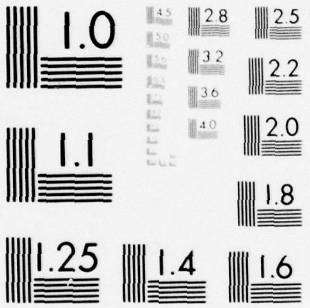
AD-A037 839 NAVAL TRAINING EQUIPMENT CENTER ORLANDO FLA F/G 5/5
DELAY OF VISUAL FEEDBACK IN AIRCRAFT SIMULATORS.(U)
MAR 77 G L RICARD, J A PUIG
UNCLASSIFIED NAVTRAEQUIPC-TN-56 NL

1 OF 1
ADA037839

END
DATE
FILMED
4-77



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

D

NW

TECHNICAL NOTE: NAVTRAEQUIPCEN TN-56

DELAY OF VISUAL FEEDBACK IN AIRCRAFT SIMULATORS

Human Factors Laboratory
Naval Training Equipment Center
Orlando, Florida 32813

March 1977

Final Report for Period November 1966 to March 1977

DoD Distribution Statement

Approved for public release; distribution unlimited.

NAVAL TRAINING EQUIPMENT CENTER

ORLANDO, FLORIDA 32813

NAVAL TRAINING EQUIPMENT CENTER
ORLANDO, FLORIDA 32813

Technical Note: NAVTRAEQUIPCEN TN-56

DELAY OF VISUAL FEEDBACK IN AIRCRAFT SIMULATORS

GILBERT L. RICARD and JOSEPH A. PUIG
Human Factors Laboratory

March 1977

Approved:

JAMES S. DUVA
Head, Human Factors Laboratory

J. F. HARVEY
Director
Research and Technology Department

NAVAL TRAINING EQUIPMENT CENTER

ORLANDO, FLORIDA 32813

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(14) 1. REPORT NUMBER
NAVTRAEQUIPCEN-TN-56

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER
(9)

4. TITLE (and Subtitle)
(6) Delay of Visual Feedback in Aircraft Simulators.

5. TYPE OF REPORT & PERIOD COVERED
Final Technical Note
Nov 1976 – Mar 1977,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
(10) Gilbert L./Ricard and Joseph A./Puig

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Human Factors Laboratory
Naval Training Equipment Center
Orlando, Florida 32813

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NAVTRAEQUIPCEN Task No. 7744

11. CONTROLLING OFFICE NAME AND ADDRESS
Commanding Officer
Naval Training Equipment Center
Orlando, Florida 32813

12. REPORT DATE
(11) March 1977

13. NUMBER OF PAGES
38

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Naval Air Systems Command
Instrumentation and Flight Control (AIR 340D)
Washington, D. C. 20361

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release, distribution unlimited.

(12) 44p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DDC
APR 6 1977
C

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Display delay (lag)
Human factors
Flight simulator specifications
Piloting control
Delay compensation
Visual displays

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The literature of the manual control of systems incorporating delays in the presentation of visual information is reviewed for the development of specifications for flight simulator visual displays. Several cases are presented where display delays have affected the use of operational simulation devices, and the means currently used to contend with those delays are discussed. Two approaches to preparing specifications are offered and available information relevant to each is presented.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

390462

4B

PREFACE

This note provides information concerning the effects of delays of visual feedback on human control performance during simulations of flight, and its purpose is to present data that may be useful for the development of specifications for simulators using visual systems. Hopefully such specifications will be able to relate the amount of time delay that pilots can tolerate to the sorts of aircraft usually simulated or flying tasks performed.

We have tried to make the note serve two purposes. First, it reviews the literature of the control of both simple systems and flight simulators incorporating display delays, and second, it describes two approaches for contending with time delays in simulation systems. A number of the more relevant papers have been annotated in an appendix, and a glossary of many of the terms of this area has been included.

Several people associated with the Naval Training Equipment Center have proofread this note, and we thank them. They are: Stanley Collyer, William Harris, Melvin Montemerlo, Don Norman, Vincent Sharkey, and Richard Webster.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

BACKGROUND AND LITERATURE REVIEW

Interest in the temporal accuracy of human performance extends to the beginnings of experimental psychology. Reaction time experiments, for instance, can be traced back to 1795 when it was discovered that astronomers could be characterized by individual differences of their observation times of stellar passages (Boring, 1929). Since that time, a great deal of effort has been expended on defining the psychological and physiological variables that determine a human being's response timing, and tasks have been used that require either discrete or continuous performance. Of current interest are the effects created by the transmission-type delays inherent in those research and training simulators that use computer generated imagery (CGI) visual display systems. Generally speaking, those delays of visual feedback produce decreased accuracy of control and reduced fidelity for the simulation (Chalk and Wasserman, 1976). As a result, there have been several attempts to improve those devices for flying situations where precise control is essential.

CONTROL SYSTEM TIME DELAYS

Lags between control input and system output are an integral part of mechanical devices, and simulations of such systems will include these sorts of delays. In addition, however, simulators often introduce delays of their own that act to reduce fidelity. These delays come from sources such as the sampling rates of digital controllers, the inertia of components of visual and motion systems, and the processing time required by CGI system display processors.

Communication systems often involve delays where the output of the system is a faithful representation of its input, only it appears after a fixed amount of time. This form of delay is referred to as a dead-time, or transmission, or transport delay, and the response of a system incorporating such a time delay is shown in Figure 1a. Here we can see that a step input is reproduced as a step output (after the delay); its form is not affected, and only the phase of its components would be changed. Transport delays, even when extremely small (e.g. $<$ 0.06 second), tend to degrade human control performance when compensatory displays are used, and their presence can usually be detected by the controller (Beil and Warrick, 1949). The phase shift introduced by a transport delay is linear with frequency, small for low-frequency components and large for high-frequency ones, and this limits the frequency with which an irregular track can be followed. A problem is created when the delay becomes long enough that the phase of components that the pilot is trying to control approaches -180°,

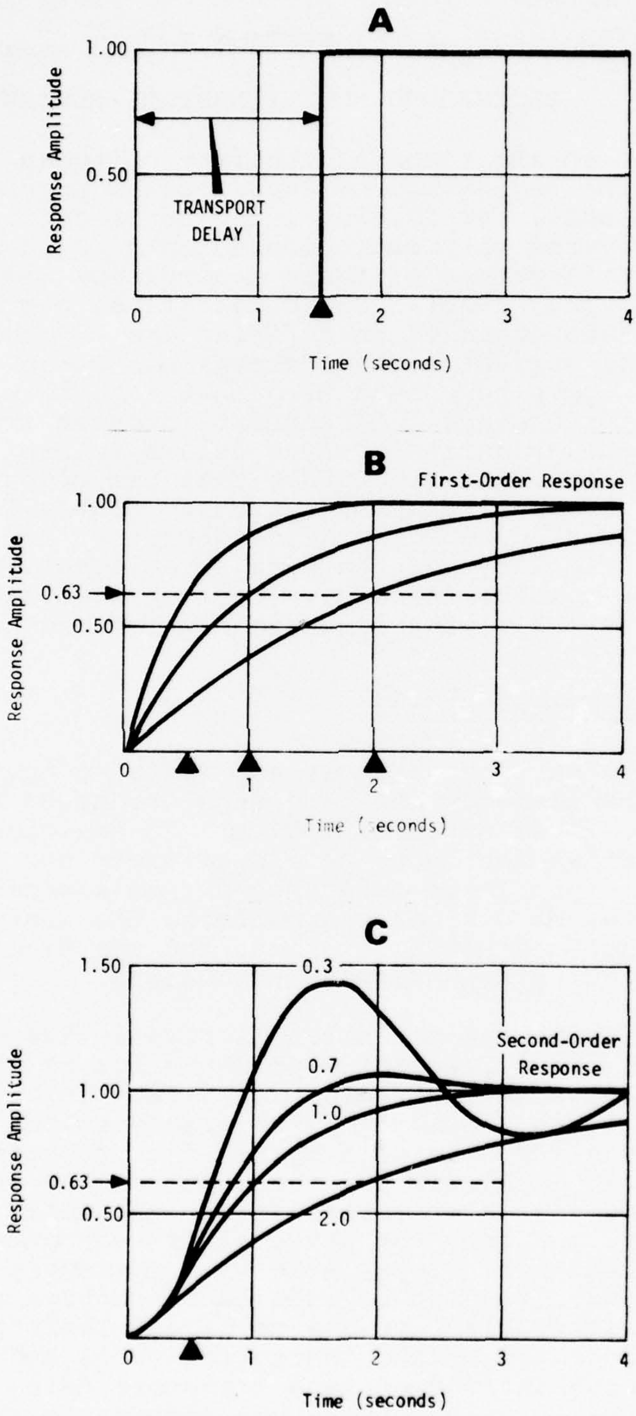


Figure 1. Responses of first- and second-order systems to a unit step input. ▲ indicates the measured delay or time constant. For the first-order system, τ = 1/2, 1, and 2 seconds. The second-order system τ = 1/2 second and responses for damping ratios of 0.3, 0.7, 1.0, and 2.0 are depicted.

so that control inputs aimed at correcting a displayed error will only add to it. Thus, the only way an operator can compensate for the presence of such a delay is by knowing where the track will be a corresponding time ahead and then by responding accordingly. To an extent, this is possible with pursuit displays or predictable forcing functions (Poulton, 1969).

First- and second-order systems display exponential and sigmoid responses respectively to step inputs, and the delays that they produce are frequency-dependent. In this sense, such systems act as low-pass filters by not affecting low-frequency inputs and by attenuating high-frequency ones. For a first-order system, the measure of the time delay it produces is its time constant (τ) - the time taken by the system to reach about 63 percent (1-1/e) of its final value. τ can be related to the filtering action of the system as, in the frequency domain, input frequencies above $1/\tau$ Hz are attenuated at a rate asymptoting to -6 dB per octave, and this attenuation rate is accompanied by a phase lag that approaches -90°. In Figure 1b, we have presented responses of first-order systems with τ set to 1/2, 1, and 2 seconds to show the effect of varying the system's time constant.

When another integration is added to a first-order system to produce a second-order system, the first-order attenuation rate and phase lag are doubled, but the exact response of the second-order system depends on two parameters, its time constant and damping ratio. A damping ratio is the present system damping over a "critical" value that does not allow the response to overshoot, and in Figure 1c, we show the effect of different values of this ratio. Here we have set $\tau = 1/2$ second, and responses for damping ratios between 0.3 and 2.0 are shown. Damping ratios less than 1.0 allow the system to attain its final valve quickly, but they also allow the response to overshoot that value. The form of the response for such dampings is a damped oscillation that finally settles at the value of the input. Critical damping provides a system that approaches its input value as fast as possible with no overshoot, and values of damping greater than 1.0 produce system responses that become progressively more slow.

The phase lags produced by first- and second-order systems can either improve or degrade performance, depending upon their interactions with other aspects of the simulation system dynamics. For example, Rockway (1954) showed that when the system gain is optimally set, a first-order lag placed before the machine output will degrade control performance, but that when the gain is set too high (causing continual overshooting), the lag will reduce the amplitude of the system output and thus serve to improve the system's controllability. The beneficial effect of a first- or second-order lag usually is a result of the accompanying attenuation of the system's response over the spectral region of the lag. When a system is optimally (or realistically) set and the trade-off of response attenuation vs. phase lag is less favorable, an added time delay between system input and output would only make the system more difficult to control.

LIMITATIONS OF MANUAL CONTROL

Considerable data exist on the temporal accuracy of human performance, and these data have been obtained with the techniques of both experimental psychology and control engineering. The time to respond to a signal - the simple reaction time - has been defined in a variety of contexts, and quasi-linear engineering models have developed analogous measures for the cases of continuous dynamic control. Both types of data have been used to estimate the frequency limits of human control.

Although there is wide moment-to-moment variation, the average time to respond is about 250 milliseconds if a choice is required and, if no choice is involved, about 150 milliseconds. Ongoing behavior can be envisioned as a series of responses to discrete stimuli, and in test situations where signals have been quickly repeated, the reaction time can go as high as 500 milliseconds. Birmingham and Taylor (1961, p. 73) have effectively presented the use of such measurements for the estimation of the human bandpass:

> "If the evidence on human response intermittency is accepted, it is possible to infer the highest input frequency which the man can successfully follow. Practical experience indicates that at least four samples per cycle are required to reproduce the waveform of the input with reasonable fidelity. If this is taken as a minimal figure, it follows that the human, responding on an average of twice per second, will be able to follow with some success, frequencies no higher than 0.5 cycle per second. Of course, the lower the input frequency, the more samples per cycle will be obtained, with the result that the fidelity of reproduction will increase as the input frequencies drop.
>
> Translating cycles per second into radians per second, our inferences lead to the specification of the human bandpass as the region between zero and three radians per second."

Usually, human control performance is a bit more flexible than such an analysis suggests. Even when random forcing functions are tracked, enough information is available for short-term prediction so that significant control energy can extend to above 1 to 2 Hz.

Pew (1974) has suggested that whether one describes control behavior using differential equations or reaction time extrapolations is more a matter of convenience than anything else, so that whether human control behavior is basically intermittent or not need not necessarily concern us here.

The main advantage of the control systems engineering approach to describing human control performance is the compatability of its measures to the needs of equipment designers. Frost (1972) and Young (1973) provide introductions to these techniques and to McRuer's crossover model (McRuer, Graham, Krendel, and Reisener, 1965; McRuer and Jex, 1967; and McRuer and Krendel, 1974), one of the more widely used models of piloting control because it provides a number of measures of the pilot's characteristics and of pilot-plus-system performance. This model, developed to provide a frequency-domain description of pilot behavior, regards the pilot as composed of a number of simple elements: a gain, an indifference threshold, a transport delay, a source of noise, and lead/lag terms that can be adjusted for the task at hand. More simply, he can be regarded as an amplifier (gain) with the lead/lag and transport delay elements combined into an effective time delay.

Measurements of pilots' gain show it can vary over a 20 dB range, and estimates of their transport delay usually approach a minimum of about 200 milliseconds. It is this delay along with the lead/lag adjustments a pilot can make that will determine how well he will control a given system. The model's usefulness lies in the success with which it can relate measures of system performance such as crossover frequency and phase margin to changes of task variables. Generally, pilots try to force the system to crossover somewhere between three to five radians per second with a phase margin of 25° to 45°. These values are affected most strongly by the dynamics of the system being controlled and the bandwidth of the forcing function used, but they are typical for the control of high performance aircraft.

It should be noted that this is an engineering model and does not take into account the difficult-to-quantify human factors common in flying simulations. The information processing requirements of various side tasks, differences of pilot personality and performance style, and the requirements of different flying tasks - all will determine how much time the pilot can devote to controlling his aircraft and, through him, will affect measures of system performance, particularly its phase margin. Some recent work has recorded piloting control measures during tasks with different attentional requirements (Wickins, 1976 and Gopher and Wickins, 1976), and the results showed pilots modified their control activity in response to these different requirements. The work is important here since a transport delay inserted into a simulation can also require information processing on the pilot's part by making it necessary for him to project aircraft position ahead of that which is displayed.

CONTROL OF SYSTEMS WITH DELAYS

A number of studies have measured the effect that time delays have on tracking performance. Initially these were Air Force-sponsored laboratory studies designed to obtain information for aircraft control requirements. Later the National Aeronautics and Space Administration (NASA) sponsored work where the transmission delays involved in the remote control of lunar vehicles were simulated, and recently the processing delays of computer generated visual displays for flight simulators have been studied.

Much of the early work used rather elementary tracking tasks. Usually a pointer had to be centered by manipulating a control stick or knob. A forcing function was applied to the pointer, most often this was a sinusoid or the sum of two or three sinusoids, and performance was scored as the time within a tolerance. Warrick (1949) first placed a transport delay between the output of a system and its display, and he was soon followed by several reports of the effects of display lags (Levine, 1953a, b; Senders and Levine, 1953; Rockway, 1954; Warrick, 1955; Conklin, 1957; Garvey, Sweeney, and Birmingham, 1958; and Levine, Senders, Morgan, and Doxtater, 1964). All of these studies have shown delays to be harmful to skilled performance. Levine (1953a, b) and Senders and Levine (1953) placed a first-order lag before their subjects' display and showed that as the time constant of the lag increased, accuracy of control decreased, but it was Rockway (1954) who showed that the filtering aspects of a lag could have beneficial effects depending upon other parameters of the control system. The rest of these papers are fairly similar to the Warrick (1949) and Levine (1953a, b) reports, and this literature has been nicely summarized by Muckler and Obermayer (1964). One exception is Garvey, Sweeney, and Birmingham (1958) who placed first-order filters before either the input to their system or the subject's display. While the displayed signal was the same in either case, they showed that the effect of such manipulations on the scored tracking error depends upon where the filter was placed. As the subject can be regarded as injecting noise into the control system, if a filter is placed after this process (before the display), scored error is much larger than if the subject produced noise is removed.

A study of the long transmission delays encountered during the remote control of spacecraft is that of Leslie (1966) where transport delays as long as 10 seconds were investigated. His results, predictable from pilot modeling theory, argued that a delay limits the allowable bandwidth of the forcing function or, given a constant bandwidth for the disturbance, forces the operator to lower his crossover frequency. Gain crossover regression has been observed before, but Leslie extended observations to very long delays where even this tactic disintegrates into a move-and-wait strategy.

These tracking studies became relevant to the design of flight simulator visual systems when it became obvious that the calculation time of the display processor introduced significant transport delays into flight simulations. O'Conner, Shinn, and Bunker (1973) reported that pilot induced roll-axis oscillations appeared during some flying tasks when a CGI system was added to Device 2F90, and Healy and Cooper (1973) and Harris (1975) have attempted to measure and reduce the effect of that delay which is in excess of 100 milliseconds. Larson and Terry (1975) mentioned that the Advanced Simulator for Pilot Training (ASPT) at Williams Air Force Base displayed similar problems, especially for such piloting tasks, as formation flying, where accurate control of the device was necessary. In their report, Larson and Terry described the ASPT CGI system delay as between 126 to 193 milliseconds, depending upon when aircraft position information was made available to the display processor. We might note that the ASPT visual displays are a prototype system and that their delay will be reduced somewhat by newer and faster aircraft dynamics processors. However that CGI system delays are a continuing problem for simulations of responsive aircraft is indicated in the Naval Air Test Center (1976) report on the S-3A trainer fitted with the VITAL III visual system. The preliminary tests indicate that this system may also display controllability problems during certain maneuvers. Although disturbing, these results are not very surprising given that automobile simulators have displayed similar control problems when their displays have been delayed (Smith and Kaplan, 1970).

We know that control problems are encountered when there are display delays in the range found in current CGI systems, and several studies have tried to see how delays will interact with other aspects of a simulation or have measured pilot control inputs to obtain quantitative data for the development of compensations. Weener (1974) inserted, before a display, dynamics with different natural frequencies to simulate the z-axis translational servo motor response of a modelboard visual system. Two aircraft with different short-period characteristics were simulated so that interactions between the simulated airframe, the disturbance input, and the display dynamics could be examined. Weener found that for his higher performance simulated aircraft (having a higher frequency and less damped short-period response), the more the display dynamics would limit the pilot's performance. Increasing the display's natural frequency helped, but for his more sensitive airframe, setting the natural frequency to five times the airframe's short-period response still produced manual control performance worse that his no-display-dynamics comparison condition.

Queijo and Riley (1975) have approached the problem of display delays by varying the handling qualities of simulated aircraft when transport delays were inserted before their pilots' television display. Seventeen combinations of short-period and damping were used to vary the aircraft's longitudinal axis handling qualities and a measure of pilot workload was used to assess performance. They found that as the handling qualities were made poorer, the acceptable delay decreased and that even rather small delays - on the order of 47 milliseconds - could affect pilot performance for some aircraft configurations. Variables that increased the task complexity also decreased the acceptable delay. Miller and Riley (1976, 1977) extended this work by activating the NASA Langley simulator's motion base and finding that providing these cues extended the range of delays a pilot could tolerate when flying a given aircraft configuration.

These studies measured the success of the pilot's control performance at the output of the system, but a clear picture of the differences of pilot input under delay and no-delay conditions is presented by Cooper, Harris, and Sharkey (1975) who measured pilot control inputs during the presence and absence of a 100 milliseconds display delay. Amplitude spectra for each control axis, as well as difference spectra of the differences (across frequency) of pilot inputs under the delayed and non-delayed conditions, were presented. Such data are useful as they show where in the frequency domain adjustments must be made in order to aid control in the presence of display delays.

SECTION II

DATA FOR SPECIFICATIONS

One approach to forming specifications for visual display system delays would be to define a maximum total transport delay that the entire simulator plus visual system should not exceed. This would set a requirement that equipment designers can translate into cost. As the hardware and software of visual systems undergoes development, we would expect these costs to be reduced. A second approach would be to take the characteristics of available equipment into account and to develop computer software that will make the displays acceptable. At the present time, this has taken the form of developing predictive algorithms to predict future aircraft states and then limiting the spectrum of the signals that influence the displayed translational and rotational parameters of the aircraft.

ALLOWABLE DELAYS

From pilot modeling theory (the McRuer references), we know that pilots will adjust their crossover frequency and phase margin so that the system they are controlling will remain stable and so that a quantity like root-mean-square error will be minimized. Two variables have been found that strongly affect pilots' control actions: the dynamics of the system they control and the characteristics of the forcing function. These findings come from laboratory experiments, and McDonnell (1968) has aided the generalization of these data by equating the conditions of those experiments to the Cooper and Harper (1969) scale of aircraft handling qualities. By knowing the characteristics of the airframe and the pilots rating of them, one can make an educated guess about how the aircraft will be controlled and how an added transport delay will affect performance in a simulator. Some of the figures from the McDonnell report will illustrate this extrapolation.

Figures 2 and 3 display the effects of varying the amplitude and bandwidth of a system's forcing function for both a rate control (K/s) and an acceleration control (K/s^2) system. In Figure 2, the Cooper-Harper rating is given for the two sets of dynamics for several amplitudes of the disturbance input. Here the input disturbance is scaled in terms of the standard deviation (σ_i) of the deflection of the oscilloscope beam that formed the subject's display. Higher numbers on the Cooper-Harper scale indicate poorer handling qualities, and in the figure it can be seen that as the flying task is made more difficult by (a) forcing the pilot to contend with high amplitude turbulence, (b) having him control second-order rather than first-order dynamics, or (c) inserting high frequency components into the turbulence, his numerical ratings of the task increase, reflecting his poorer performance. Figure 3 provides some indication why this occurs. Some data from the main McRuer report are included for comparison. Conditions that were rated low (as the acceleration control ones were) required more integrations on the part of the pilot than the higher-rated ones and this forced his effective time delay to be longer. More effort is required to maintain system stability under these conditions, and one would expect that an added delay would only increase the pilot's control problem.

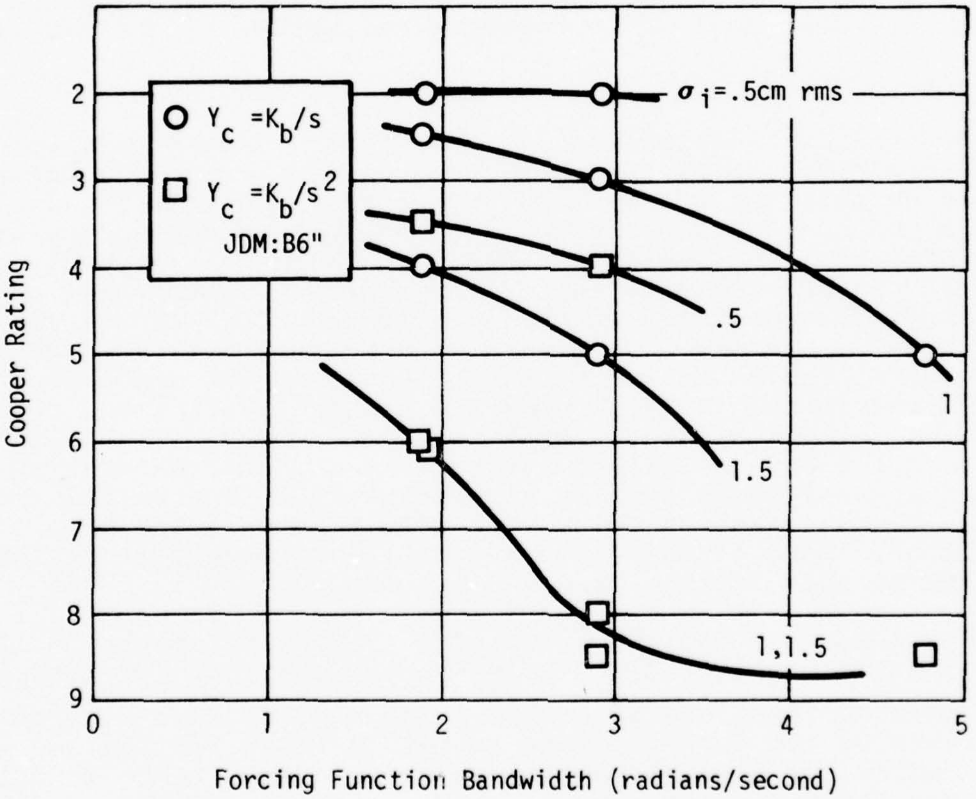


Figure 2. Effect of disturbance bandwidth and system dynamics on pilot ratings (Data from McDonnell, 1968).

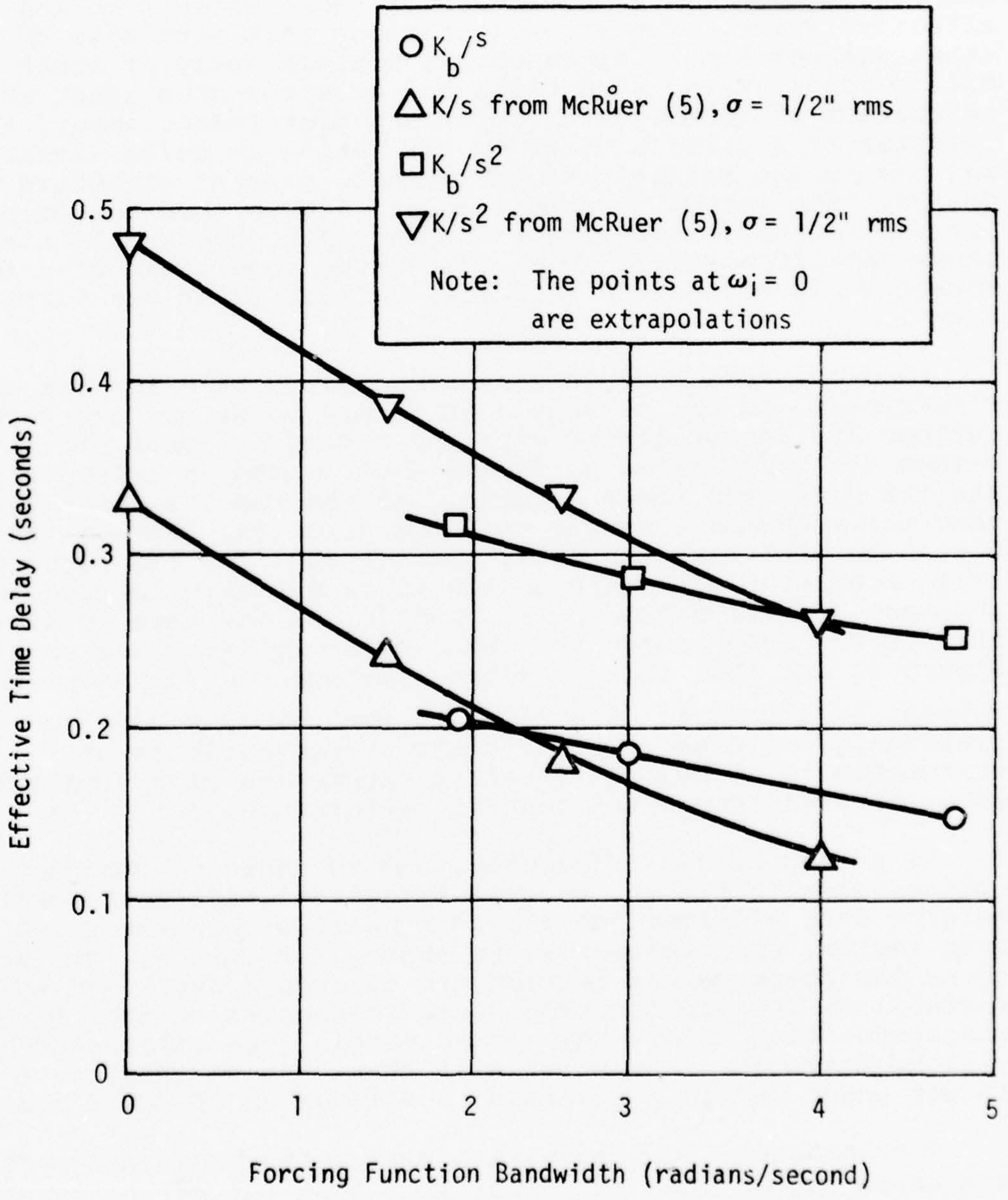


Figure 3. Variation of effective time delay with forcing function bandwidth (Data from McDonnell, 1968).

Along with parameters of disturbance input, the dynamics of the system the pilot controls is a source of variables that will affect piloting control behavior, mostly the pilot's effective time delay. In Figure 4 are presented measurements of the pilot's time delay taken as a subject "flew" a variety of systems that forced him to adopt different delays. Cooper-Harper ratings of the different configurations were taken, and the figure displays the relation of these ratings to the pilot's effective delay. Those configurations that were easy to fly (that allowed him to approach his minimum delay of about 200 milliseconds) were rated high, and were the ones least affected by changes of turbulence. For a set disturbance input, the relation of a pilot's delay to his rating is quite linear, allowing one to use rating data to estimate pilots' effective time delays. The dotted functions in the figure show the effect of increasing the forcing function bandwidth, and should a set of these data become available, the flying conditions of a simulation could be used to estimate the time delay the pilot would adopt.

When the same sort of measurements are made for the pilot-plus-system, as are presented in Figure 5, we can see that the ratings are almost linear with phase margin. Most of the system dynamics listed in Figure 4 were used in order to generate the different phase margins, and the results clearly show that the more phase margin that the pilot can produce, the better he will like the task. Notice that for the rate control (K/s) condition of Figure 4, the pilot was able to produce his shortest effective time delay, and it was for this condition that he was able to produce the largest system phase margin in Figure 5, and that this situation is reversed for acceleration control (K/s^2). This function, as the one in Figure 4, presumably could be related to the characteristics of the turbulence to allow one to relate parameters of a simulation to pilot preferences and control performance.

As a step in that direction, and to indicate the control options open to pilots, we have translated different phase margins into milliseconds for components within the pilot crossover region, and these data are shown in Figure 6. The abcissa gives the phase margin between the pilot's control and system instability for various crossover frequencies so that when a transport delay equals this phase margin, the pilot-plus-system will be unstable. The pilot will then have to generate a larger phase margin <u>or</u> regress to a lower crossover frequency.

For instance, suppose that a high performance aircraft was being simulated under conditions that forced the turbulence to be relatively wide-band, and the pilot controlled the simulator such that the system crossed over at six radians per second. Now if a 150 millisecond total transport delay were incorporated into the device, it would be unlikely that

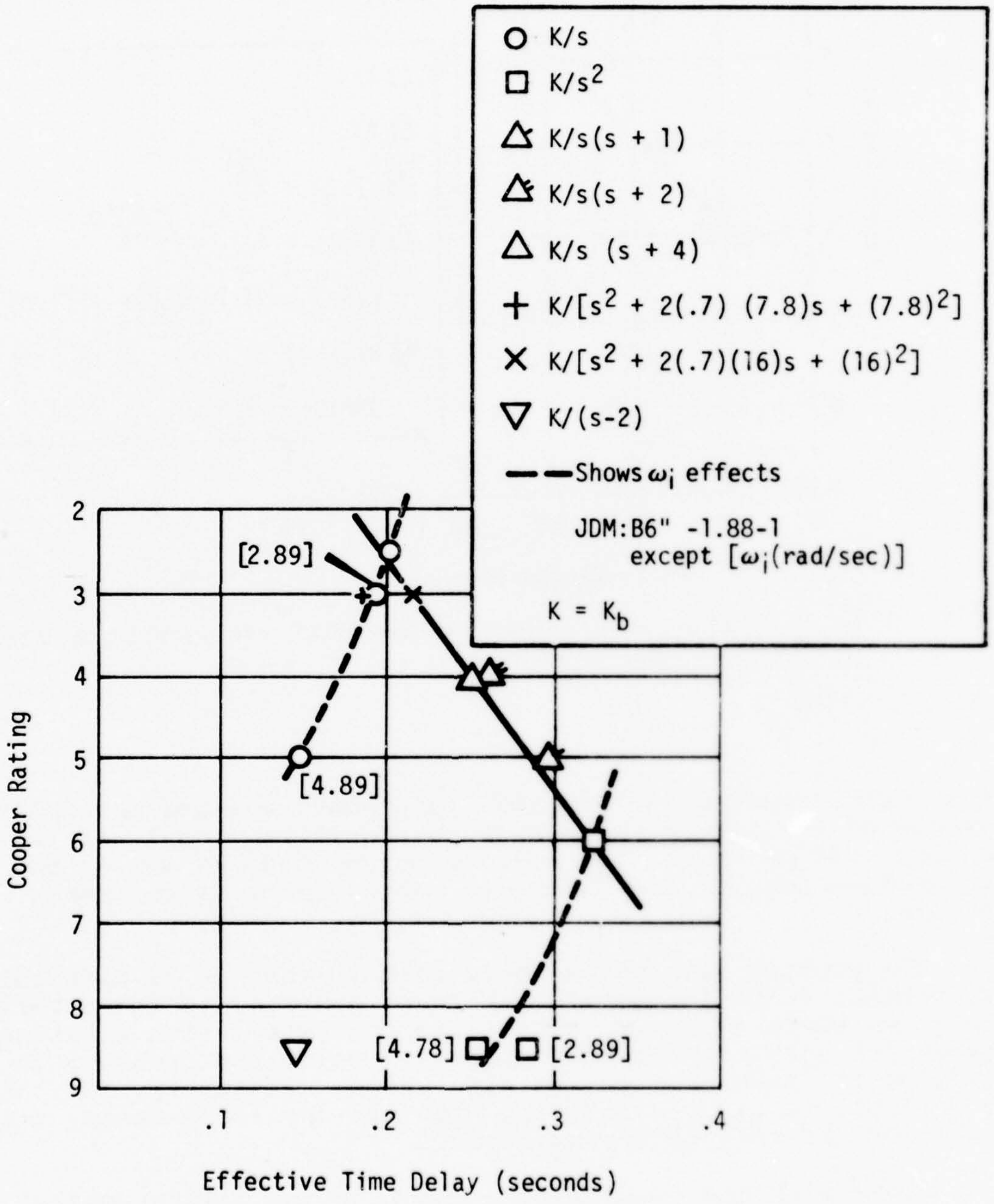


Figure 4. Variation of pilot rating with effective time delay (Data from McDonnell, 1968).

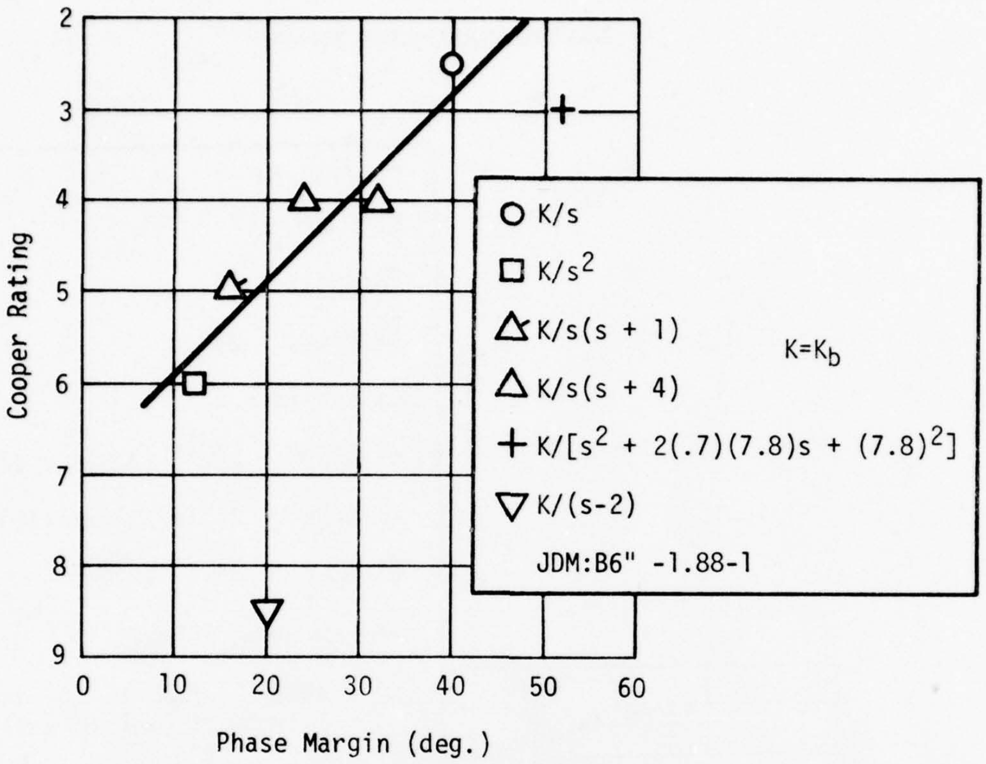


Figure 5. Variation of Cooper rating with phase margin (Data from McDonnell, 1968).

the pilot could adjust his lead to produce a phase margin in excess of 45°, so he would have to crossover at a lower frequency. If he chose four radians per second, he would have to produce better than 33° phase margin in order to remain stable.

The problem with using these data is that it is difficult to predict where the pilot will cause a system to crossover. On tasks where subjects control simple systems with constant bandwidth disturbances, the crossover point can probably be related to parameters of the simulation. Presently, for the complications of actual flying with its ancillary tasks, pilot behavior can only be approximated.

Along with the problem of predicting the pilots control activity, more of the difficulty of specifying a maximum allowable delay for flight simulator CGI systems can be seen in Figure 7. From Queijo and Miller's (1975) data, we have extracted an iso-error curve for variations of the airframe's short-period response over the range of frequencies found in modern

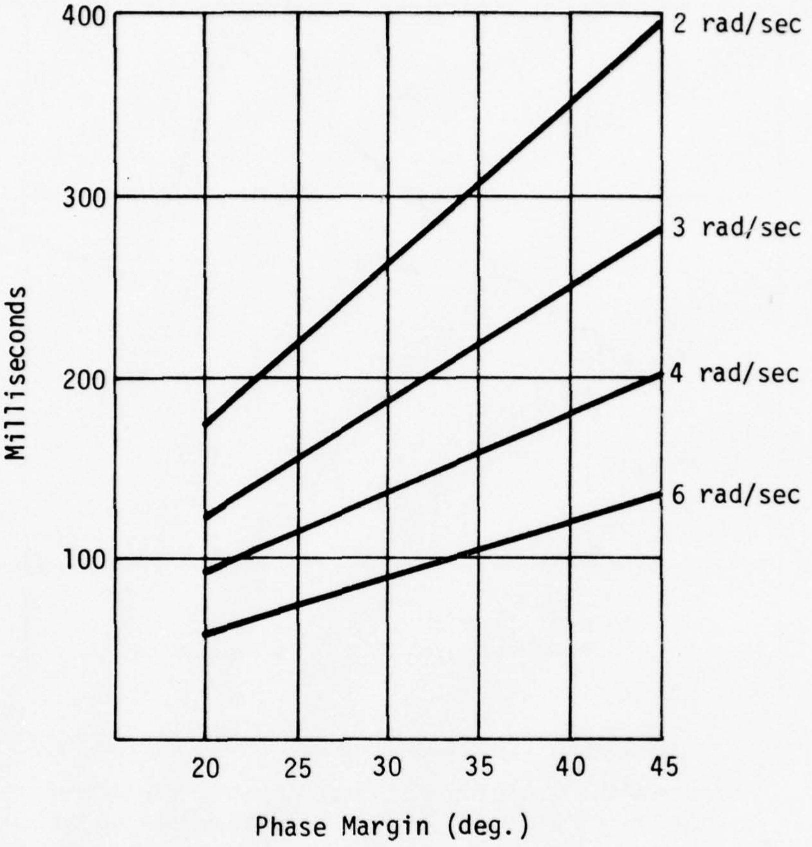


Figure 6. Translation of phase margin into milliseconds for several crossover frequencies.

aircraft (Teper, 1969, and Heffley and Jewell, 1972). The function depicts the total transport delay required to produce a 10 percent increase of tracking error for short-period frequencies of 1.5 to 5.5 radians per second. Here we have tried to select data representative of simulations of demanding aircraft in that configurations were chosen so that $L_\alpha = 2.0$ and the short-period damping was ≤ 1.0. The number of observations per combination of short-period and damping ratio varied and was not large, so the relation might well be regarded as tentative. When averaging over damping ratios could be done, it was and the solid line represents these results. Open circles indicate the individual data with the damping ratio along side.

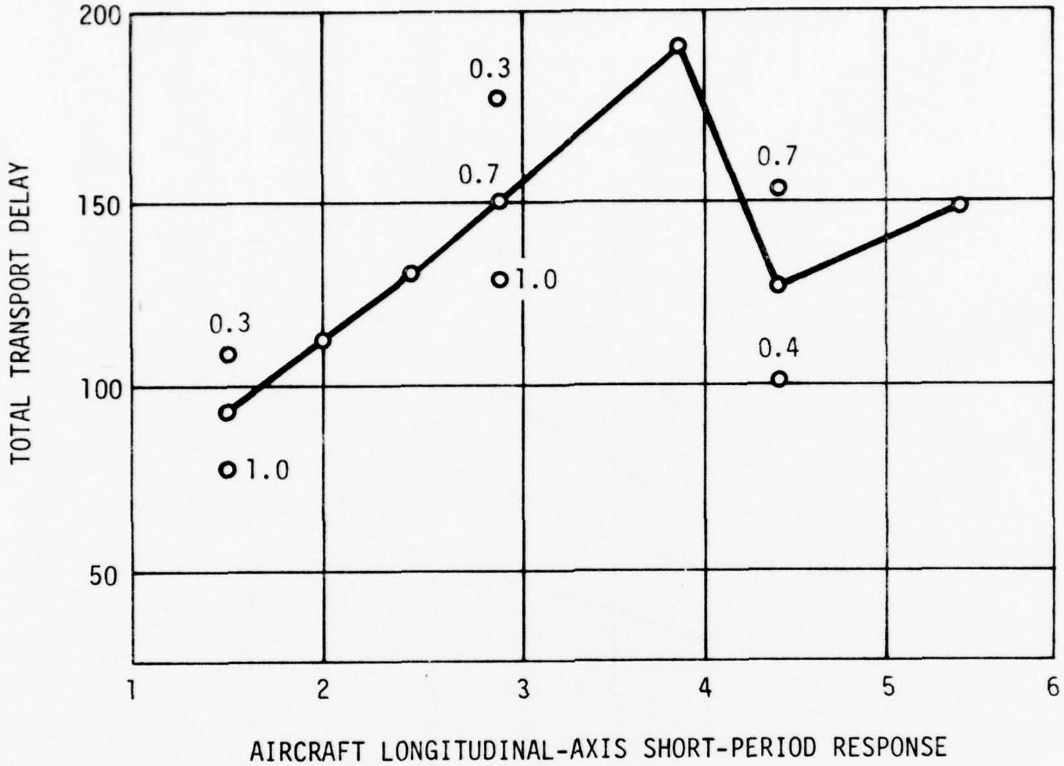


Figure 7. Relation of transport delay and airframe short-period response for a 10 percent increase of tracking error. Numbers indicate short-period damping ratio. Data extracted from Queijo and Miller (1975).

Two trends related to the current problem are evident. First, the iso-error curve represents the tolerable delay for a constant performance criterion, and this curve appears to have a maximum at about four radians per second. For low-frequency short-period responses, the aircraft is sluggish and the tolerable delay is small; for high-frequency responses (above four radians per second), the aircraft is too sensitive to allow long delays. Apparently about four radians per second is an optimal short-period roll-off point for control in the presence of a delay. Since the choice of a 10 percent increase-of-error criterion was arbitrary, it is the form of this function that is important, not the absolute amounts of time delay allowable. Second, for those short-period frequencies where several data points were available (representing different amounts of damping), there is a reversal of their order as the four radians per second point is passed. Below that point, simulations involving more responsive, less damped longitudinal axis responses can tolerate longer delays than can the more damped conditions. This trend seems to reverse above four radians per second, as there the added responsiveness of a small short-period damping ratio only adds to the pilot's control problem and only shorter delays can be tolerated. Presumably if iso-error curves could be plotted over short-period frequencies for different damping ratios, the curves for the less damped conditions would have their maxima at lower frequencies than the ones for the more heavily damped conditions. These findings should be explored as it would allow aircraft parameters to be related to total system delays for acceptable levels of control error.

Clearly aircraft dynamics and piloting control are complicated, and the specification of an allowable delay is dependent upon parameters of the airframe being simulated as well as on the pilot's skill. In the face of the paucity of data that would allow us to trade-off system cost vs performance, some decision must be made, and informal opinion, for instance, has it that simulation system delays should not exceed phase lags of 30° to 45° at one Hertz (83 to 125 milliseconds). Evidence that the maximal acceptable time delay is within this range can be found in several of the reports annotated in Appendix A.

SIGNAL SPECTRUM LIMITS

A related approach is to compensate systems for the presence of display delays by changing the driving software to take the delay's presence into account. Much like the idea of a predictor display (Smith and Kennedy, 1976), the problem here is to predict over the short time intervals involved in the computer processing of visual scenes without adding significantly to the total processing time. This approach first started as attempts to adjust motion base drive signals for actuator lags, and Parrish, Dieudonne, Martin, and Copeland (1973) used a simple linear projection of aircraft rotational axis values to compensate their actuator. Ashworth and Parrish (1976) then followed this development by designing a filter to compensate for nonlinearities in the Langley simulator's washout of motion cues.

Attempts to compensate for CGI system delays started with O'Conner, Shinn, and Bunker's (1973) description of software changes to reduce the roll-axis sensitivity of Device 2F90. Various aileron-response-to-stick-deflection relations were tried without much success, and finally a dead-band about the centered position of the control stick was chosen as a temporary adjustment. When the ASPT simulator became operational, Larson and Terry (1975) described the use of Taylor's series to predict aircraft position values either one half or one iteration of the dynamics processor and CGI system. Later the compensation scheme developed for the ASPT was a second-order Adams integration using a variable integration interval

(Gum and Albery, 1976). At first this was coupled to the Taylor series extrapolation, but the CGI system still displayed an objectional lack of smoothness, leading to the present use of just the Adams integration technique.

At the Naval Training Equipment Center, Ricard, Norman, and Collyer (1976) have reduced the noise inherent in prediction schemes by adding a single-pole Butterworth filter after the prediction sequence but before the pilot's display. Their experiments indicated that setting that filter's break point just above one half Hertz (four to five radians per second) was optimal for the reduction of tracking error. Hopefully, this technique will allow for the compensation of transport delays across different simulators, by preventing high-frequency noise in the control system's feedback signal from reaching the visual display. The technique has been extended by Cyrus (1977) who integrated this filter and ASPT's Adams integration into a general technique for compensating for CGI system delays, and this development is currently under test.

SECTION III

SUMMARY

An ever-present danger for the design of aircraft simulators is the tendency to focus on hardware requirements. Most often, human controllers dynamically interact with the machines they control, and the timeliness of responses, on the part of both the man and the machine, can affect the quality of that interaction.

A lack of appreciation of the importance of time delays can produce simulators poorly suited for training. The need exists to define more precisely the limits for time delays, especially for flight simulators, as these limits can affect the design of visual displays, of motion bases (including seat cushion dynamics), or of any sensor display that requires dynamic interaction of crew members with the system. Limits for time delays not only have a significant impact on operator performance, but on requirements for computer size and iteration rate as well. This paper presented data that should help equipment designers, especially those working with visual displays, to take into account likely performance of the human being who will operate or be trained by a machine.

REFERENCES

Ashworth, B. R. and Parrish, R. V. A visual motion simulator for general aviation compensated within the nonlinear adaptive washout for actuator lag. Proceedings of AIAA Visual and Motion Simulation Conference. Dayton, Ohio, 1976.

Beil, W. C. and Warrick, M. J. Studies in perception of time delay. American Psychologist, 1949, 4, 303.

Birmingham, H. P. and Taylor, F. V. "A design philosophy for man-machine control systems." In Sinaiko, H. W. (Ed.) Selected Papers on Human Factors in the Design and Use of Control Systems. New York: Dover Publications, Inc., 1961.

Boring, E. G. A History of Experimental Psychology. New York: The Century Company, 1929.

Chalk, C. R. and Wasserman, R. An assessment of the role of simulators in military tactical flight training. Calspan Technical Report AK-5970-F-1, Calspan Corporation, Buffalo, New York, September, 1976.

Conklin, J. E. Effect of control lag on performance in a tracking task. Journal of Experimental Psychology, 1957, 53, 261-268.

Cooper, F. R., Harris, W. T., and Sharkey, V. J. The effect of delay in the presentation of visual information on pilot performance. Technical Report NAVTRAEQUIPCEN IH-250, Naval Training Equipment Center, Orlando, December, 1975.

Cooper, G. E. and Harper, R. P. The use of pilot rating in the evaluation of aircraft handling qualities. Technical Note TN D-5153, NASA Ames Research Center, April, 1969.

Cyrus, M. A general method for compensating transport lags in computer image generation visual displays for flight simulators. Air Force Human Resources Laboratory Flying Training Division Technical Report AFHRL-TR-77-6 (In preparation).

Frost, G. "Man-machine dynamics." In VanCott, H. P. and Kinkade, R. G. (Eds.) Human Engineering Guide to Equipment Design. U.S. Government Printing Office, Washington, DC 1972.

Garvey, W. D., Sweeney, J. S., and Birmingham, H. P. Differential effects of "display lags" and "control lags" on the performance of manual tracking systems. Journal of Experimental Psychology, 1958, 56, 8-10.

Gopher, D. and Wickins, C. Strategies and attention allocation in dual-task performance. Aviation Research Laboratory Technical Report ARL-76-2, University of Illinois at Urbana-Champaign, January, 1976.

Gum, D. R. and Albery, W. B. Integration of an advanced CGI visual and simulator system. Proceedings of AIAA Visual and Motion Simulation Conference, Dayton, Ohio, April, 1976.

Harris, W. T. Device 2F90 flying qualities and performance evaluation and discrepancy correction. Technical Report NAVTRAEQUIPCEN IH-245, Naval Training Equipment Center, Orlando, September, 1975.

Healy, L. D. and Cooper, F. R. Verification of simulator performance by frequency response measurement. Proceedings of the 6th NTEC/Industry Conference. NAVTRAEQUIPCEN IH-226, November, 1973.

Heffley, R. K. and Jewell, W. F. Aircraft handling qualities data. Systems Technology Inc. Technical Report 1004-1, Hawthorne, CA, May, 1972.

Larson, D. F. and Terry, C. ASUPT visual Integration technical report. Singer-Simulation Products Division Technical Report ASUPT-82, Binghamton, March, 1975.

Leslie, J. M. Effects of time delay in the visual feedback loop of a man-machine system. NASA Technical Report CR-560, 1966.

Levine, M. Tracking performance as a function of exponential delay between control and display. Wright Air Development Center Technical Report 53-236. Wright-Patterson Air Force Base, Ohio, October, 1953a.

Levine, M. Transfer of tracking performance as a function of delay between the control and display. Wright Air Development Center Technical Report 53-237, Wright-Patterson Air Force Base, Ohio, November, 1953b.

Levine, M., Senders, J. W., Morgan, R. L., and Doxtater, L. Tracking performance as a function of exponential delay and learning. Aerospace Medical Research Laboratory Technical Report AMRL-TR-64-104. Wright-Patterson Air Force Base, Ohio, November, 1964.

McDonnell, J. D. Pilot rating techniques for the estimation and evaluation of handling qualities. Air Force Flight Dynamics Laboratory Technical Report AFDDL-TR-68-76. Wright-Patterson Air Force Base, Ohio, December, 1968.

McRuer, D. T., Graham, D., Krendel, E., and Reisener, Jr., W. Human pilot dynamics in compensatory systems. Air Force Flight Dynamics Laboratory Technical Report AFFDL-TR-65-15. Wright-Patterson Air Force Base, Ohio, July, 1965.

McRuer, D. T. and Jex, H. R. A review of quasi-linear pilot models. Institute of Electrical and Electronic Engineers Transactions on Human Factors in Electronics, 1967, 8, 231-249.

McRuer, D. T. and Krendel, E. S. Mathematical models of human pilot behavior. AGARDograph AG-188, January 1974.

Miller, Jr., G. K. and Riley, D. R. The effect of visual-motion time delays on pilot performance in a pursuit tracking task. Proceedings of the AIAA Visual and Motion Simulation Conference, Dayton, Ohio, 1976.

Miller, Jr., G. K. and Riley, D. R. Effect of visual motion time delay on pilot performance in a simulated pursuit tracking task, Technical Note TN D-8364, NASA Langley Research Center, January, 1977.

Muckler, F. A. and Obermayer, R. W. Control system lags and man-machine system performance. NASA Contractor Report NASA CR-83. July 1964.

Naval Air Test Center. Flight fidelity evaluation of the S-3A weapon systems trainer, device 2F92, with the VITAL III visual system, device 2B34A; Fourth and final report. Naval Air Test Center Report of Test Results, July, 1976.

O'Conner, F. E., Shinn, B. J., and Bunker, W. M. Prospects, problems, and performance. A case study of the first pilot trainer using CGI visuals. Proceedings of the 6th NTEC/ Industry Conference, NAVTRAEQUIPCEN IH-226, November, 1973.

Parrish, R. V., Dieudonne, J. E., Martin, Jr., D. J., and Copeland, J. L. Compensation based on linearized analysis for a six-degree-of-freedom motion simulator. Technical Note TN D-7349, NASA Langley Research center, November, 1973.

Pew, R. W. "Human perceptual-motor performance." In Kantowitz, B. H. (Ed.) Human Information Processing: Tutorials in Performance and Cognition, Hillsdale, N. J.; Lawrence Earlbaum Associates, 1974.

Poulton, E. C. "Tracking." In Bilodeau, E. A. and Bilodeau, I. M. (Eds.) Principles of Skill Acquisition. New York: Academic Press, 1969.

Queijo, M. J. and Riley, D. R. Fixed-base simulator study of the effect of time delays in visual cues on pilot tracking performance. Technical Note TN D-8001, NASA Langley Research Center, October, 1975.

Ricard, G. L., Norman, D. A., and Collyer, S. C. Compensating for flight simulator CGI system delays. Proceedings of the 9th NTEC/Industry Conference, NAVTRAEQUIPCEN IH-276, November, 1976.

Rockway, M. R. The effect of variations in control-display and exponential time delay on tracking performance. Wright Air Development Center Technical Report 54-618, Wright-Patterson Air Force Base, Ohio, December, 1954.

Senders, J. W. and Levine, M. Further analysis of tracking performance as a function of exponential delay. Wright Air Development Center Technical Report 53-413, Wright-Patterson Air Force Base, Ohio, December, 1953.

Smith, K. U. and Kaplan, R. Effects of visual feedback delay on simulated automobile steering. Journal of Motor Behavior, 1970, 2, 25-36.

Smith, R. L. and Kennedy, R. S. Predictor displays: A human engineering technology in search of a manual control problem. Pacific Missile Test Center Technical Publication TP-76-05. Point Mugu, CA, June, 1976.

Teper, G. L. Aircraft stability and control data. Systems Technology Inc. Technical Report 176-1, Hawthorne, CA, April, 1969.

Warrick, M. J. Effect of transmission-type control lags on tracking accuracy. USAF Technical Report 5916, Wright-Patterson Air Force Base, Ohio, September, 1949.

Warrick, M. J. Effect of exponential-type control lags on the speed and accuracy of positioning a visual indicator. Wright Air Development Center Technical Note 55-348, Wright-Patterson Air Force Base, Ohio, June, 1955.

Weener, E. F. The effect of simultor dynamics on pilot response. NASA Contractor Report CR-132459, October, 1974.

Wickins, C. D. The effects of divided attention on information processing in manual tracking. Journal of Experimental Psychology: Human Perception and Performance. 1976, 2, 1-13.

Young, L. R. "Human Control Capabilities." In Parker, Jr., J. F. and West, V. R. (Eds.) Bioastronautics Data Book. U.S. Government Printing Office, Washington, DC 1973.

APPENDIX A

Several of the more useful references of this note have been annotated to give the reader the flavor of the work. Some of them are grouped according to the simulation facility or type of apparatus and procedures used in the study, and occasionally important observations are underlined.

Reference	Cooper, Harris, and Sharkey (1975)
Delay	100 milliseconds
Task	Subjects "flew" carrier approaches with and without a delay inserted before the visual scene. In the first experiment, the number of trials needed to complete three successive arrestments was measured. In experiment 2, pilot control inputs were recorded and their spectra compared for the delay and no-delay conditions.
Apparatus	The Naval Training Equipment Center's TRADEC F-4 flight simulator was used. It is equipped with a four degree-of-freedom motion base and is driven by a Xerox Data System Sigma 7 computer. An Evans and Southerland line drawing system cathode ray tube formed the pilots' 19° by 19° field-of-view display.
Comments	No differences were seen in the mean number of trials needed to reach criterion, but the pilots exercised their skills differently under delayed conditions. Their lateral axis control inputs differed significantly for the delayed and non-delayed presentations.

References	Larson and Terry (1975), Gum and Albery (1976), and Cyrus (1977).
Delay	ASPT visual system delay ranges from 126 to 193 milliseconds.
Task	A wide variety of tasks are flyable in the ASPT, but the greatest control problems related to display delays are seen during formation flying.
Apparatus	The Advanced Simulator for Pilot Training at Williams AFB. A General Electric computer image generation system drives seven cathode ray tubes equipped with infinity optics for each of two T-37B cockpits, and both simulators have G-seats and six degree-of-freedom synergistic motion bases.

Comments	Attempts to compensate the delay significantly improve the pilots' ability to perform formation flying in the simulator. Pilots preferred to have the display delay minimized as much as possible, and much of this work has been aimed at removing the "jitter or flutter" from the displays. The greatest impact of the transport delay was on the control of the aircraft's roll angle. Currently the ASPT displays are being smoothed by an Adams integration technique followed by a first-order, low-pass filter.

- -

References	Queijo and Riley (1975), Miller and Riley (1976), and Miller and Riley (1977).
Delays	Delays of 47 to 547 milliseconds in increments of 31 milliseconds were used.
Task	Subjects pursued a target aircraft that was performing sinusoidal oscillations of altitude, and a side task was used to maintain a constant workload for the pilot.
Apparatus	The NASA Langley Research Center Visual-Motion simulator with a six degree-of-freedom motion base and closed-circuit television display was employed. For some studies, the motion base was inactive. Lateral axis handling qualities were kept constant, and 17 combinations of short-period and damping were chosen to vary the aircraft longitudinal axis handling qualities.
Comments	Either increasing the task complexity or degrading the aircraft handling qualities reduced the acceptable display delay. Adding relatively complete motion cues extended the delay that could be tolerated for a given aircraft configuration. Usually longer delays could be tolerated for configurations receiving better pilot ratings.

- -

Reference	Ricard, Norman, and Collyer (1976).
Delays	Delays of 17.5 to 1400 milliseconds in multiples of 50 milliseconds were included.
Task	Subjects controlled an artificial horizon display where two sets of aircraft dynamics could be inserted. The task was straight-and-level flight in the face of mild turbulence.

Apparatus	An oscilloscope configured to represent an artificial horizon formed a compensatory tracking display, and subjects entered their control inputs via a two-axis, spring-centered, side-arm control stick. System controllability was assessed with trained operators, and training effects were measured with naive subjects.
Comments	Almost no differences were seen between delay and no-delay conditions for the control of aircraft pitch angle, but roll-axis control became progressively worse as the display delay lengthened. Good control was harder for the higher-performance aircraft, and large and consistent individual differences of performance were obtained. Roll errors and control stick deflections tended to increase when the delay exceeded 100 milliseconds.

* * *

Reference	Warrick (1949).
Delays	Delays of 0 to 320 milliseconds were used.
Task	Subjects maintained a fixed position for a pointer by rotating a control knob.
Apparatus	An indicator consisting of a DC recording oscillograph wired to a Wheatstone bridge produced an inked trace whose position the subject controlled. The subject's control knob served as one arm of the bridge and could be used to null voltage changes in the other arm. Disturbances of 6 and 30 Hz were used, and display delays were introduced by covering the pen and the paper immediately drawn upon. Scoring was accomplished by an electric clock driven by a relay closed by zero voltage across the bridge.
Comments	Lags as short as 40 milliseconds could affect performance, although for a single 6 Hz sine wave input, little deterioration in control was found with a delay of 80 milliseconds. Generally, for transport delays, a linear deterioration of control performance was found as delay increased.

* * *

References	Levine (1953a,b), Senders and Levine (1953), Warrick (1955), and Levine, Senders, Morgan, and Doxtater (1964).
Delays	Exponential lags ranging from 0 to 3000 milliseconds were used.

Tasks	These studies used compensatory tracking tasks; most often this meant centering a blip on an oscilloscope face, but for one study, the indicator of a D-C meter was the target. Usually the subject was provided a rotory control knob to control the cursor's movement.
Apparatus	The D-C meter indicator or oscilloscope blip was driven by sine wave voltage changes produced by rotating cams. Voltage from the subject's control was used to null the disturbance and keep the pointer centered. Different control/display ratios were used over these studies, and the usual measure of performance was the time that the indicator was within a tolerance.
Comments	The Levine papers report linear decreases of time on target as the delay lengthened, but they fit their data with two line segments. For delays less than 150 milliseconds, the slope of the fitted segment was much greater than for the longer delays. Warrick found a similar appearing relation and expressed it as a negative exponential function.

GLOSSARY

Here we have defined many of the technical terms used in this note and in the literature of piloting control. Often we avoided the rigor of a technical definition in favor of more informal information; hopefully this will increase the note's usefulness.

ACCELERATION CONTROL SYSTEM - Control system with dynamics such that a displacement of the input produces a proportional change of the acceleration of the system output. In Laplace notation, such dynamics are represented as a gain (K) and two integrations $(1/s \cdot 1/s)$ or K/s^2.

ADAMS INTEGRATION - The integration scheme most widely used in flight simulation. Only a function's value and first derivative are needed, and the digital computation of a new value is fast, requiring only two additions, one multiplication, and one right shift.

AIDING - A technique of feed-forward system compensation where derivatives of the system output are added to that output to force the system to be more responsive.

ATTENUATION RATE - The rate at which a filter attenuates according to frequency. If a test signal of frequency (f) is passed through a filter with a -6 dB/octave attenuation rate, the signal amplitude at frequency (2f) would be reduced by 6 dB relative to its amplitude at (f).

BODE PLOT - A figure depicting, across frequency, the amplitude ratios and phase relations of the output of a system relative to its input. A straight-line approximation to the amplitude and phase plots is often used to determine the system's transfer function.

BREAK FREQUENCY - The frequency at which a filter changes its rate of attenuation.

CONTROL ORDER - The highest power of the Laplace operator (s) that appears in the denominator of a system's transfer function.

COMPENSATORY DISPLAY - A display with a movable indicator and a reference point for that indicator. The difference between system output and input (error) forms the signal for the movable element, and the operator uses the display to null that signal.

COMPUTER GENERATED IMAGERY SYSTEM - A system for presenting digitally greated visual scenes. Usually a three dimensional model is reduced into its component edges that form vectors in a defined space. The model is then transformed into a true perspective picture for a given point of view. Movement can be created by changing either the position of sets of vectors or the point of view. Both require recomputation of the true perspective image.

CROSSOVER FREQUENCY - The frequency at which the open-loop amplitude ratio is unity, i.e., at which the system's output crosses over from greater-than to less-than unity gain.

CROSSOVER REGION - The spectral region of the crossover point. For systems with aircraft dynamics, this is usually the region between two and six radians per second.

DAMPING RATIO - For a second-order system, it is the ratio of the present system damping to a "critical" value. Damping ratios from 1.0 to 0 provide systems that are increasingly unstable, and values above 1.0 produce systems that are more and more sluggish. Critical damping (damping ratio = 1.0) just allows the system to respond to an input without overshooting its final value.

EFFECTIVE TIME DELAY - A measure of the delay associated with a pilot's control inputs. It is a measurement that could be regarded as the sum of his transport delay and what lead/lag adjustments the pilot can make.

FILTER - A device that attenuates components of a time series according to frequency. The rate of attenuation changes at the break or natural frequency of the filter, with attenuation increasing with frequency above the break for low-pass filters and decreasing for high-pass filters. These elements can be combined to produce band-pass filters, with attenuation increasing on both sides of a spectral band, or a band-reject filter with attenuation increasing within a band. The rate of attenuation increases with the order of the filter, with perhaps the commonest configuration - a Butterworth filter - producing -6 dB/octave attenuation and a -90° phase lag for each integration the filter performs.

FIRST-ORDER LAG - The phase lag created by passing a signal through a first-order filter. This is probably the commonest sort of delay in electronic equipment where the response to a step input is a simple exponential curve.

FORCING FUNCTION - An external disturbance applied to a system, usually requiring action on the part of the operator. For simulations of flying, this could be a random disturbance designed to mimic atmospheric turbulence or an indication of the flight path required of the aircraft.

FREQUENCY - Cycles per unit of time of a periodic waveform, measured as radians per second or cycles per second (Hz).

GAIN CROSSOVER REGRESSION - The controller's lowering of the system crossover frequency (regressing to a lower crossover point), usually seen as a technique for maintaining system stability.

HANDLING QUALITIES RATINGS - Ratings of the flying qualities of aircraft usually obtained from pilots. These ratings are a function of several parameters of the airframe, but can usually be interpreted as a measure of how easy it is to fly a given aircraft. Cooper-Harper ratings form a 10-point scale from a rating of 1 for an excellent, undemanding aircraft, to a rating of 10 for an unflyable one.

INDIFFERENCE THRESHOLD - A threshold for control action below which the displayed error is ignored. In pilot modeling theory, it is used to indicate that small components of displayed signal are often not responded to.

L_α - The nondimensional value of CL_α, the rate of change of aircraft lift with angle of attack.

PHASE LAG/LEAD - For systems subjected to cyclic inputs, the temporal relation of output to input can be expressed as a phase angle. If the corresponding portion of the output waveform appears later than the input, it is a phase lag; the reverse is a phase lead.

PHASE MARGIN - The difference between the phase angle of the crossover frequency and -180°. For controllable systems, the phase angle of the crossover frequency falls short of -180°, and the magnitude of this difference is a measure of the relative stability of the system. Most process control systems would be acceptable with a 30° phase margin, but the system would be easier to control with a larger margin. A system with a 0° phase margin, for instance, would oscillate continuously.

PILOT INDUCED OSCILLATIONS - Oscillations often seen in the aircraft roll angle, but occasionally in the pitch angle, that are produced by the pilot's input lagging the state of the aircraft. These are seen in simulators where there is a significant delay in the presentation of visual information.

PHUGOID FREQUENCY - A long-period aircraft pitch angle oscillation on the order of one cycle per minute.

POWER OR AMPLITUDE SPECTRUM - The function relating power or amplitude per unit frequency for the components of a time-varying signal. It gives the relative concentration of energy in the signal, and can be used to estimate the order and break frequency of a system through which the signal has been passed.

PREDICTIVE OR PREDICTOR DISPLAY - Such a display shows a future state of a system given its present state and inputs. This is usually accomplished by having a model of a system operating parallel to the real system.

PURSUIT DISPLAY - A display with two movable elements, one driven by the forcing function and one driven by the system output. The positions of the indicators give the values for the input and output functions, and the difference between them is the error. A slight advantage is gained by using such a display as the operator can observe the input waveform.

QUICKENING - A technique of feedback compensation for a control system where the derivatives of the signal sent to the system's display are added to the displayed signal. The machine's dynamics are not changed, only the display's.

RATE CONTROL SYSTEM - Control system dynamics where a displacement of the input produces a proportional change of the rate of change of the system output. The Laplace representation of this would be a gain (K) times an integration (1/s) or K/s.

REACTION TIME - The time required to respond - often measured to the beginning of an overt response, but sometimes includes the response execution time. Reaction time measurements can represent the simple time to react, to make a choice, or to perform a recognition.

SECOND-ORDER LAG - The phase lag created by passing a signal through a second-order filter. Such a system responds to a step input with an S-shaped, sigmoid response.

SHORT-PERIOD - An aircraft pitch angle oscillation on the order of one cycle per second.

STEP INPUT - A common signal waveform used to evaluate the response characteristics of systems. The waveform consists of an instantaneous change of input amplitude created at a given time. Another signal used for analytic purposes, for instance, is a sinusoid.

TAYLOR SERIES - An infinite series that can be fit to continuous functions. If the value of a function f(t) is known at (t), Taylor's series can be used to calculate the function's value at (t+h). Higher order derivatives are used to weigh successive terms in the series, so that usually the first three terms (the value of f(t) and the first two derivatives) are used to approximate f(t+h).

TIME CONSTANT - The time required after a step input for a first-order system to reach 63 percent of its steady state value. The reciprocal of the time constant would be the break frequency for an equivalent filter.

TRANSPORT, TRANSMISSION, OR DEAD-TIME DELAY - A delay between the input to a system and the appearance of its output where the output waveform is delayed a fixed time interval. This form of delay is created by the time taken to transmit signals vast distances or the processing time needed to create signals.

TRANSFER FUNCTION - The ratio of output to input for a system, generally expressed in terms of the complex Laplace operator (s). Terms in the numerator (s) differentiate (provide lead) and denominator terms (1/s) integrate (provide lag). A free (s) acts as a pure integration or differentiation, otherwise a term acts as a filter.

ABBREVIATIONS AND SYMBOLS

ASPT	Advanced Simulator for Pilot Training
CGI	Computer Generated Imagery
CL_α	Dimensional valve of the lift curve slope
dB	Decibel - a logarithmic scale of power ratios.
h	Integration or sampling interval
Hz	Hertz - the unit of cycles per second
K_B	Best gain (K) for a given set of system dynamics (from McDonnell, 1968).
L_α	Nondimensional valve for the lift curve slope
s	Complex Laplace operator
t	Time
τ	Time constant
W_i	Bandwidth of the system disturbance input
x,y,z	Axis system to locate aircraft in space, usually with reference to the earth.
Y_c	Transfer function of the controlled element (system plus display).

HUMAN FACTORS DISTRIBUTION LIST

NOTE

Mailing labels are prepared, when needed, as a computer listing, the source of which is updated on a weekly basis. It is not practical to prepare distribution lists each time labels are prepared. Therefore such lists are prepared semiannually, and a slight discrepancy may exist between the addressees on this list and those appearing on the labels used to distribute this publication.

HUMRRO Central Division, Suite 400 Plaza Bldg, Pace Blvd at Fairfield,
Pensacola, FL 32505

USA Aeo Medical Research Lab, ATTN: Dr M. A. Hofman, P O Box
577, Ft Rucker, AL 36360

Director Human Engineering Lab, USA Aberdeen Research Development
Center, ATTN: Dr John W. Weisz, Aberdeen Proving Grounds, MD
21005

HQ, USA Training and Doctrine Command, ATTNG-CTS, Ft Monmouth,
NJ 07703

Commandant, USA Field Artillary School, Target Acquisition Dept, ATTN:
Eugene C. Rogers, Ft Sill, OK 73503

Director Human Relations Research Organization, 300 N Washington St,
Alexandria, VA 22314

Human Relations Research Organization, Division No. 1, Systems Operation,
300 N Washington St., Alexandria, VA 22314

USA Research Institute Behavior, Social Sciences, 1300 Wilson Blvd,
Arlington, VA 22209

Chief Research Office, Office Deputy Chief of Staff for Personnel, Dept
of Army, Washington, DC 20310

Asst Secretary Navy, R-D, Dept of Navy, ATTN: Dr S. Koslov 4E741,
Washington, DC 20350

Chief Naval Research, Code 458, Dept of Navy, Arlington, VA 22217

HUMAN FACTORS DISTRIBUTION LIST (CONT)

Chief Naval Research, Psychological Sciences, Code 450, Dept of Navy,
Arlington, VA 22217

Chief Naval Operations, OP-991B, Dept of Navy, ATTN: M. K. Malehorn,
Washington, DC 20350

Chief Naval Operations, OP-987P10, Dept of Navy, ATTN: Dr R. G. Smith,
Washington, DC 20350

Chief Naval Operations, OP-987P7, Dept of Navy, ATTN: CAPT H. J.
Connery, Washington, DC 20350

Chief Naval Material, MAT 031M, Washington, DC 20360

Chief Naval Material, 0344, C P 5, Room 1044, Dept of Navy, ATTN:
Arnold I. Rubinstein, Washington, DC 20360

Bureau Naval Personnel, ATTN: PERS-OR Arlington Annex, Washington,
DC 20370

Commandant of Marine Corps, Code AO3C, Washington, DC 20380

Library, Navy Personnel Research & Development Center, San Diego,
CA 92152

ERIC Clearinghouse on Educational Media (Technical), Stanford University,
Stanford, CA 94305

Grumman Aerospace Corp, Plant 47, ATTN: Mr Sam Campbell, Bethpage,
LI, NY 11714

Texas Technical University, Psychology Dept, Box 4100, ATTN: Dr
Charles Holcomb, Lubbock, TX 79409

American Psychology Association, Psychology Abstracts, Executive Editor,
1200 17th St NW, Washington, DC 20036

CO, Navy Submarine Base New London, ATTN: Psychology Section, Box
00, Groton, CT 06340

Scientific Technical Information Office, NASA, Washington, DC 20546

Director, Defense Research and Engineering, ATTN: LCOL H. Taylor, OAD
E&LS, Washington, D.C. 20301

HUMAN FACTORS DISTRIBUTION LIST (CONT)

Naval Aerospace Medical Institute, NAVAEROSPREGMEDCEN, ATTN:
Chief Aviation Psychology Division, Pensacola, FL 32512

CO, Naval Health Research Center, San Diego, CA 92152

Commander, Naval Air Systems Command, Code 03, Washington, DC 20361

Commander, Naval Sea Systems Command 047C12, ATTN: CDR George
N. Graine, Washington, DC 20362

Commander, Naval Electronic Systems Command, Code 03, Washington,
DC 20360

Commander, Naval Supply Systems Command, Code 03, Washington,
DC 20376

Commander, Naval Sea Systems Command, Code 03, Washington, DC 20360

Commander, Naval Air Development Center, ATTN: Human Engineering
Branch, Warminster, PA 18974

Human Factors Engineering Division, NAVAIRDEVCEN, Code 4024, ATTN:
LCDR Charles Theisen, Warminster, PA 18974

CO, PAC MISS TEST CTR, ATTN: Hd Human Factors, Engineering Branch,
Pt Mugu, CA 93042

Chief Naval Reserve, Code 02, New Orleans, LA 70146

Chief Naval Education and Training, Code N-5, ATTN: B. C. Stone,
NAS, Pensacola, FL 32508

Chief Naval Education and Training, Code 00A, ATTN: Dr W. Maloy,
NAS, Pensacola, FL 32508

CO, Naval Technical Training, ATTN: Code 016, NAS Memphis,
Millington, TN 38054

Chief Naval Air Training, ATTN: J. L. Ulatoski, NAS, Corpus Christi,
TX 78419

HUMAN FACTORS DISTRIBUTION LIST (CONT)

Chief Naval Technical Training, Code 34, ATTN: Dr Harding, NAS
Memphis 75, Millington, TN 38054

CO, NAVED TRAINSUPPCENPAC, Fleet Station PO Bldg, Code N, ATTN:
Mr. Rothenberg, San Diego, CA 92132

Chief Naval Education and Training Support, Code N-2, Bldg 45, ATTN:
Dr Charles Havens, NAS, Pensacola, FL 32509

Chief Naval Education and Training Support, Code N-241, NAS, Pensacola,
FL 32509

US Air Force Human Resources Lab, AFHRL-AS, Advance Systems Division,
Wright-Patterson AFB, OH 45433

US Air Force Human Resources Lab, AFHRL/OR Occupational Manpower
Relations Division, Lackland AFB, TX 78236

US Air Force Human Resources Lab, AFHRL/SM Computational Sciences
Division, Lackland AFB, TX 78235

HQ, Air Training Command, XPT, ATTN: Dr John Meyer, Randolph AFB,
TX 78148

US Air Force Human Resources Lab/DOJZ, Brooks AFB, TX 78235

Chief, Institute Technical Division, ADC DOTI, ATTN: Mr R. E. Coward,
Ent AFB, CO 80912

HQ, US Air Force Systems Command, DLSL, Office Scientific Research,
Andrews AFB, Washington, DC 20331

US Air Force Human Resources Lab, AFHRL-TT, Technical Training
Division, Lowry AFB, CO 80230

US Air Force Human Resources Lab, AFHRL-FT, Flying Training Division,
Williams AFB, AZ 85224

ASD SMSE, ATTN: Mr Harold Kottmann, Wright-Patterson AFB, OH
45433

ENET, ATTN: Mr Arthur Doty, Wright-Patterson AFB, Dayton, OH 45433

HUMAN FACTORS DISTRIBUTION LIST (CONT)

Commander, Navy Air Force, US Pacific Fleet, NAS North Island, San
Diego, CA 92135

Commander, Training Command, ATTN: Educational Advisor, US Pacific
Fleet, San Diego, CA 92147

Commander, Training Command, ATTN: Educational Advisor, US
Atlantic Fleet, Norfolk, VA 23511

USAF Human Relations Lab, Personnel Research Division, Lackland AFB,
TX 78236

Chief, ARI Field Unit, P. O. Box 2086, Fort Benning, GA 31905

Chief, ARI Field Unit, P. O. Box 476, Fort Rucker, AL 36360

HQ, Fort Belvoir Medical Dept Activity HSA-CHC (Project PACOMED),
Fort Belvoir, VA 22060.

Chief, Naval Education & Training Liaison Office, AF Human Resources
Laboratory, Flying Training Div, Williams AFB, AZ 85224

Chief of Naval Operations (OP-596), Navy Department, Washington, DC
20350

Commander, Naval Air Systems Command, Naval Air Systems Command
Headquarters, (AIR 413), Washington, DC 20361

Commander, Naval Air Systems Command, Naval Air Systems Command
Headquarters, (AIR 340F), Washington, DC 20361

OTHER DISTRIBUTION

Defense Documentation Center Cameron Station Alexandria, Virginia 22314	12
Naval Training Equipment Center	51
Dr. John K. Lauber Mail Stop #239-3 NASA Ames Research Center Moffet Field, CA 94035	1
Mr. Donald R. Riley NASA Langley Research Center Hampton, VA 23665	1