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Lead/Lag Dynamics to Compensate for Display Delays

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Problems of control produced by delays in flight simulators are reviewed and related data that were available from an earlier experiment are analyzed. That study used a lead/lag transfer function to compensate for delays inserted into a closed-loop system, and pilot control performance was measured using various amounts of lag for a given setting of lead. Those data indicated that—based upon the changes of phase and gain associated with subjects' best control performance—an optimal ratio of lead to lag could be determined. Best performance was produced by a maximum phase lead of approximately 0.08 deg per 1 ms of delay for total system delays greater than 175 ms.

Nomenclature

G_{cc} = roll-to-pitch cross coupling
h = integration interval
K, L = scaling constants
S = Laplace transform
X_n = particular value of a time series
X'_n = first derivative of X_n
ϕ = roll angle
θ = pitch angle
τ_n = high-pass filter time constant
τ_d = low-pass filter time constant
δ_e = elevator stick input
γ_a = aileron stick input

Introduction

SOME of the techniques used to create simulations of flight can negatively affect the performance of the pilot using the simulator. A case in point is the production of delays in flight simulation systems by the vast number of calculations needed to simulate the aerodynamic responses of an aircraft, to collect and display data for the control of flight instruction, and to provide computer-generated images for visual display systems. These are transport-type delays created by the simulation program's iterative calculations of aircraft parameters and the use of that information for further calculations necessary to drive displays. As the requirements of training or research dictate an increase of the number of edges in a computer-generated image, or the addition of computer-generated simulations of sensors such as low-light level TV or forward-looking infrared, all other things being equal, the time between pilot control input and system response will increase. Poorer pilot control performance results. Several papers exist that review the manual control of systems with delayed feedback[1-3] and an appreciation of the importance of timing problems in flight simulators can be found in Gum and Albery.[4]

Because the position of the simulated aircraft must be known before a computer-produced visual image is recalculated, and because of the fact that for the most part those calculations are serial, there will always be delays in digitally controlled simulations. Important questions for the simulation community are then: How much delay is tolerable for what kinds of flying tasks? Can a maximum tolerable delay be specified for a particular cue-providing system, or axis of control, and how would this delay relate to the type of aircraft being simulated?

When pilots attempt to maintain a constant method of control in the presence of delayed feedback, they are forced to reduce their phase margins. For instance, in the 3-5 rad/s region of the spectrum where the gain vs frequency curve for the pilot-plus-system crosses over from greater to less than unity gain, pilots like to maintain a phase margin of 25-45 deg. Computer generation of images for visual displays presently takes about 100 ms and this time would reduce the pilot's phase margin by 17-28 deg, depending upon the location of the gain crossover point. Human controllers exposed to delayed visual feedback will attempt to generate more of a phase lead for their control inputs and, failing this, will then reduce their crossover frequency and possibly increase their low-frequency gain in order to minimize system error.[5]

How these tendencies relate to flying an aircraft is often not clear. Models of piloting control describe strategies of tracking behavior used by pilots when the display is a compensatory one. Usually a forcing function is used to create error to be nulled, no additional cues are provided, and the task is simply to control a single-loop system. When computer-generated visual displays are added to flight simulators, often no change is seen in the pilot's control of flying tasks such as free flight. It is only when the task requires accurate control of the aircraft that pilot-induced oscillations are seen, usually along the lateral axis, but sometimes along the longitudinal one as well. Traditionally, the requirement of maintaining an orientation or position relative to an external object close to the simulated aircraft has caused pilots to induce oscillations when a significant delay was present. The pilot can clearly see how small responses of his aircraft shift him from an "ideal" position and the system delay prevents him from making the small quick control inputs that would correct the error. Pilot-induced oscillations have been seen during formation flight[6] for instance, and we would expect that they would also be seen in simulations of air-to-air refueling as well.

Some work has related the amount of tolerable delay to the handling qualities of the aircraft being simulated. Using the National Aeronautics and Space Administration Langley Research Center's Visual-Motion Simulator in a fixed-based mode, Queijo and Miller[7] have shown that the delay which could be tolerated was related to the short-period frequency of

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simulated aircraft, and that the more complex the flying task, the shorter was this tolerable delay.

Their flight task was pursuit tracking of an aircraft image that underwent sinusoidal changes of altitude. To increase the complexity of their primary flying task, a side task was added, or the frequency of oscillation of the lead aircraft was increased. Over the ranges of short-period frequencies and dampings used in their study, the maximum delay that seemed to be tolerable without affecting the subjects' flying performance or control style was about 141 ms.

Evidence that additional cues can affect the magnitude of the delay that can be tolerated for a given task was presented by Miller and Riley[8,9] who showed that when the motion platform of the Visual-Motion Simulator was activated, the tolerable delay for a simulation of a given aircraft was extended. Over ranges of short-period frequencies of 1.50-3.00 rad/s and damping ratios of 1.59-0.30, they found that best tracking was associated with a complete set of four degree-of-freedom motion cues (pitch, roll, heave, and sway). When this set was reduced, tracking performance deteriorated and delays had more of an effect on control performance. Their demonstration of the usefulness of motion cues is similar to that of Junker and Price[10] who concluded that motion cues provide additional cueing which enable pilots to generate low-frequency lead.

When delays in a simulation system cause problems of manual control, the usual engineering response is to adjust some of the values that are passed from one subsystem to another. The typical adjustment is to provide some "lead" by adding derivative information back onto a time series, in this case, the one passed from the flight dynamics processor to the computer image generation system. For a function $x=f(t)$, the form of this adjustment has been:

$$X_{n+1} = X_n + h/2\{f(KX'_n, LX'_{n-1})\} \tag{1}$$

Such a rule provides a phase advance to counteract a part of the system delay, but it also amplifies the high-frequency components of the signal being adjusted. For display systems that have wide bandwidths (such as a visual display for computer generated images), the result is an annoying jitter of the image when $f(t)$ contains high-frequency components. Usually such high-frequency excitation of simulation systems comes from pilots of the devices themselves.

Pilots are normally encouraged to control their craft using smooth movements of the controls; however, those flying tasks which require accurate control and quick response to easily perceived error encourage pilots to abandon this tactic for high-frequency "bumpy" movements of the control stick. In such tasks, software delays and the adjustments for them have caused problems.

As a response to this situation, Ricard, Norman, and Collyer[11] added a low-pass filter to a first-order lead to adjust the pitch and roll angles of a simulated aircraft over a prediction span—in their case the duration of a delay. The control system they used is depicted in Fig. 1. They had subjects control an artificial horizon display where a delay

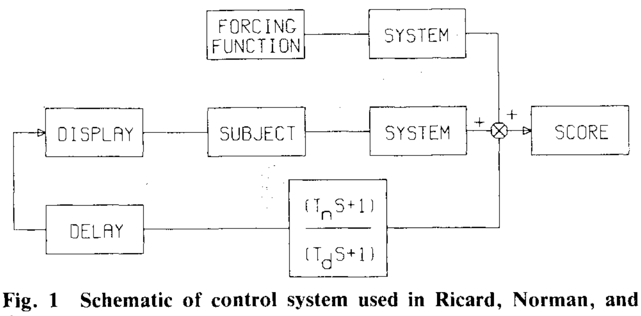

Fig. 1 Schematic of control system used in Ricard, Norman, and Collyer experiment.

could be inserted before the display. Several experiments were performed that either inserted a delay, and then predictor and then the low-pass filter, or examined the acquisition of control skill under a variety of conditions of delay of visual feedback. In this report we will examine the data of their second experiment to make suggestions about the sort of compensation that may aid the manual control of systems containing delays.

Description of Experiment

In their experiment, Ricard, Norman, and Collyer had subjects use a two-axis, side-arm controller to provide inputs for a simulated artificial horizon display. The task was to maintain a straight and level attitude in the presence of mild turbulence. Wideband random numbers were filtered to approximate the spectrum of atmospheric turbulence and these were then passed through the aerodynamic equations before the resulting errors of pitch and roll angle were displayed for the subject to null. An oscilloscope with a 5 in. diameter CRT face was used for the display and subjects were seated so that this subtended a visual angle of 15-20 deg. Thus the task was compensatory tracking with a fairly narrow field-of-view display.

The dynamic responses of their system were those of a light, fixed wing jet flying an altitude of 30,000 ft and an airspeed of 430 knots. They were simulated by having the displayed pitch and roll angles produced by the following equations. The change of pitch angle per deflection of the control stick was given by:

$$\frac{\theta}{\delta_e} = 0.55\,\frac{(102.04S+1)(0.73S+1)}{\left(\dfrac{S^2}{0.004}+\dfrac{0.14S}{0.063}+1\right)\left(\dfrac{S^2}{18.23}+\dfrac{0.99S}{4.27}+1\right)} \tag{2}$$

and changes of roll angle per deflection of the control were produced as:

$$\frac{\phi}{\delta_e} = 5.57\,\frac{\left(\dfrac{S^2}{3.46}+\dfrac{0.48S}{1.86}+1\right)}{S(0.16S+1)\left(\dfrac{S^2}{3.53}+\dfrac{0.48S}{1.88}+1\right)} \tag{3}$$

These values were limited to pitch angles of ± 8 deg and roll angles of ± 45 deg. A cross-coupling of the lateral axis of control to the longitudinal one was simulated by the addition of a downward "gust" of turbulence to the longitudinal axis according to the following:

$$G_{cc} = 0.73\left(1-\frac{1}{\cos\Phi}\right) \tag{4}$$

To assess control performance, quantities that could be accumulated in real time and which were felt to reflect significant aspects of pilots' control activities were measured. These were, for both axes of control, the absolute system error, the size of the deflections of the control stick, and the relative spectral power within the band of 2-6 rad/s where pilots usually cause the gain curve of the system-plus-themselves to crossover.[12] These were sampled at 20 Hz and then integrated and averaged over the length of each trial.

Delays were then inserted into the feedback loop, but before the values of pitch and roll angle were displayed, they were "adjusted" to compensate for the delay. This involved estimating a future value for each variable and then passing this predicted value through a first-order, low-pass filter. Thus the jitter produced by high-frequency control inputs could be attenuated by setting the filter appropriately, and pilots could take advantage of the phase lead being provided without annoying noise.

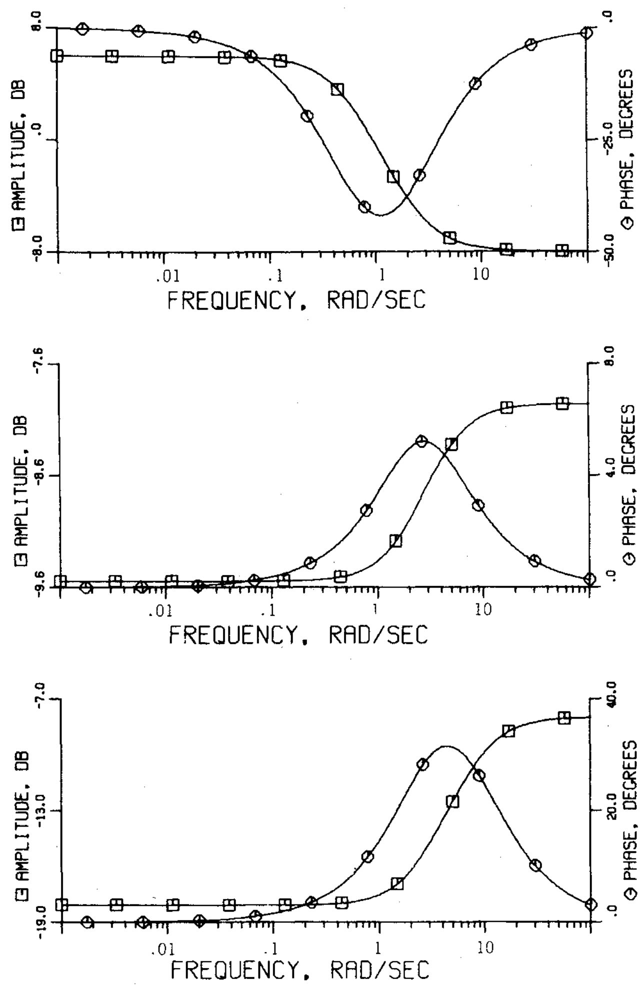

Fig. 2 Bode plots of phase (○) and amplitude (□) changes produced by various settings for the lead/lag transfer function. $\tau_n = 400$ ms, and for a) $1/\tau_d = 0.5$ rad/s; b) $1/\tau_d = 3.0$ rad/s; and c) $1/\tau_d = 8.0$ rad/s. Note the changes of scaling for gain and phase.

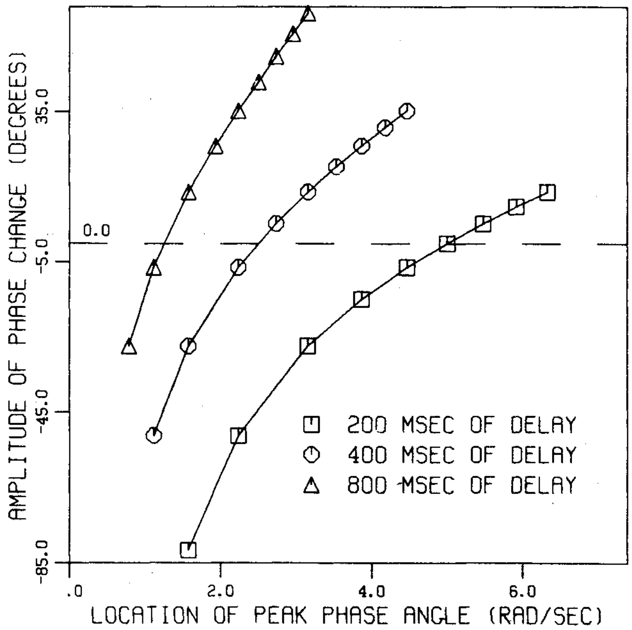

Fig. 3 Maximum changes of phase as function of their location, produced by the conditions of testing used by Ricard, Norman, and Collyer.

Specifically, the adjustment rule was a first-order lead/lag transfer function of the form $(\tau_n S + 1)/(\tau_d S + 1)$ where the ratio τ_n/τ_d determined whether a phase lead or lag was formed. To show how such a transfer function operates, Fig. 2 presents the gain and phase plots for a constant value of τ_n using various break points of the filter $(1/\tau_d)$. For a low-frequency setting of the filter the lead/lag function generates a phase lag with a maximum of 42 deg which is centered at 1.1 rad/s, and for a high-frequency setting, a phase lead of 31 deg is produced that is located at 4.4 rad/s. At an intermediate setting of the filter, lead is balanced by lag, and close to a unitary transfer function can result. The gain plots for these functions indicate the changes of output amplitude that accompany these changes of phase. To indicate the range of conditions of testing of the Ricard, Norman, and Collyer study, Fig. 3 presents the maximum change of phase (either a lead or a lag) as a function of the location of these maxima for the conditions of that experiment. For all conditions of delay, the lowest values of $1/\tau_d$ produced a phase lag that quickly changed into a lead as higher and higher values of $1/\tau_d$ were used. Both the magnitude of this lag and the point where it crossed over to a lead are dependent upon τ_n, the display delay. τ_n was always set to the delay of the visual feedback presented the subjects, and the experiment tested manual control for various settings of $1/\tau_d$. These were varied over a range where preliminary data had indicated best performance would be found.

Four subjects were asked to control the system for 2 min. trials with inserted delays of 200, 400, and 800 ms and break points for the low-pass filter of 1/2, 1, 2, 3, 4, 5, 6, 7, and 8 rad/s. A combination of these values was used to determine the testing conditions for a particular trial, and performance for a given combination was taken as the average of five such trials. The subjects were tested on all settings for a given delay before being switched to a new one; other than that, the order of testing was random. Usually they performed 18 trials per day.

Results and Discussion

The results of that experiment, averaged across subjects, are presented in Fig. 4. For the control of both pitch and roll, analyses of variance revealed that there were effects due to both the presence of the transport delay and the various values of $1/\tau_d$. For each of our six measures, the effect of delay was significant at the $p < 0.001$ level as was the effect of manipulating $1/\tau_d$ except for the measures of pitch error and crossover power. The error score indicated that varying $1/\tau_d$ was significant at $p < 0.05$ and was not significant for the measure of crossover power. No interactions were significant. These results are not particularly surprising, but it is the form of the functions relating the measures to the break points of the filters that is important here. For the control of both the pitch and roll axis the measures of the system error and the pilots' deflections of the control stick were reduced as higher and higher values of $1/\tau_d$ are used. This is reasonable as controllers cannot be expected to null error which they cannot see, but of considerable importance is the indication of an upward turn of these functions for high values of $1/\tau_d$. This seemed most pronounced for the measures of the deflection of the control stick, and some subjects seemed to display this trend more than others. While the low-frequency downward leg of these functions clearly would be related to the addition of needed information to the display, the upward leg we feel reflects the degree to which an individual tried to null high-frequency error. Subjects who reported they ignored high-frequency activity of the display tended to show this effect less. Correlated with these changes of system error and control stick deflection, the measure of relative power within the crossover band tended first to increase and then later to decrease as the break point of the filters was raised.

These V- or U-shaped functions seem to reflect in a fairly straightforward manner the changes of control style necessary

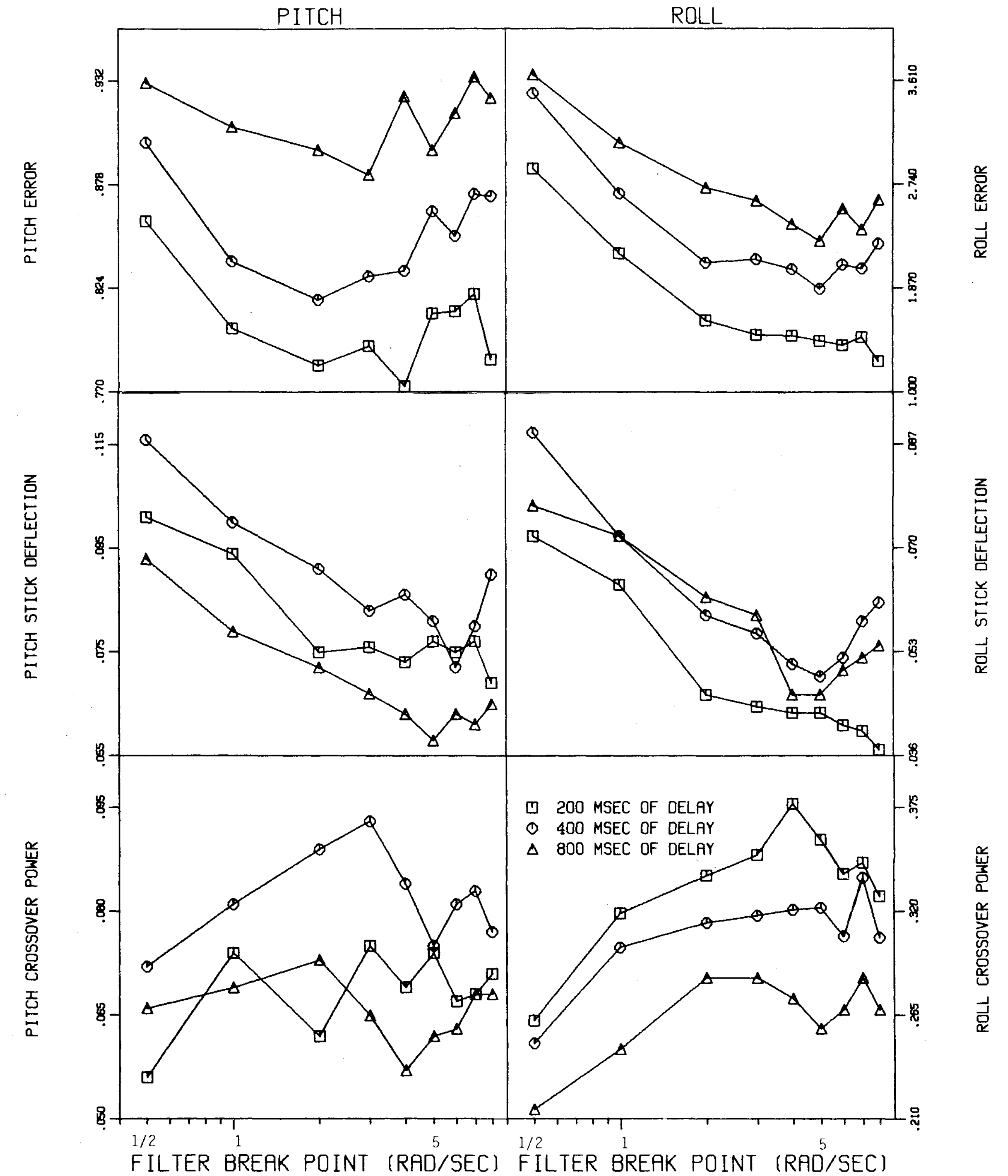

Fig. 4 Mean control performance as a function of filter break points for delays of 200, 400, and 800 ms. System error, control stick deflections, and relative power between 2 and 6 rad/s for pitch angle control are presented on the left and those for control of the roll angle on the right.

for these conditions of testing. In another experiment using these system dynamics, Ricard, Norman, and Collyer showed that controllers' responses to the insertion of delay was to reduce their relative control power within the crossover region and make larger deflections of the control stick as the delay (and system error) increased. In these data, the nonmonotonic functions are taken as reflecting the relative contributions of phase lag and phase lead as $1/\tau_d$ is changed for a set value of τ_n. For small values of $1/\tau_d$, the increased lag causes the control system to be sluggish so that high-frequency errors are integrated and cannot be corrected. At large values of $1/\tau_d$, phase lead predominates and the increased responsiveness of the display encourages the controller to lower his gain crossover point and increase his low-frequency gain. Presumably intermediate values of $1/\tau_d$ provide an appropriate ratio of lead to lag and this is reflected as better control performance. The extent to which human controllers respond to such manipulations of the signals that drive a

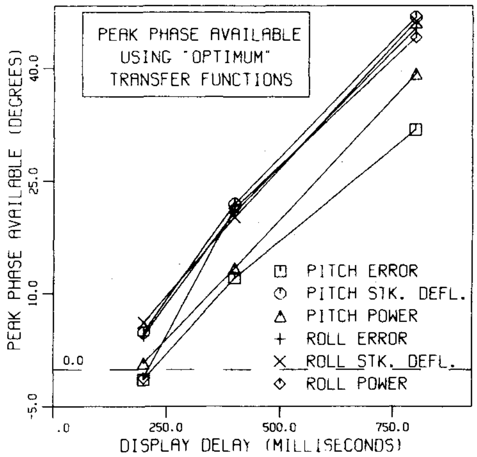

Fig. 5 Maximum changes of phase associated with conditions of best performance for the data of Fig. 4.

visual display will determine the depth of these V- or U-shaped functions.

This analysis of the changes of control behavior seen in Fig. 4 led us to measure an optimal τ_n/τ_d ratio by determining the minima (in the case of the error and stick deflection measures) and maxima (for the crossover power) of those functions. This we did by fitting to a least-squares criterion a second-order polynomial to each function of Fig. 4 and then solving for the inflection point of the fitted curve. This point was taken as the optimal value for τ_d for the particular value of τ_n, and these values were used to form a new transfer function that represented the phase and gain changes related to best control performance. By taking the value of $1/\tau_d$ that represents "best performance" and solving for the maximum phase change produced by these new values of τ_n and τ_d, we can indicate the amount of phase lead or lag that human controllers seem to prefer or need for best control performance. For the three conditions of delay for which we had data, the maximum change of phase produced by the fitted

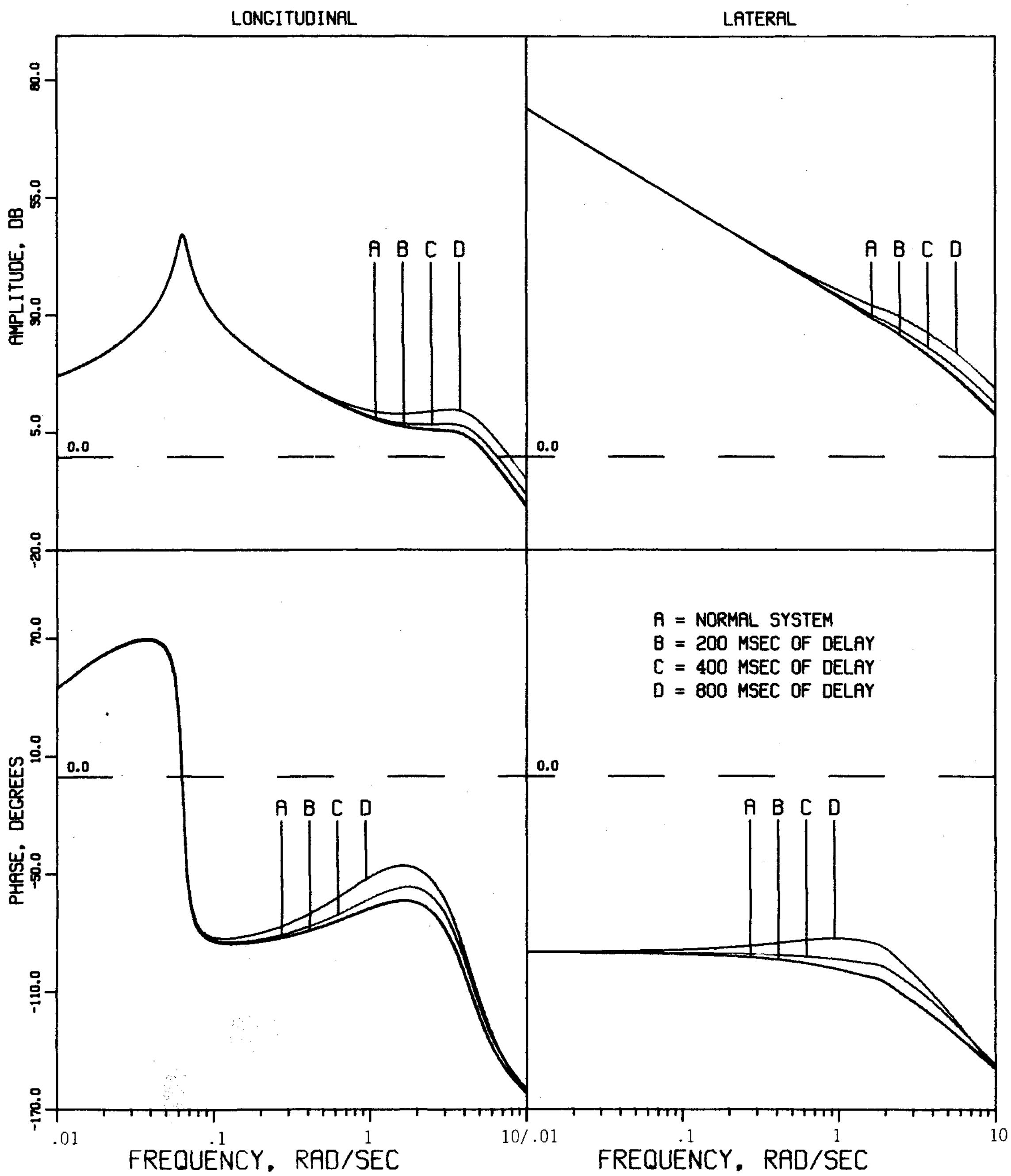

Fig. 6 Amplitude and phase plots of system defined by Eqs. (2) and (3), and of delayed and compensated output of that system. Values of τ_n and τ_d used here are the same as those used to obtain the peak phase changes shown in Fig. 5.

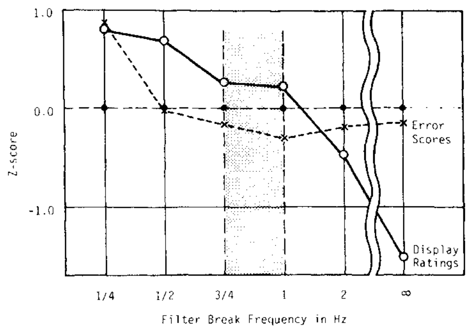

Fig. 7 Control performance and pilot opinion as a function of low-pass filter break point (data collected using the ASPT simulator). Cross-hatched area indicates an acceptable setting for $1/\tau_d$.

transfer function is presented in Fig. 5 where each curve represents the estimate based upon a given measure. The striking feature of these data is the similarity of the estimates. All of them indicate that human controllers prefer a phase lead that gets larger with longer delays, but all indicate that, in the range of 150-200 ms of delay, the amount of lead that produces best performance has reached zero! Above that point, lead is needed at a rate of about 0.07-0.08 deg per 1 ms of delay. For a 400 ms delay, for instance, best control performance was produced by a maximum phase advance of only 18 deg. Not obvious from the figure are the changes of location of these maxima to lower and lower frequencies as the display delay is made longer. The peak of little more than 2 deg of phase lead for a 200 ms delay was centered at 0.83 Hz, while the over 40 deg of lead for the 800 ms delay was centered at about 0.4 Hz. For these subjects then, the nature of the delay compensation that seemed to be preferred was one where a larger and larger phase lead was centered at a lower and lower frequency.

To indicate the actual system our subjects were controlling, in Fig. 6, we present Bode plots of the normal system plus those for the conditions of delay. The curves labeled B, C, and D had the appropriate transport delay inserted along with the optimal settings of τ_n and τ_d for the lead/lag network thus the figure provides open-loop amplitude and phase plots for conditions of delay and compensation for it. Settings of lead and lag that do not evaluate to unity will change the open-loop characteristics of a controlled system, and the point of presenting Fig. 6 is to indicate the extent of such changes. Only for the longest delay, for instance, is there a noticeable change of amplitude in the region above 1 rad/s. Along the longitudinal axis of control this amounted to an increase of about 4 dB and a maximum phase advance of about 18 deg. Interestingly enough, the phase plots indicate that our settings of lead and lag based on best control performance provided more of a phase advance than was necessary in the region below 2 rad/s. Quite likely subjects controlling simulations of aircraft prefer to have delays compensated within the pilot crossover region of 3-5 rad/s, and the lower-frequency mismatch was a necessary result of using a lead/lag network to provide this compensation.

Should the data of Fig. 5 be extended to shorter delays, we might suggest that for systems with delays of less than 150-200 ms a phase lag would be the preferred change of the display signals and that this should be centered at still higher frequencies. This seems reasonable as it is the presence of the delay that prevents controllers from effectively dealing with high-frequency error. By eliminating it from a visual display, better control behavior may be produced in certain situations. This may not always be the case though; the analysis we have presented here was based on data collected on a narrow field-of-view system, with a fairly taxing forcing function producing error to be nulled, and with none of the auxiliary tasks characteristic of flying real aircraft.

As an example of a more realistic situation, Ricard, Cyrus, Cox, Templeton, and Thompson[13] performed a similar experiment using the Advanced Simulator for Pilot Training at Williams AFB where performance of flying formation and pilots' opinions of the noisiness of the display were related to values of $1/\tau_d$. A summary of their data is presented in Fig. 7 where a normalized control score (the average of pitch and roll errors) is presented along with the pilots' normalized rating of the "noisiness" of the computer-generated display. The normal lead-generating software of the ASPT was used for this study, and break points for the low-pass filter were used that span the range discussed here, along with a no filtering condition (the ∞ break point). Clearly once a high enough break point was used so that control was not impaired, further increases of $1/\tau_d$ had no effect. Even when compared to no filtering, the higher values of $1/\tau_d$ did not affect control performance, but they did strongly affect pilots' opinions of the display. Filtering clearly produced a more acceptable image than no filtering even though this was not reflected in measures of aircraft control.

Summary

We presented the analysis in this paper because we feel that a lead/lag form of delay compensation seems to be useful, even though it may produce smaller amounts of phase lead than other methods of adjusting signals for visual displays. It seems that even for difficult tasks, only small peaks of phase change are needed to aid manual control and that in realistic simulations of flight, changes of piloting control may not be evident, but that some other metric—probably of opinion or preference for a particular value of $1/\tau_d$—is likely to show an effect.

Acknowledgment

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