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 configura­
tions 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
The space shuttle control stick is different than a conventional aircraft 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 ($T_p$) values for the shuttle stick and a more conventional stick. The experiment used two system time delays. Variations in the values of $T_p$ 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:

\[ Y_C = \frac{K_C\lambda}{s - \lambda} \]

where \( \lambda \) 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 \( \tau_P \) 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. \( \lambda \) is increased as a function of time and error magnitude, making the system more unstable until control is lost. The value of \( \lambda \) 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 \( \lambda_C \) 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 $\lambda_C$ values were recorded for each run, and the average for the 15 runs was computed for each case. The $\lambda_C$ 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 $\lambda_C$ 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 $T_p$ 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 $T_d$) is on the left and the data for the 250 msec added system delay run (296 msec $T_d$) 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 $T_p$ values with and without added system delay. The shuttle and the light conventional manipulator had similar $T_p$ values. The shuttle and light conventional sticks both had the same $T_p$ (200 msec) value for runs with no added system delay. On runs with added system delay, the shuttle stick $T_p$ 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 $T_p$ 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 $T_p$ 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 $T_p$ 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 $T_p$ 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
integrator lag. The time delay in the controlled elements of figure 9 would also require pilot compensation (or lead); an increase, therefore, in $\tau_p$ 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


Table 1 Control stick characteristics

<table>
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<th>Characteristics</th>
<th>Pitch</th>
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<tr>
<td>Shuttle stick</td>
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<tr>
<td>Breakout, in-lb</td>
<td>1.2</td>
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<tr>
<td>Travel, deg</td>
<td>±19.5</td>
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<tr>
<td>Gradient, in-lb/deg</td>
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<tr>
<td>Pivot point, in*</td>
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<tr>
<td>Heavy conventional stick</td>
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<tr>
<td>Breakout, in-lb</td>
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<tr>
<td>At stop, lb</td>
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<td>Travel, in</td>
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<td>Pivot point, in*</td>
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<td>Light conventional stick</td>
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<tr>
<td>Pivot point, in*</td>
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*Measured from middle of palm point on control stick.
Figure 1. *Space shuttle rotational hand controller.*

Figure 2. *Conventional control stick.*
Figure 3. Pitch axis stick shaping.

Figure 4. Critical task tester block diagram and root locus.
Figure 5. Critical task tester.

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

Figure 8. Pilot time delays for pencil controller.
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.