NASA Technical Memorandum 86030

NASA-TM-86030 19860009853

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February 1986

# NASA
National Aeronautics and
Space Administration

# Comparison of Pilot Effective Time Delay for Cockpit Controllers Used on Space Shuttle and Conventional Aircraft

Cynthia M. Privoznik and Donald T. Berry
Ames Research Center, Dryden Flight Research Facility, Edwards, California

1986

**NASA**

N86-19324 #

SUMMARY

A study was conducted at the Dryden Flight Research Facility of NASA Ames
Research Center (Ames-Dryden) to compare pilot effective time delay for the space
shuttle rotational hand controller with that for conventional stick controllers.
The space shuttle controller has three degrees of freedom and nonlinear gearing.
The conventional stick has two degrees of freedom and linear gearing.  Two spring
constants were used, allowing the conventional stick to be evaluated in both a light
and a heavy configuration.  Pilot effective time delay was obtained separately for
pitch and roll through first-order, closed-loop, compensatory tracking tasks.  The
tasks were implemented through the space shuttle cockpit simulator and a critical
task tester device.  A total of 900 data runs were made using four test pilots and
one nonpilot (engineer) for two system delays in pitch and roll modes.  Results
showed that the heavier conventional control stick had the lowest pilot effective
time delays.  The light conventional control stick had pilot effective time delays
similar to those of the shuttle controller.  All configurations showed an increase in
pilot effective time delay with an increase in total system delay.

INTRODUCTION


The space shuttle hand controller is different from a conventional aircraft
stick in that it rotates in three degrees of freedom with short pivot lengths, while
a conventional control stick has a more translational movement in two degrees of
freedom with longer pivot lengths (figs. 1 and 2).  Previous studies conducted by
Systems Technology, Inc., under NASA contract (refs. 1 and 2) show that pilot effec-
tive time delay varies with stick stiffness and the order of the controlled element.
Any time delay, whether it consists of pilot delay or vehicle system delay, is a
critical parameter in aircraft handling qualities.  For example, pilot-induced
oscillations can occur during such critical tasks as landing and in-flight refueling
when excessive time delays exist.  The pilot effective time delay can be an impor-
tant component of the total time delay when the pilot is in the loop.  In some
situations, a small change in vehicle system time delay results in large changes in
handling qualities (ref. 3).

A study was made at NASA Ames-Dryden to compare pilot effective time delay, $\tau_e$,
for the space shuttle controller with that of more conventional stick controllers.
Pilot effective time delay was obtained through a first-order, closed-loop, compen-
satory tracking task.  This critical task uses an unstable controlled element where
the instability is increased with time.  Eventually, a critical point is reached
where the unstable system cannot be controlled and the amount of instability at that
point is an indication of the pilot effective time delay.

A critical task tester (CTT) that implements the critical task (fig. 3) was
used to obtain $\tau_e$ values for the space shuttle rotational controller and the two

conventional control stick configurations in both the pitch and roll axes at two system delays, with four test pilots and one nonpilot (engineer). The CTT was developed by Systems Technology, Inc., under previous NASA contracts.

NOMENCLATURE

CTT         critical task tester

e           base of natural system of logarithms (2.718)

j           imaginary number, $\sqrt{-1}$

$K_c$        controlled element constant

$K_p$        pilot describing function constant

s           Laplace operator

$Y_c$        controlled element

$Y_p$        pilot describing function

$\lambda$           inverse time constant, 1/sec

$\lambda_{crit}$     inverse time constant at critical time, 1/sec

$\tau_d$         total system delay, msec

$\tau_e$         pilot effective time delay, msec

$\Delta\tau_e$        increment in pilot effective time delay, msec

$\omega$           frequency, rad/sec

DESCRIPTION OF EQUIPMENT

Three control stick configurations were installed in the space shuttle cockpit simulator located in the Ames-Dryden simulation laboratory. One configuration was the space shuttle rotational hand controller, which has three degrees of freedom and nonlinear gearing. A more conventional two-degree-of-freedom control stick equipped with two different spring constants constituted the other two configurations. This control stick had linear gearing and was center-mounted; however, the pivot point was between that of a conventional aircraft stick and a sidestick. The conventional stick was first tested with a stiff set of springs (heavy conventional stick) and later with a softer set of springs (light conventional stick). The designations

"light," "heavy," and "conventional" are only relative, however, as the force gradients are lighter and pivot arms are shorter for this stick than that used in most aircraft center sticks. This is because the stick was a general-purpose engineering simulator stick and represented a compromise of a broad range of characteristics. The important characteristics of the three control stick configurations are presented in table 1 and figure 4.

The control stick signal, which is processed through the cockpit simulator, is operated with a 40-msec frame time and is then sent through the CTT. The total inherent time delay between pilot input and the CTT is 46 msec. The average sampling delay associated with the frame time accounts for 20 msec, and computation time accounts for 26 msec.

The CTT requires that the operator control a display indicator separately for pitch mode and roll mode. The operator is described by

$$Y_p = K_p \, e^{-\tau_e s}$$

where $Y_p$ is the pilot describing function, $K_p$ is the pilot describing function constant, e is the base of the natural system of logorithms (2.718), $\tau_e$ is the pilot effective time delay, and s is the Laplace operator. This first-order critical task uses an unstable controlled element

$$Y_c = K_c \, \lambda/(s - \lambda)$$

where $Y_c$ is the controlled element, $K_c$ is the controlled element constant, and $\lambda$ is the inverse time constant. Figure 5 shows a block diagram and root locus of the total system without added system delay using a first-order Pade approximation for the $e^{-\tau_e s}$ term. As $\lambda$ is increased as a function of time and error magnitude, the system becomes more unstable until control is lost. At that critical point, the value of $\lambda$ approximates the reciprocal of the pilot effective time delay, $\tau_e$ equals $1/\lambda_{crit}$. Additional information may be found in references 1 and 4.

The pitch and roll indicators are displayed on an oscilloscope as a horizontal bar that moves vertically in pitch and pivots about the center in roll. The $\lambda_{crit}$ values are read directly from a voltmeter. Figures 3 and 6 show the setup of the equipment.

TEST PROCEDURE

The test subjects for this study consisted of four test pilots and one nonpilot engineer. The subjects were oriented to the setup for the experiment through a series of trial runs. Gain settings in pitch and roll for each stick were determined from these trial runs by averaging the values preferred by each subject. The gain settings are as follows:

| Stick control | Pitch gain | Roll gain |
|---|---|---|
| Space shuttle | 1 | 3/4 |
| Heavy conventional | 3/4 | 1/3 |
| Light conventional | 3/4 | 1/3 |

A series of 15 runs for each configuration was conducted in the pitch and roll axes. The runs were repeated adding a system delay of 250 msec. Each of the five subjects made 180 runs, for a total of 900 test runs. The $\lambda_{crit}$ values were recorded for each run, and the average for the series was computed for each subject (tables 2 and 3). The $\lambda_{crit}$ values, which were read directly from the voltmeter, contain the 46-msec inherent time delay but not the added system delay of 250 msec when applied. (A time delay of 250 msec was chosen to simulate the total system delay nearer the value of that for the space shuttle.)

## RESULTS AND DISCUSSION

The average $\lambda_{crit}$ value from each series of 15 runs was converted to time delay; the 46-msec inherent time delay was subtracted from this value to obtain the pilot effective time delay (table 4). Figures 7 and 8 show the average $\tau_e$ value of each test subject as well as the combined average (solid bar) of all the subjects. Data for no added time delay (46 msec $\tau_d$) are on the left, and data for 250-msec added time delay (296 msec $\tau_d$) are on the right for each configuration.

Based on the combined average, the heavy conventional control stick had the lowest $\tau_e$ values for both pitch and roll, with and without added time delay (figs. 7 and 8). The shuttle rotational hand controller had the next lowest $\tau_e$ values in roll with no added time delay, while the light conventional stick had the next lowest $\tau_e$ values for pitch and roll with added time delay. The shuttle controller and light conventional stick had the same $\tau_e$ value (200 msec) for pitch with no added time delay. The highest $\tau_e$ values were for the shuttle controller in pitch and roll with added system time delay and for the light conventional stick in pitch and roll without added time delay. Scatter can be observed in the data in figures 7 and 8, but the trends with any given test subject seem to be consistent.

The changes in $\tau_e$ values between the shuttle controller and the control sticks, with and without added time delay, are evident in figures 7 and 8. Effective time delay for each subject increased when 250 msec was added to the system. On the average, the shuttle controller showed the most change — 70 msec in pitch and 60 msec in roll. For the heavy conventional stick, the average increase in pilot effective time delay was 50 msec in both pitch and roll. The average increase for the light conventional stick was 60 msec in pitch and 40 msec in roll.

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These data show that the changes in pilot time delay caused by of differences in manipulator characteristics, are much less than the changes in pilot time delay caused by differences in total system time delay. This is consistent with results (unpublished) obtained from previous tests conducted by System Technology, Inc., under NASA contract NAS2-4405 (fig. 9). The data show very small changes in $\tau_e$ for a first-order controlled element as the gradient for a pencil controller changes from a free (unconstrained) to a rigid (force) stick. However, for a second-order controlled element, the $\tau_e$ is much larger and more sensitive to stick force gradient. Figure 10 presents the results of the Ames-Dryden experiment in a format similar to that in figure 9.

Figures 9 and 10 cannot be directly compared because of the differences in controller geometry, gradient, and controlled element time delay. However, some observations regarding general trends are valid. The increase in $\tau_e$ for the second-order controlled element (fig. 9) can be attributed to the additional mental processing which the pilot must perform to compensate for the integrator lag. The time delay in the controlled elements of figure 10 would also require pilot compensation (or lead); an increase in $\tau_e$ would therefore be expected. The change in pilot time delay for this experiment is not as large as that seen in figure 9. However, the variation in stick gradient for this experiment is not nearly as extreme as that used in figure 9. Perhaps even more significant is the difference in compensation required for the time delay compared to the integrator lag.

CONCLUSIONS

The space shuttle rotational hand controller and a more conventional control stick with two different spring constants were evaluated in both the pitch and roll axes using a first-order, closed-loop, compensatory tracking task implemented through a critical task tester device. Five test subjects performed a total of 900 data runs, that investigated total system delays of 46 msec and 296 msec. The data indicate that the heavy conventional controller had the lowest pilot effective time delay values in both control modes with and without added system time delay. The light conventional stick had effective pilot time delay characteristics that were similar to those of the space shuttle rotational controller.

Pilot effective time delay for all types of controllers tested increased with an increase in total system delay. The changes in pilot effective time delay, caused by increases in system time delay, were much more significant than changes caused by different controller characteristics.

*Ames Research Center*
*Dryden Flight Research Facility*
*National Aeronautics and Space Administration*
*Edwards, California, October 11, 1984*

REFERENCES

1. Jex, H.R.; McDonnell, J.D.; and Phatak, A.V.: A "Critical" Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time, Part I: Theory and Experiments with a First-Order Divergent Controlled Element. NASA CR-616, 1966.

2. McDonnell, J.D.; and Jex, H.R.: A "Critical" Tracking Task for Man-Machine Research Related to the Operator's Effective Delay Time, Part II: Experimental Effects of System Input Spectra, Control Stick Stiffness, and Controlled Element Order. NASA CR-674, 1967.

3. Berry, D.T.; Powers, B.G.; Szalai, K.J.; and Wilson, R.J.: In-Flight Evaluation of Control System Pure Time Delays. J. Aircraft, vol. 19, no. 4, Apr. 1982, pp. 318-323.

4. Peters, R.A.; Jex, H.R.; and Hogue, J.R.: Operation Manual Critical Task Tester MK 8A2 Modified. Working Paper 423-1R, Systems Technology, Inc., rev. 1984.

TABLE 1. — SHUTTLE CONTROLLER AND CONVENTIONAL
STICK CHARACTERISTICS

| Characteristic | Pitch-axis value | Roll-axis value |
|---|---|---|
| Shuttle rotational hand controller | | |
|   Breakout, cm-N (in-lb) | 13.6 (1.2) | 11.3 (1.0) |
|   Travel, deg | ±19.5 | ±19.5 |
|   Gradient, cm-N/deg (in-lb/deg) | 13.6 (1.2) | 37.3 (3.3) |
|   Pivot point, cm (in)[a] | 0.0 (0.0) | 8.9 (3.5) |
| Heavy conventional stick | | |
|   Breakout, cm-N (in-lb) | 5.6 (0.5) | 2.3 (0.2) |
|   At stop, N (lb) | 48.9 (11.0) | 48.0 (10.8) |
|   Travel, cm (in) | 5.1 (2.0) | ±5.1 (2.0) |
|   Gradient, cm-N/deg (in-lb/deg) | 59.9 (5.3) | 59.9 (5.3) |
|   Pivot point, cm (in)[a] | 17.8 (7.0) | 17.8 (7.0) |
| Light conventional stick | | |
|   Breakout, cm-N (in-lb) | 5.6 (0.5) | 2.3 (0.2) |
|   At stop, N (lb) | 28.9 (6.5) | 26.7 (6.0) |
|   Travel, cm (in) | ±5.1 (2.0) | ±5.1 (2.0) |
|   Gradient, cm-N/deg (in-lb/deg) | 33.9 (3.0) | 21.5 (1.9) |
|   Pivot point, cm (in)[a] | 17.8 (7.0) | 17.8 (7.0) |

[a]Measured from middle of palm point on control stick.

TABLE 2. — INVERSE TIME CONSTANT AT CRITICAL TIME,
$\lambda_{crit}$, FOR PITCH AXIS

(a) No added delay

| Subject | Test run | | | | | | | | | | | | | | | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | |
| | $\lambda_{crit}$, rad/sec | | | | | | | | | | | | | | | |
| Shuttle rotational hand controller | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.6 | 4.2 | 4.0 | 3.7 | 4.1 | 3.5 | 3.8 | 4.1 | 4.3 | 3.9 | 3.1 | 4.6 | 4.3 | 3.7 | 3.8 | 3.9 |
| Test pilot 2 | 4.1 | 3.9 | 4.1 | 4.2 | 4.6 | 4.5 | 4.5 | 4.4 | 4.3 | 4.0 | 4.4 | 4.4 | 4.5 | 4.6 | 4.8 | 4.4 |
| Test pilot 3 | 4.3 | 4.4 | 3.6 | 4.2 | 3.6 | 3.7 | 3.8 | 3.8 | 3.7 | 3.6 | 3.4 | 3.6 | 3.4 | 3.9 | 4.0 | 3.8 |
| Test pilot 4 | 4.6 | 5.0 | 4.9 | 4.1 | 4.9 | 4.4 | 4.7 | 4.6 | 5.1 | 5.0 | 4.7 | 5.0 | 4.4 | 5.1 | 4.4 | 4.7 |
| Nonpilot (engineer) | 3.2 | 3.9 | 3.8 | 4.0 | 3.3 | 3.0 | 3.5 | 4.2 | 2.9 | 4.0 | 3.5 | 4.0 | 3.8 | 3.5 | 3.9 | 3.6 |
| Heavy conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 4.4 | 4.2 | 4.5 | 4.4 | 4.7 | 4.8 | 5.1 | 4.3 | 4.6 | 4.8 | 4.4 | 4.3 | 4.8 | 5.0 | 5.1 | 4.6 |
| Test pilot 2 | 5.6 | 4.5 | 4.8 | 4.8 | 4.6 | 4.5 | 5.0 | 4.3 | 4.5 | 4.4 | 4.7 | 5.2 | 4.8 | 4.7 | 4.8 | 4.8 |
| Test pilot 3 | 3.1 | 3.7 | 3.8 | 3.2 | 4.1 | 3.0 | 4.0 | 4.0 | 4.2 | 4.5 | 4.3 | 3.8 | 3.1 | 3.6 | 4.0 | 3.8 |
| Test pilot 4 | 5.2 | 5.0 | 4.2 | 5.0 | 5.0 | 5.0 | 4.8 | 5.1 | 4.7 | 4.8 | 5.5 | 4.3 | 4.5 | 4.4 | 5.6 | 4.9 |
| Nonpilot (engineer) | 4.9 | 4.7 | 4.7 | 5.0 | 4.4 | 4.9 | 4.2 | 4.0 | 4.5 | 3.7 | 4.4 | 4.1 | 4.3 | 4.4 | 4.7 | 4.5 |
| Light conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.6 | 4.0 | 3.8 | 3.5 | 3.7 | 3.0 | 4.2 | 3.9 | 4.0 | 4.2 | 3.8 | 3.9 | 4.4 | 3.5 | 4.2 | 3.9 |
| Test pilot 2 | 4.3 | 4.6 | 4.9 | 4.6 | 4.4 | 4.7 | 4.6 | 4.4 | 4.3 | 4.3 | 3.8 | 4.2 | 4.4 | 4.1 | 3.8 | 4.4 |
| Test pilot 3 | 3.5 | 3.3 | 4.3 | 3.8 | 4.5 | 4.0 | 3.9 | 4.2 | 4.2 | 3.6 | 4.5 | 3.4 | 4.3 | 5.0 | 4.0 | 4.0 |
| Test pilot 4 | 4.0 | 3.9 | 3.8 | 4.7 | 4.1 | 4.1 | 4.5 | 4.0 | 4.2 | 4.8 | 4.3 | 3.8 | 4.2 | 4.3 | 4.5 | 4.2 |
| Nonpilot (engineer) | 4.2 | 4.2 | 3.9 | 4.4 | 4.2 | 3.8 | 3.9 | 3.8 | 3.8 | 3.6 | 4.0 | 4.5 | 4.1 | 4.4 | 3.9 | 4.1 |

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TABLE 2. — CONCLUDED

(b)  250-msec added delay

| Subject | Test run | | | | | | | | | | | | | | | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | |
| | $\lambda_{crit}$, rad/sec | | | | | | | | | | | | | | | |
| Shuttle rotational hand controller | | | | | | | | | | | | | | | | |
| Test pilot 1 | 2.9 | 3.1 | 3.4 | 3.1 | 3.0 | 3.3 | 3.1 | 3.0 | 3.0 | 3.2 | 3.0 | 2.9 | 2.8 | 3.5 | 2.6 | 3.1 |
| Test Pilot 2 | 3.0 | 3.1 | 3.3 | 2.9 | 2.9 | 2.7 | 2.7 | 2.6 | 2.7 | 3.1 | 3.6 | 3.4 | 3.1 | 2.8 | 2.9 | 3.0 |
| Test Pilot 3 | 2.9 | 2.9 | 3.7 | 3.1 | 3.2 | 3.2 | 3.8 | 3.3 | 2.7 | 3.0 | 3.3 | 3.1 | 3.7 | 3.3 | 3.4 | 3.2 |
| Test Pilot 4 | 3.2 | 2.9 | 2.8 | 3.1 | 3.5 | 3.4 | 3.1 | 3.3 | 3.2 | 3.2 | 3.1 | 3.6 | 3.4 | 3.5 | 3.3 | 3.2 |
| Nonpilot (engineer) | 3.3 | 3.1 | 3.1 | 3.2 | 3.1 | 3.3 | 2.9 | 3.3 | 2.8 | 2.9 | 3.0 | 2.8 | 3.2 | 3.1 | 2.9 | 3.1 |
| Heavy conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.8 | 3.5 | 3.4 | 3.2 | 3.6 | 3.8 | 3.3 | 3.3 | 2.5 | 3.4 | 3.8 | 3.2 | 3.4 | 3.9 | 3.2 | 3.4 |
| Test pilot 2 | 3.7 | 3.5 | 3.6 | 3.4 | 4.0 | 3.8 | 3.4 | 3.0 | 3.7 | 3.7 | 3.0 | 3.9 | 3.9 | 3.5 | 3.3 | 3.6 |
| Test pilot 3 | 3.3 | 4.1 | 3.6 | 3.4 | 3.7 | 4.3 | 3.1 | 3.5 | 3.5 | 3.4 | 3.6 | 3.8 | 3.6 | 3.7 | 3.0 | 3.6 |
| Test pilot 4 | 4.1 | 3.6 | 3.5 | 3.6 | 3.3 | 3.7 | 3.7 | 3.2 | 3.8 | 3.3 | 3.3 | 4.0 | 3.9 | 3.4 | 3.0 | 3.6 |
| Nonpilot (engineer) | 4.2 | 3.4 | 3.7 | 3.8 | 3.7 | 4.1 | 3.6 | 3.8 | 3.8 | 3.8 | 3.8 | 3.6 | 3.8 | 3.2 | 3.9 | 3.8 |
| Light conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.8 | 3.5 | 3.7 | 3.8 | 3.7 | 3.3 | 3.9 | 3.4 | 3.7 | 3.6 | 3.8 | 4.1 | 3.5 | 3.1 | 3.9 | 3.7 |
| Test pilot 2 | 3.4 | 3.4 | 3.7 | 3.4 | 3.3 | 3.1 | 3.0 | 3.4 | 3.2 | 3.3 | 3.0 | 2.8 | 3.2 | 4.2 | 2.9 | 3.3 |
| Test pilot 3 | 3.3 | 3.8 | 3.1 | 3.8 | 3.2 | 3.4 | 3.3 | 3.3 | 3.2 | 2.7 | 3.1 | 2.6 | 3.0 | 3.5 | 3.1 | 3.2 |
| Test pilot 4 | 2.9 | 2.9 | 2.5 | 2.8 | 3.0 | 3.1 | 3.1 | 2.5 | 3.0 | 2.9 | 3.0 | 2.9 | 3.4 | 2.9 | 3.2 | 2.9 |
| Nonpilot (engineer) | 3.5 | 3.1 | 2.8 | 2.8 | 3.4 | 2.9 | 2.8 | 3.1 | 3.1 | 3.5 | 3.3 | 2.9 | 2.9 | 2.7 | 3.9 | 3.1 |

TABLE 3. — INVERSE TIME CONSTANT AT CRITICAL TIME,
$\lambda_{crit}$, FOR ROLL AXIS

(a)  No added delay

| Subject | Test run | | | | | | | | | | | | | | | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | |
| | $\lambda_{crit}$, rad/sec | | | | | | | | | | | | | | | |
| Shuttle rotational hand controller | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.8 | 2.9 | 3.6 | 3.5 | 3.3 | 3.6 | 4.4 | 3.3 | 3.9 | 3.5 | 3.3 | 3.2 | 3.4 | 3.4 | 4.2 | 3.6 |
| Test pilot 2 | 4.0 | 4.0 | 4.0 | 4.4 | 4.1 | 4.3 | 3.9 | 4.6 | 4.1 | 4.0 | 4.1 | 4.8 | 4.7 | 4.4 | 4.8 | 4.3 |
| Test pilot 3 | 4.7 | 3.9 | 3.8 | 3.9 | 4.2 | 4.1 | 4.2 | 3.8 | 4.6 | 4.2 | 4.8 | 4.4 | 3.8 | 4.0 | 3.5 | 4.1 |
| Test pilot 4 | 4.4 | 4.6 | 4.6 | 4.8 | 4.2 | 4.6 | 4.7 | 4.4 | 4.6 | 5.3 | 4.9 | 4.9 | 5.2 | 4.4 | 4.8 | 4.7 |
| Nonpilot (engineer) | 3.9 | 3.6 | 3.6 | 3.9 | 3.8 | 3.9 | 4.4 | 3.8 | 4.1 | 4.0 | 3.9 | 3.9 | 3.5 | 3.6 | 3.6 | 3.8 |
| Heavy conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 4.3 | 3.6 | 4.2 | 4.0 | 3.9 | 4.2 | 4.4 | 3.8 | 3.9 | 4.0 | 3.6 | 4.2 | 4.2 | 4.1 | 4.8 | 4.1 |
| Test pilot 2 | 4.6 | 5.1 | 4.9 | 4.4 | 4.6 | 4.5 | 4.7 | 4.5 | 5.0 | 4.5 | 5.0 | 4.7 | 4.9 | 5.4 | 4.7 | 4.8 |
| Test pilot 3 | 4.0 | 3.9 | 4.4 | 4.3 | 4.3 | 4.1 | 4.0 | 3.8 | 5.2 | 4.4 | 4.1 | 4.3 | 4.0 | 4.4 | 3.3 | 4.2 |
| Test pilot 4 | 5.0 | 5.2 | 5.2 | 6.1 | 4.7 | 6.0 | 5.3 | 5.7 | 4.9 | 5.4 | 4.9 | 6.2 | 5.2 | 5.6 | 4.5 | 5.3 |
| Nonpilot (engineer) | 3.1 | 3.9 | 4.3 | 3.6 | 3.9 | 4.2 | 3.8 | 3.5 | 3.6 | 4.6 | 3.9 | 4.8 | 5.0 | 4.4 | 4.5 | 4.1 |
| Light conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 4.1 | 3.6 | 3.6 | 3.2 | 3.4 | 3.7 | 3.2 | 3.2 | 4.0 | 3.8 | 4.0 | 3.8 | 3.9 | 3.4 | 3.3 | 3.6 |
| Test pilot 2 | 4.4 | 4.2 | 3.6 | 4.5 | 4.8 | 4.8 | 4.8 | 4.7 | 4.7 | 4.6 | 4.5 | 4.8 | 4.6 | 4.4 | 5.2 | 4.6 |
| Test pilot 3 | 3.8 | 4.1 | 3.6 | 4.2 | 3.6 | 4.3 | 3.4 | 3.5 | 3.7 | 3.6 | 3.7 | 4.1 | 4.4 | 3.1 | 3.2 | 3.8 |
| Test pilot 4 | 4.5 | 4.6 | 4.8 | 4.4 | 4.9 | 4.3 | 4.0 | 4.7 | 4.4 | 4.3 | 5.0 | 5.4 | 4.7 | 4.7 | 4.5 | 4.6 |
| Nonpilot (engineer) | 3.6 | 4.1 | 3.7 | 3.8 | 4.1 | 4.5 | 3.9 | 4.2 | 4.5 | 3.9 | 4.1 | 4.1 | 4.0 | 4.3 | 3.9 | 4.1 |

TABLE 3. — CONCLUDED

(b)   250-msec added delay

| Subject | Test run | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Avg. |
| | $\lambda_{crit}$, rad/sec | | | | | | | | | | | | | | | |
| Shuttle rotational hand controller | | | | | | | | | | | | | | | | |
| Test pilot 1 | 2.9 | 2.7 | 2.7 | 2.7 | 2.4 | 2.8 | 3.2 | 3.4 | 2.5 | 2.7 | 2.8 | 3.2 | 2.9 | 2.9 | 3.1 | 2.9 |
| Test Pilot 2 | 3.8 | 3.3 | 3.1 | 3.2 | 3.3 | 3.8 | 3.8 | 3.4 | 3.7 | 3.1 | 3.2 | 3.3 | 3.3 | 3.3 | 3.4 | 3.4 |
| Test Pilot 3 | 3.3 | 3.3 | 3.2 | 3.2 | 3.6 | 3.2 | 3.0 | 3.1 | 3.4 | 2.7 | 3.3 | 3.8 | 3.8 | 3.3 | 3.4 | 3.3 |
| Test Pilot 4 | 3.7 | 3.9 | 3.4 | 4.0 | 3.2 | 4.2 | 3.8 | 4.2 | 3.4 | 3.7 | 4.1 | 3.5 | 3.8 | 3.9 | 3.4 | 3.8 |
| Nonpilot (engineer) | 3.2 | 3.1 | 3.4 | 3.1 | 3.3 | 3.4 | 3.6 | 3.0 | 3.2 | 3.0 | 3.4 | 3.5 | 3.4 | 3.2 | 3.4 | 3.3 |
| Heavy conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.3 | 3.6 | 2.9 | 3.1 | 3.3 | 3.7 | 3.3 | 3.1 | 3.2 | 4.0 | 3.0 | 3.2 | 3.4 | 3.0 | 2.9 | 3.3 |
| Test pilot 2 | 4.2 | 3.8 | 3.4 | 3.9 | 4.0 | 4.1 | 3.1 | 3.4 | 4.0 | 4.1 | 4.2 | 4.0 | 4.3 | 4.0 | 4.4 | 3.9 |
| Test pilot 3 | 3.2 | 3.4 | 3.8 | 3.8 | 3.1 | 3.2 | 3.9 | 3.3 | 3.6 | 2.9 | 3.4 | 3.0 | 3.2 | 3.5 | 3.6 | 3.4 |
| Test pilot 4 | 3.6 | 4.1 | 4.1 | 3.8 | 4.0 | 3.8 | 3.6 | 4.1 | 3.8 | 4.0 | 4.5 | 4.2 | 4.5 | 4.6 | 4.2 | 4.1 |
| Nonpilot (engineer) | 3.6 | 3.5 | 3.5 | 3.8 | 3.7 | 3.9 | 3.7 | 3.3 | 4.2 | 3.7 | 3.2 | 4.0 | 3.3 | 3.3 | 3.6 | 3.6 |
| Light conventional stick | | | | | | | | | | | | | | | | |
| Test pilot 1 | 3.8 | 3.5 | 3.2 | 3.3 | 3.5 | 3.3 | 3.8 | 3.2 | 3.5 | 3.3 | 3.4 | 3.7 | 3.4 | 3.3 | 3.5 | 3.5 |
| Test pilot 2 | 3.6 | 3.9 | 3.6 | 3.9 | 4.2 | 3.6 | 4.2 | 3.8 | 4.1 | 4.0 | 3.9 | 4.1 | 3.9 | 3.6 | 3.7 | 3.9 |
| Test pilot 3 | 3.9 | 3.2 | 3.5 | 3.4 | 3.7 | 3.4 | 3.0 | 2.8 | 4.0 | 3.7 | 3.5 | 3.5 | 3.9 | 4.2 | 3.4 | 3.5 |
| Test pilot 4 | 3.2 | 3.3 | 3.5 | 3.4 | 3.3 | 3.4 | 3.2 | 2.9 | 3.1 | 3.3 | 3.5 | 3.4 | 3.6 | 3.7 | 3.4 | 3.4 |
| Nonpilot (engineer) | 3.0 | 3.4 | 3.4 | 3.4 | 3.5 | 3.5 | 3.5 | 3.5 | 3.7 | 3.4 | 3.3 | 3.3 | 3.4 | 3.1 | 3.3 | 3.4 |

TABLE 4. — AVERAGE PILOT EFFECTIVE DELAY, $\tau_e$, VALUES[a]

| Subject | Pitch axis | | Roll axis | |
|---|---|---|---|---|
| | No added delay | 250-msec added delay | No added delay | 250-msec added delay |
| | Average $\tau_e$, msec | | Average $\tau_e$, msec | |
| Shuttle rotational hand controller | | | | |
| Test pilot 1 | 210 | 280 | 230 | 300 |
| Test Pilot 2 | 180 | 280 | 180 | 240 |
| Test Pilot 3 | 210 | 260 | 190 | 250 |
| Test Pilot 4 | 160 | 260 | 160 | 220 |
| Nonpilot (engineer) | 230 | 280 | 210 | 250 |
| Heavy conventional stick | | | | |
| Test pilot 1 | 170 | 240 | 200 | 260 |
| Test pilot 2 | 160 | 230 | 160 | 200 |
| Test pilot 3 | 220 | 230 | 190 | 240 |
| Test pilot 4 | 160 | 230 | 140 | 200 |
| Nonpilot (engineer) | 170 | 220 | 200 | 230 |
| Light conventional stick | | | | |
| Test pilot 1 | 210 | 220 | 230 | 240 |
| Test pilot 2 | 180 | 250 | 170 | 210 |
| Test pilot 3 | 200 | 260 | 220 | 230 |
| Test pilot 4 | 190 | 290 | 170 | 250 |
| Nonpilot (engineer) | 200 | 270 | 200 | 250 |

[a]All values have inherent delay of 46 msec subtracted from them.

TABLE 5. — DIFFERENCES IN AVERAGE PILOT EFFECTIVE
TIME DELAYS, WITH AND WITHOUT ADDED SYSTEM DELAY

| Subject | Pitch axis | Roll axis |
|---|---|---|
| Shuttle rotational hand controller | | |
|   Test pilot 1 | 70 | 70 |
|   Test pilot 2 | 100 | 60 |
|   Test pilot 3 | 50 | 60 |
|   Test pilot 4 | 100 | 60 |
|   Nonpilot (engineer) | 50 | 40 |
|   Average[a] | 70 | 60 |
| Heavy conventional stick | | |
|   Test pilot 1 | 70 | 60 |
|   Test pilot 2 | 70 | 60 |
|   Test pilot 3 | 10 | 50 |
|   Test pilot 4 | 70 | 60 |
|   Nonpilot (engineer) | 50 | 30 |
|   Average[a] | 50 | 50 |
| Light conventional stick | | |
|   Test pilot 1 | 10 | 10 |
|   Test pilot 2 | 70 | 40 |
|   Test pilot 3 | 60 | 10 |
|   Test pilot 4 | 100 | 80 |
|   Nonpilot (engineer) | 70 | 50 |
|   Average[a] | 60 | 40 |

[a]Least significant digit was rounded off.
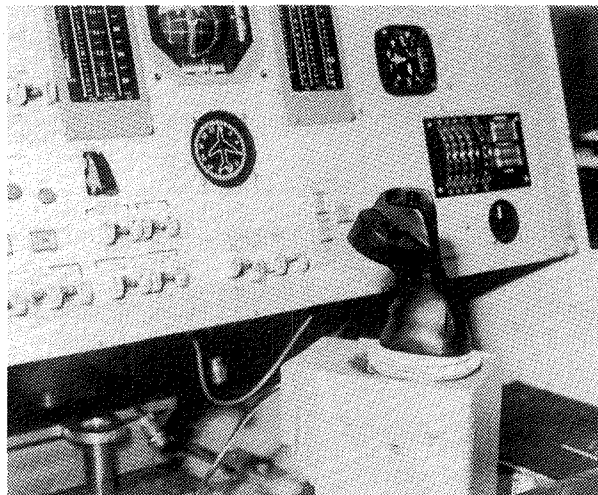


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Figure 1.  Space shuttle rotational
hand controller.
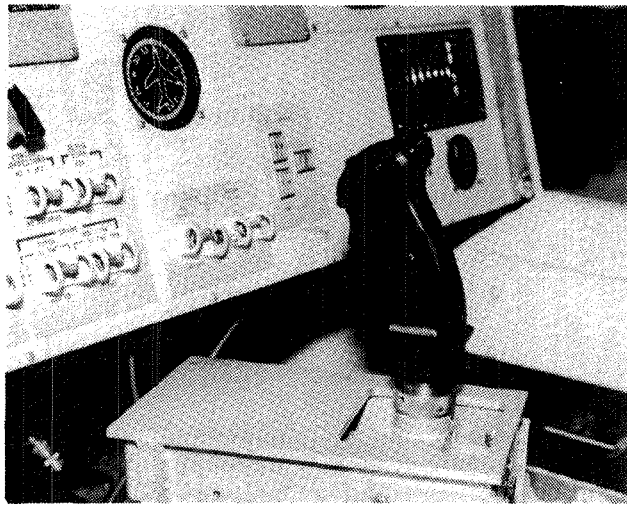
ECN 24919A

*Figure 2. Conventional aircraft controller.*
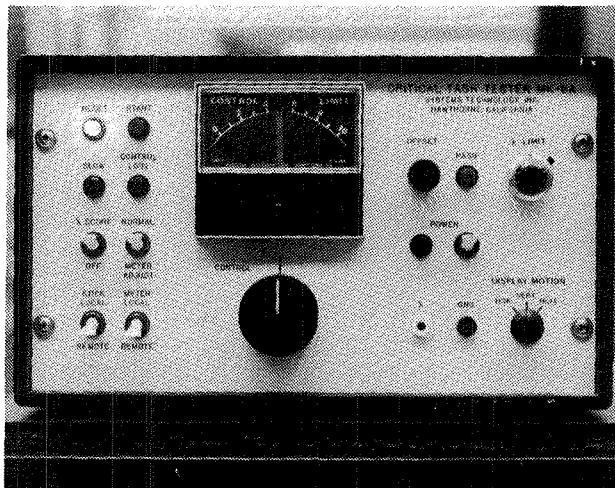


ECN 24923A
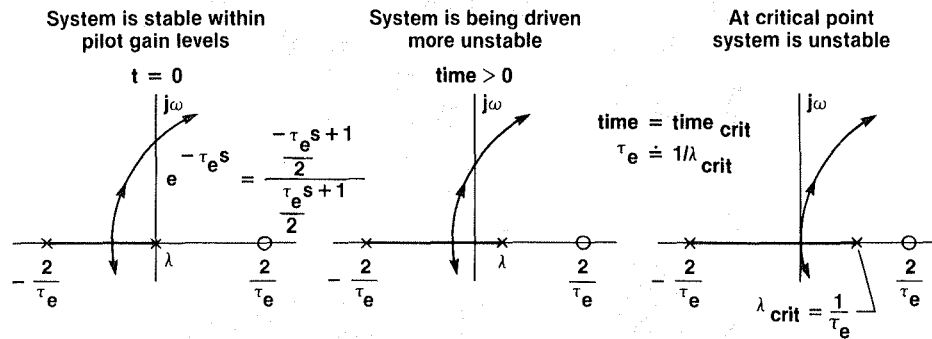
*Figure 3. Critical task tester.*
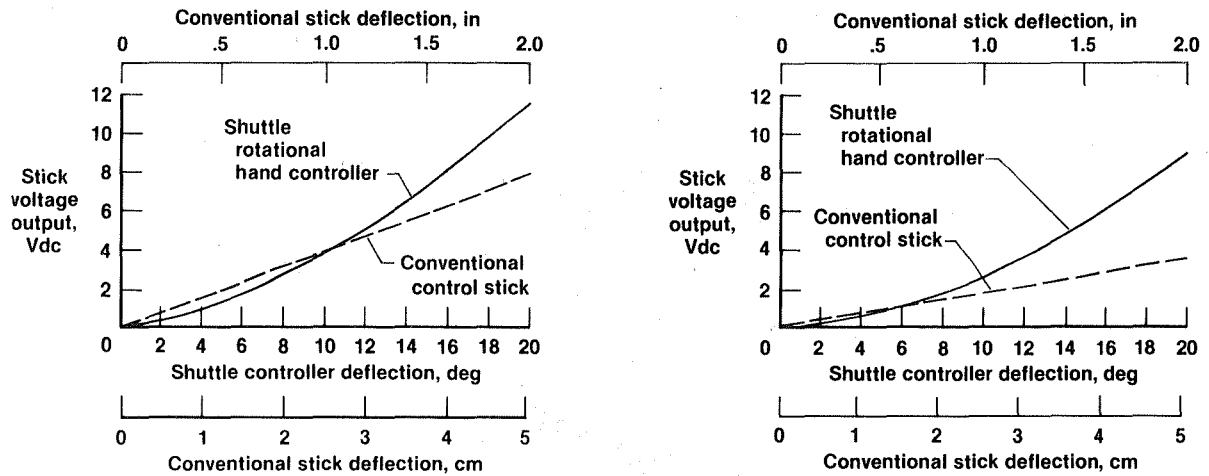
*(a) For roll axis.*  *(b) For pitch axis.*

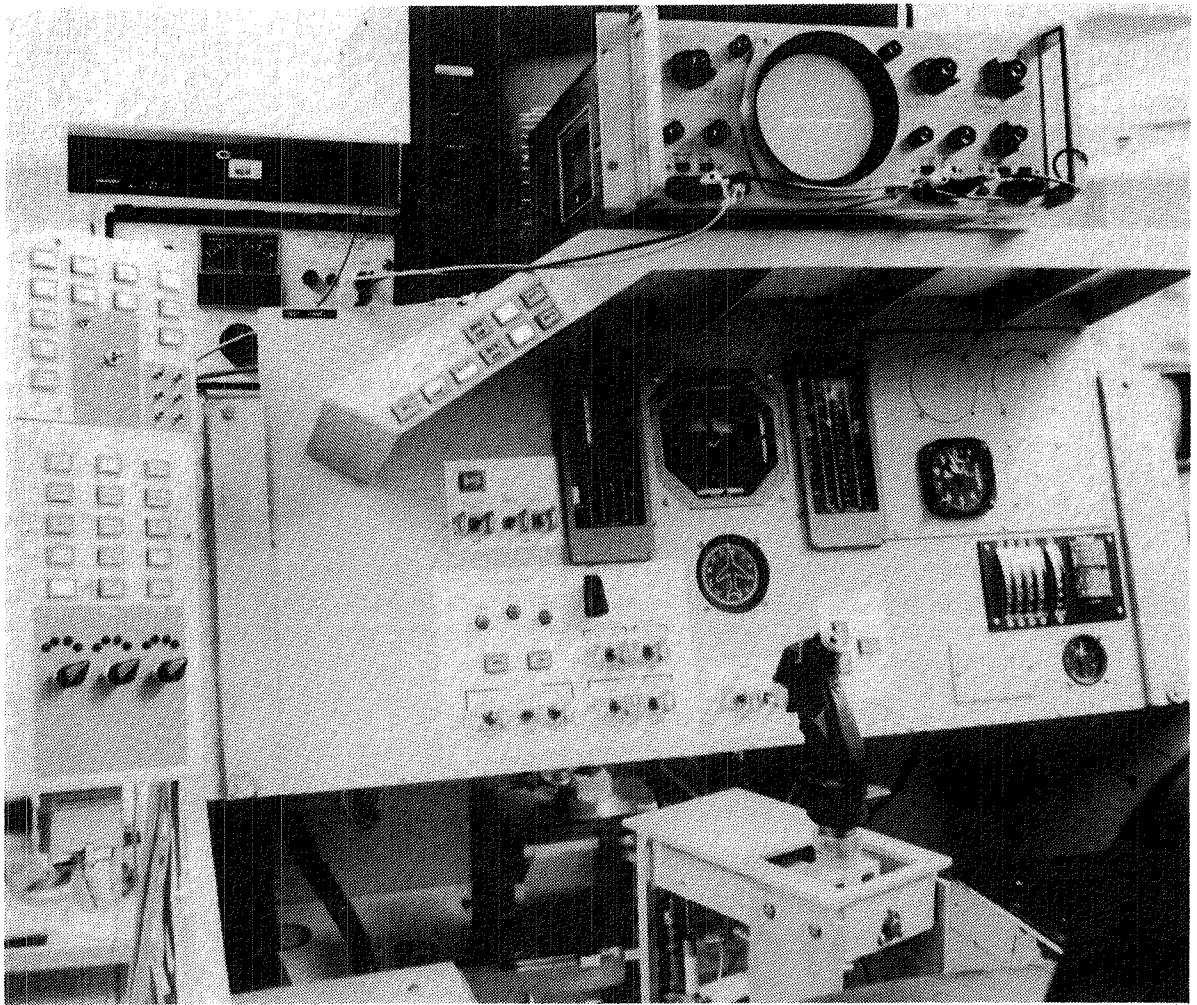*Figure 4. Stick shaping for shuttle and conventional aircraft controllers.*
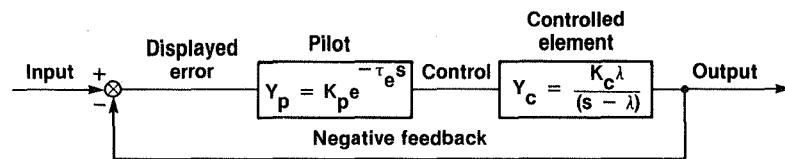


*(a) Block diagram.*



*(b) Root locus.*

*Figure 5. Total system without added system delay.*

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ECN 24924A

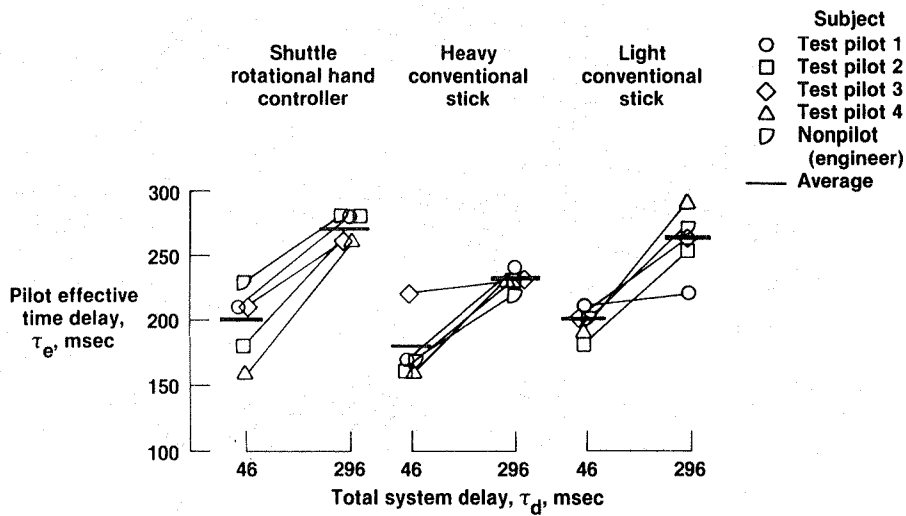*Figure 6. Experimental equipment setup in space shuttle simulator cockpit.*

*Figure 7. Summary of pilot effective time delay results for pitch control. (The 46-msec plot points are for inherent delay; the 296-msec plot points are for inherent plus added delay.)*
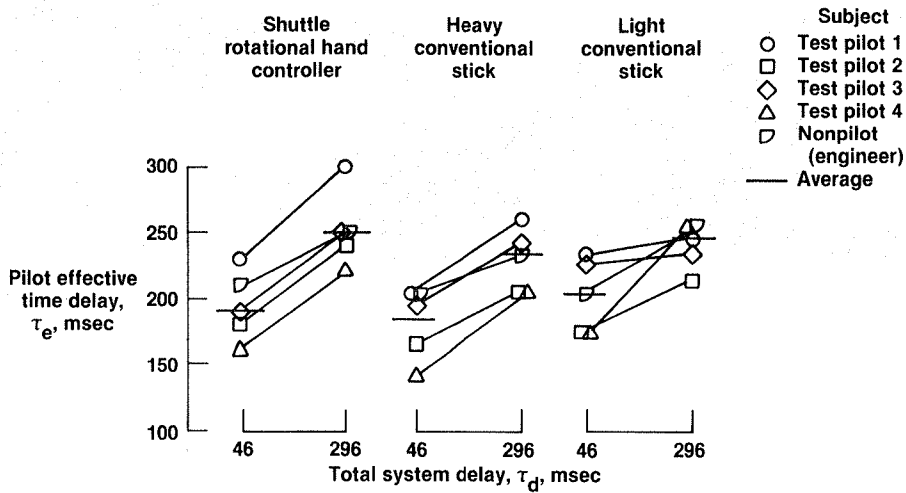


*Figure 8. Summary of pilot effective time delay results for roll control. (The 46-msec plot points are for inherent delay; the 296-msec plot points are for inherent plus added delay.)*
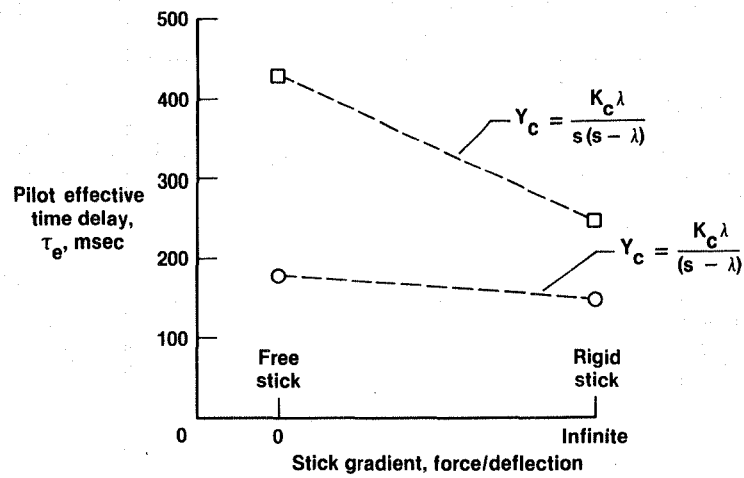
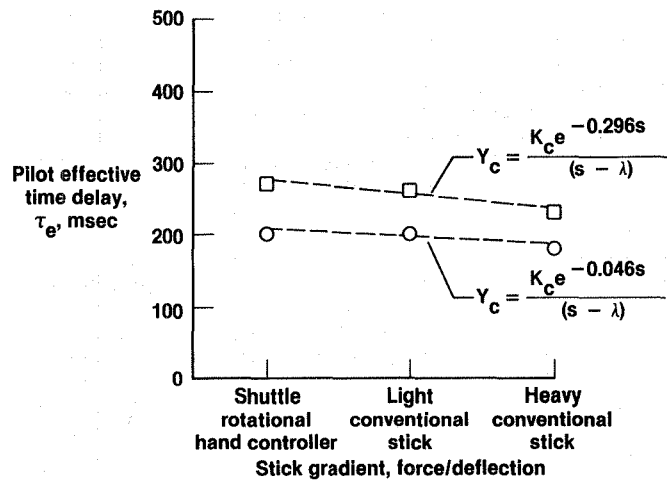*Figure 9. Pilot effective time delays for pencil control stick.*

$$Y_c = \frac{K_c \lambda}{s(s - \lambda)}$$

$$Y_c = \frac{K_c \lambda}{(s - \lambda)}$$



*Figure 10. Pilot effective time delays for space shuttle and conventional aircraft controllers.*

$$Y_c = \frac{K_c e^{-0.296s}}{(s - \lambda)}$$

$$Y_c = \frac{K_c e^{-0.046s}}{(s - \lambda)}$$

| 1. Report No.<br>NASA TM-86030 | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 4. Title and Subtitle<br>Comparison of Pilot Effective Time Delay for Cockpit Controllers Used on Space Shuttle and Conventional Aircraft | | 5. Report Date<br>February 1986 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>Cynthia M. Privoznik and Donald T. Berry | | 8. Performing Organization Report No.<br>H-1222 |
| | | 10. Work Unit No.<br>RTOP 505-35-21 |
| 9. Performing Organization Name and Address<br>NASA Ames Research Center<br>Dryden Flight Research Facility<br>P.O. Box 273<br>Edwards, California 93523-5000 | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered<br>Technical Memorandum |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Washington, D.C. 20546 | | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract

A study was conducted at the Dryden Flight Research Facility of NASA Ames Research Center (Ames-Dryden) to compare pilot effective time delay for the space shuttle rotational hand controller with that for conventional stick controllers. The space shuttle controller has three degrees of freedom and nonlinear gearing. The conventional stick has two degrees of freedom and linear gearing. Two spring constants were used, allowing the conventional stick to be evaluated in both a light and a heavy configuration. Pilot effective time delay was obtained separately for pitch and roll through first-order, closed-loop, compensatory tracking tasks. The tasks were implemented through the space shuttle cockpit simulator and a critical task tester device. A total of 900 data runs were made using four test pilots and one nonpilot (engineer) for two system delays in pitch and roll modes. Results showed that the heavier conventional control stick had the lowest pilot effective time delays. The light conventional control stick had pilot effective time delays similar to those of the shuttle controller. All configurations showed an increase in pilot effective time delay with an increase in total system delay.

| 17. Key Words (Suggested by Author(s))<br>Cockpit simulators<br>Controllers<br>Pilot performance<br>Pilot time delay<br>Space shuttle | 18. Distribution Statement<br>Unclassified — Unrestricted<br><br>STAR category 8 | | |
|---|---|---|---|
| 19. Security Classif. (of this report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of Pages<br>18 | 22. Price*<br>A02 |

*For sale by the National Technical Information Service, Springfield, Virginia 22161.

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