COMPENSATING FOR FLIGHT SIMULATOR CGI SYSTEM DELAYS

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INTRODUCTION

Modern flight training simulators are usually equipped with digital computers that measure the pilot's control activities, determine the simulated aircraft's responses, and provide student performance data for the instructor. Recent developments have made it possible to extend digital processing techniques to the generation of visual images, allowing an entirely computer-controlled training environment where a flight dynamics processor calculates the responses of a simulated aircraft and a computer generated imagery (CGI) system presents the changing visual scene to the pilot via a graphics display.

Digital control systems can encounter timing problems when their processing involves numerous calculations. In the past, the time taken by a digital machine to compute the dynamics of a flight simulation has not been a serious constraint on the use of simulators. With the addition of CGI systems, however, the delays imposed by calculation times are having an effect on simulator utilization. The temporal sequence of information flow needed to update a computer generated visual scene is depicted in Figure 1. Usually two

measure the operator's control inputs at rates of 15 to 32 samples per second, allowing aircraft position information to be available with minimal delays ranging from 66 to about 31 milliseconds. Currently available CGI systems take about 100 milliseconds to update their images, creating total system delays from approximately 100 to 200 milliseconds between the measurement of the pilot's inputs to the simulator and the visual presentation to him of its response. Actual delay values may vary slightly depending upon when the dynamics processor makes the results of its calculations available to the CGI system.

The problem introduced by adding a CGI system delay to delays already created by the dynamics processor of a simulation system was highlighted in Device 2F90, a TA4J Operational Flight Trainer, when it was noticed (after the addition of a CGI visual system) that flyers of the trainer tended to produce pilot induced oscillations on the last leg of the carrier approach task. In that device, the severity of these roll-axis oscillations was reduced by changing the aileron response to control stick deflection, but oscillations were still encountered, especially if a large roll input was made during the last 1/8 mile of the carrier approach (O'Conner, Shinn,
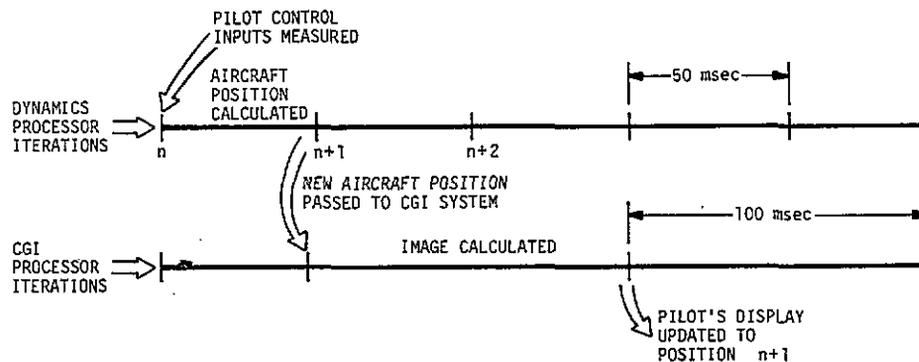

Figure 1. Sequence of Calculations in a Typical CGI Display System.

processors are used; one to control the simulator and one to do the graphics processing. The simulator controller measures the pilot's control inputs, calculates the new aircraft position, and makes the new position available to the graphics processor. The CGI system then obtains the new position of the simulated aircraft and calculates a new visual image to represent it. Present simulation systems can

and Bunker, 1973; or Harris, 1975). A similar situation was encountered using the Advanced Simulator for Undergraduate Pilot Training at Williams Air Force Base. Test pilots experienced an undesirable roll-axis instability during the landing approach and formation flying tasks (Larson and Terry, 1975). Presumably this is due to that device's 126 to 193 millisecond total transport delay.

Recent Work

The effects of inserting various types of delays into feedback control systems that contain human controllers have been studied for some time, and it is well recognized that the presence of delays affects the controllability of systems. Air Force sponsored studies on first-and second-order lags and on transport (dead-time) delays indicate that the control of compensatory systems that have random forcing functions is affected by any type of delay, but that transport delays, which allow no system response for the duration of the delay, are most disruptive. Because pilot performance is affected by short delays, the reduction of the effects of transport delays in the visual systems of flight simulators is an important consideration.

Research at the National Aeronautics and Space Administration Langley Research Center has assessed the effects that small transport delays have on pilot performance when those delays were inserted into the visual display of a flight simulator. Queijo and Riley (1975) had experienced controllers perform a "following" task in a fixed-base simulator where a "target" aircraft underwent slow sinusoidal oscillations of altitude and the task was to follow the target. Dead-time delays ranging from 50 to 300 milliseconds were inserted before the visual display. The amount of delay that could be tolerated was found to be related to ratings of the flying qualities of a variety of simulated aircraft. Only small delays could be allowed in high-performance aircraft simulations before their presence was objectionable and flying performance suffered. When the subjects flew simulations of aircraft with better handling qualities, longer delays had less of an adverse effect on performance.

These results were extended by Miller and Riley (1976) who activated the motion base of the simulator and varied the frequency of the altitude changes that their pilots had to follow. As might be expected, they found that when the frequency of the target plane's oscillations was raised, the subjects' performance under even small delays became poor. They also found that the use of the motion base extended the range of delays that could be easily accommodated. The demonstration that either the handling qualities of the simulated aircraft or the difficulty of the flying task can determine the extent to which dead-time delays can disrupt performance indicates the need to develop compensations for CGI visual systems. As we try to simulate more sophisticated aircraft or to teach the more complicated flying tasks, we might expect display delays to be increasingly detrimental.

At the Naval Training Equipment Center, Cooper, Harris, and Sharkey (1975) have measured the differences in piloting performance that display delays produce. Using the TRADEC F-4 simulator and a carrier landing task, they measured the amplitude spectra of the forces and deflections that experienced pilots exerted on the simulator's controls in the presence and absence of a 100 milli-second visual system delay. By subtracting the spectra obtained under no-delay conditions from similar spectra obtained under the delay, they obtained a difference spectrum for each control axis. This spectrum presents the differences (across frequency) of the pilot's control inputs that characterize control in the presence of a 100 millisecond delay. Information of this nature is useful as it indicates where in the frequency domain action can be taken to compensate for the effects of delays.

The Prediction Problem

As the dynamics processor iterates, it calculates a series of values with the aircraft's present position being represented by the most recent calculations. In practice, a running estimation of a value for the next member of this series, X_{n+1}, can be made by placing the most recent term, X_n, and the immediately preceding terms, X_{n-1}, X_{n-2}, etc., into a prediction equation of the form:

$$X_{n+1} = X_n + f \text{ (multiple terms)}.$$

The most recent term, X_n, is given the most weight and a set of other terms are used to adjust X_n to approximate the future value. The simplest case of this approach is a linear prediction scheme where X_n and the instantaneous slope of the function, $\dot{X}_n$, are combined such that the predicted value is a linear extension of the function from point X_n:

$$X_{n+1} = X_n + K\dot{X}_n,$$

where K is the prediction span. This type of prediction scheme has value for flight simulators as both X_n and $\dot{X}_n$ are usually available for each iteration of the dynamics processor, and little processor time is used to calculate X_{n+1}.

An obvious, simple, and quick formulation, linear prediction has been used where CGI system delays have existed, and has involved an adjustment of the aircraft position values before they are passed to the graphics processor. A problem arises because $K\dot{X}_n$ is a product, so that if either K or $\dot{X}_n$ becomes large, the adjustment to X_n can also become large. The potential for this condition exists in simulations of responsive, high-performance aircraft and/or where the CGI

system has long processor delays. Usually the processor delay remains constant, and the use of a linear projection scheme results in an amplification of the high-frequency responses of the simulated airframe. For aircraft responses which are low in frequency, the predicted value of X_{n+1} does not change much from one iteration of the dynamics processor to the next, but the amplification of the high-frequency responses produces values for X_{n+1} that can fluctuate quite a bit, causing a "jitter" in the visual display. Test pilots evaluating simulators have found the degree of this jitter annoying (Larson and Terry, 1975), and when they were allowed to vary the temporal extent of the linear extrapolation, they adjusted K to a fraction of the true CGI system delay.

This brings us to the real problem in compensating for CGI system delays, and that is the development of a rule for limiting the amount by which X_{n+1} is allowed to differ from X_n. If an aircraft parameter is allowed to change too slowly, the simulation will appear sluggish relative to the real aircraft, but on the other hand, if the rate of change is too high, the visual display will have reduced acceptability because of the imposed jitter. Since the visual system delay is relatively constant for a given system, we have decided not to limit the interval over which a parameter will be projected, but to reduce the amount that a compensation scheme can amplify high-frequency responses by passing adjusted parameters through a low-pass filter. To see if such an adjustment sequence has any utility, we have developed and evaluated a delay compensation scheme that represents the least complex example of this approach, where the extrapolation for the entire delay from X_n to X_{n+1} is linear and the low-pass filter is first order (i.e., has a 6dB per octave attenuation rate above the break frequency).

The Present Effort

Our efforts to develop compensations for visual system delays of the sort found in CGI systems have involved two approaches. In preliminary experiments, we found very little decrement in the performance of a tracking task in which a 200 millisecond delay had been inserted. At about this time, the Cooper, Harris, and Sharkey study found that differences in performance measures such as trials-to-criterion were almost nonexistent for experienced pilots. We suspected that this result was obtained because the experienced pilots had developed the ability to quickly assess the dynamics of the system they were controlling and to change their style accordingly. This feeling was reinforced by their second experiment where differences of measures of the pilots' control inputs were found between the delay and no-delay conditions. We felt that experienced subjects might not be best for the assessment of delay compensations developed for flight trainers, but that they would be ideal for the definition of the limits of piloting control for a given simulator under given conditions. Thus, in order to develop compensations for display delays, we used a two-stage procedure where the effects of experimental manipulations were tested using subjects familiar with the control tasks and the training usefulness of the developed compensation was assessed using naive, untrained subjects.

Control performance under a variety of conditions was measured by having either trained or naive subjects "fly" the system depicted in Figure 2. The compensatory display was an oscilloscope configured to represent an artificial horizon, and the subjects entered their control inputs via a two-axis spring-centered, side-arm control stick. Two types of aircraft, designated Task 1 and Task 2, could be simulated. The
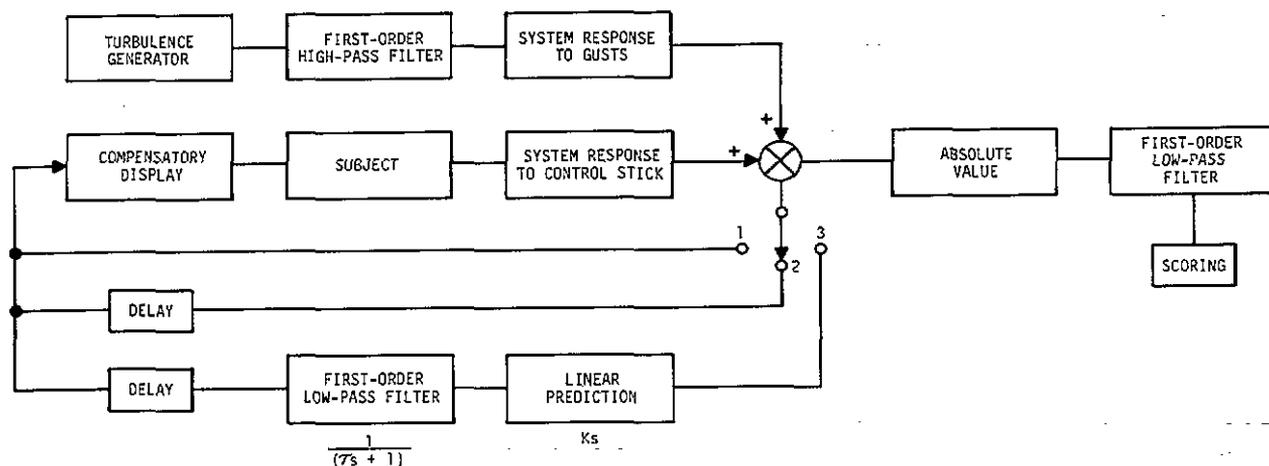
Figure 2. Block Diagram of the Control System and Experimental Conditions.

dynamics of Task 1 were representative of flying a general aviation, light, twin-engine craft, while Task 2 represented flying a high-performance jet interceptor. For both tasks, the subjects were asked to control the horizon indicator so as to maintain a straight-and-level attitude in the face of mild turbulence.

At the end of each two-minute trial, measures of the subject's control performance were available from the scoring system. Models of piloting control suggest that pilots adjust the size and timing of their control inputs to make the system-plus-controller conform to certain requirements, and our measures were chosen to reflect those adjustments (see McRuer, Graham, Krendel, and Reisener, 1965). In the first two experiments where subjects experienced with the system dynamics were tested, the absolute system error, the size of the control stick deflections, and their relative spectral power within a frequency band in the pilot "crossover" region (two to six radians/second) were measured. These measures were integrated and averaged over the length of a trial. In the third experiment, where naive subjects were trained, trials-to-criterion was added to the measure set. Criterion performance was expressed in terms of the displayed pitch and roll error of the aircraft, and, to be considered "trained," the naive subjects had to be able to maintain the system pitch and roll errors under 1° and 3°, respectively, for two consecutive trials. For our tasks, this represents a high-performance criterion, although the experienced subjects were able to generate average error well below these limits.

The three-position switch in the error feedback loop of Figure 2 indicates the conditions under which data were collected. When the switch is in position 1, the error signals from the dynamics portion of the simulator software are immediately available to the display, and the only delay is the calculation time for the displayed values. For our tasks, this time averaged to be 17.5 milliseconds. Changing the feedback switch to position 2 allowed us to insert transport delays into the loop. Our simulation iterated 20 times a second, and these delays were programmed to be multiples of that 50 millisecond period. While delays of any length could be inserted, we did not examine performance under any longer than 1400 milliseconds. Feedback switch position 3 represents the conditions under which we have developed and evaluated compensations for display delays. With this feedback loop, aircraft parameters were compensated and delayed before they reached the visual display. For each experimental condition, the span of prediction was equal to the display delay.

RESULTS OF EXPERIMENTS

Experiment 1

Our first interest was to see how the insertion of a display delay affected our performance measures. In the first two experiments, subjects' control performance was indicated by three scores. The error which a subject produced was used to reflect how controllable he found the system, and the stick deflection and relative power scores were used to indicate the control technique he used to generate that error. Experienced subjects were used in these two experiments, and their data are presented as individual functions in the resulting graphs. In this experiment, performance under a variety of delays was observed, and our control measurements for Tasks 1 and 2 are plotted separately in Figure 3. Only measurements for roll-axis control are presented as almost no differences were seen between delay and no-delay conditions for the control of the pitch axis.

From the plots of system error at the top of the figure, several trends are evident. Controllability gets worse with long delays, and good control is harder for the higher performance aircraft. Both of these results are as one might expect. In addition, however, our subjects displayed large and consistent individual differences. On both tasks, some of the subjects generated up to twice the error that others did, and the rank order of their error scores does not change from the first task to the second.

The stick deflection measure shows a pattern similar to that obtained from the error scores. Subjects who initially made large stick deflections responded to small delays by reducing the size of their control movements, but eventually larger and larger control deflections were needed to cope with the longer delays.

Our third measure, the relative power in the crossover region, shows striking differences between subjects. Some subjects hardly changed the extent to which they were making movements within this frequency region while others showed large differences. As the delay inserted into Task 1 was lengthened, the initial response of some was to insert more power into the crossover band. They later removed it as the delay became still longer. Our high-performance task did not allow subjects this flexibility, and power scores which were high for a zero delay displayed a steady decline with lengthening delays. Clearly subjects differ in the extent to which a display delay affects the accuracy and style with which they control even a simple flight simulation.
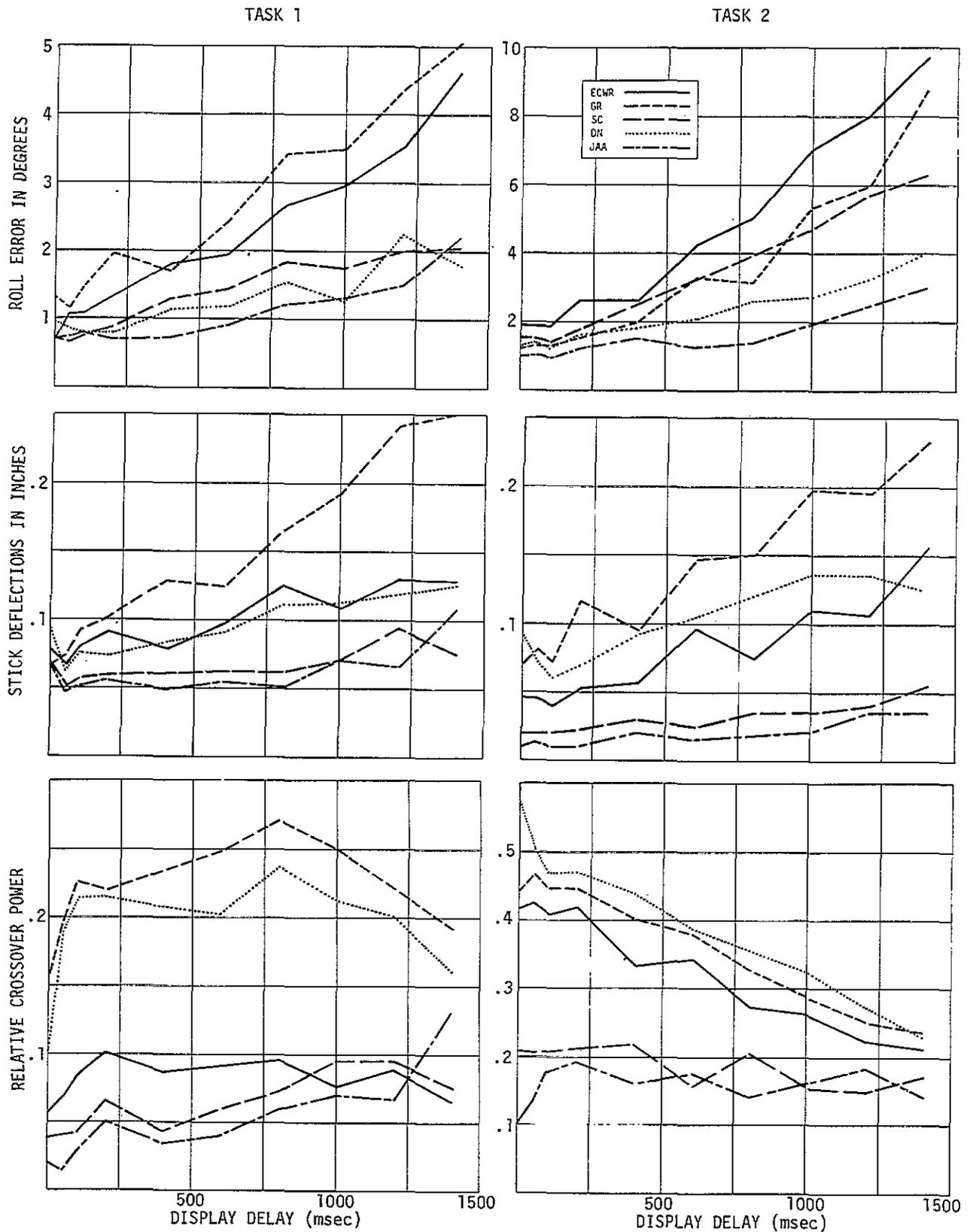
TASK 1 TASK 2

Figure 3. Experiment 1: Control Measures as a Function of Magnitude of Display Delay.

Experiment 2

In the second experiment, we varied the point at which the filter of our compensation scheme began to attenuate the values passed through the third feedback path of Figure 2. This would allow us to fix the break frequency of that filter so that the training usefulness of a good linear predictor-filter scheme could be determined. Subjects were tested on the control of Task 2 for several fixed delays. Only the data for the 400 millisecond delay condition are presented in Figure 4, as they are representative of the results obtained with both shorter and longer delays.

Break frequencies for the filter were chosen to span the pilot crossover region. In Figure 4, it can be seen that this systematically affected the subjects' error scores. As the break frequency was raised, the error scores became smaller, up to a point. This finding is not surprising as subjects cannot null error which they cannot see. In addition, these functions appear to have a minimum at about four to five radians/second, as some subjects tended to increase their error above that region. It is our impression that the increase of system error seen above the four

to five radians/second region is a function of the compulsiveness with which the subject tried to null the displayed error. When the break frequency of the compensation filter was set above that region, some of the "jitter" introduced by the linear prediction was displayed, and subjects who attempted to null the high-frequency error tended to add more than they removed.

As in the first experiment, the other control measures responded systematically. The stick deflection scores went through a minimum between four to six radians/second, and for some subjects, a high-frequency increase was present. As the compensation filter passed more components of the error signal and the display appeared more responsive, the subjects increased the power they placed in the crossover region. This occurred until a break frequency of two to three radians/ second was reached; beyond that point, the crossover power remained relatively constant. The dotted lines of Figure 4 represent the average value of each measure for the zero-delay condition. It can be seen that a break frequency can be chosen for which the system error, the stick deflection, and the crossover power scores are close to their non-delayed values.
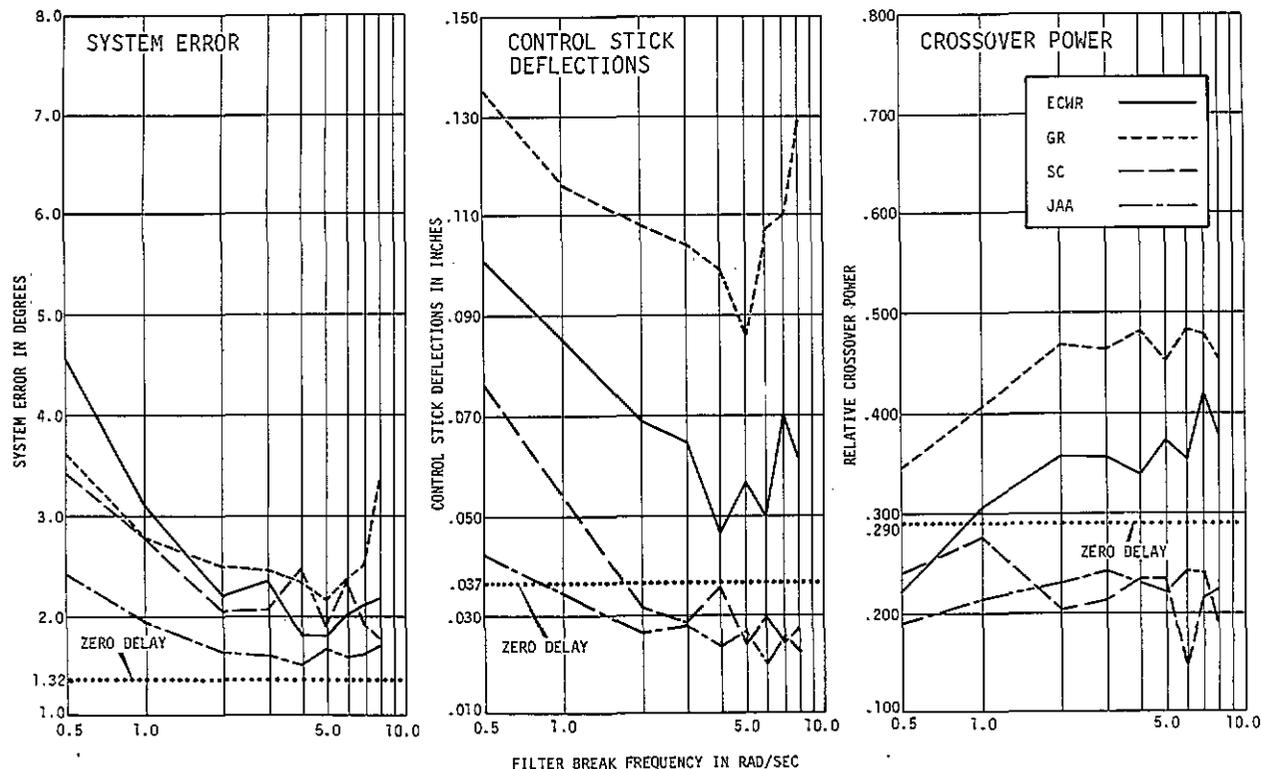

Figure 4. Experiment 2: Control Measures for Task 2 as a Function of Break Frequency of Compensation Filter. Inserted Delay Equals 400 Milliseconds.

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Experiment 3

In this experiment, we decided to fix the break frequency of the compensation filter and determine how inexperienced subjects would acquire the control skill under delayed or delayed-and-compensated conditions. This experiment was designed as an acquisition and transfer study where subjects first learned to control the display using the Task 1 dynamics and then were transferred to Task 2. A delay with or without the linear prediction and filter was inserted into Task 1 and our main interest was in the training time (trials to criterion) that the various conditions required. Since we were also interested in how subjects would respond on a new non-delayed task, all subjects were asked to perform at least one trial on the transfer task. This task contained no delay and was performed after criterion was reached on Task 1. Our testing sessions had a twenty-trial limit so that they could be easily scheduled, and this required that subjects reach criterion on Task 1 by at least the nineteenth trial.
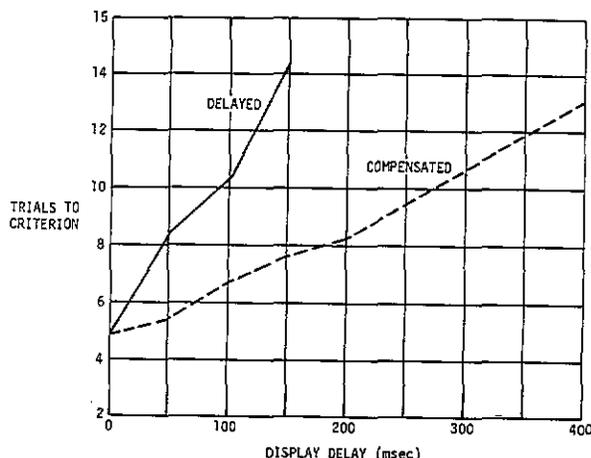

Figure 5. Experiment 3: Mean Trials to Criterion for Task 1. Break Frequency of Compensation Filter set to 4.5 Radians/Second.

Figure 5 presents the trials-to-criterion data for conditions that represent all three positions of the feedback switch in Figure 2. The training time necessary to master our normal undelayed system is presented as the zero-delay point, and the time needed when delays from 50 to 150 milliseconds were inserted into the feedback loop is presented in the upper function marked "delayed." Conditions where the display delay exceeded 150 milliseconds were not thoroughly tested as many subjects did not reach criterion within the nineteen-trial limit. The lower function labeled "compensated" presents the data collected using the third feedback loop of Figure 2. Here the

break frequency of the compensation filter was fixed at 4.5 radians/second, and with this filter setting, display delays of up to 400 milliseconds were included in the experiment.

Clearly the amount of practice needed to reach criterion performance increases as longer delays are inserted into the feedback loop. It is also evident that training time is increased at a lower rate when the delay is compensated. Both plots seem to be simple linear functions of the magnitude of the display delay.

It is possible that acquiring the control skill under a particular delay condition might encourage subjects to perform in ways unique to that delay. So, to test for this possibility, we analyzed (across delay conditions) the control measures obtained on the last acquisition and the first transfer trials. Differences of these measurements on the last acquisition trial would indicate whether subjects developed different styles of control to produce criterion performance, and differences on the transfer trial would indicate if subjects trained under various delay conditions would control differently on a standard undelayed test. Our subjects were trained to an error score criterion so we expected that the measurements of system error would not differ, and they did not on either the acquisition or transfer trial. In addition, no differences were seen across delayed or compensated conditions in the stick deflection or relative power scores. Apparently having subjects meet a strict performance criterion forced them to be homogeneous in their control style, and it merely took them longer to master the skill when a display delay was present. Using the delay compensation reduced the training time necessary for this mastery.

CONCLUSION

From these experiments, several conclusions can be drawn which may affect the use of flight training simulation systems that contain CGI system display delays.

1. Addition of a low-pass filter to the linear prediction scheme appears to have overcome the limitations of that technique and to have significantly increased its training usefulness. Linear estimation of future values of aircraft parameters is greatly improved by removing the "jitter" associated with that technique with an appropriate filter.

2. In flight training systems that contain significant dead-time display delays, equivalent trainee performance can be produced using fewer training trials if this form of delay compensation is used. Even with this rather simple compensation approach, a 40% reduction in training time was achieved by making an adjustment for a display delay.

The reduction may be further increased by tailoring the compensation scheme to a particular control axis of the airframe or to the requirements of a given flying task.

3. When subjects train on one system and then go to perform on another, there is always the question of transfer. In the case of CGI system delays, there is the potential that trainees will learn to "fly the simulator" and will acquire skills under conditions of a display delay that will produce negative transfer for nondelayed tasks. Happily, our data indicated no evidence of this tendency, and we suspect that it was because the subjects were trained to a performance standard. If a training program allows a fixed amount of training time where not all of the trainees may acquire the skill at the same rate, negative transfer effects may appear.

4. The error tolerances that served as training criteria in our third experiment were both narrow and constant throughout a trial. For some flying tasks, such as carrier approach or weapons delivery, performance tolerances become progressively more narrow as the task progresses. In contrast, tasks such as formation flying or aerial refueling demand narrow performance tolerances over an extended period of time. While a compensation for CGI system delays is potentially useful in all areas of flight simulation, we would expect that improvements resulting from the use of such a scheme would be more dramatic for tasks of the latter category.

5. The filtered linear projection scheme seemed successful enough to warrant further work on delay compensations tailored to flying tasks. The difference spectra of Cooper, Harris, and Sharkey's study appear to have a 12 decibel per octave high-frequency attenuation rate, suggesting that we can change our low-pass filter to a second-order one, allowing its break frequency to be set higher while still attenuating the high-frequency responses strongly enough to reduce the display "jitter" to acceptable levels. Such a change may not affect measures such as the system error, but it should be reflected in higher test or instructor pilot ratings of the acceptability of a simulation.

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