	7.2798	6.8873	7.4469	8.1833	9.1019	11.3172	11.4705	
	1.2911	.6791	1.3713	.9751	2.9819	4.2431	2.2458	
Counts per minute	33.3	33.8	29.7	29.4	26.6	22.1	22.8	
	2.44	2.19	2.19	1.31	5.34	5.75	6.09	
$\bar{\delta}_a$	.023444	.020412	.024720	.025143	.029326	.034350	.032983	
	.006648	.003407	.004577	.003828	.010595	.009464	.009091	
$\bar{\delta}_e$	.003994	.003752	.004426	.004705	.005058	.005938	.005660	
	.000944	.000807	.000879	.000415	.001859	.000959	.000627	
$\bar{\delta}_a \cdot$	.064594	.057654	.071046	.068285	.080040	.090328	.084448	
	.016114	.013610	.013774	.011338	.026456	.019755	.018836	
$\bar{\delta}_e \cdot$	.017290	.016164	.018332	.018890	.019788	.022643	.021603	
	.003901	.004064	.003144	.001657	.006503	.004276	.002060	

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 5; Subject 1;  $\omega_n = 3.0$ ;  $\zeta = 0.30$ ;  $L_\alpha = 2.0$ ;  $M_\alpha = -9.4$ ;  $M_q = 0.20$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	8	7	8	7	8	7		7
Vertical error	3.5351	3.6561	3.6579	3.9112	3.7018	4.0877		4.0002
	.2691	.3051	.3575	.5456	.3828	.5386		.7934
Horizontal error	1.9489	1.7666	2.1775	2.3582	1.8916	2.3909		2.7737
	.4703	.2469	.5349	.5752	.3889	.9037		.8626
Total error	5.4837	5.4227	5.8354	6.1771	5.5934	6.4788		6.7739
	.5587	.4782	.8525	1.0772	.6026	1.3923		1.4060
Counts per minute	36.9	36.0	36.1	34.0	35.3	33.2		31.5
	4.49	3.13	4.38	4.64	2.91	2.95		6.13
$\bar{\delta}_a$	.029665	.031597	.032953	.036767	.033168	.035800		.041971
	.007986	.009303	.008911	.009229	.006155	.005899		.018276
$\bar{\delta}_e$	.005737	.006210	.005938	.006560	.006368	.006709		.006939
	.001351	.001349	.001716	.001711	.001026	.001068		.001701
$\sigma_{\bar{\delta}_a}$	.093228	.104919	.098873	.106061	.098416	.098095		.111049
	.029968	.037535	.029508	.036916	.018341	.018737		.029904
$\sigma_{\bar{\delta}_e}$	.025376	.028184	.025458	.028013	.026141	.026563		.026685
	.008852	.008465	.008258	.009318	.004951	.005316		.007365

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 6; Subject 1;  $\omega_n = 3.0$ ;  $\zeta = 0.70$ ;  $L_\alpha = 2.0$ ;  $M_\alpha = -4.5$ ;  $M_q = -2.2$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	11	6	6	10	7	7	6	6
Vertical error	3.7283	3.7954	3.8944	4.3138	4.5202	5.0496	4.2254	7.5819
	.3594	.1966	.5694	.8885	.4529	.8473	.5212	3.6003
Horizontal error	2.6889	2.6588	2.4545	3.7393	3.4573	3.9310	3.6475	7.5316
	.7846	.7922	.7617	1.9468	.6443	1.0683	1.1787	3.8493
Total error	6.4170	6.4535	6.3987	8.0540	7.9766	8.5438	7.8730	15.1129
	1.0482	.8470	1.3097	2.5951	.6989	1.9580	1.6218	7.2658
Counts per minute	36.2	36.2	36.6	31.2	31.0	29.9	28.0	23.5
	3.04	2.79	3.84	4.45	2.31	5.37	6.05	5.83
$a_{\delta_a}$	.049535	.047510	.051015	.052425	.060650	.058475		.073360
	.008125	.005756	.000629	.004900	.000989	.004419		.009518
$a_{\delta_e}$	.008875	.008593	.010160	.010895	.011335	.011068		.013020
	.000341	.001329	.000354	.001422	.000403	.002026		.001146
$a_{\delta_a}$	.154400	.144700	.154900	.160400	.169700	.163400		.194850
	.027290	.002121	.008485	.001980	.003111	.000707		.003889
$a_{\delta_e}$	.035560	.032315	.037505	.037750	.038300	.037480		.038025
	.003154	.002694	.001534	.002475	.001245	.003592		.001110

<sup>a</sup>Only 2 data points obtained at each value of time delay.

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 7; Subject 1;  $\omega_n = 3.0$ ;  $\zeta = 1.0$ ;  $L_\alpha = 2$ ;  $M_\alpha = -1.0$ ;  $M_q = -4.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	9	8	8	9	8	7	6	7
Vertical error	3.6981	3.6692	3.6655	3.9197	4.3900	4.4492	5.5602	5.6101
	.1737	.2402	.2810	.2509	.4545	.7299	.9168	.8797
Horizontal error	2.2284	2.0812	2.5326	2.8685	3.9091	3.3373	6.0457	6.8175
	.4090	.2268	.6742	.8678	1.8971	.5215	1.9693	4.1328
Total error	5.9265	5.7510	6.1981	6.7202	8.2991	7.7864	11.6059	12.4493
	.5047	.2502	.9342	.9839	2.1197	1.0769	2.8209	4.9347
Counts per minute	35.1	35.8	35.9	32.8	29.9	29.2	22.3	23.7
	4.64	4.05	3.66	4.17	4.61	3.40	2.02	5.15
$\delta_a$	.041862	.042661	.039460	.044594	.045755	.049969	.060973	.052389
	.007656	.007233	.007407	.008918	.011220	.006104	.004089	.009036
$\delta_e$	.007986	.008020	.008105	.009014	.009238	.009734	.011528	.010846
	.001541	.001166	.001452	.001894	.001771	.001646	.001166	.002157
$\sigma_a$	.116907	.116581	.106730	.117698	.113130	.124559	.148490	.126884
	.030235	.020262	.027173	.024475	.031666	.024707	.018259	.032148
$\sigma_e$	.029137	.028164	.027085	.028567	.026674	.028167	.034085	.028096
	.008633	.005847	.007057	.005955	.006231	.006579	.003865	.006159

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 8; Subject 1;  $\omega_n = 2.83$ ;  $\zeta = 1.59$ ;  $L_\alpha = 2$ ;  $M_\alpha = 6.0$ ;  $M_q = -7.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	9	7	8	8	8	7	6	7
Vertical error	4.2760	4.4376	4.9518	5.0152	5.9948	7.1148	7.2305	7.1692
	.5194	.5779	.5093	1.0692	1.0113	2.2738	1.7371	.8766
Horizontal error	3.3095	3.8669	3.8880	4.0867	5.5355	7.1174	7.4655	7.5794
	.5785	1.6072	.6480	1.4679	2.0361	3.2556	2.8203	2.5920
Total error	7.5856	8.3046	8.8401	9.1016	11.5303	14.2625	14.6959	14.7490
	.9601	2.0845	.8845	2.3640	2.8148	5.1206	4.0578	3.4448
Counts per minute	24.9	23.1	21.4	21.1	17.1	15.2	13.4	14.1
	3.23	3.45	1.68	4.82	4.81	4.21	2.31	3.32
$\bar{\delta}_a$	.053223	.048481	.051094	.054169	.057659	.063166	.070675	.067136
	.017954	.009237	.006725	.011303	.010157	.008604	.013415	.020367
$\bar{\delta}_e$	.011624	.010429	.010979	.012109	.012715	.013527	.015818	.014464
	.003776	.002239	.001464	.002507	.002150	.001156	.001855	.002888
$\dot{\bar{\delta}}_a$	.147220	.128721	.143193	.142520	.144270	.158853	.179372	.162479
	.049466	.017448	.017293	.034309	.021779	.026665	.046560	.059457
$\dot{\bar{\delta}}_e$	.036882	.033211	.031870	.035996	.033375	.036066	.040582	.036473
	.011846	.007534	.005859	.008202	.005276	.003013	.006597	.007684





TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 10; Subject 1;  $\omega_n = 4.0$ ;  $\zeta = 0.30$ ;  $L_\alpha = 2$ ;  $M_\alpha = -15.2$ ;  $M_q = -0.40$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	6	7		7
Vertical error	3.1437	3.1824	3.2815	3.3123	3.3598	3.3196		3.4516
	.0856	.0869	.1253	.1612	.1564	.1362		.1652
Horizontal error	1.5200	1.5975	1.7099	1.7203	1.7343	1.8001		1.9373
	.2838	.4011	.2359	.3124	.3179	.4322		.5663
Total error	4.6595	4.7366	4.9914	5.0326	5.0941	5.1216		5.3879
	.3542	.3432	.2521	.4642	.3432	.5108		.6541
Counts per minute	43.5	43.5	42.8	42.0	41.6	43.1		39.8
	2.77	2.02	1.38	3.51	1.28	3.06		1.55
$\bar{\delta}_a$	.024944	.025760	.026047	.027561	.031777	.028047		.031639
	.002860	.005088	.005707	.006547	.006540	.002560		.006395
$\bar{\delta}_e$	.005207	.005534	.005210	.005464	.005952	.005604		.006147
	.000673	.000899	.000431	.000656	.000738	.000426		.000829
$\dot{\bar{\delta}}_a$	.077850	.078813	.075597	.085563	.091253	.078591		.085667
	.009843	.014802	.011326	.022552	.013827	.007090		.011115
$\dot{\bar{\delta}}_e$	.020849	.021393	.019707	.021480	.023047	.020654		.022883
	.002576	.004039	.002692	.004357	.003785	.001096		.003982

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 11; Subject 1;  $\omega_n = 4.0$ ;  $\zeta = 1.50$ ;  $L_\alpha = 2$ ;  $M_\alpha = 4.0$ ;  $M_q = -10.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7		7
Vertical error	3.3851	3.3912	3.5451	3.6832	3.7396	3.8191		4.2760
	.2319	.2438	.2003	.2353	.3566	.2445		.4148
Horizontal error	1.5880	1.4917	1.7852	1.8395	1.9827	2.1333		3.0891
	.2667	.2996	.4319	.3706	.2563	.4752		.6035
Total error	4.9731	4.8829	5.3306	5.5226	5.7223	5.9524		7.3652
	.4642	1.4883	.5648	.4334	.5941	.6733		.7556
Counts per minute	45.6	43.6	44.6	42.4	42.8	39.3		33.0
	3.78	3.91	3.76	2.84	4.70	4.15		2.96
$\bar{\delta}_a$	.033987	.036481	.033946	.038087	.042314	.042011		.051781
	.005255	.002497	.005989	.005940	.005769	.003897		.006997
$\bar{\delta}_e$	.009391	.009570	.009611	.010753	.010706	.010986		.012700
	.000851	.001114	.001646	.001028	.001126	.000511		.000832
$\delta_a^{\cdot}$	.114360	.114643	.111011	.119513	.127229	.124414		.135888
	.021361	.007272	.020090	.021670	.020090	.007817		.018820
$\delta_e^{\cdot}$	.031493	.031611	.031390	.032889	.033680	.032961		.034295
	.003532	.000247	.005640	.004884	.006626	.003026		.002641

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 12; Subject 1;  $\omega_n = 4.5$ ;  $\zeta = 0.40$ ;  $L_\alpha = 2$ ;  $M_\alpha = -17.1$ ;  $M_q = -1.6$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	5	8	7	6	5	5
Vertical error	3.5225	3.7061	3.7990	3.6253	3.9530	3.9344	3.8746	3.9843
	.2417	.3959	.4618	.3901	.7641	.6504	.2274	.2606
Horizontal error	2.5564	3.7137	3.4784	3.7152	4.3394	3.9039	4.2818	4.9884
	.8105	2.1089	2.0047	1.5651	3.0075	1.5798	1.6225	1.2631
Total error	6.0795	7.4197	7.2768	7.3404	8.2872	7.8379	8.1564	8.9727
	1.0314	2.4393	2.3872	1.8248	3.7542	2.0041	1.7160	1.1695
Counts per minute	32.8	30.4	27.4	29.1	31.4	28.2	28.9	24.3
	3.50	3.75	4.76	2.26	5.02	6.07	2.03	4.16
$\bar{\delta}_a$	.041676	.049519	.049166	.053945	.051240	.055183	.065144	.063052
	.008076	.007001	.007490	.003926	.014969	.009660	.006046	.007538
$\bar{\delta}_e$	.007540	.008684	.008436	.008699	.008453	.009380	.009946	.009946
	.001143	.001181	.000559	.000877	.001861	.001526	.000451	.001623
$\dot{\bar{\delta}}_a$	.105463	.124677	.114588	.126680	.117341	.123538	.149214	.126390
	.023482	.022581	.013731	.016590	.029067	.020081	.008904	.015588
$\dot{\bar{\delta}}_e$	.028719	.032406	.029000	.030753	.027634	.030803	.033790	.030264
	.005320	.005271	.002448	.003401	.004879	.003733	.002432	.005739

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 13; Subject 1;  $\omega_n = 4.5$ ;  $\zeta = 0.70$ ;  $L_\alpha = 2$ ;  $M_\alpha = -11.65$ ;  $M_q = -4.3$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	8	6	8	6	7	6		6
Vertical error	3.4259	3.2882	3.5022	3.3565	3.7609	3.6997		3.8655
	.3097	.1396	.2243	.1798	.3200	.2673		.3551
Horizontal error	1.7047	1.5103	2.1735	1.9471	1.9785	2.2287		3.2909
	.4380	.1868	.5108	.3685	.9329	.5300		1.3887
Total error	5.2029	4.7985	5.6757	5.3035	6.1749	5.9284		7.1561
	.5499	.2551	.7099	.3953	1.3418	.7029		1.4832
Counts per minute	42.3	42.0	39.9	40.0	40.4	38.8		33.5
	6.95	3.38	5.84	6.16	5.13	2.93		7.55
$\delta_a$	.039191	.035497	.044563	.042650	.040633	.042573		.055185
	.010898	.006180	.007995	.008186	.006169	.006791		.012783
$\delta_e$	.008258	.007868	.008446	.008760	.008747	.008872		.009917
	.000898	.000885	.000924	.000751	.000809	.001206		.000904
$\sigma_a$	.124056	.115250	.131910	.127328	.119556	.128532		.149562
	.023110	.021409	.016662	.010826	.009552	.018419		.030591
$\sigma_e$	.034973	.031473	.033279	.034920	.033533	.034060		.035467
	.005879	.007075	.004575	.002991	.003980	.006881		.005114

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 14; Subject 1;  $\omega_n = 4.5$ ;  $\zeta = 1.5$ ;  $L_\alpha = 2$ ;  $M_\alpha = 2.7$ ;  $M_q = -11.5$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	9	8	7	8	8	6	6	6
Vertical error	3.3412	3.4086	3.6914	3.4793	3.7652	3.9334	4.0925	4.4400
	.1777	.1868	.3182	.2664	.2685	.2329	.3089	.4983
Horizontal error	2.2244	2.0181	2.0229	2.0711	2.7725	2.5122	3.1388	4.3221
	.5779	.2265	.6105	.5657	.9275	.4066	.7343	1.8763
Total error	5.5650	5.4267	5.7147	5.5504	6.5377	6.4456	7.2314	8.7853
	.7260	.3289	.6776	.6727	1.0927	.4663	.7370	2.2607
Counts per minute	38.9	38.1	37.7	36.2	34.5	33.5	28.3	27.1
	2.91	1.51	3.14	5.29	4.18	3.78	3.09	5.11
$\delta_a$	.040499	.043851	.042347	.045919	.046965	.047852	.055803	.059658
	.007638	.007437	.007469	.009733	.004874	.008333	.003001	.006014
$\delta_e$	.008460	.009545	.009474	.009679	.010476	.011107	.013252	.012712
	.001184	.000970	.001197	.001279	.001083	.001277	.001578	.001401
$\dot{\delta}_a$	.115750	.127401	.114470	.126520	.127248	.127223	.145732	.148010
	.022361	.023716	.020949	.021696	.013694	.021714	.006568	.016508
$\dot{\delta}_e$	.028576	.031921	.028621	.030913	.029849	.030033	.033965	.031372
	.004154	.004809	.003444	.004137	.002981	.004202	.003754	.001938

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 15; Subject 1;  $\omega_n = 5.5$ ;  $\zeta = 1.0$ ;  $L_\alpha = 2$ ;  $M_\alpha = -12.25$ ;  $M_q = -9.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7		6
Vertical error	3.2626	3.3031	4.3434	3.4769	3.3781	3.4668		3.9557
	.1433	.1469	.1329	.2173	.1920	.1835		.6703
Horizontal error	1.4652	1.4649	1.6947	1.9099	1.7849	1.7352		3.3461
	.4243	.2524	.2926	.4215	.4633	.4051		1.0714
Total error	4.7278	4.7680	5.0380	5.3867	5.1630	5.2020		7.3021
	.4721	.3310	.2505	.6072	.5791	.5038		1.7179
Counts per minute	42.2	41.7	39.9	38.7	39.5	40.6		32.4
	4.08	3.56	4.14	4.06	3.44	3.13		4.75
$\delta_a$	.039678	.042274	.045219	.045641	.049192	.047719		.059453
	.006545	.007459	.008739	.003491	.007675	.004396		.005800
$\delta_e$	.008559	.009184	.008812	.009554	.009517	.009727		.011570
	.000532	.000596	.000583	.000661	.000674	.000837		.001267
$\delta_a \cdot$	.116059	.122511	.128810	.124207	.131079	.131427		.129842
	.015936	.015659	.022575	.006321	.015908	.013849		.011945
$\delta_e \cdot$	.030337	.032407	.031083	.032526	.031244	.032980		.034265
	.004875	.004828	.004729	.002444	.003826	.002656		.003869

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 16; Subject 1;  $\omega_n = 3.0$ ;  $\zeta = 0.7$ ;  $L_\alpha = 1$ ;  $M_\alpha = -5.8$ ;  $M_q = -3.2$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	9	9	9	9	9	10		9
Vertical error	3.5259	3.5558	3.5339	3.5424	3.7094	3.7262		4.1148
	.2009	.2161	.2734	.2659	.3258	.3042		.5575
Horizontal error	1.5950	1.7377	1.8017	1.7337	2.0486	2.3479		3.6146
	.3316	.4959	.4407	.5803	.6971	.7623		1.3301
Total error	5.1209	5.3273	5.3349	5.2761	5.7580	6.0741		7.7294
	.4749	.6361	.6242	.8169	.9367	1.0266		1.7060
Counts per minute	44.1	41.5	42.2	41.9	41.9	39.5		34.8
	2.92	1.74	3.51	4.32	3.19	3.44		4.52
$\delta_a$	.042467	.045118	.044017	.046043	.043976	.049135		.057774
	.009044	.004941	.008950	.006617	.003045	.004541		.007485
$\delta_e$	.008409	.008021	.008492	.008771	.008807	.009042		.010294
	.001023	.000849	.001064	.001080	.000681	.000805		.001141
$\sigma_a$	.135402	.133118	.130477	.136707	.131429	.134198		.147999
	.024717	.014226	.021559	.017949	.005398	.014973		.014197
$\sigma_e$	.034489	.032410	.033291	.033803	.033153	.033318		.034997
	.004718	.002940	.004069	.005381	.002818	.003504		.003587

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 17; Subject 1;  $\omega_n = 2.83$ ;  $\zeta = 1.59$ ;  $L_\alpha = 1$ ;  $M_\alpha = 0$ ;  $M_q = -8.0$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	8	7		6
Vertical error	3.6920	3.7951	3.8295	3.7460	3.8908	3.8746		4.6488
	.2752	.4807	.5057	.3929	.2801	.2204		.9050
Horizontal error	1.4474	1.9358	1.8529	2.0751	2.2592	2.3403		2.7587
	.4014	.2856	.4809	.2886	.5438	.8013		.7702
Total error	5.1395	5.7308	5.6827	5.8211	6.1499	6.2152		7.4072
	.6498	.7199	.9190	.6084	.7117	.9360		1.4953
Counts per minute	45.2	42.5	42.6	40.3	39.7	40.6		35.3
	3.53	3.62	5.60	2.89	2.63	2.83		5.14
$\delta_a$	.037111	.041931	.042850	.046287	.050295	.045950		.051222
	.004631	.005434	.007432	.006713	.008562	.003071		.006113
$\delta_e$	.009923	.010478	.011400	.010641	.011602	.011357		.012663
	.000897	.001001	.001891	.001566	.001383	.001075		.000975
$\delta_a^*$	.126557	.131377	.138259	.138986	.145775	.134429		.139883
	.015840	.021320	.026325	.021150	.017720	.009484		.017360
$\delta_e^*$	.035941	.036132	.039100	.035953	.036060	.035848		.034387
	.003713	.006221	.007876	.005630	.003856	.003743		.003603



TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 6; Subject 1; Double-target frequency;  $\omega_n = 3.0$ ;  $\zeta = 0.70$ ;  $L_\alpha = 2$ ;  $M_\alpha = -4.5$ ;  $M_q = -2.2$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7	7	7
Vertical error	7.3439	7.4158	8.0641	7.8007	9.4878	8.6865		9.9849
	.3779	.2475	.5432	.4215	2.9934	.7492		1.2988
Horizontal error	2.3622	2.6646	2.5966	3.1980	4.4175	4.1748		7.0418
	.3362	.7891	.5069	.7321	1.5219	1.6974		1.5825
Total error	9.7061	10.0803	10.6609	10.9984	13.9053	12.8610		17.0264
	.6230	.9729	.7605	.9446	4.4028	2.3290		2.6219
Counts per minute	39.8	37.6	36.0	34.6	30.1	30.0		22.3
	4.61	4.07	3.08	3.74	4.44	3.45		4.37
$\delta_a$	.045214	.046634	.048914	.051934	.060099	.057634		.068801
	.007498	.004574	.006416	.004889	.006192	.005413		.004743
$\delta_e$	.012134	.013957	.012690	.013283	.013586	.013817		.014759
	.001507	.001051	.000648	.001065	.000839	.000638		.000893
$\dot{\delta}_a$	.144757	.145157	.143200	.152686	.167171	.157886		.165457
	.024200	.012300	.017640	.008391	.010890	.015560		.014370
$\dot{\delta}_e$	.040743	.040701	.039760	.041414	.040570	.040393		.040014
	.006013	.005222	.003868	.004288	.004298	.002378		.004415

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 2; Subject 2;  $\omega_n = 1.5$ ;  $\zeta = 1.0$ ;  $L_\alpha = 2$ ;  $M_\alpha = -0.25$ ;  $M_q = -1.00$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	6	6	5	5	6	6		6
Vertical error	4.4601	4.9719	4.8183	5.6266	4.9027	5.9716		8.9444
	.7114	1.2634	.2707	1.4871	.5291	1.2198		1.8486
Horizontal error	2.9130	3.5601	3.0611	3.8155	3.0907	5.0103		10.2007
	.5246	1.3076	.7410	.9327	.7312	3.1388		3.3933
Total error	7.3734	8.5320	7.8794	9.4421	7.9934	10.9819		19.1466
	1.2101	2.4600	.9141	2.0833	0.7647	3.5912		4.8280
Counts per minute	51.2	48.5	46.4	42.9	42.6	38.0		22.8
	2.68	5.10	3.50	2.15	5.56	5.45		5.19
$\delta_a$	.016535	.018875	.016574	.020434	.018828	.020987		.024728
	.003296	.002639	.002987	.003069	.003917	.004525		.003023
$\delta_e$	.004692	.005629	.005243	.006757	.006476	.006598		.009047
	.000724	.001183	.001034	.000942	.000618	.000428		.000701
$\sigma_a$	.047395	.055215	.047380	.057332	.055595	.060932		.066635
	.012820	.008292	.010450	.010670	.015180	.015180		.014990
$\sigma_e$	.016797	.019955	.018010	.022202	.021510	.021237		.026470
	.002785	.003669	.003550	.002567	.003033	.002266		.004361

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 5; Subject 2;  $\omega_n = 3.0$ ;  $\zeta = 0.30$ ;  $L_\alpha = 2$ ;  $M_\alpha = -9.40$ ;  $M_q = 0.20$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7	7	
Vertical error	3.2455	3.4671	3.7356	3.4509	3.7798	3.8264	4.2245	
	.2329	.2938	.3975	.6736	.3953	.3904	.5913	
Horizontal error	2.3034	2.4311	2.9044	2.3707	2.8688	2.5359	4.3687	
	.6977	.4883	1.0537	.6806	1.0238	.5575	1.2162	
Total error	5.5489	5.8982	6.6401	5.8214	6.6489	6.3624	8.5932	
	.7501	.5925	1.3048	.8973	1.2009	.7730	1.6106	
Counts per minute	61.4	60.6	59.4	61.3	59.1	58.2	54.1	
	3.98	3.17	4.13	3.71	4.03	4.89	4.41	
$\bar{\delta}_a$	.015121	.014673	.015029	.015372	.020267	.020031	.027010	
	.003526	.001798	.003397	.004796	.004673	.004042	.002709	
$\bar{\delta}_e$	.002987	.002951	.003305	.002980	.003872	.003791	.004615	
	.000557	.000426	.000701	.000715	.000839	.000713	.000372	
$\dot{\delta}_a$	.037151	.036142	.037074	.035987	.045517	.047907	.060929	
	.006560	.004057	.009262	.010500	.009566	.010170	.006887	
$\dot{\delta}_e$	.009793	.009020	.009807	.009078	.011996	.011912	.014497	
	.002510	.001895	.002155	.002380	.003187	.002912	.001158	

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 6; Subject 2;  $\omega_n = 3.0$ ;  $\zeta = 0.70$ ;  $L_\alpha = 2$ ;  $M_\alpha = -4.50$ ;  $M_q = -2.20$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	6	5	6	5	5	5		5
Vertical error	3.5753	3.5893	3.7109	3.7515	3.8521	4.0477		4.3404
	.2810	.4142	.2335	.3106	.3249	.7989		.8281
Horizontal error	3.7890	3.4180	3.1739	3.7881	4.2334	5.2078		5.8217
	1.2466	.3972	.6989	.8915	1.2073	3.7125		3.0242
Total error	7.3643	7.1073	6.8848	7.5395	8.0857	9.2556		10.1620
	1.2546	.7148	.7373	1.1073	1.4082	4.4257		3.8380
Counts per minute	56.8	54.2	56.1	47.4	48.5	44.7		40.8
	6.11	5.30	5.06	7.49	5.94	15.66		6.10
$\bar{\delta}_a$	.019888	.020488	.022460	.020956	.020736	.025042		.026878
	.004669	.001455	.008305	.003462	.004352	.010220		.002597
$\bar{\delta}_e$	.004398	.004361	.004545	.004739	.004757	.005308		.005129
	.000543	.000325	.000513	.000343	.000508	.001304		.000397
$\sigma_a$	.087590	.093854	.091057	.084710	.087374	.088977		.095405
	.016560	.013510	.014070	.010780	.008402	.012710		.010340
$\sigma_e$	.024646	.024292	.024292	.023126	.024818	.024977		.024073
	.001888	.003038	.001945	.001364	.001574	.002334		.002263

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 9; Subject 2;  $\omega_n = 3.0$ ;  $\zeta = 2.0$ ;  $L_\alpha = 2$ ;  $M_\alpha = 11.00$ ;  $M_q = -10.00$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7		7
Vertical error	4.0560	4.0365	4.2096	4.7323	4.5619	4.5507		5.7848
	.6739	.5240	.5398	.7090	.5191	.8601		.4474
Horizontal error	2.2324	2.5269	2.7932	3.0349	2.3509	2.6643		3.4278
	.5685	.5813	.7056	.9619	.5806	1.1701		.5041
Total error	6.2883	6.5733	7.0028	7.7669	6.9129	7.2149		9.2126
	.9467	1.0644	1.1808	1.6017	1.0485	1.8715		.7114
Counts per minute	59.7	58.7	57.4	56.3	54.5	54.7		49.4
	2.86	3.38	1.93	4.58	3.37	4.57		3.26
$\delta_a$	.020110	.019677	.023559	.026221	.026767	.027886		.030580
	.005431	.004236	.005504	.003904	.005781	.005332		.003073
$\delta_e$	.006957	.007307	.007959	.008717	.009057	.008849		.010974
	.000863	.000761	.000446	.000836	.001629	.001240		.001517
$\dot{\delta}_a$	.055571	.054194	.062601	.070350	.068364	.072246		.074751
	.012500	.009156	.012910	.009209	.011457	.014500		.008423
$\dot{\delta}_e$	.020756	.021283	.023040	.024594	.024750	.023700		.026624
	.001525	.002024	.001561	.002362	.002784	.002083		.002700

TABLE III.— Continued

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 13; Subject 2;  $\omega_n = 4.5$ ;  $\xi = 0.70$ ;  $L_\alpha = 2$ ;  $M_\alpha = -11.65$ ;  $M_q = -4.30$

Parameter	Data for units of time delay $\tau$ of —							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	7	7	7	7	7	7		7
Vertical error	3.5335	3.3263	3.3687	3.5875	3.6698	3.7015		3.9292
	.2670	.2387	.3947	.1320	.6066	.2560		.5712
Horizontal error	2.1671	2.3567	2.5530	2.4701	2.9303	2.7005		3.4509
	.3594	.5483	.5730	.5511	.7187	.3801		.5898
Total error	5.7004	5.6830	5.9216	6.0576	6.6001	6.4023		7.3801
	.3408	.6571	.8507	.6456	.9967	.4697		1.1247
Counts per minute	64.8	62.4	62.9	61.8	59.1	59.7		55.6
	2.16	2.39	2.04	2.57	3.21	3.45		2.55
$\bar{\delta}_a$	.022734	.025274	.025814	.025829	.031087	.029959		.041243
	.003287	.005046	.002596	.002546	.003405	.003730		.003391
$\bar{\delta}_e$	.005462	.005500	.005910	.006286	.006285	.006390		.007849
	.000685	.000613	.000430	.000896	.000750	.000533		.000944
$\sigma_a$	.064280	.069263	.069741	.071654	.086839	.079169		.107871
	.009830	.016730	.007679	.008232	.011010	.010120		.008238
$\sigma_e$	.015789	.016089	.017570	.018941	.019630	.019316		.024529
	.002962	.004208	.002061	.002416	.003684	.002426		.002638

TABLE III.- Concluded

[One unit of time delay is 0.03125 second. Top value is mean value; lower value is standard deviation.]

Configuration 16; Subject 2;  $\omega_n = 3.0$ ;  $\zeta = 0.70$ ;  $L_\alpha = 1$ ;  $M_\alpha = -5.80$ ;  $M_q = -3.20$

Parameter	Data for units of time delay $\tau$ of -							
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5
	Number of test points							
	4	4	4	4	4	4	4	4
Vertical error	3.8679	3.8344	3.9319	4.0965	4.2879	3.9152		3.8877
	.3834	.2859	.2310	.2438	.4575	.2816		.1631
Horizontal error	2.4018	1.8837	2.1437	2.0041	2.7310	2.2976		3.0236
	.8092	.3149	.6511	.2597	.9705	.2752		1.1357
Total error	6.2697	5.7180	6.0756	6.1006	7.0180	6.2127		6.9113
	1.0223	.4441	.8723	.4008	1.3724	.2835		1.2363
Counts per minute	58.6	60.9	60.4	60.5	59.2	58.9		55.7
	4.21	3.89	1.61	2.47	1.84	4.44		2.16
$\bar{\delta}_a$	.020390	.023993	.024438	.024120	.027065	.026810		.030433
	.004182	.005211	.006596	.003353	.005726	.005696		.002317
$\bar{\delta}_e$	.005233	.005973	.005490	.006053	.005975	.005990		.006313
	.000739	.000644	.000929	.000799	.001063	.000430		.000586
$\dot{\delta}_a$	.053965	.062640	.061683	.059635	.066500	.064965		.067298
	.007501	.010802	.018239	.010413	.013869	.014134		.007509
$\dot{\delta}_e$	.016553	.019268	.017008	.018713	.017685	.018718		.018723
	.006769	.003729	.005670	.005423	.005198	.002992		.004748

TABLE IV.— SUBJECT DETECTION OF PERFORMANCE DEGRADATION

[TASK: Subject was to indicate whether he thought his performance had degraded with respect to the “zero” time-delay performance.]

Subject response summary		
Units of time delay $\tau$	Subject response	
	Correct	Incorrect
1.5	---	---
2.5	15	10
3.5	13	13
4.5	17	10
5.5	18	6
6.5	22	0
7.5	15	2
9.5	14	0

Configurations used							
Configuration	1	2	6	7	8	9	15
Number of runs	38	41	9	12	11	13	31



TABLE V.— WORK-LEVEL INDICATOR

$$WLI = A\bar{c} + B(\bar{\delta}_a + \bar{\delta}_e)$$

Subject	Configuration	A	B	Units of time delay $\tau$ of —								
				1.5	2.5	3.5	4.5	5.5	6.5	7.5	9.5	
1	1	0.0240	14.2927	0.990	1.006	1.031	0.997	0.965	1.009			
	2	.0196	12.1841	.996	.991	1.023	.994	.996	1.005			0.997
	3	.0166	11.2616	.971	1.015	1.014	.995	1.005	1.007			.993
	4	.0188	14.6570	1.028	.989	.985	.990	1.004	1.006			.995
	5	.0193	8.0496	.997	.999	1.009	1.005	.999	.983			1.001
	6	.0160	7.2976	1.005	.988	1.031	.961	1.021	.985			1.006
	7	.0132	10.5690	.989	1.007	.976	.999	.975	1.017	1.060		.981
	8	.0195	8.9230	1.064	.976	.971	1.003	.961	.981	1.033		1.003
	9	.0161	10.6704	1.012	.979	1.029	.988	.990	.992	1.012		.994
	10	.0178	7.2659	.994	1.002	.989	.988	1.015	1.012			.983
	11	.0142	8.1383	1.000	.993	.987	.999	1.038	.989			.993
	12	.0213	6.0901	.997	1.001	.933	1.000	1.030	1.072			.961
	13	.0161	7.0022	1.015	.982	1.015	1.006	.998	.986			.997
	14	.0152	8.2158	.992	1.016	.997	1.005	.995	.992	.996		1.005
	15	.0100	10.7599	.942	.972	.982	.982	1.028	1.025			1.089
	16	.0145	7.3138	1.012	.990	.996	1.009	.994	.998			1.002
	17	.0141	7.5501	.992	.995	1.010	.998	1.027	1.005			.980
2	2	.0100	22.4523	.973	1.022	.994	1.031	.985	.993		.991	
	5	.0144	6.7579	1.007	.992	.979	1.007	1.014	.999		.993	
	6	.0093	19.7460	1.008	.995	1.055	.948	.955	1.015		1.011	
	9	.0130	8.1869	.998	.984	1.004	1.018	1.002	1.012		.982	
	13	.0132	5.6610	1.015	.998	1.010	.998	.992	.994		1.012	
16	.0141	5.2603	.961	1.016	1.009	1.012	1.009	1.003		.979		

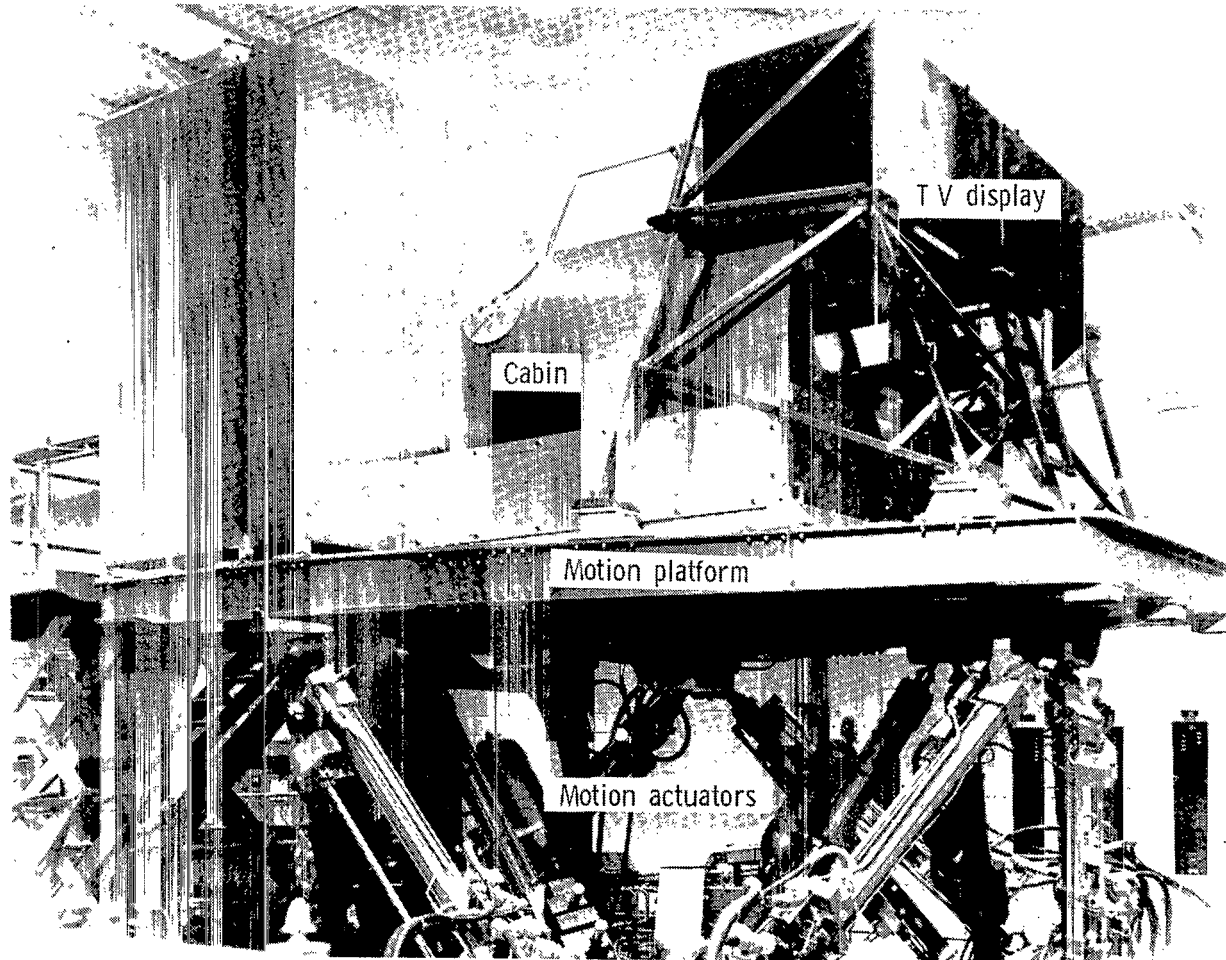
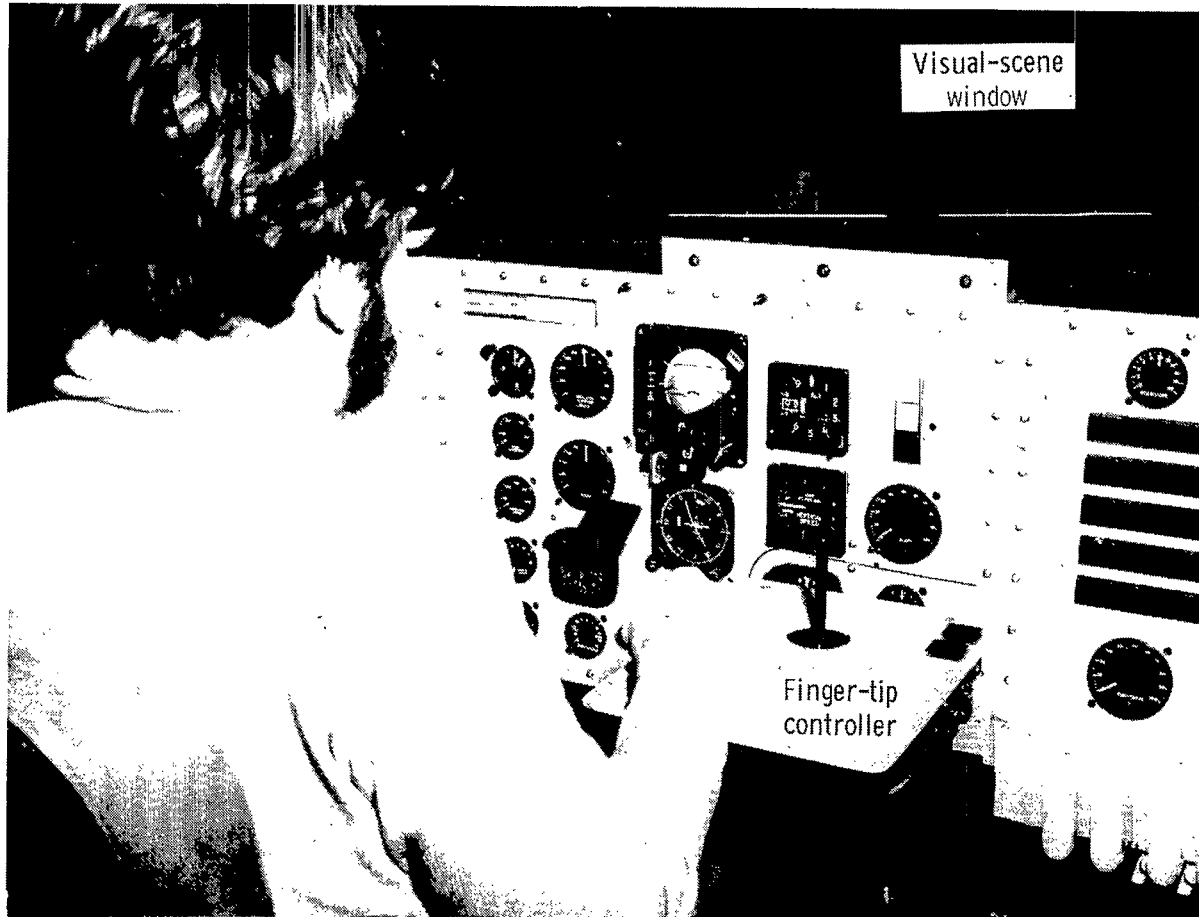
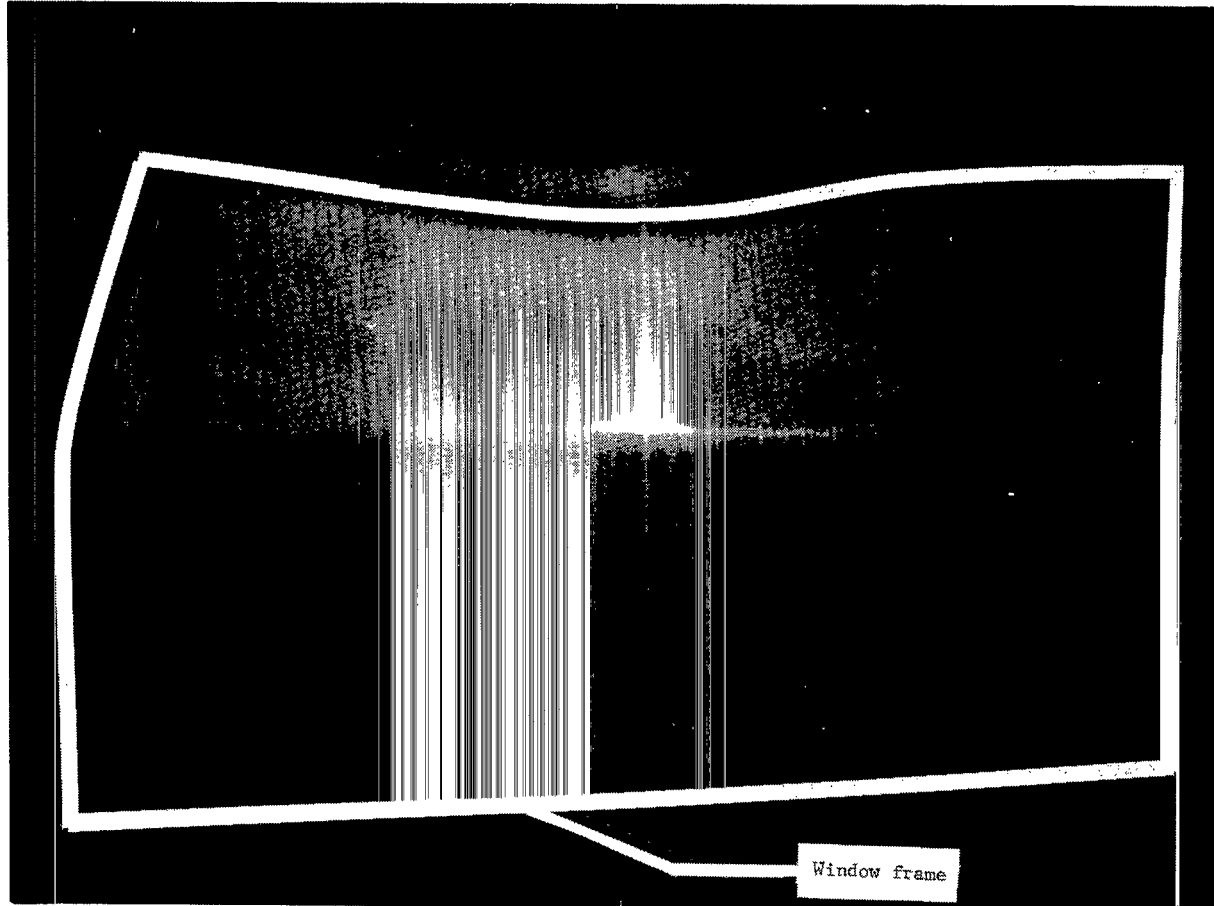


Figure 1.- Langley six-degree-of-freedom-vision-motion simulator. L-73-7163.1



L-75-1306.1

Figure 2.- Cockpit interior showing two-axis finger-tip controller. (Instruments and throttles are not activated for tests.)



L-75-3154.1

Figure 3. Photograph of visual scene observed by the subject when the tracker aircraft was nearly aligned with the target.

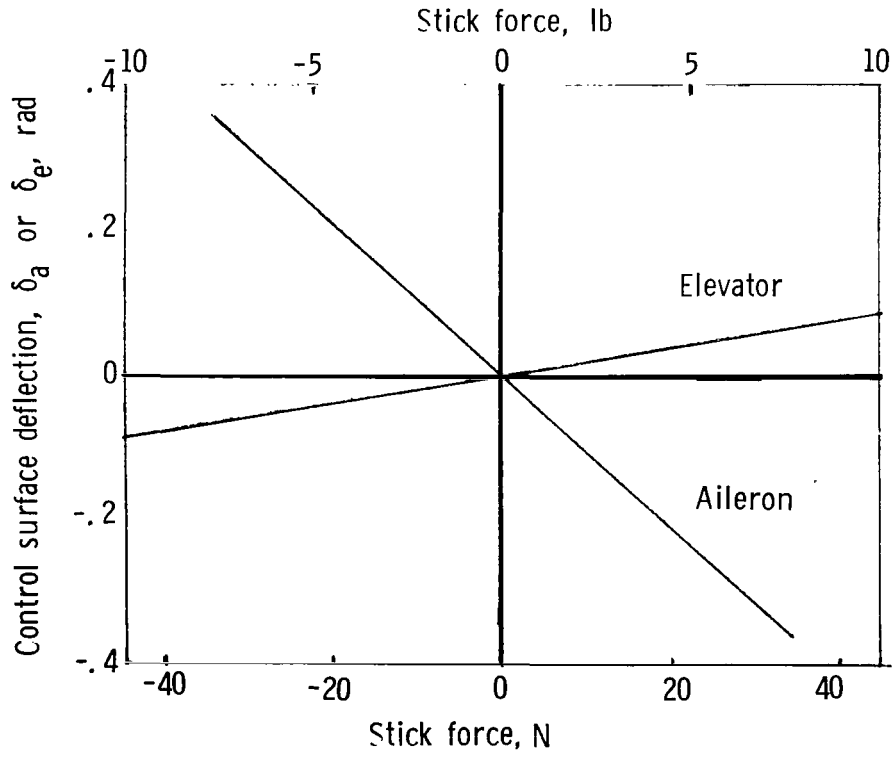
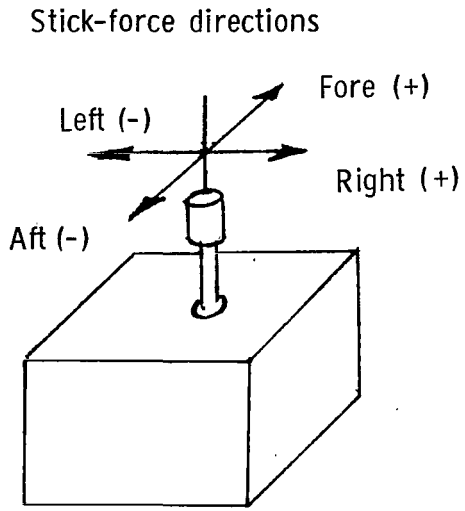


Figure 4.- Two-axis stick-force characteristics.

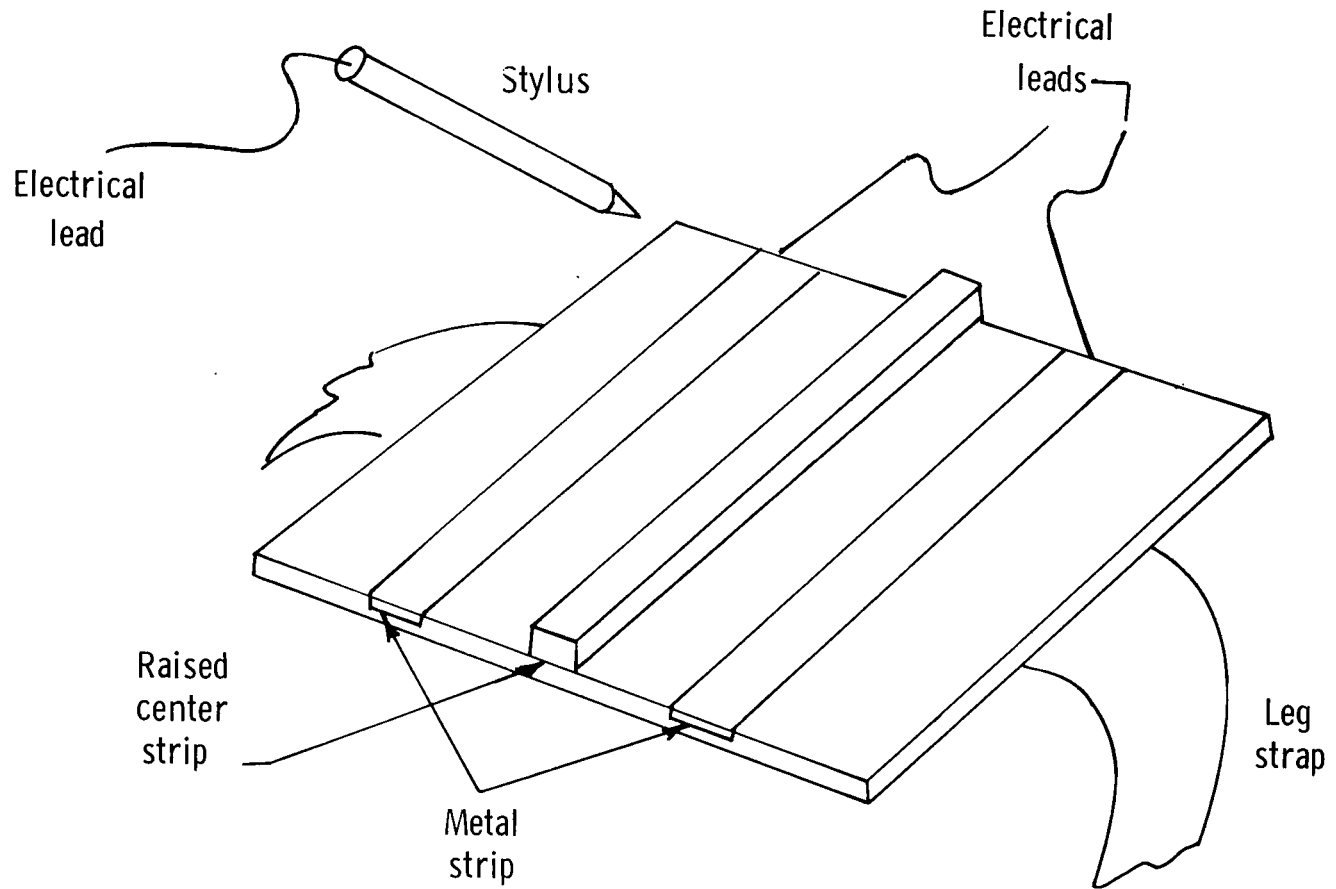


Figure 5.- Sketch of secondary task board and stylus.

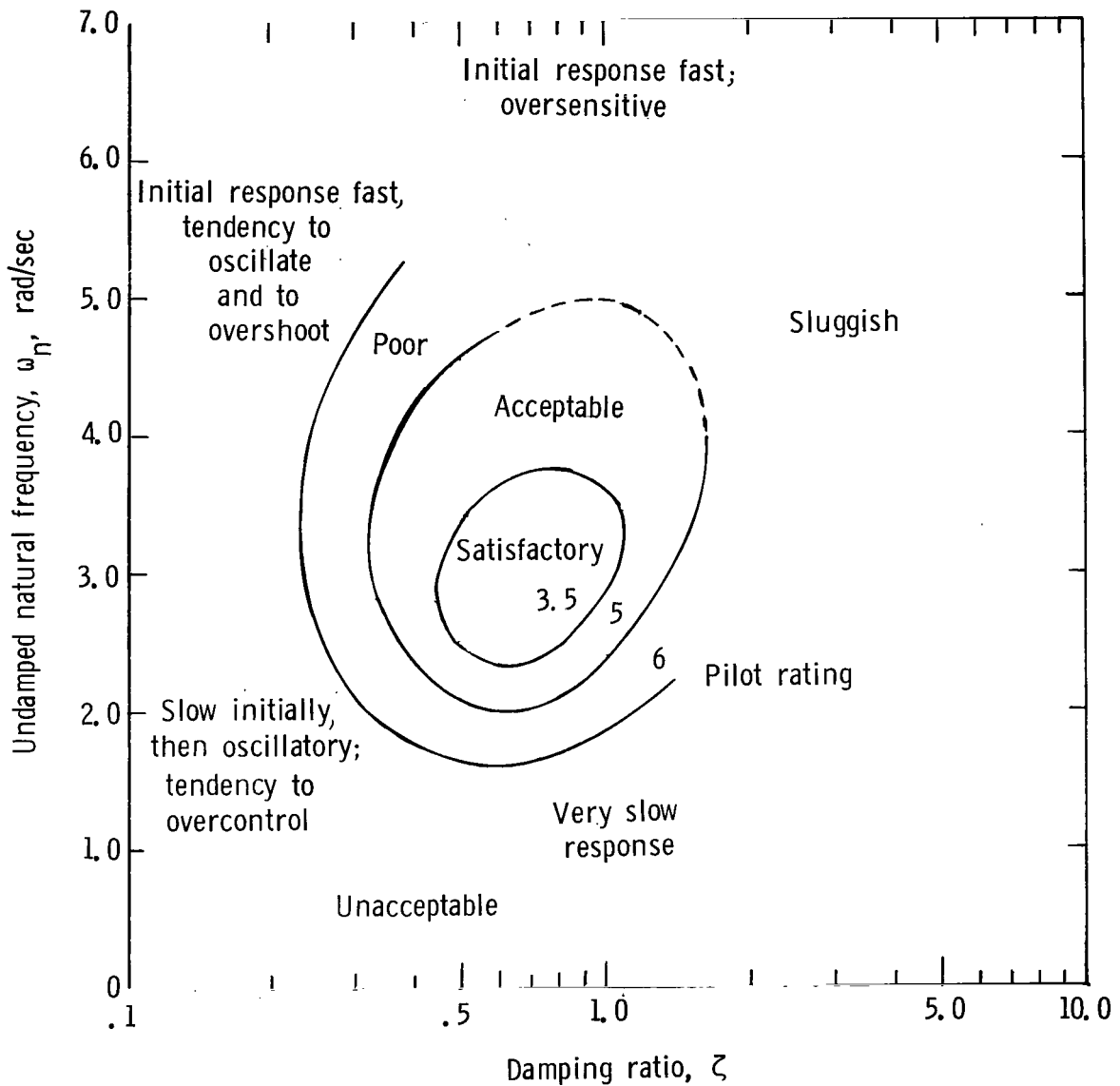


Figure 6.- Longitudinal short-period handling-qualities chart.

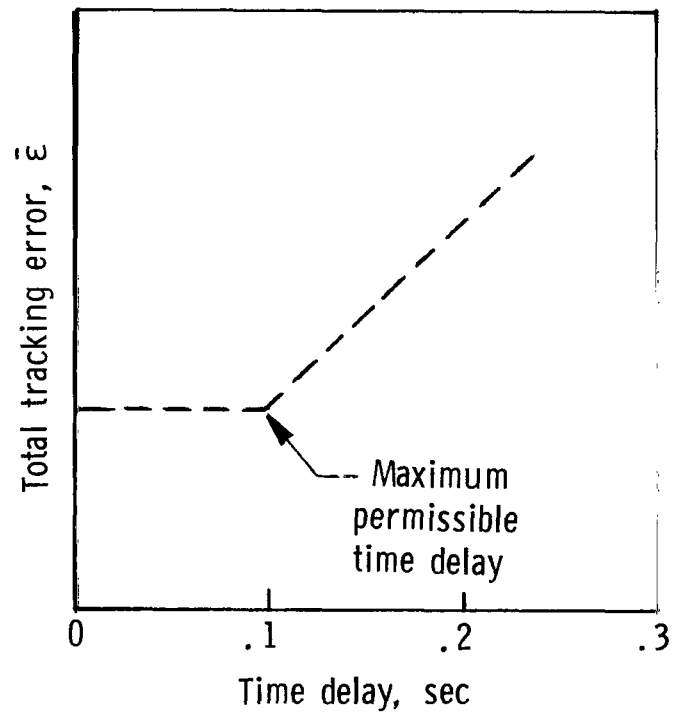
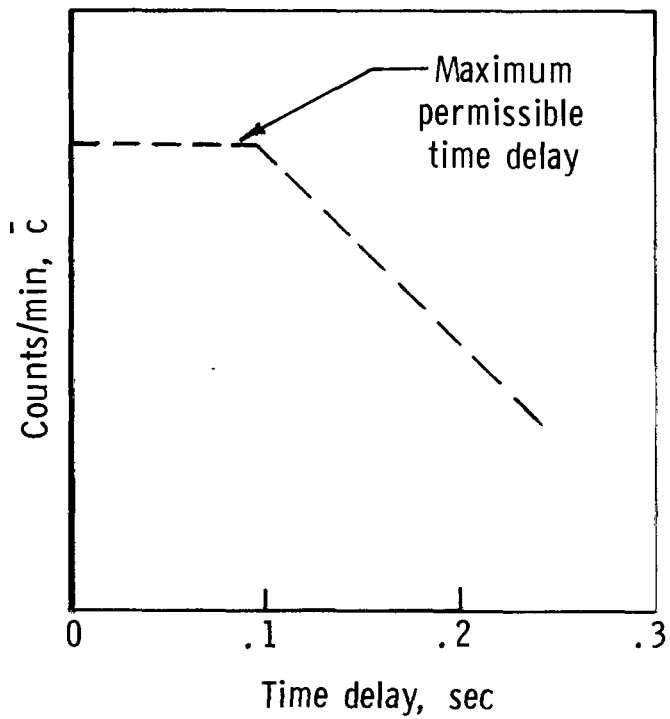
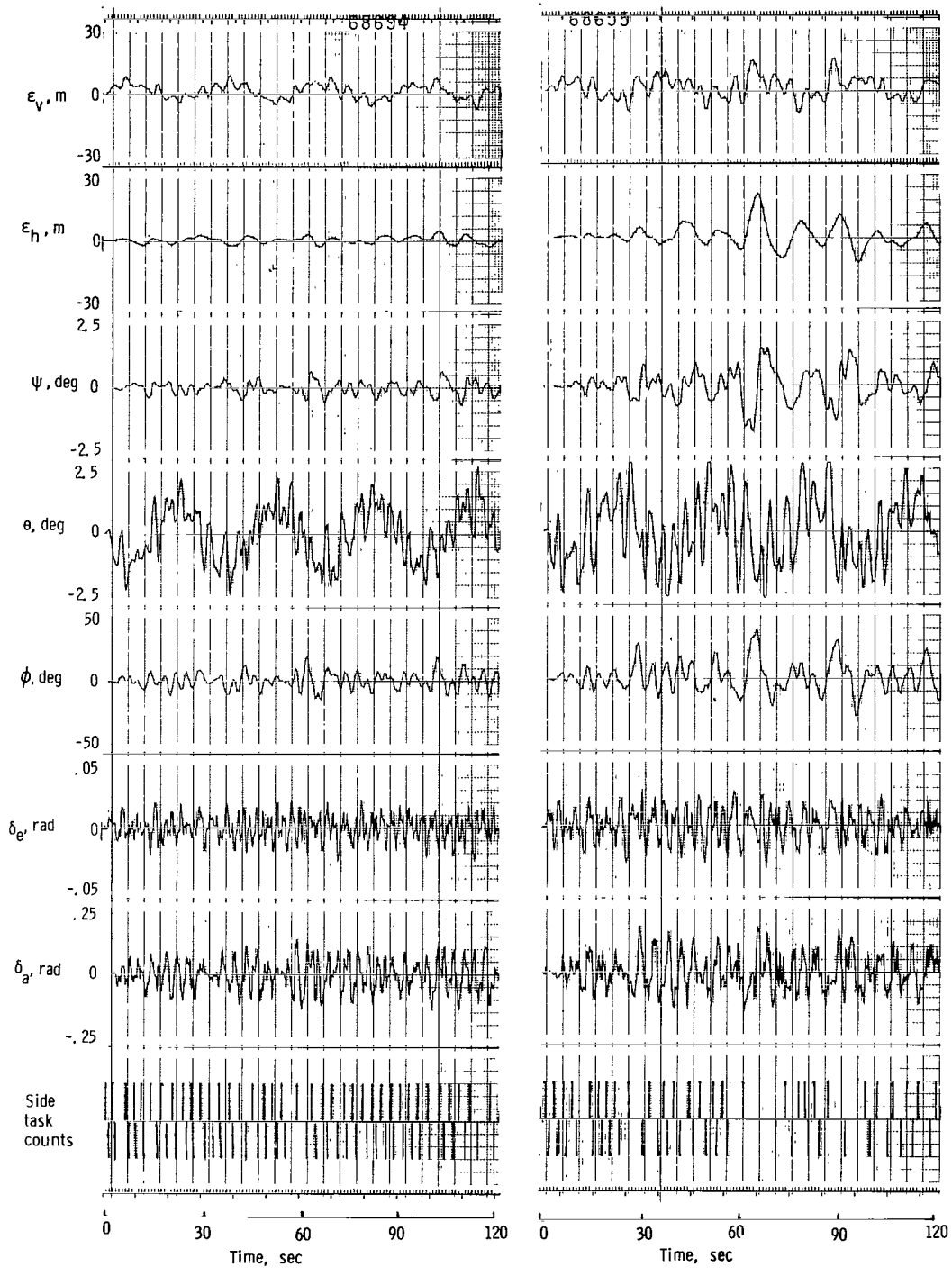


Figure 7.- Anticipated variation of counts and tracking error with time delay for one airplane configuration.

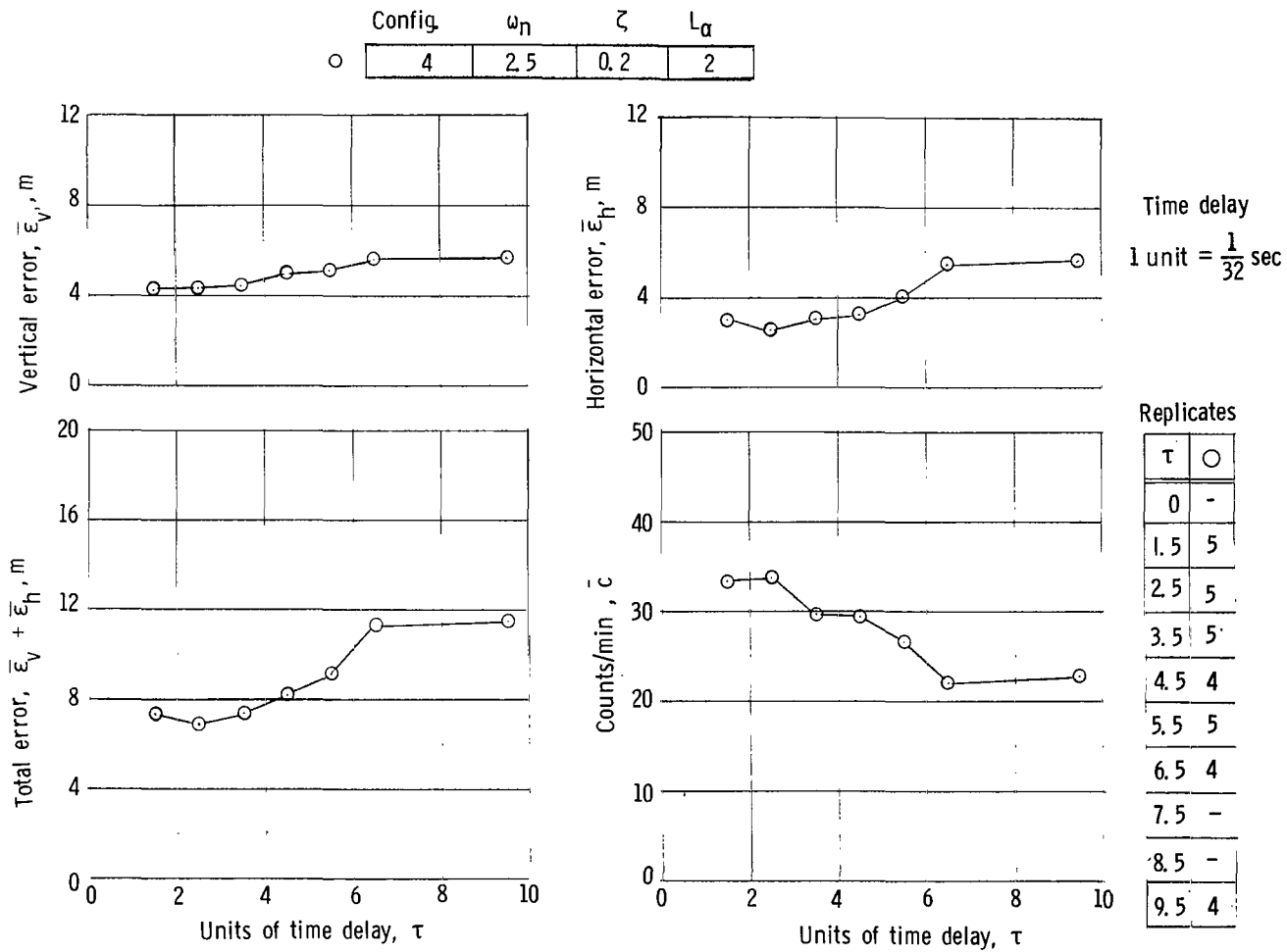




(a) Configuration 6;  $\tau = 1.5$ .

(b) Configuration 6;  $\tau = 9.5$ .

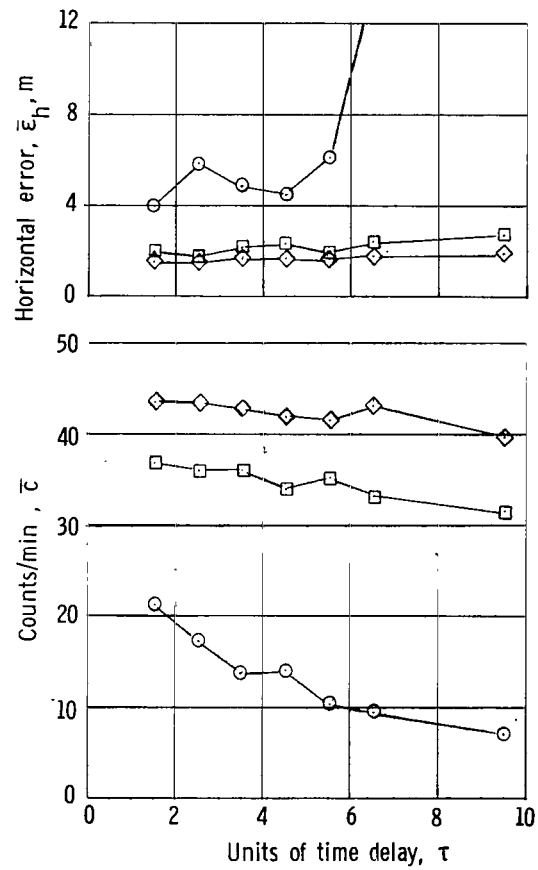
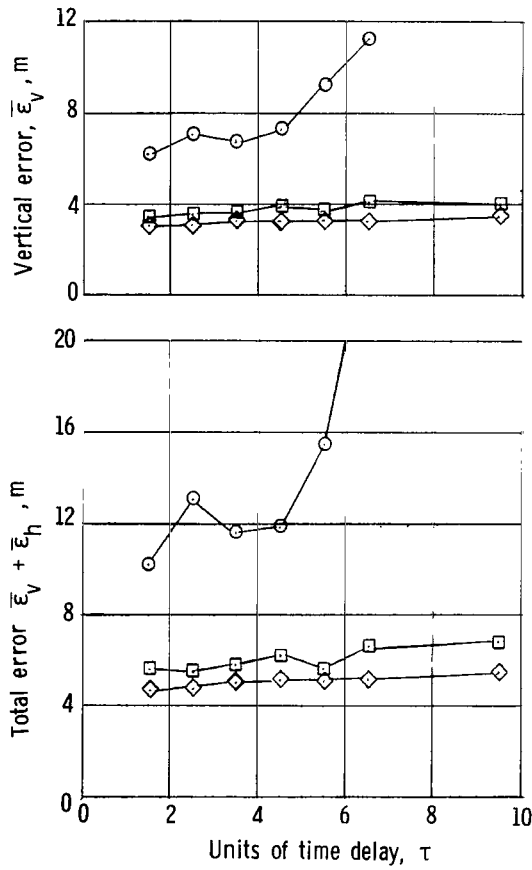
Figure 8.- Time histories for two flights having different time delays made by subject 1.



(a) Data for  $\zeta = 0.2$ .

Figure 9.- Basic data (arithmetic means for tracking error and secondary task score) as a function of time delay for various vehicle configurations flown by subject 1.

Config.	$\omega_n$	$\zeta$	$L_a$	
○	1	1.5	0.3	2
□	5	3.0	.3	2
◇	10	4.0	.3	2

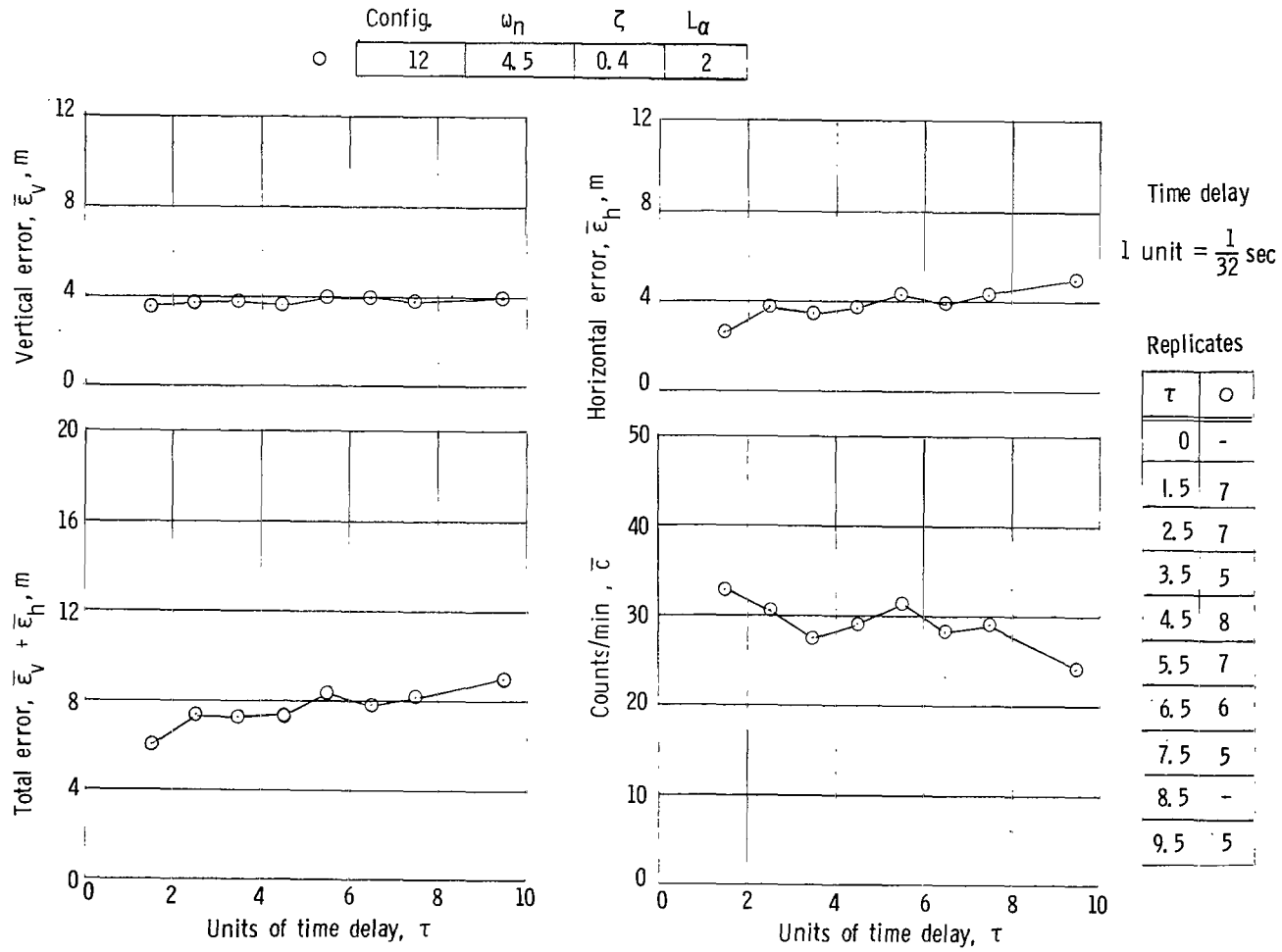


Time delay  
1 unit =  $\frac{1}{32}$  sec

Replicates			
$\tau$	○	□	◇
0	-	-	-
1.5	7	8	7
2.5	7	7	7
3.5	7	8	7
4.5	7	7	7
5.5	6	8	6
6.5	2	7	7
7.5	-	-	-
8.5	-	-	-
9.5	1	7	7

(b) Data for  $\zeta = 0.3$ .

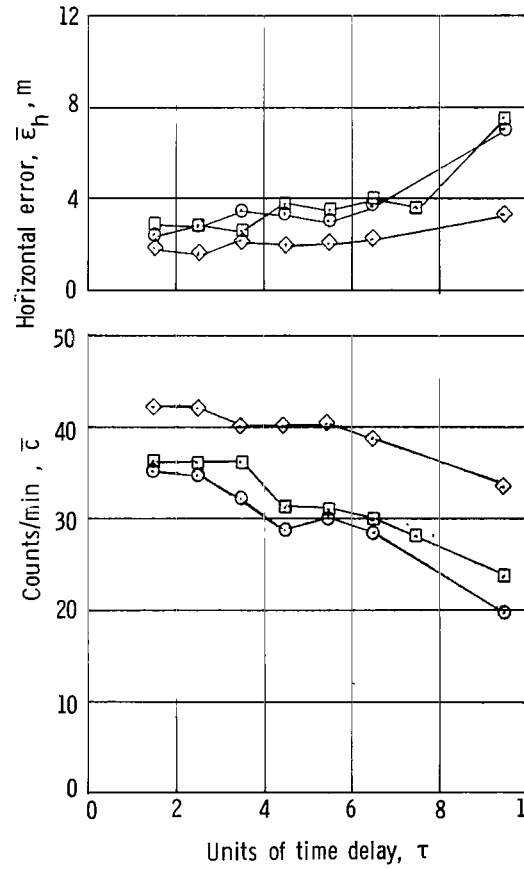
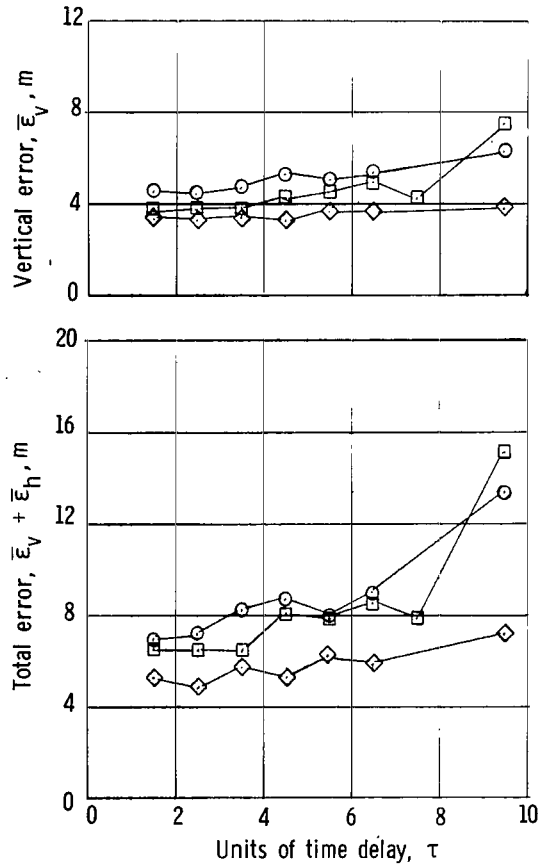
Figure 9.- Continued.



(c) Data for  $\zeta = 0.4$ .

Figure 9.- Continued.

Config.	$\omega_n$	$\zeta$	$L_\alpha$	
○	3	2.0	0.7	2
□	6	3.0	.7	2
◇	13	4.5	.7	2



Time delay  
1 unit =  $\frac{1}{32}$  sec

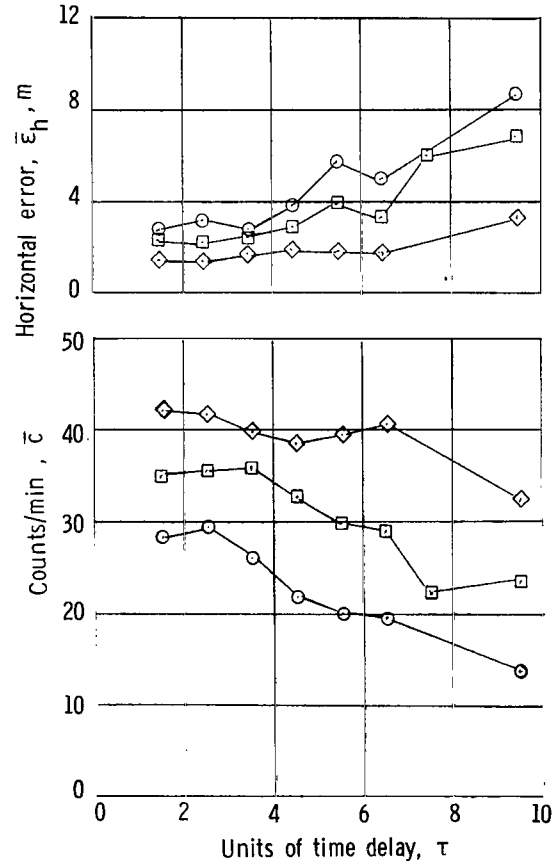
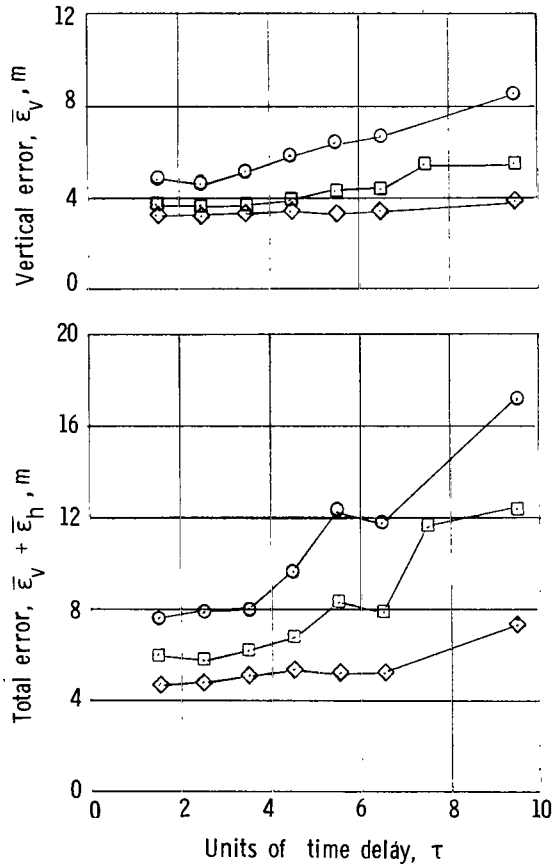
Replicates

$\tau$	○	□	◇
0	-	-	-
1.5	7	11	8
2.5	7	6	6
3.5	7	6	8
4.5	7	10	6
5.5	7	7	7
6.5	7	7	6
7.5	-	6	-
8.5	-	-	-
9.5	7	6	6

(d) Data for  $\zeta = 0.7$ .

Figure 9.- Continued.

Config.	$\omega_n$	$\zeta$	$L_\alpha$
○	2	1.0	2
□	7	1.0	2
◇	15	1.0	2



Time delay  
1 unit =  $\frac{1}{32}$  sec

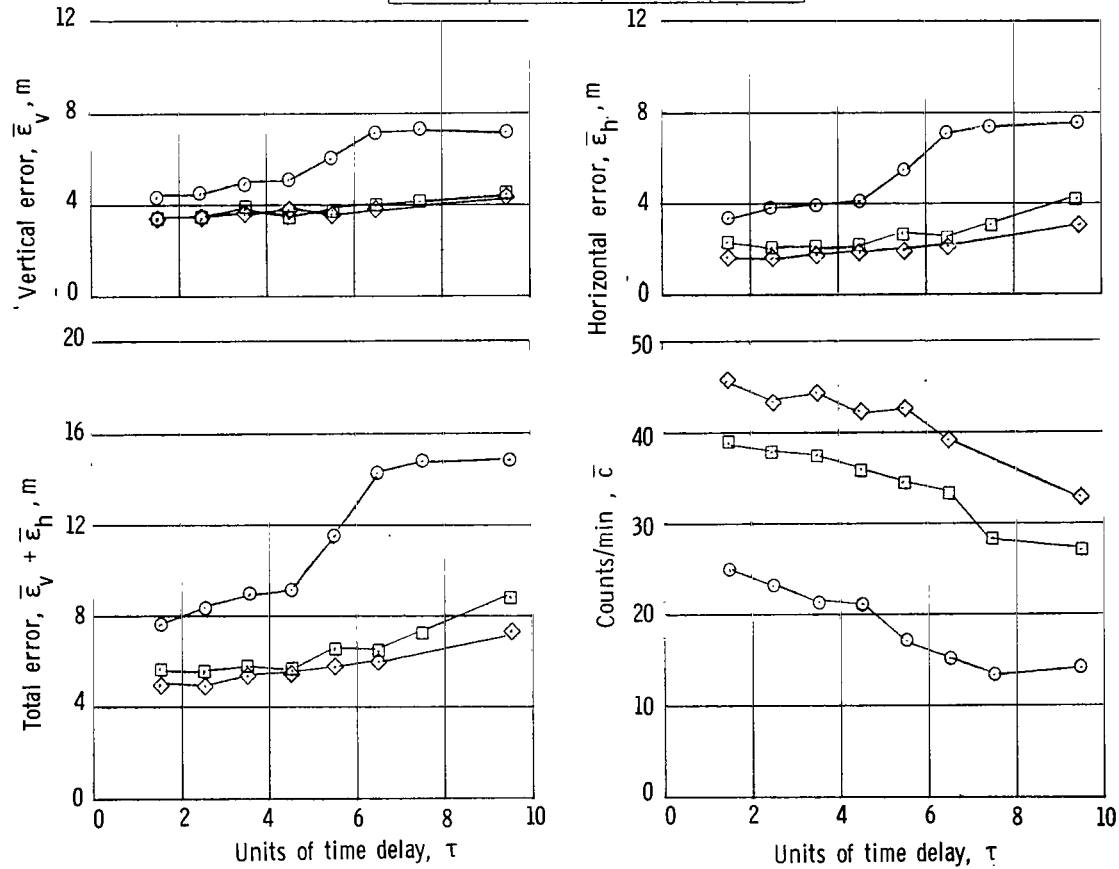
Replicates

$\tau$	○	□	◇
0	-	-	-
1.5	4	9	7
2.5	6	8	7
3.5	6	8	7
4.5	6	9	7
5.5	5	8	7
6.5	6	7	7
7.5	-	6	-
8.5	-	-	-
9.5	4	7	6

(e) Data for  $\zeta = 1.0$ .

Figure 9.- Continued.

	Config.	$\omega_n$	$\zeta$	$L_a$
○	8	2.83	1.59	2
□	14	4.5	1.5	2
◇	11	4.0	1.5	2



Time delay  
1 unit =  $\frac{1}{32}$  sec

Replicates			
$\tau$	○	□	◇
0	-	-	-
1.5	9	9	7
2.5	7	8	7
3.5	8	7	7
4.5	8	8	7
5.5	8	8	7
6.5	7	6	7
7.5	6	6	-
8.5	-	-	-
9.5	7	6	7

(f) Data for  $\zeta = 1.5$  and 1.59.

Figure 9.- Continued.

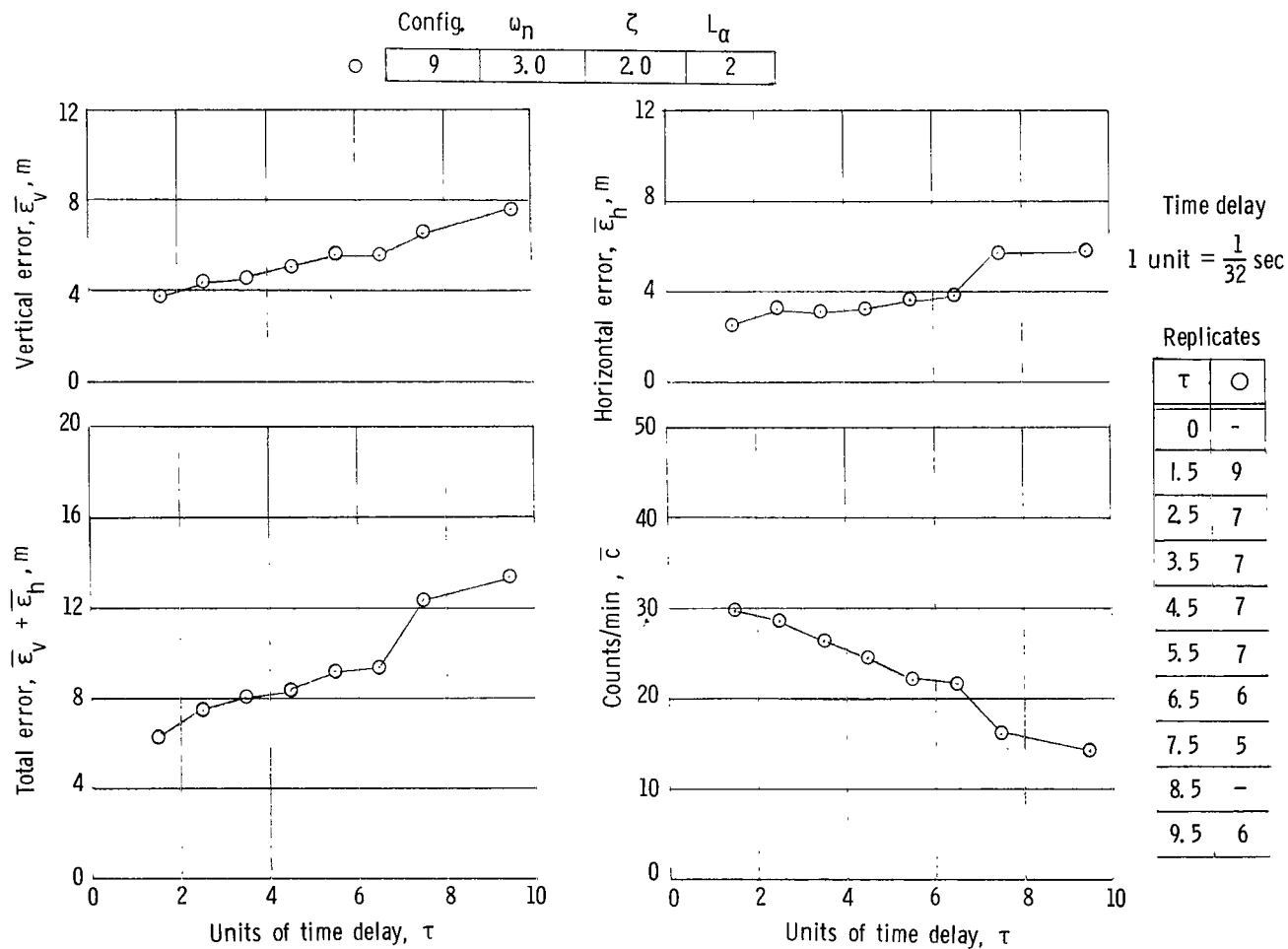
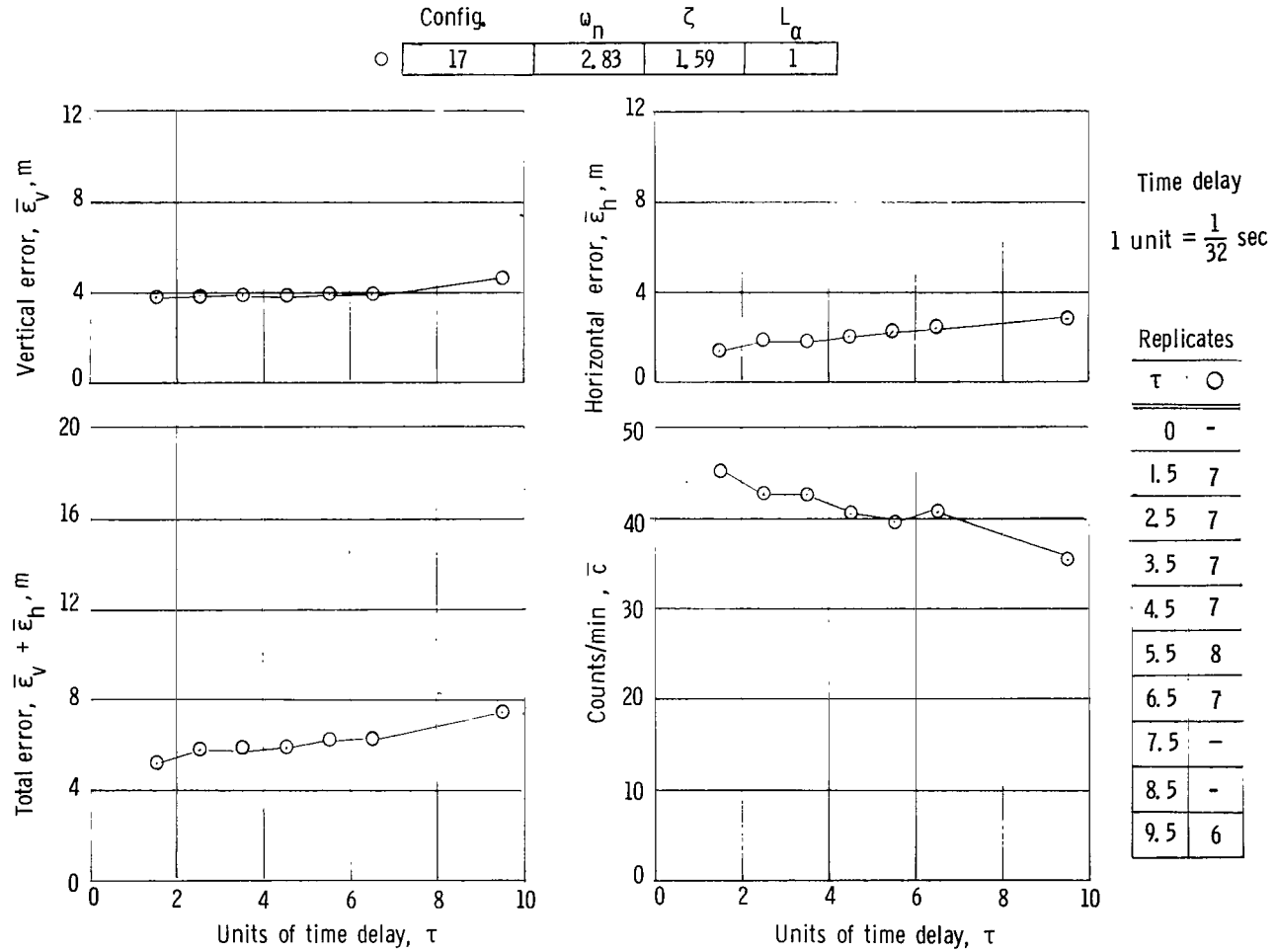
(g) Data for  $\zeta = 2.0$ .

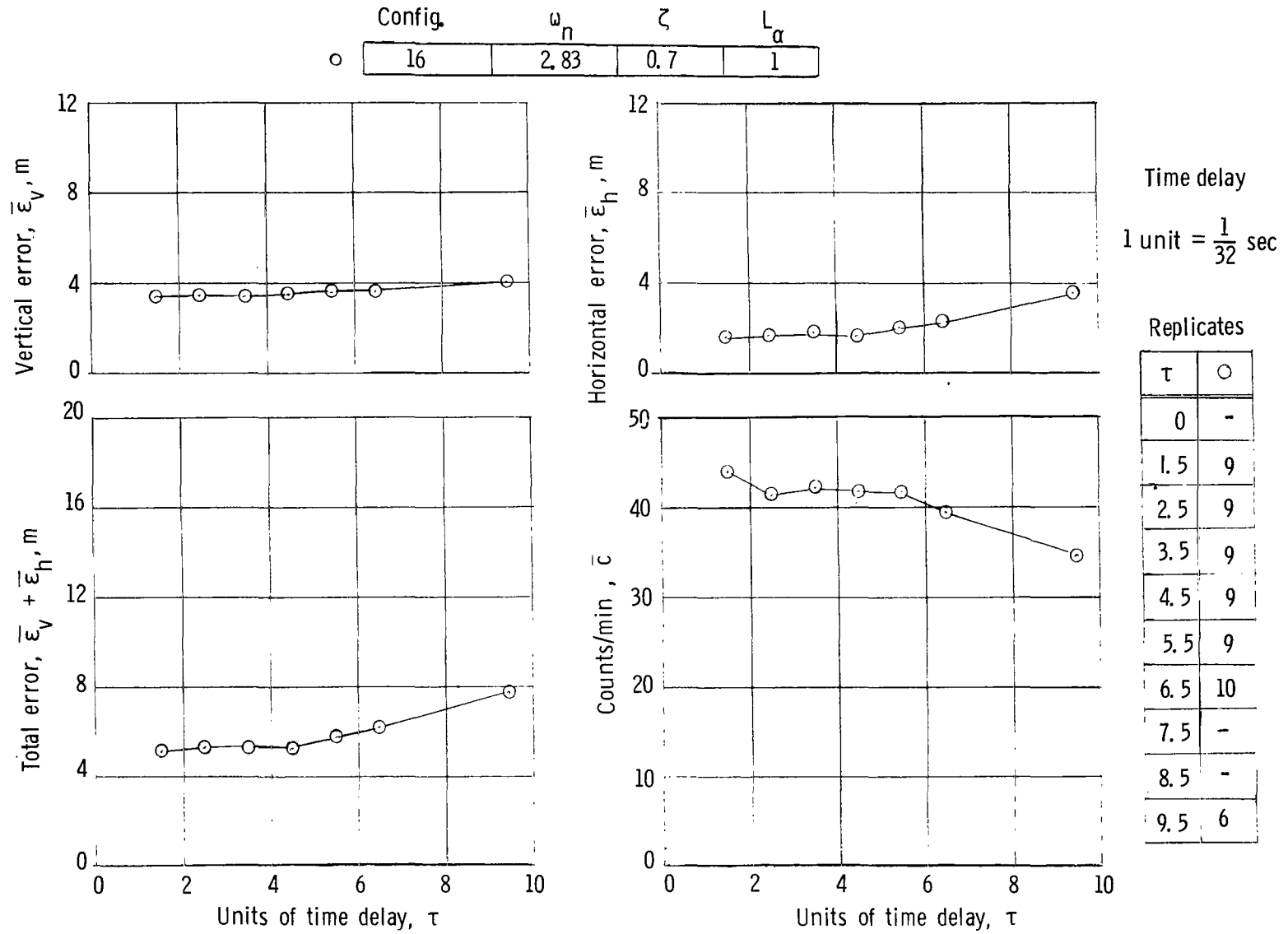
Figure 9.- Continued.





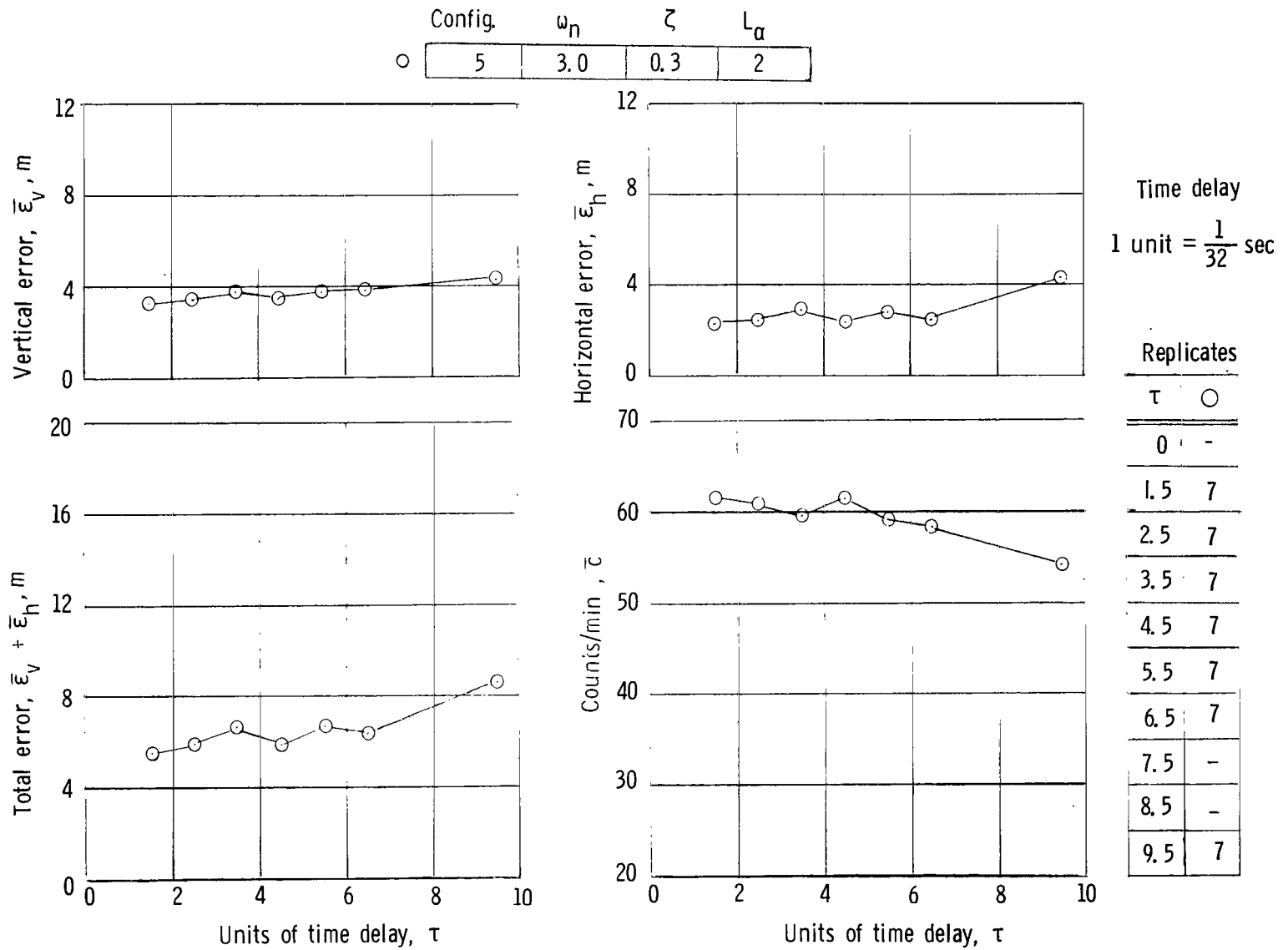
(h) Data for  $\zeta = 1.59$  for  $L_\alpha = 1$ .

Figure 9.- Continued.



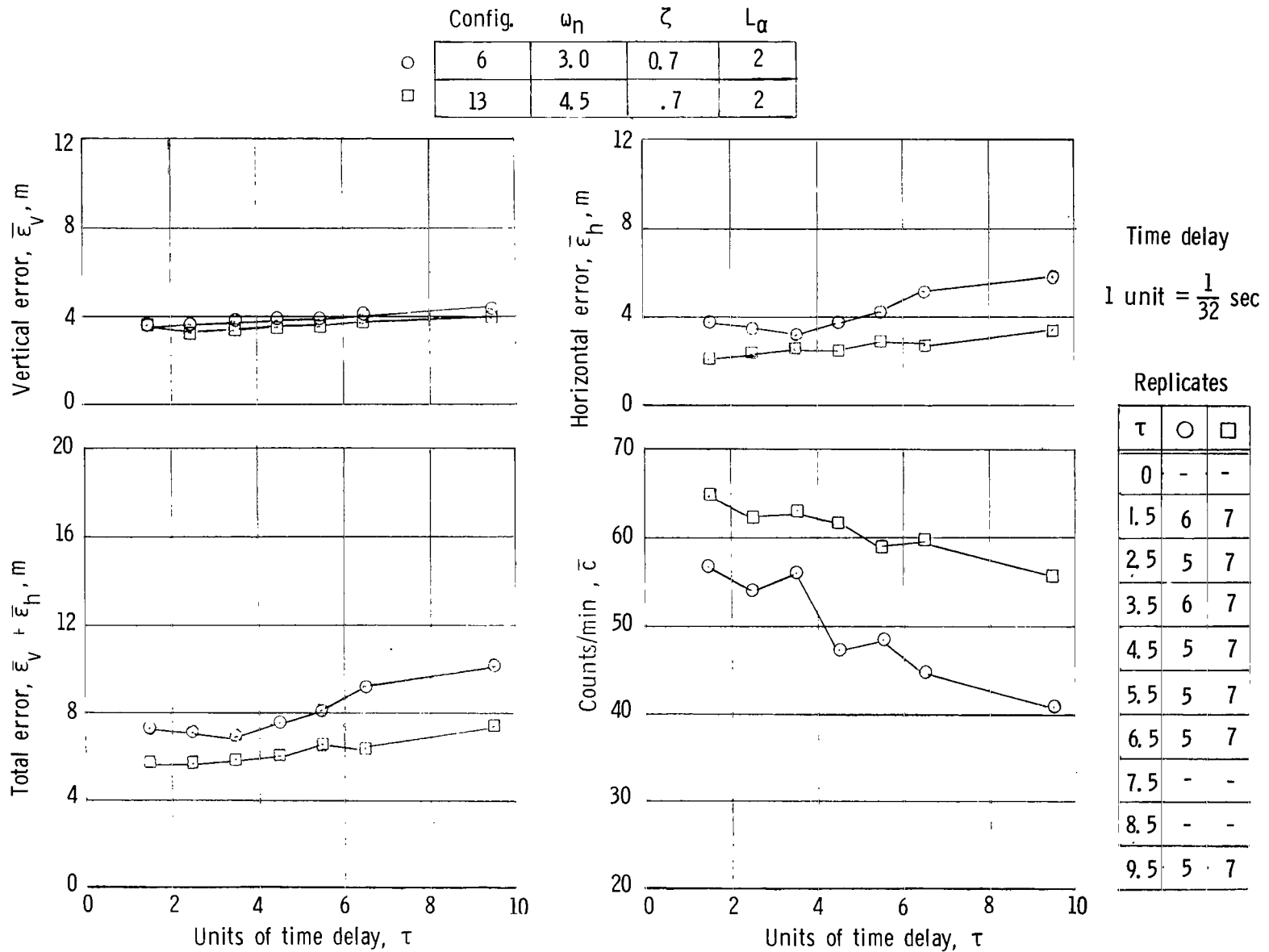
(i) Data for  $\zeta = 0.7$  for  $L_\alpha = 1.0$ .

Figure 9.- Concluded.



(a) Data for  $\zeta = 0.3$ .

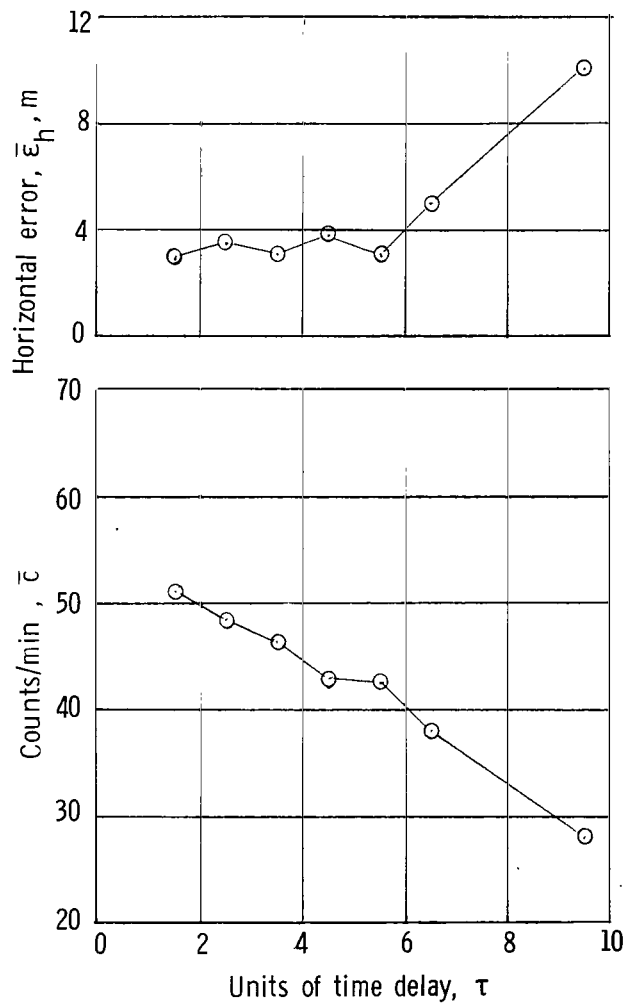
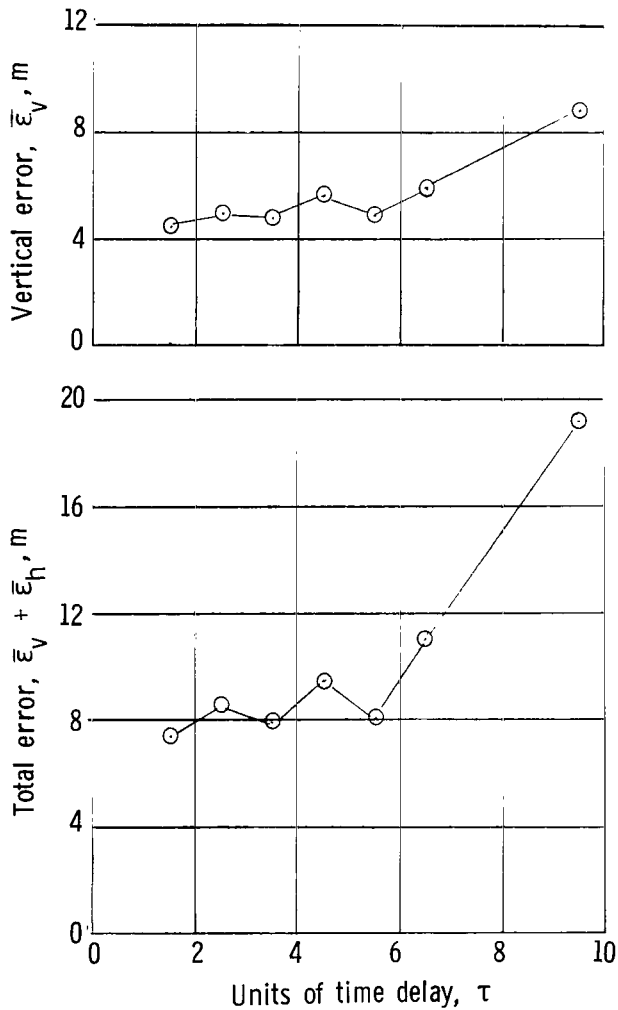
Figure 10.- Basic data (arithmetic means for tracking error and secondary task score) as a function of time delay for various configurations flown by subject 2.



(b) Data for  $\zeta = 0.7$ .

Figure 10.- Continued.

Config.	$\omega_n$	$\zeta$	$L_\alpha$	
○	2	1.5	1.0	2



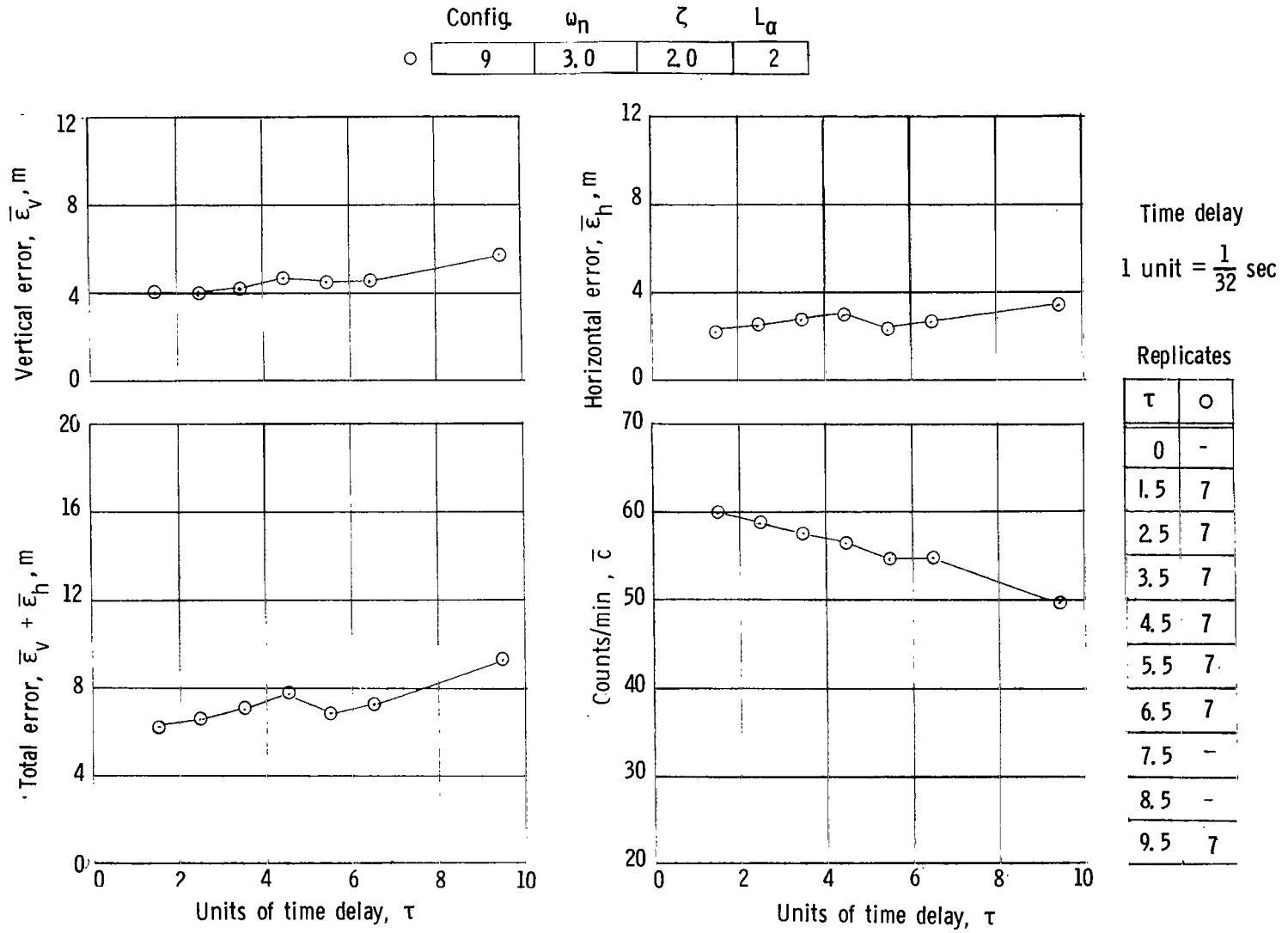
Time delay  
1 unit =  $\frac{1}{32}$  sec

Replicates

$\tau$	○
0	-
1.5	6
2.5	6
3.5	5
4.5	5
5.5	6
6.5	6
7.5	-
8.5	-
9.5	6

(c) Data for  $\zeta = 1.0$ .

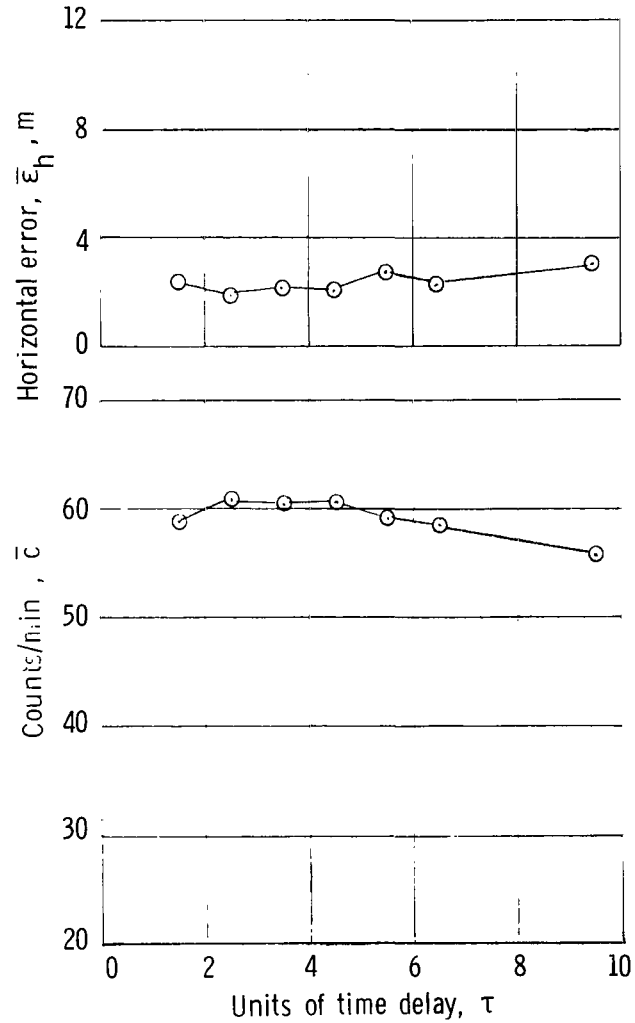
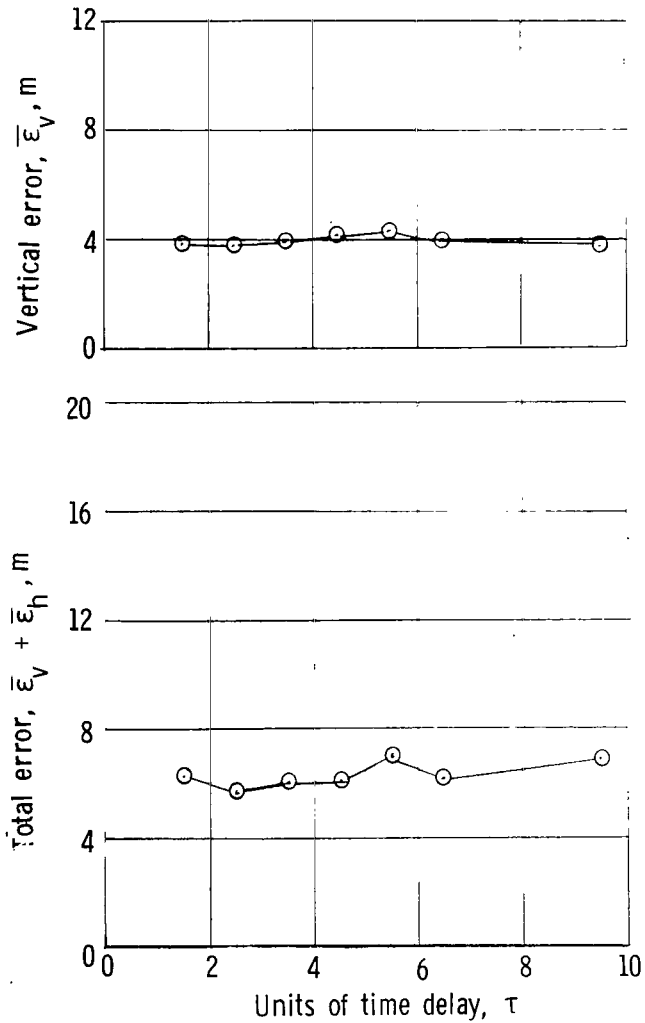
Figure 10.- Continued.



(d) Data for  $\zeta = 2.0$ .

Figure 10.- Continued.

Config.	$\omega_n$	$\zeta$	$L_\alpha$	
○	16	3.0	0.7	1

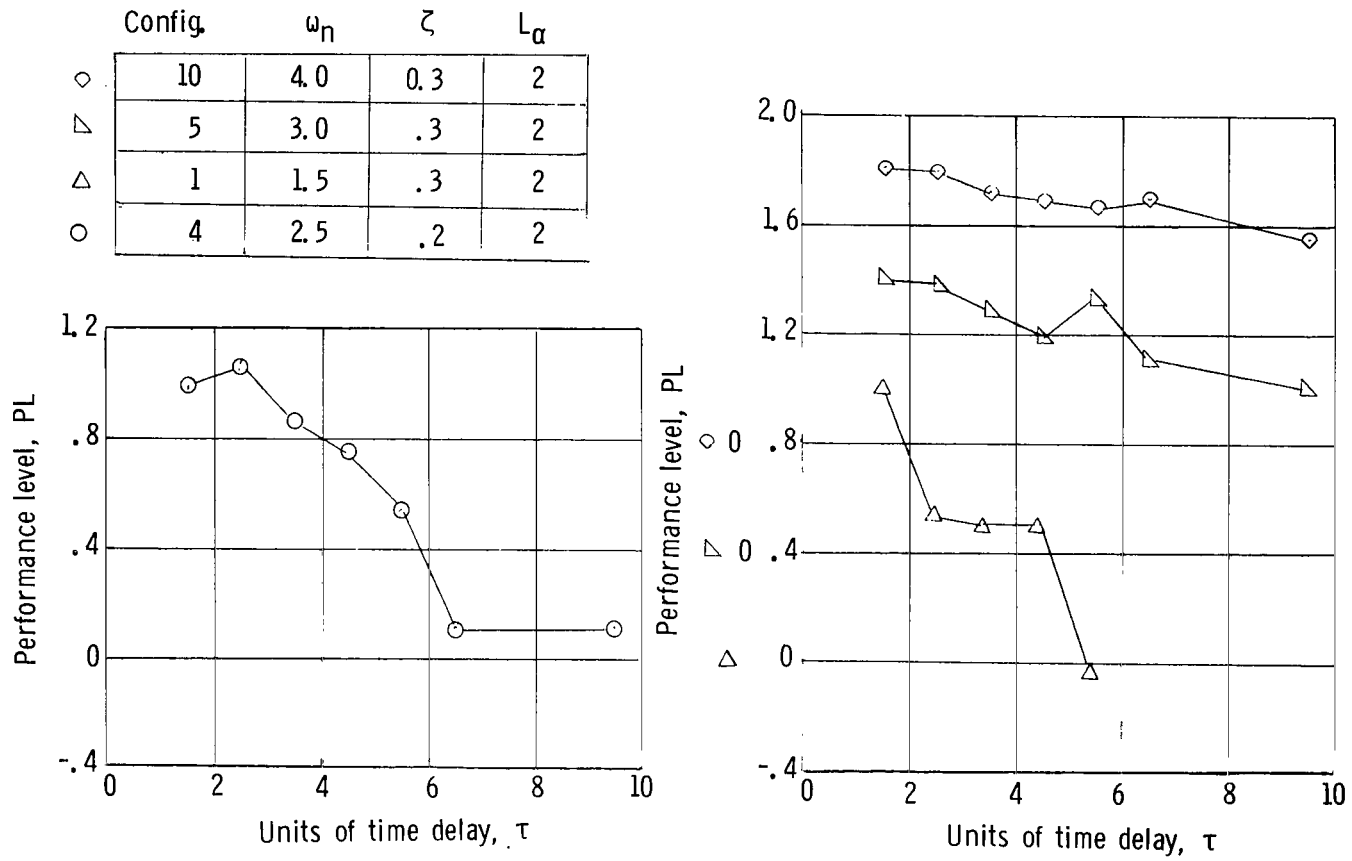


Time delay  
1 unit =  $\frac{1}{32}$  sec

Replicates	
$\tau$	○
0	-
1.5	4
2.5	4
3.5	4
4.5	4
5.5	4
6.5	4
7.5	-
8.5	-
9.5	4

(e) Data for  $\zeta = 0.7$  but with  $L_\alpha = 1.0$ .

Figure 10.- Concluded.

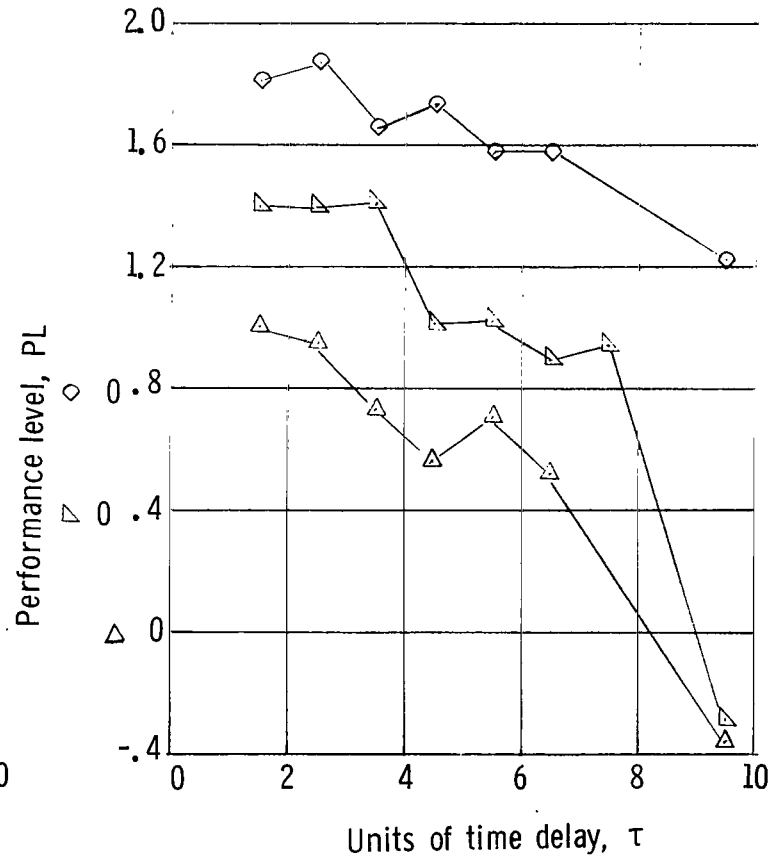
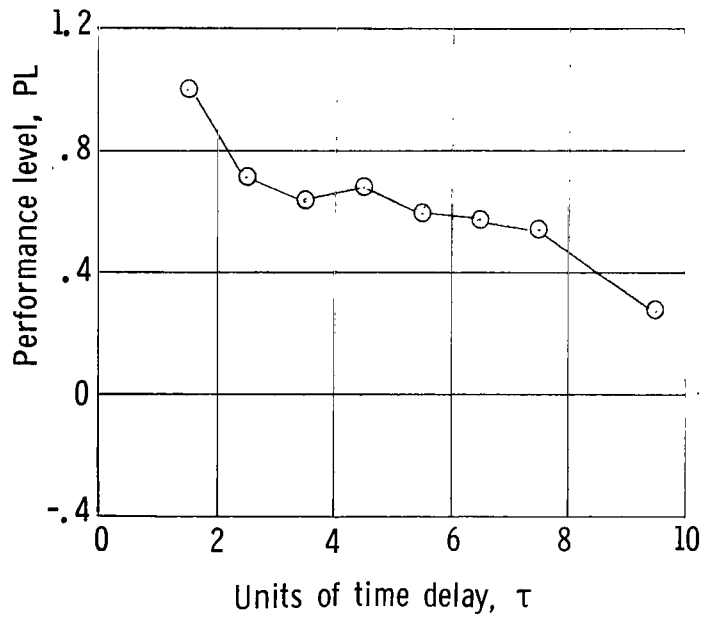


(a) Results for subject 1.  $\zeta = 0.2$  and  $0.3$ .

Figure 11.- Variation of performance level with time delay.

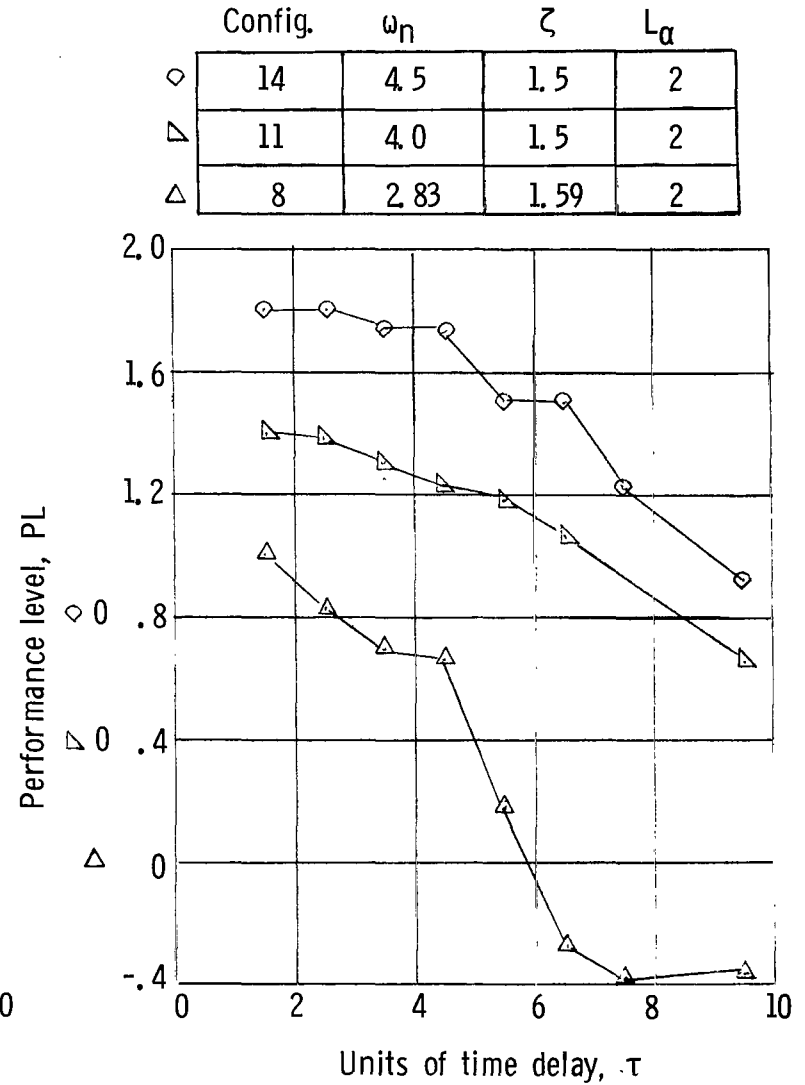
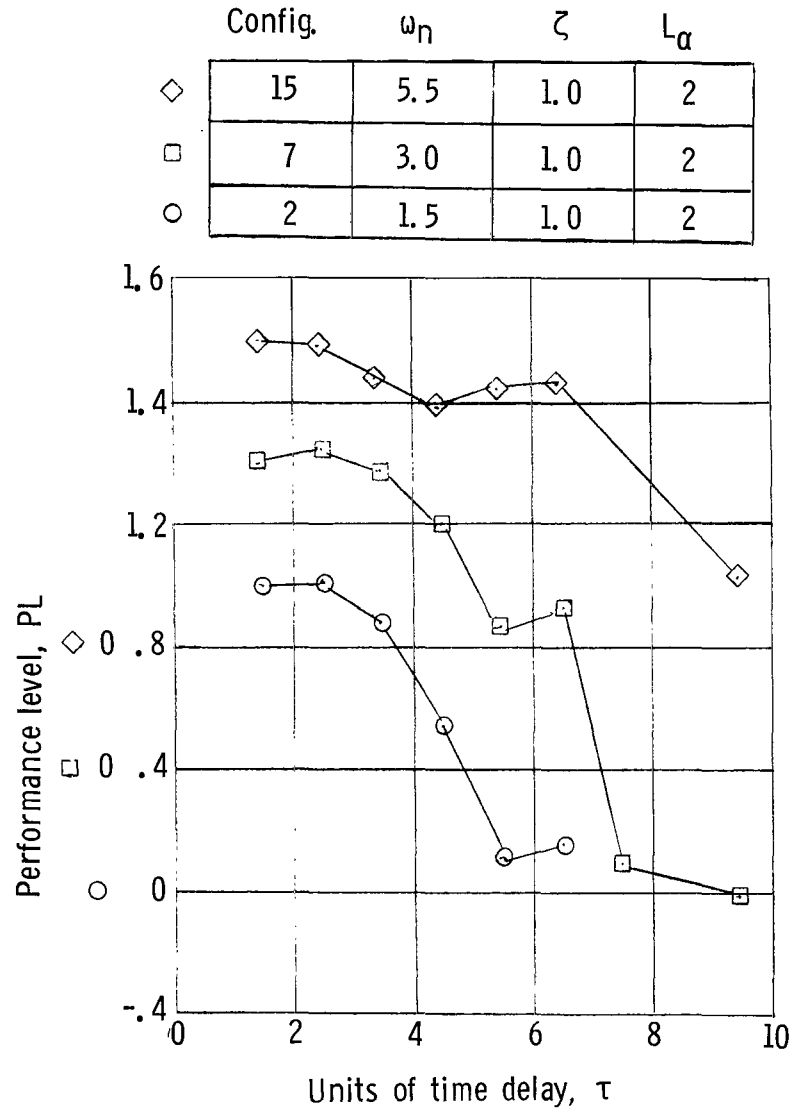


Config.	$\omega_n$	$\zeta$	$L_\alpha$
○	13	4.5	0.7
△	6	3.0	.7
△	3	2.0	.7
○	12	4.5	.4



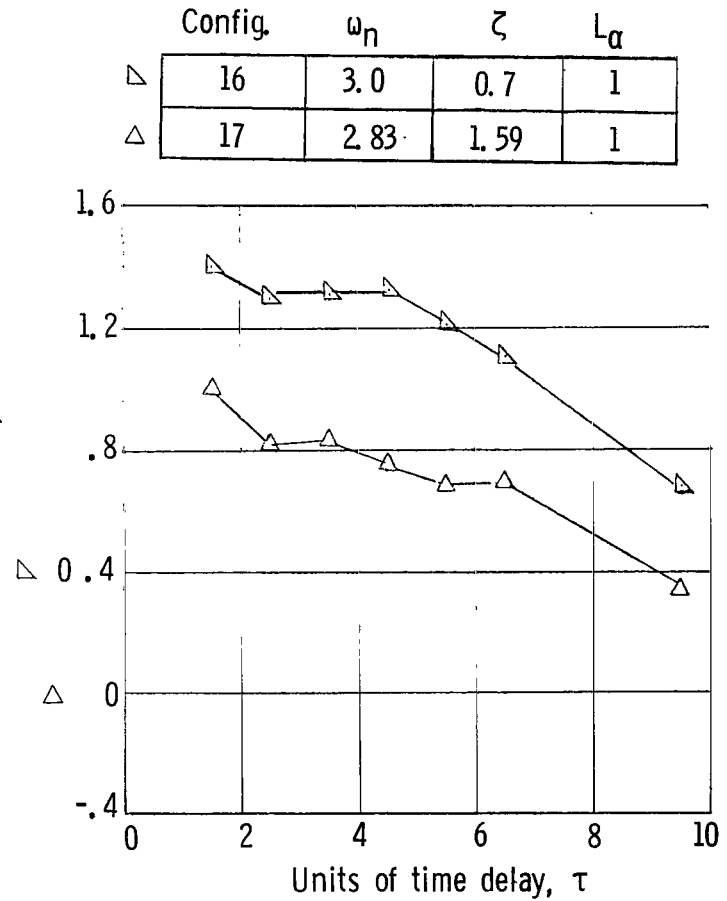
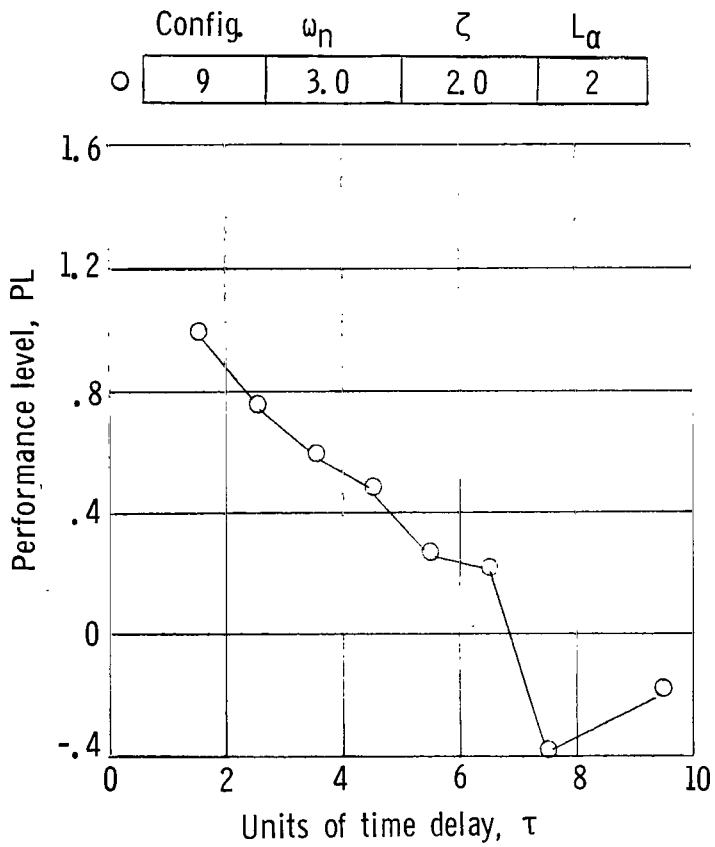
(b) Results for subject 1.  $\zeta = 0.4$  and  $0.7$ .

Figure 11.- Continued.



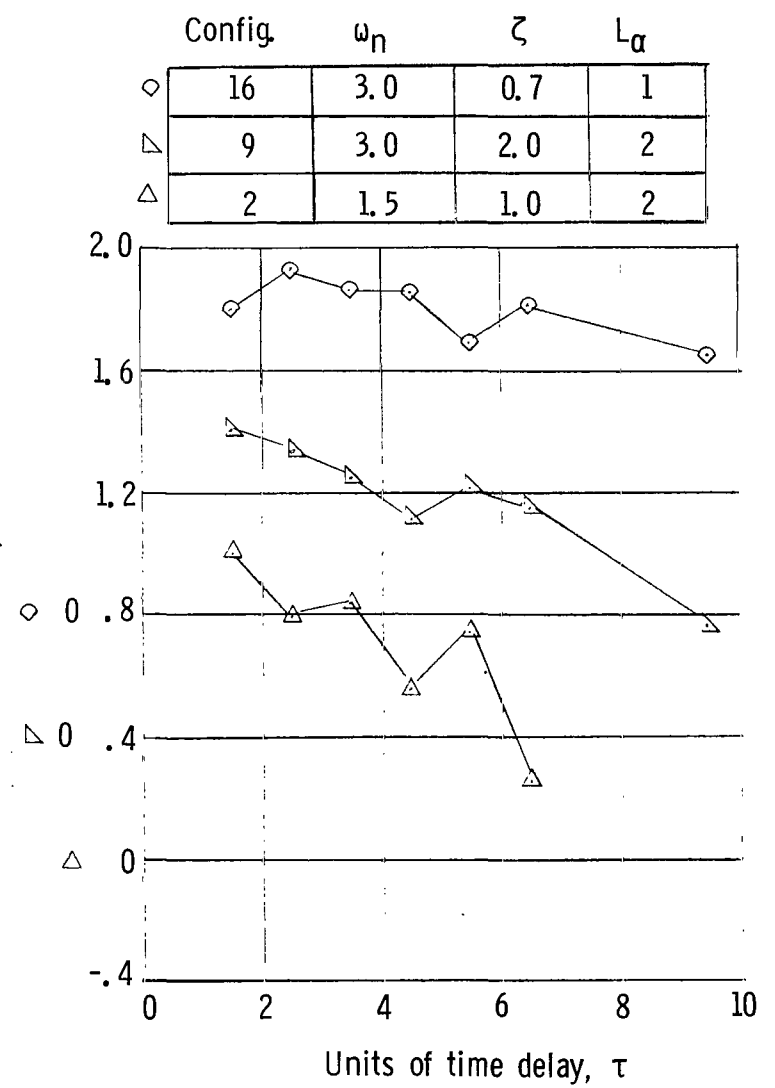
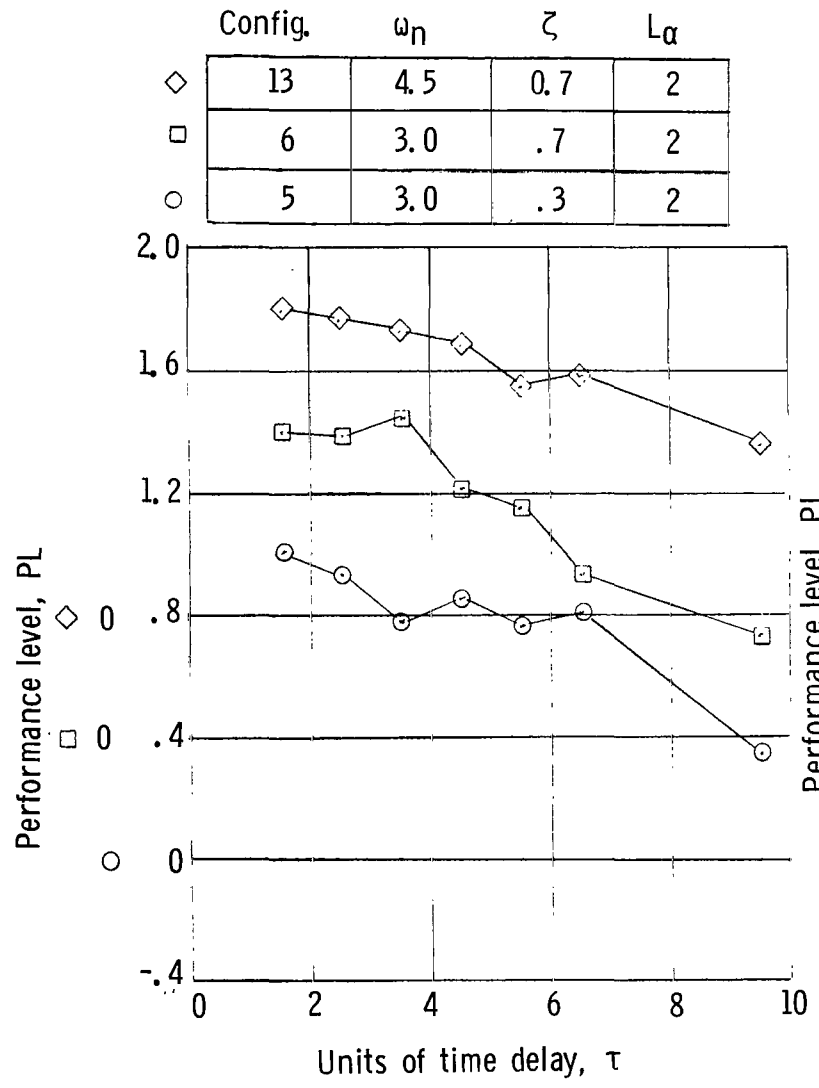
(c) Results for subject 1.  $\zeta = 1.0, 1.5, \text{ and } 1.59.$

Figure 11.- Continued.



(d) Results for subject 1.  $\zeta = 2.0$  and two configurations with  $L_\alpha = 1.0$ .

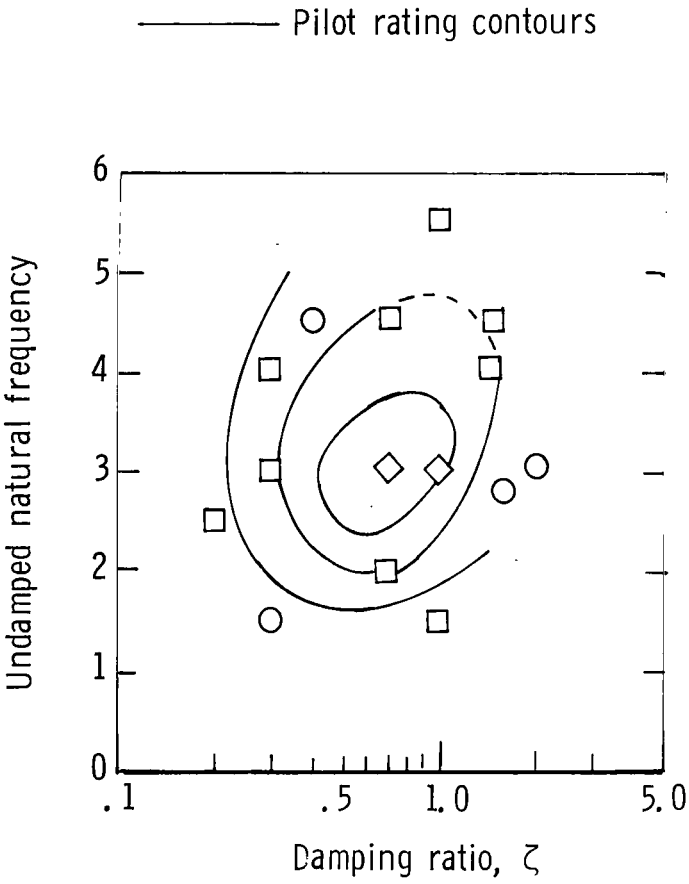
Figure 11.- Continued.



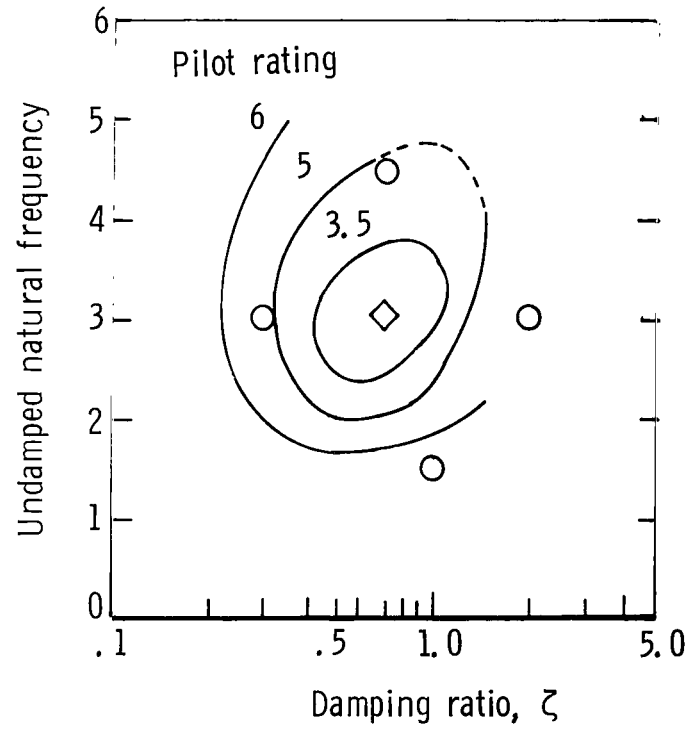
(e) Results for subject 2.

Figure 11.- Concluded.

Symbols	○	□	◇
Units of acceptable time delay	1.5 or less	2.5	3.5



(a) Subject 1.



(b) Subject 2.

Figure 12.- Frequency-damping plots for handling qualities and acceptable time delay.  
Data for  $L_\alpha = 2$ .



907 001 C1 U A 750912 S00903DS  
DEPT OF THE AIR FORCE  
AF WEAPONS LABORATORY  
ATTN: TECHNICAL LIBRARY (SUL)  
KIRTLAND AFB NM 87117

POSTMASTER: If Undeliverable (Section 158  
Postal Manual) Do Not Return

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

## NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

**TECHNICAL REPORTS:** Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

**TECHNICAL NOTES:** Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

**TECHNICAL MEMORANDUMS:** Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

**CONTRACTOR REPORTS:** Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

**TECHNICAL TRANSLATIONS:** Information published in a foreign language considered to merit NASA distribution in English.

**SPECIAL PUBLICATIONS:** Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

**TECHNOLOGY UTILIZATION PUBLICATIONS:** Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

*Details on the availability of these publications may be obtained from:*

**SCIENTIFIC AND TECHNICAL INFORMATION OFFICE**

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**  
Washington, D.C. 20546