MEASUREMENTS OF PILOT TIME DELAY AS INFLUENCED BY CONTROLLER CHARACTERISTICS AND VEHICLE TIME DELAYS

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ABSTRACT

A study to measure and compare pilot time delay when using a space shuttle rotational hand controller and a more conventional control stick was conducted at NASA Ames Research Center's Dryden Flight Research Facility. The space shuttle controller has a palm pivot in the pitch axis. The more conventional controller used was a general-purpose engineering simulator stick that has a pivot length between that of a typical aircraft center stick and a sidestick. Measurements of the pilot's effective time delay were obtained through a first-order, closed-loop, compensatory tracking task in pitch. The tasks were implemented through a space shuttle cockpit simulator and a critical task tester device. The study consisted of 450 data runs with four test pilots and one nonpilot, and used three control stick configurations and two system delays. Results showed that the heavier conventional stick had the lowest pilot effective time delays associated with it, whereas the shuttle and light conventional sticks each had similar higher pilot time delay characteristics. It was also determined that each control stick showed an increase in pilot time delay when the total system delay was increased.

NOMENCLATURE

CTT   critical task tester

e   base of natural system of logarithms (2.718)

K_c controlled element constant

j   imaginary number

K_p operator describing function constant

s   LaPlace operator

SHARP   Summer High School Apprentice Research Program

Y_c controlled element

Y_p operator describing function

λ inverse time constant, rad/sec

λ_c inverse time constant at critical time

τ_d total system delay, sec

τ_p pilot effective time delay, sec

ω frequency

INTRODUCTION

The space shuttle control stick is different than a conventional air-craft stick in that it has a palm pivot in the pitch axis and is essentially a wrist rotation controller. A conventional controller has a longer pivot length and a more translational movement. Because of this difference there is an interest in how this may affect pilot time delay. Past studies conducted by Systems Technology Incorporated (refs. 1 and 2) have shown a difference in pilot effective time delay due to manipulator characteristics and the order of the controlled element. Total system time delays, which consist of pilot and vehicle system delays, are critical parameters in aircraft handling qualities. For example, pilot-induced oscillations can be encountered in critical tasks such as landing and inflight refueling when excessive time delays exist. The pilot's effective time delay can be an important component of the total system time delay when the pilot is in the loop. In some circumstances small changes in vehicle system time delays result in large changes in flying qualities (ref. 3).

In a study performed at NASA Ames Research Center's Dryden Flight Research Facility, a critical task tester (CTT) was used to obtain pilot effective time delay (τ_p) values for the shuttle stick and a more conventional stick. The experiment used two system time delays. Variations in the values of τ_p are used to show how the shuttle stick compares to a more conventional control stick and what effect the total system delay has on the pilot's effective time delay.

At the completion of this experiment, the equipment was available for the NASA Summer High School Apprentice Research Program (SHARP). A high school student in a science and engineering program measured operator time delay for a diverse group of subjects, mostly SHARP students. Results as a function of background and flying experience are briefly summarized in this paper.

DESCRIPTION OF EQUIPMENT

Three control stick configurations were used in this study with the shuttle cockpit simulator in the Ames Dryden simulation laboratory. One configuration was a space shuttle stick, which is a three-degree-of-freedom rotational manipulator with nonlinear gearing. The other two configurations used a more conventional general-purpose engineering simulation stick with two different spring constants. All sticks were center mounted. The

general-purpose stick was used in a variety of engineering simulators and represented a compromise among a broad range of stick characteristics. It had two degrees of freedom and linear gearing; however it had a pivot point between that of a typical aircraft center stick and a sidestick. This general-purpose stick was tested first with a stiff set of springs and was designated the heavy conventional stick. Later, a softer set of springs was installed to obtain the light conventional stick. The designations light, heavy, and conventional are only relative, however, since the force gradients are lighter and pivot arms are shorter for this stick than that used in most aircraft center sticks. For stick characteristics see table 1 and figures 1, 2, and 3.

The control stick signal that is processed through the cockpit simulator is operated with a 40-msec frame time and is sent through the CTT. The total inherent time delay between the pilot input and the CTT was 46 msec; 20 msec was due to the average sampling delay of the 40 msec frame time, and 26 msec was due to the computation time.

The CTT uses a first-order compensatory tracking task with an unstable controlled element:

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

where λ is the inverse time constant. Under these conditions it can be assumed that the operator can be described by:

$$Y_p = K_p e^{-\tau_p s}$$

where τ_p is the pilot's effective time delay. Figure 4 shows the block diagram and root locus of these elements using a first-order Pade' approximation for the $e^{-\tau_p s}$ term. λ is increased as a function of time and error magnitude, making the system more unstable until control is lost. The value of λ at that critical point approximates the reciprocal of the operator's effective time delay, $\lambda_c = 1/\tau_p$. This simplified summary is based on more detailed explanations of the critical tracking task theory which includes systems with additional system delays. These explanations can be found in references 1 and 2.

The pitch indicator is displayed on an oscilloscope as a horizontal bar that moves vertically in pitch. The λ_c values are read directly from a voltmeter. Figures 5 and 6 show the setup of the equipment.

TEST PROCEDURE

The test subjects for this study included four test pilots and one non-pilot engineer. All of the subjects were orientated to the experimental setup through a series of trial runs.

A series of 15 runs for each of the three stick configurations was conducted. Adding runs with a system delay of 250 msec brought the total number

of runs for each of the five test subjects to 90. The λ_c values were recorded for each run, and the average for the 15 runs was computed for each case. The λ_c values, which were read directly off the voltmeter, contained the 46 msec inherent time delay but did not contain the added system delay of 250 msec when it was applied. A time delay of 250 msec was chosen to simulate the total system delay nearer to the value of the space shuttle. The total average λ_c value from each set of 15 runs was converted to time delay and the 46 msec computational delay was subtracted from it to obtain the pilot's total effective time delay.

RESULTS AND DISCUSSION

Figure 7 shows the averaged τ_p values for each subject and the total average for all the subjects; these averages are denoted by solid bars. The data obtained from the runs with no added time delay (46 msec τ_d) is on the left and the data for the 250 msec added system delay run (296 msec τ_d) is on the right for each stick. Based on the total average for all the test subjects, the heavy conventional control stick had the lowest τ_p values with and without added system delay. The shuttle and the light conventional manipulator had similar τ_p values. The shuttle and light conventional sticks both had the same τ_p (200 msec) value for runs with no added system delay. On runs with added system delay, the shuttle stick τ_p was slightly higher than with the light conventional stick. Scatter can be seen in the data in figure 7 but the trends with any given pilot look very consistent.

The changes in τ_p values for each control stick because of added system delay are evident in figure 7. In every case the subject's effective time delay increased with an added system delay of 250 msec. On the average, the shuttle controller showed the most change: 70 msec. For the heavy conventional stick the average increase in subject delay was 50 msec. The average increase for the light conventional stick was 60 msec.

These data show that the changes in pilot time delay due to differences in manipulator characteristics are much less than the changes in pilot time delay due to differences in total system time delay. This is consistent with previous results (fig. 8). These data are unpublished results obtained under NASA Contract NAS2-4405 with Systems Technology, Incorporated. The data show very small changes in τ_p for a first-order controlled element as the gradient for a pencil controller changes from a rigid (force) stick to a free (unconstrained) stick. However, for a second-order controlled element, the τ_p is much larger and more sensitive to stick force gradient. Figure 9 presents the results of the Ames Dryden experiment in a format similar to that in figure 8. Figures 8 and 9 cannot be directly compared because of the differences in controller geometry, gradient, and controlled element time delay. However, some observations on gross trends are valid. The increase in τ_p for the second-order controlled element (Y_c, fig. 8) can be attributed to the additional mental processing the pilot must perform to compensate for the

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integrator lag. The time delay in the controlled elements of figure 9 would also require pilot compensation (or lead); an increase, therefore, in τ_p would be expected. The change in pilot time delay for this experiment is not as large as that seen in figure 8. However, the variation in stick gradient for this experiment is not nearly as extreme as that used in figure 8. Perhaps even more significant is the difference in compensation required for the time delay compared to the integrator.

The secondary experiment conducted by a SHARP student was done in a similar manner to that of the primary experiment except that only one control stick configuration was used (the light Ames Dryden stick); the subjects included SHARP students and some adults. None of the subjects were professional pilots, although some were amateur pilots. The results of this experiment are summarized in figures 10 and 11. Figure 10 compares results of the secondary and primary experiments, and indicates that previous piloting experience did not affect the pilot's time delay; nonpilots, amateur pilots, and professional pilots scored alike. The student investigator, a video game enthusiast, correlated the results with video game playing experience. These results are shown in figure 11, and improvements in the raw score are shown as the number of video games played per week increased.

Although these data are insufficient to be statistically conclusive, they do suggest some interesting speculation. For example, the indication that pilot time delay is affected by video game experience, but not real-world piloting experience, suggests that laboratory setups that are too "game-like" may not give the same results as an operational environment. This, however, does not impair the usefulness of laboratory results in establishing trends and measuring differences.

CONCLUDING REMARKS

The space shuttle manipulator controller and a more conventional controller with two different force gradients were evaluated in the pitch axis using a first-order, closed-loop, compensatory tracking task implemented through a critical task tester device. Five test subjects performed a total of 450 data runs using the three control stick configurations with a total system delay of 46 and 296 msec. The data indicate that the heavy conventional controller had the lowest effective pilot time delay values associated with it, with and without the added system delay. The shuttle and light conventional controllers had similar pilot time delay characteristics. Each control stick experiment showed an increase in pilot time delay when there was an increase in total delay.

Changes in pilot time delay because of increases in system time delay were much more significant than changes because of manipulator characteristics.

A secondary experiment using the critical task tester indicated that the pilot time delay is unaffected by previous piloting experience but is influenced by video game experience.

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, Donald T.; Powers, Bruce G.; Szalai, Kenneth 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.

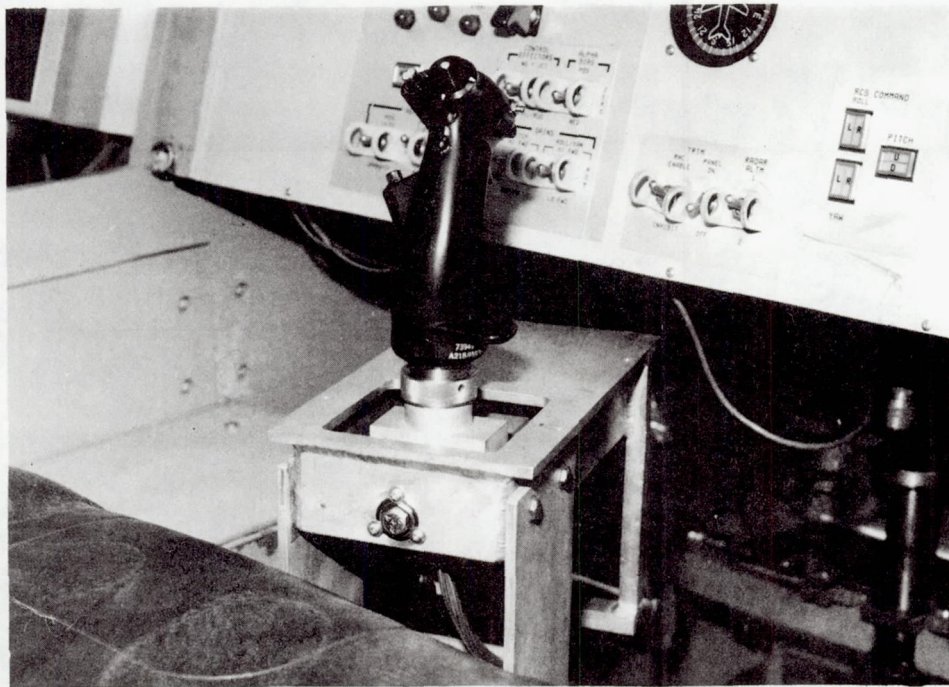Table 1 Control stick characteristics

Characteristics	Pitch
Shuttle stick	
Breakout, in-lb	1.2
Travel, deg	±19.5
Gradient, in-lb/deg	1.2
Pivot point, in*	0
Heavy conventional stick	
Breakout, in-lb	0.5
At stop, lb	11.0
Travel, in	±2.0
Gradient, lb/in	5.3
Pivot point, in*	7.0
Light conventional stick	
Breakout, lb	0.5
At stop, lb	6.5
Travel, in	±2.0
Gradient, lb/in	3.0
Pivot point, in*	7.0

*Measured from middle of palm point on control stick.
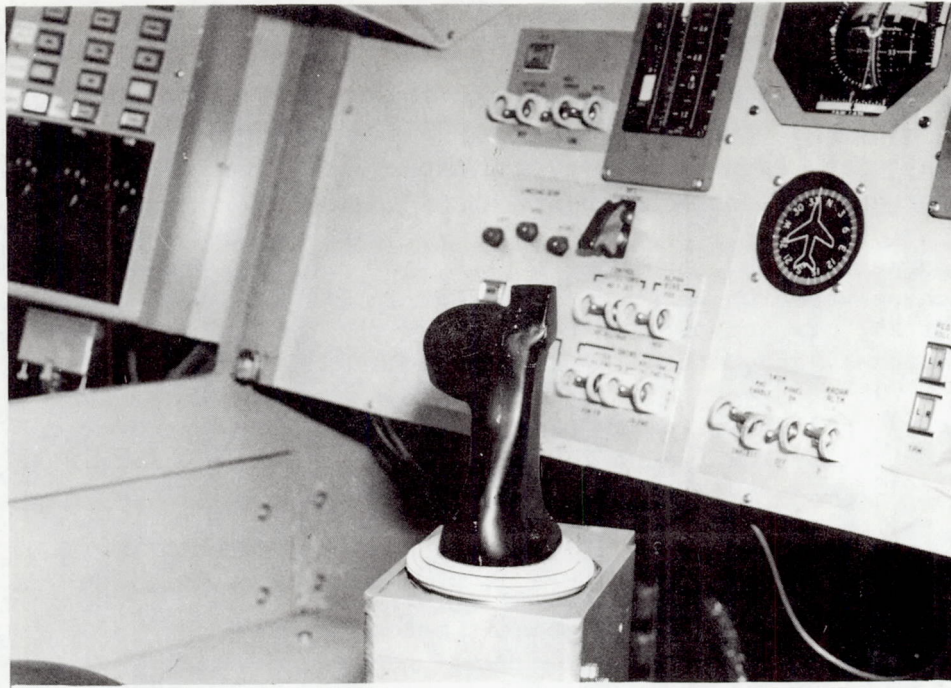
ECN 24922A

Figure 1. Space shuttle rotational hand controller.

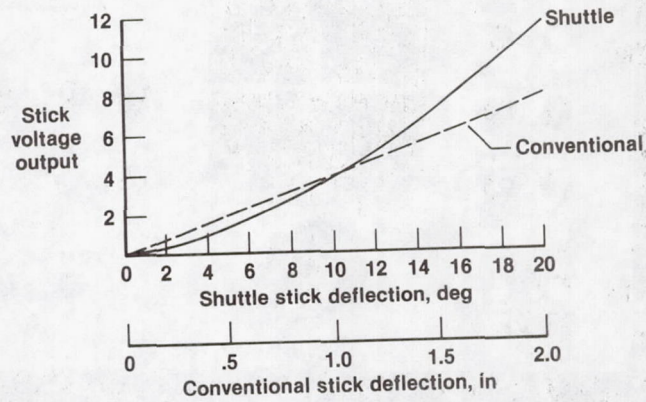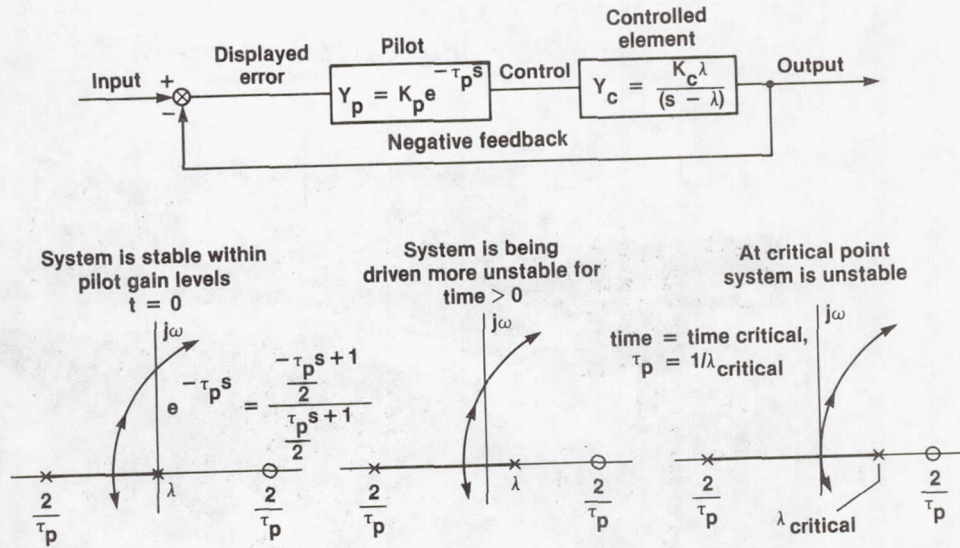ECN 24919A

Figure 2. Conventional control stick.

Stick voltage output

12
10
8
6
4
2

Shuttle

Conventional

0 2 4 6 8 10 12 14 16 18 20

Shuttle stick deflection, deg

0 .5 1.0 1.5 2.0

Conventional stick deflection, in

Figure 3. Pitch axis stick shaping.

Displayed error   **Pilot**   **Controlled element**

Input $+$

$Y_p = K_p e^{-\tau_p s}$ **Control** $Y_c = \dfrac{K_c \lambda}{(s - \lambda)}$ **Output**

$-$

Negative feedback

System is stable within pilot gain levels
$t = 0$

$j\omega$

$e^{-\tau_p s} = \dfrac{-\dfrac{\tau_p s}{2} + 1}{\dfrac{\tau_p s}{2} + 1}$

$\dfrac{2}{\tau_p}$ λ $\dfrac{2}{\tau_p}$

System is being driven more unstable for time > 0

$j\omega$

$\dfrac{2}{\tau_p}$ λ $\dfrac{2}{\tau_p}$

At critical point system is unstable

$j\omega$

time = time critical, $\tau_p = 1/\lambda_{critical}$

$\dfrac{2}{\tau_p}$ $\lambda_{critical}$ $\dfrac{2}{\tau_p}$
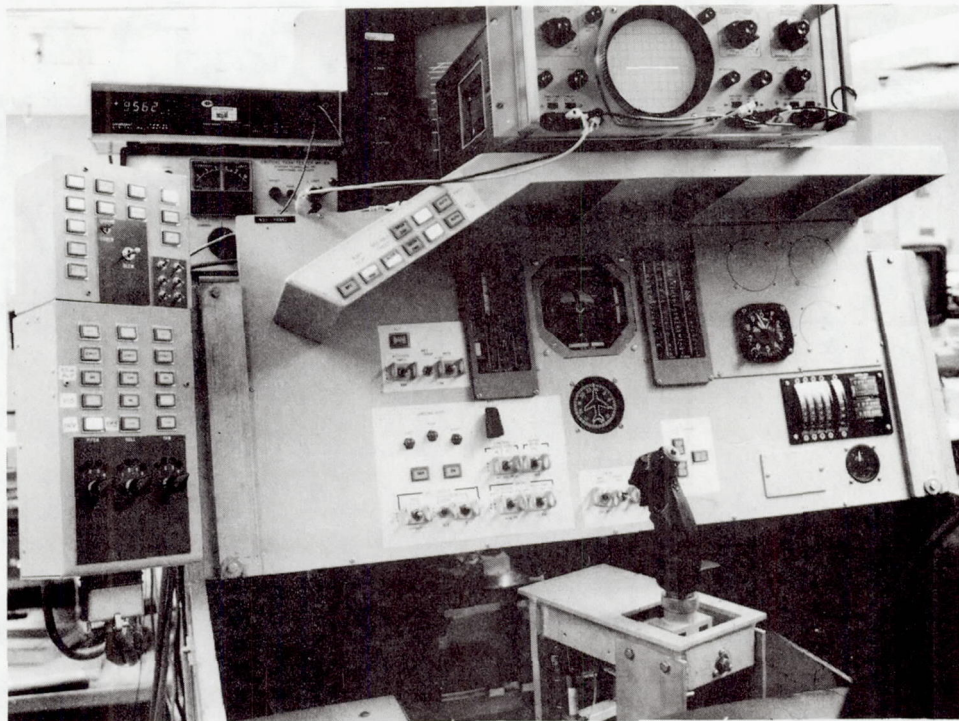
Figure 4. Critical task tester block diagram and root locus.

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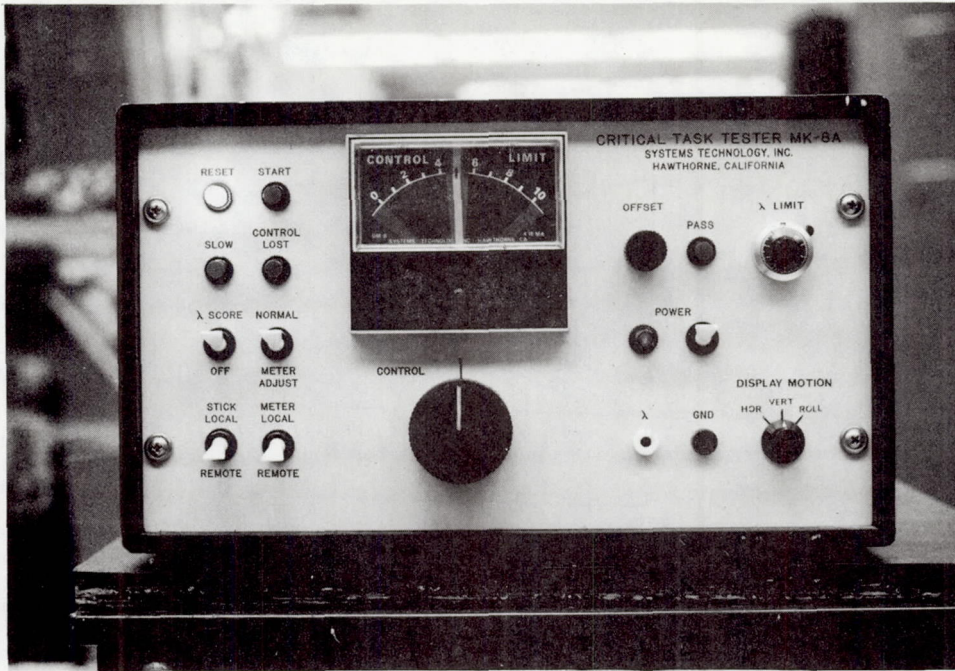
ECN 24923A

Figure 5. Critical task tester.

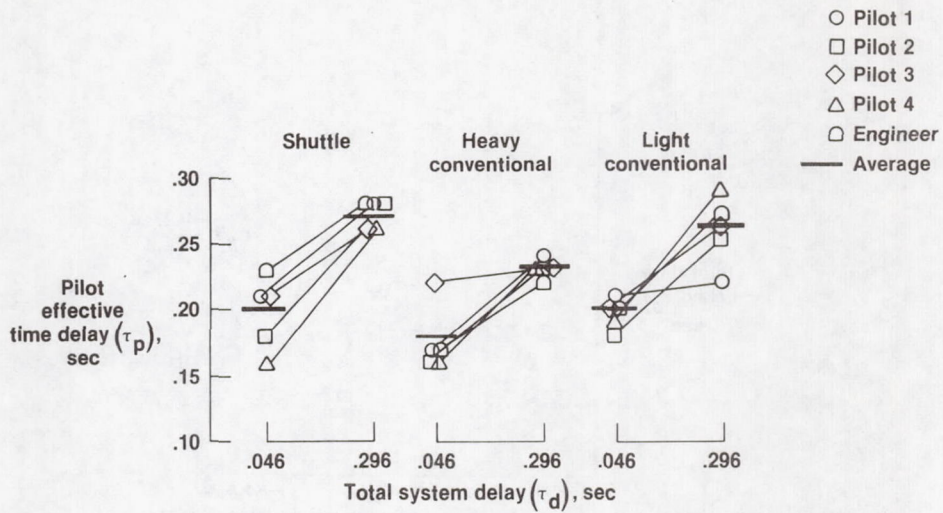ECN 24924A

Figure 6. Simulator cockpit.
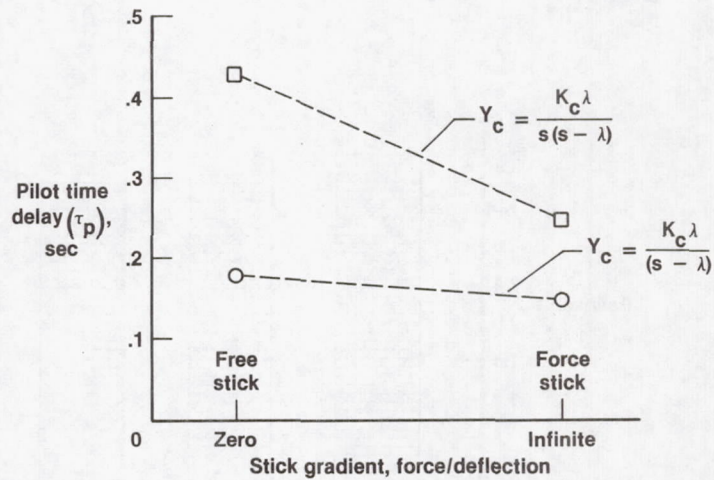
Figure 7. Summary of pilot time delay results.
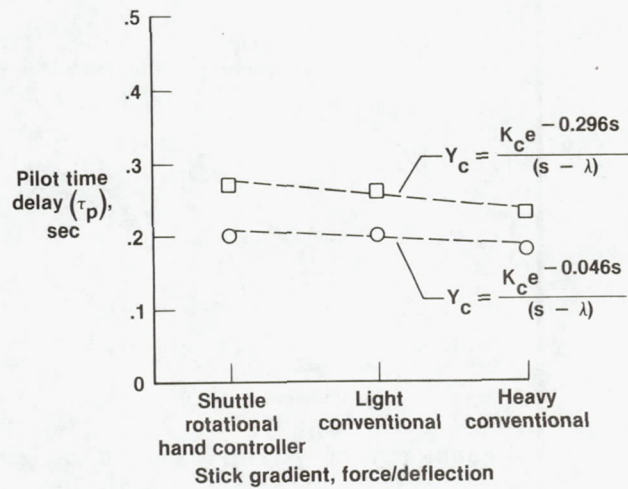

Figure 8. Pilot time delays for pencil controller.

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

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

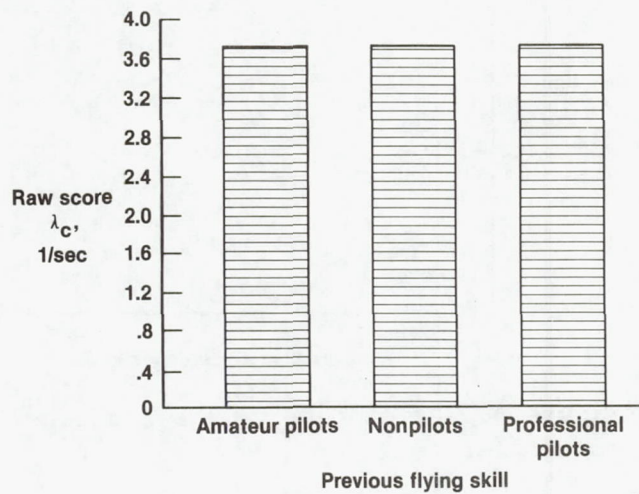*Figure 9. Pilot time delays for shuttle and conventional control sticks.*
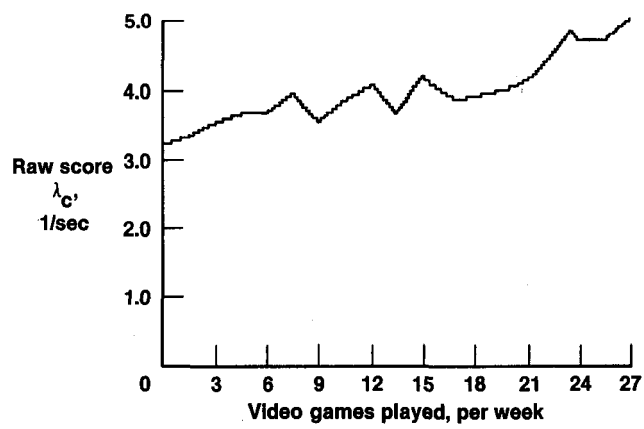

Figure 10. Raw scores as a function of flying skill.

Figure 11. *Raw scores as a function of video games played.*