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SUMMARY

Experiments have been conducted to determine the variability in a human subject's control stick response to the stimulus of displayed displacement and of rate of change of displacement to aid in the implementation of the time variations to be included in a linear model of the human subject. Additional tracking tests were made to obtain a definition of the characteristics of the random signal to be added to the model. These two factors, the time variations and the random signal, were then added to the linear model, and the resulting composite model was placed in analog representations of single-loop and multi-loop systems. The results demonstrate that this composite model reproduces the dynamic characteristics of the time histories and mean-square system error which more closely match the response obtained with the human subject than does the linear model.

INTRODUCTION

Research reported in references 1, 2, 3, and 4, in which parameter tracking model matching methods were used, has provided constant-coefficient linear models that approximate human response in compensatory tracking tasks. These investigations have also indicated that human subjects are not linear constant-coefficient operators but also produce some uncorrelated high-frequency control output in addition to that portion of the output that is linearly correlated with the displayed error input signal. Also, these investigations and the studies reported in references 5 and 6 indicate that a proper model of human response should include time-varying gains. Tests discussed in reference 7, which attempted to synthesize single-loop manually controlled systems, showed that linear constant-coefficient pilot models did not exactly reproduce the desired response but provided better control in that the system root-mean-square error was smaller than the error obtained with the human subject. In reference 3, studies of a multiloop system indicated that linear pilot models provided a good indication of the stability and performance of the system but again did not exactly reproduce the human response.

In this paper the hypothesis that the model of the human operator should contain time-varying gains and a random signal is tested. A block diagram of the proposed model in a single-axis compensatory control loop is shown in figure 1. To determine the amount of variability in the subject's response to the stimulus of displayed displacement and of rate of change of displacement, open-loop response tests were made. Also, additional tracking studies, which involved changes in the mean-square value of the disturbance function, were made to obtain additional information on the amplitude of the added noise contained in the subject's output. These factors were then included in the model, and this composite model was placed in the control loop in place of the human subject. The same disturbance function used in the tracking tests with the human pilot was presented to the model-controlled system, and the dynamic characteristics of the time histories and measured mean-square system error were obtained for comparison.

The time-varying gains and the noise which are added to the linear model represent refinements that are of interest if a precise prediction or confirmation of system performance, structural loads, or control effort or fuel used is desired.

SYMBOLS

D	disturbance, volts
K	general gain
K_1	model static gain
K_2	model lead gain
K_4	noise gain
n	noise, volts
s	Laplace operator, second^{-1}
t	time, seconds
δ	control stick deflection, volts
ϵ	system error, volts
ζ	damping ratio
θ	system output, volts

τ model lag breakpoint frequency, radians per second

ω_n system natural frequency, radians per second

TESTS

Variations in Gain

Previous investigations in which models have been matched to human responses have indicated that humans could be best matched with models which contain variable coefficients rather than with constant-coefficient models. The idea that a human will not respond to a given stimulus of the system in exactly the same way each time that stimulus is encountered is certainly a reasonable conclusion. Evidence that a human controller is time varying is contained in records of system error such as figure 2(a). These records were obtained from closed-loop compensatory tracking tests performed in a fixed-base simulator in which the subject was observing an oscilloscope display and manipulating a side-arm controller. The dynamics of the controlled element were of the acceleration type as represented by K/s^2. The subject was a research test pilot. The disturbance function was the random disturbance shown in figure 2(a). It was obtained by passing the output of a noise generator through two first-order filters with break frequencies of 1 radian per second. The system error was the compensatory error displayed on the oscilloscope and presented in figure 2(a). Although it is clear that the system characteristics are of a stable nature in general, instances can be seen throughout the record of divergent oscillations; these divergences indicate a reduction in system stability for a period of approximately 5 seconds. That these short periods of apparent instability are not related to the random disturbance signal is illustrated by figure 2(b) in which the forcing function is a pure sine wave with a frequency of 0.25 radian per second. Again short periods of apparent instability are evident. These changes in system characteristics could only result from changes in the pilot's response.

Although references 1, 5, and 6 indicate that the human response is time varying, they do not provide quantitative data on these time variations. To obtain these data, tests were conducted in which the subject made open-loop controller movements in response to the stimulus of displayed displacement and of rate of change of displacement. Four research test pilots (D, K, M, and N) and three engineers (G, H, and I) served as subjects in these open-loop tests. The subjects were seated in front of a 21-centimeter oscilloscope display and operated a small side-arm controller in response to the displayed signal. A photograph of the experimental setup is shown as figure 3. Displacement signals between 0 and ±10.5 centimeters from a fixed reference mark and rate signals between 0 and ±80 centimeters per second, which moved from either the top or the bottom of the oscilloscope, were presented to the subjects. The subjects were seated with their eyes located approximately 75 centimeters from the oscilloscope, so that in terms of line of sight the displacements were from 0 to ±0.14 radian and the rates were from 0 to ±1.1 radians per second. The subjects were instructed to respond to the displacement in one case and to the rate of change in the other by moving the control stick to a displacement they thought was appropriate and holding that position for about 3 seconds or long enough to establish their selected stick deflection. They were told not to try to establish any particular gain between the displayed signal and controller deflection but only to be as consistent as possible. They were shown the maximum signal during their instruction and were asked to move the controller to its maximum deflection, and to adjust their response so as not to require more than maximum stick deflection. The subjects were then presented the signals in random order with 30 increments being used between zero and the maximum signal. They were each presented with 40 trials in four different sessions for a total of 160 trials for both the displacement and the rate signals. Each trial took approximately 15 seconds to complete.

Random Signal

The difference between the model output and the human output obtained in the model matching tests of reference 1 shows a high-frequency signal whose amplitude is a fairly large fraction of the pilot's output. Although this difference may be partially due to the time variations in the pilot's response and the inability of the model-matcher parameter adjustment to follow exactly these variations, the relatively high frequency of the difference indicates that it is also due to random noise injected by the pilot. Reference 8, a study of human tracking of pure sine-wave forcing functions, has also concluded that the human is a noise source. Additional tests aimed at obtaining a better definition of this pilot-generated noise have been conducted in conjunction with the present investigation. These tests consisted of single-axis (pitch) compensatory tracking of random inputs similar to the tests performed in reference 1, but with the addition of an experimental change in the mean-square value of the disturbance function. The subjects observed the compensatory error on a large oscilloscope (21 by 28 cm) and operated a small side-arm control (the same setup shown in fig. 3). The controller stick was 3 inches long, could be deflected ±26°, and had a maximum output of 10 volts. It had light centering springs. The controlled element dynamics, which were simulated on a computer, were $10/s^2$. The disturbance function was generated by a noise generator and filtered with two first-order filters with breakpoint frequencies of 1 radian per second. The measured mean-square values of the three different amplitudes of the disturbance functions were 5.6 volts, 15.4 volts, and 53.1 volts. The display sensitivity was 2 volts per centimeter.

The noise, or remnant, generated by the human subject in these tests was obtained by matching a linear model to the pilot and subtracting the output of the model from the output of the pilot. The model matching was done by an automatic parameter adjustment method described in reference 1. In this method a model of the form

$$\frac{\text{Output } \delta}{\text{Input } \epsilon} = \frac{K_1 \tau + K_1 K_2 s}{(s + \tau)^2}$$

is mechanized by using analog computer equipment. The three gains K_1, τ, and K_2 are adjusted to provide the best match possible. When the parameters have adjusted to steady values, the remaining difference is the remnant. The mean-square value of the remnant was determined for the present tests and the spectral density of the remnant was also determined. Three test pilots and two engineers served as subjects in the tracking tests.

It should be noted that the use of a different model form would probably result in a different remnant from that obtained in these tests. The remnant as determined in these tests should be used only with a model of the form used in these tests.

The validity of parameter tracking methods of obtaining models of human subjects has been questioned in references 9 and 10. Mathematical arguments developed in these references indicate that, although parameter tracking methods will perform as expected in the absence of any injected noise on the part of the subject, these methods will give results that are biased if such injected noise is present. Figure 4 is a time history obtained in a tracking test which illustrates the remnant or noise injected by the subject. The remnant in this test has an envelope with an amplitude between 60 and 70 percent of that of the envelope of the pilot output and is the largest remnant noted in the test series. If a model of the same form as the adjustable model and with gains similar to those measured with human subjects is placed in a control loop, the model gains are correctly determined with no remnant, as is illustrated in figure 5. To find out whether adding a random signal to the output of the model would affect the determination of the gains of the model, experiments were conducted in which the amplitude of the envelope of the injected noise was approximately 50 to 60 percent of that of the model output. In figure 6 it can be seen that when such a random noise is added to the model, time variations occur in the measured gains like those that occurred in the gains of the human subject's output. However, the average values of the gains are correct. It is therefore concluded that the bias in identification predicted in references 9 and 10 is insignificant.

RESULTS AND DISCUSSION

Variability of Subject's Response

A typical plot of a subject's open-loop static responses to rate of change of display is presented in figure 7. Straight lines define the linear boundaries of the data. These straight lines represent the maximum and minimum gain generated by the subject. The average gain was determined, and the percentage difference of the extremes from the average was calculated. These percentage deviations, which are assumed to apply whatever the average gain, are listed for each subject in table I.

Since the engineers' results in the rate tests were almost the same as the pilots' results, only the engineers were used in the study of variability of response to displacement. The results of those tests are also presented in table I. It can be seen that there is a greater variability in response to rate than in response to displacement.

For this paper it was believed that defining the boundaries of the data with linear functions and expressing the variations as a percent provided the most useful description of the data. It is, of course, possible that expressing the measured variation in terms of standard deviation might also be useful. To facilitate such a description the average gains and standard deviation of the data are presented in table II.

Remnant

The results of tests to determine the amplitude of the remnant are presented in table III. It can be seen that the mean-square error, stick deflection, and remnant progress in amplitude with an increase is amplitude of the disturbance. The ratio of remnant to stick deflection is nearly constant for each subject, with a slight tendency toward a larger ratio as stick deflection is reduced. Differences between subjects are evident, with the spread in ratio of remnant to stick deflection being from 0.46 for subject M to 0.30 for subject K.

The power spectral density of the remnant was also determined to establish remnant frequency content. Sample plots of the normalized spectral density for the subjects of table III are shown in figure 8. All these curves had the same general characteristic – that of a second-order attenuation with a breakpoint frequency of approximately 10 to 15 radians per second. Also presented in figure 8 is the amplitude ratio squared of a second-order transfer function consisting of two first-order lags with breakpoint frequencies of 10 radians per second. The good agreement shown by this comparison leads to the conclusion that the remnant can be considered as coming from a noise source that is filtered by the second-order system composed of the muscles of the arm and the inertia of the arm and control stick. A similar assumption was made in the selection of the model forms to be used in the model matcher; that is, that the command signals generated by the error and error rate would be filtered by a critically damped second-order muscle and arm system. The fact that the remnant spectral density conforms to the same general assumption with approximately the same value of breakpoint frequency as that measured by the model matcher is indeed encouraging. The two separate measures each show that the characteristics of the muscle-arm system are a critically damped frequency of 10 to 15 radians per second.

The spectral density of the remnant of subject H is somewhat different from the other four subjects in that it has a relatively large high-frequency content. Subject H, who is one of the authors of this paper and who has been associated with human response investigations for the last 5 years, has accumulated a large amount of tracking experience in the laboratory. He has developed a control style that results in the lowest mean-square error of all the subjects (table III). The low error is apparently accomplished at the expense of large control power.

The average model gains measured in the tracking tests are presented in table IV, along with the closed-loop system characteristics which were calculated by using these gains. These system characteristics were obtained by factoring the denominator of the closed-loop system transfer function which is

$$\frac{\theta}{D} = \frac{10\ K_1K_2s + 10\ K_1\tau}{s^4 + 2\tau s^3 + \tau^2 s^2 + 10\ K_1K_2s + 10\ K_1\tau}$$

A comparison of these results with those of reference 1 for subject D, who took part in both tests, shows similar gains in closed-loop characteristics. The differences that can be noted in the results are a higher lag breakpoint frequency τ and a better closed-loop damping ratio ζ in the present study. The system natural frequency is nearly the same in each study. It is believed that the reason for the improvements is the small side-arm controller used in the present study as compared with the larger center stick used in reference 1. A disturbance breakpoint frequency of 1 radian per second was used in the present study as compared with 0.25 radian per second in reference 1. However, some tests made with the 0.25-radian per second breakpoint frequency during the present study showed the same high lag breakpoint frequency; this result would indicate that the higher measured values of τ were due to the side-arm controller.

Synthesis of Human Response

The variability in pilot response to displacement and rate of change displacement and the remnant as specified by the results of the experiments previously described were added to the linear constant-coefficient model, and this composite model was placed in the control loop to determine whether it could more accurately reproduce human control. The criteria used to judge a correct reproduction were a visual inspection of the time history of the system response and the measured mean-square values of system error. The specific conditions used for these checks were those that occurred in the test of pilot M, in which the ratio of remnant to stick deflection was 0.46. This case was selected for detailed study because it contained the largest value of the measured remnant.

The time-varying characteristics of the subject's response were included in the model in the following manner. The ±30-percent variation in response to displacement was represented by placing a ±30-percent variation on the static gain K_1. The value of K_1 measured in the model matching experiments was taken to be the nominal value for the static gain. For the example case of subject M the nominal static-gain value was 4, and the variation was from 2.8 to 5.2. This variation was implemented with the use of a multiplier placed at the output of the model. The total variation in response to displayed rate of ±45 percent was obtained by including an additional ±15-percent variation in the lead gain K_2. For the example case the nominal value of K_2 was 6, and the variation was from 5.1 to 6.9.

The time characteristics of these variations were established as follows. Records such as those of figure 2 indicate that divergent, or at least poorly damped, system characteristics are often encountered in manually controlled systems for periods of approximately 5 seconds. To establish a corresponding condition, the variations in model gains were given a saw-tooth wave shape with a 20-second period. Stick deflection and lead coefficient were varied together, that is, both low or both high at the same time. The model could therefore be considered as having relatively low gains for 5 seconds, high gains for 5 seconds, and nominal gains for 10 seconds of the 20-second period. With these changes in effect, the short-period system characteristics varied from the nominal values for natural frequency of 1.9 radians per second and damping ratio of 0.27 to low values of 1.3 radians per second and 0.16 and to high values of 2.4 radians per second and 0.7.

These changes in system characteristics indicate potential changes in system performance. Exactly what changes in performance will, of course, depend on the amount of system activity that exists at particular instances in a given time history. To illustrate the general effect these system characteristics can have, figure 9 is presented. This figure presents normalized system error as a function of system natural frequency, damping ratio, and disturbance frequency. The error was obtained by placing a simplified pilot model, which consisted of only a static gain and a rate gain, in a control loop with plant dynamics of K/s^2. With this simplified model the system frequency could be changed independently by changing the pilot model static gain, and the damping ratio could be changed by changing the rate gain. The disturbances used were pure sine waves of given frequency. These factors were varied throughout the ranges given in figure 9. The figure shows the increase in system error that can be expected with decrease in natural frequency and damping ratio and increase in disturbance frequency. The simplified and idealized model used to obtain these data gives the minimum error that could be expected. Also, with a random disturbance, the error would be the summation of errors for the different disturbance frequencies, the larger part of the error resulting from the frequencies which were close to the system natural frequency. This type of result is illustrated by figure 10, which presents the disturbance and system error obtained in a manually controlled tracking test with a specially tailored disturbance function. The disturbance was a low-frequency (0.25 radian per sec) sine wave to which was added a 4-radian-per-second low-amplitude sine wave at unexpected times. The dynamics were K/s^2. The large increase in system error which results with the addition of the small 4-radian-per-second sine wave is clearly shown and indicates that a large part of this error results from that portion of the disturbance which has a frequency close to the system natural frequency.

The remnant was included in the model by adding a random signal to the output of the model at a location just before the variable gain on stick deflection, as shown in both the block diagram and computer diagram of figure 11. With this arrangement the ratio of remnant to stick deflection would remain constant even though stick-deflection gain was changing. The random signal was obtained from a noise generator and two first-order lag networks with breakpoint frequencies of 10 radians per second. The amplitude of the random signal was adjusted so that the mean-square value would provide the desired ratio of remnant to stick deflection (mean-square value). Since addition of the random signal also increased the stick deflection, it was necessary to make an iterative adjustment to obtain the desired ratio. This adjustment was performed with the model in the control loop. After one iteration it was possible to arrive at approximately the correct ratio. For subject M, the desired ratio was 0.46 and the average value for several minutes of test time obtained for the model was 0.58. The spectral density of the actual simulated noise obtained with the noise generator is shown in figure 8(b).

The results achieved by adding the time-varying gains and the random signal to the linear constant-coefficient model are illustrated in figure 12. To provide a complete comparison, the time history obtained with subject M is presented with the responses obtained by using the composite model and the linear model subjected to the same disturbance. From figure 12, it can be seen that the linear model provides better control (a lower system error) than does the human subject. The composite model gives a system error which is very similar to that obtained with the human controller but which is not an exact duplication of the wave form. For this particular example the ratios are as follows:

Controller	$\frac{\overline{n^2}}{\overline{\delta^2}}$	$\frac{\overline{\epsilon^2}}{\overline{D^2}}$
Pilot	0.46	0.64
Composite model	0.35	0.85
Linear model	0	0.44

The pilot did not perform with the same ratio of system error to disturbance (mean-square values) for each of the 3-minute tests that he made, as is illustrated in table III, and neither did the composite model. To illustrate that the spread in performance with the composite model was the same as that obtained with the human pilot, the following average $\frac{\epsilon^2}{D^2}$ data are presented:

Controller	Average $\frac{\epsilon^2}{D^2}$
Pilot M	0.78; 0.26, -0.12
Composite model	0.73; 0.37, -0.19
Linear model	0.324; 0.05, -0.024

The data show the average of the ratio of mean-square system error to disturbance and the variation for the three tests performed by the pilot, for six tests performed with the composite model, and for five tests performed with the linear model. Again an improvement in the match to the human pilot is obtained with the composite model over that obtained with the linear model.

Nearly four-fifths of the improvement achieved with the linear model was provided by the addition of the random noise. This fact is illustrated by the following average $\frac{\epsilon^2}{D^2}$ data:

Controller	Average $\frac{\epsilon^2}{D^2}$
Pilot M	0.78
Composite model	0.73
Linear model with added noise only	0.70
Linear model with variable gains only	0.43
Linear model	0.324

The similarity in the time histories of the model-generated and the pilot-generated system responses is clearly shown in figure 12. The effect of adding the varying gains and random signal is even more strikingly demonstrated when the disturbance is a pure sine wave. With this disturbance the steady-state response obtained with the linear model is also a pure sine wave. Figure 13 illustrates how the composite model gives a representation of the human response which is greatly improved over that obtained with the linear model when the disturbance is a pure sine wave.

Further evidence that supports the human-response representation of the composite model is provided by the response of the model matcher. When matching a human subject, the parameter tracking computation outputs are driven in a random fashion. When the composite-model output is matched with that of the parameter tracker, the parameter adjustments are driven in a similar manner. This agreement is illustrated in figure 14, which shows the remnant and the K_1 adjustment obtained from a test with a pilot and a similar test performed on the composite model.

For multiloop control problems, it has been shown in references 3 and 11 that the system can be well duplicated by a combination of linear constant-coefficient models located in series. Reference 3 reported results of studies of the lunar module translation and hover multiloop control task. An outer-loop pilot model responded to translation error and provided an attitude-command signal to an inner-loop model. The inner-loop model responded to this attitude error and provided the attitude-control signal. Figure 15(a) was taken from reference 3 and shows the system response obtained from a pilot-controlled simulation of the lunar translation and hover task. Figure 15(c) shows the reproduction of this maneuver obtained with linear models in control. Although the duplication is good, it lacks the random nature of the attitude response in the hover condition. By using the composite pilot model in the inner loop, the correct type of attitude response is obtained in figure 15(b). The time histories shown in figure 15 were obtained from a complete multiloop representation of the problem which used a linear pilot model in the outer loop. The time variation was included in the inner-loop pilot model, and the remnant was added at the output of the inner-loop pilot model. In this test the remnant added to the model was given an amplitude that was approximately one-half the control deflection that occurred during the hover portion of the test. This ratio was assumed to be a good representation for an average pilot.

CONCLUDING REMARKS

The data presented in this paper demonstrate that human pilot response in single-loop and multiloop control tasks can be synthesized by a linear constant-coefficient model to which are added time variation on the gains and a random signal. For multiaxis control tasks and for situations in which side tasks must be performed along with the closed-loop control of vehicle output, additional changes should be included in the model. These additions involve the reduction of certain model gains to zero for prescribed lengths of time. Other changes in the gains of the linear portion of the model that correspond to various vehicle dynamics are required. These changes include changes in lag and lead-time constants and the relative changes in static gain and the subsequent changes in system closed-loop natural frequency. By following the suggestions for synthesis of pilot response presented in this paper and in previous investigations, pilot models for a large portion of all the probable control situations can be described. The simple linear constant-coefficient models can be used to predict, or confirm, gross system performance. In detailed studies of precision of control, structural loads, and fuel requirements, the composite model can be used.

Langley Research Center,
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TABLE I.- VARIABILITY OF RESPONSE

Subject	Variability of response to rate of change of displacement, percent	Variability of response to displacement, percent
D	±56	---
K	±45	---
M	±42	---
N	±42	---
G*	±48	±38
H*	±44	±33
I*	±45	±28

*Engineer.

TABLE II.- STANDARD DEVIATION

Subject	Average rate gain, $\frac{\text{arbitrary stick deflection units}}{\text{radian/second}}$	Standard deviation	Average displacement gain, $\frac{\text{arbitrary stick deflection units}}{\text{radian}}$	Standard deviation
D	19.0	9.25	---	-----
M	17.6	8.25	---	-----
N	14.6	6.45	---	-----
G*	9.95	5.66	147	59.2
H*	18.5	7.55	216	122
I*	15.3	8.64	177	73.5

*Engineer.

TABLE III.- VARIANCES AND RATIOS

Subject	Variances				Ratios	
	Disturbance, volts^2	Error, volts^2	Stick deflection, volts^2	Remnant, volts^2	$\frac{\text{Error}}{\text{Disturbance}}$	$\frac{\text{Remnant}}{\text{Stick deflection}}$
K	5.61	2.10	1.05	0.313	0.37	0.30
	15.4	5.15	8.60	2.10	.34	.24
	53.1	19.9	14.8	2.89	.37	.20
M	5.61	3.57	.775	.356	.64	.46
	15.4	16.1	1.81	.535	1.04	.30
	53.1	35.7	11.0	3.36	.67	.30
N	5.61	1.77	8.55	2.94	.32	.34
	15.4	5.61	14.6	5.69	.36	.39
	53.1	17.4	34.7	9.62	.33	.28
G*	5.61	1.36	4.20	1.19	.24	.28
	15.4	9.26	14.3	4.46	.60	.31
	53.1	38.8	24.0	7.15	.73	.30
H*	5.61	.72	6.23	3.34	.13	.54
	15.4	2.47	10.6	5.31	.16	.50
	53.1	12.1	26.9	12.3	.23	.45

*Engineer.

TABLE IV.- AVERAGE GAINS AND SYSTEM CLOSED-LOOP CHARACTERISTICS

Subject	Disturbance, volts	Average model gains			Closed-loop characteristics		
		K_1	τ	K_2	ω_n, radians/second	ζ	Real roots
D	2.37	4	12.5	7.5	2.24	0.51	-5.9, -16.8
	3.92	4	12.0	7.5	2.24	.44	-5.9, -16.1
	7.29	5	13.0	6	2.23	.30	-7.7, -16.9
K	2.37	3	11	9	2.26	.59	-4.3, -15.0
	3.92	6	10.5	6	3.54	.36	-3.3, -15.1
	7.29	5	11	5	2.52	.27	-5.8, -14.8
M	2.37	4	13	6	1.93	.27	-8.4, -16.5
	3.92	3.5	13.5	6	1.73	.24	-9.4, -16.8
	7.29	7	16	6	2.29	.26	-10.5, -20.2
N	2.37	8	11	8	5.37	.31	-1.8, -16.9
	3.92	8	11	7	4.83	.33	-2.3, -16.5
	7.29	10	11	4	3.76	.19	-5.0, -15.6
G*	2.37	8	10	6	4.74	.25	-2.3, -15.3
	3.92	8	10	4	3.57	.18	-4.4, -14.3
	7.29	11	11	3.5	3.77	.14	-5.5, -15.4
H*	2.37	7.5	12	10	5.64	.37	-1.55, -18.2
	3.92	6	12	12	5.63	.41	-1.25, -18.1
	7.29	9	15	10	4.77	.62	-2.7, -21.3

*Engineer.

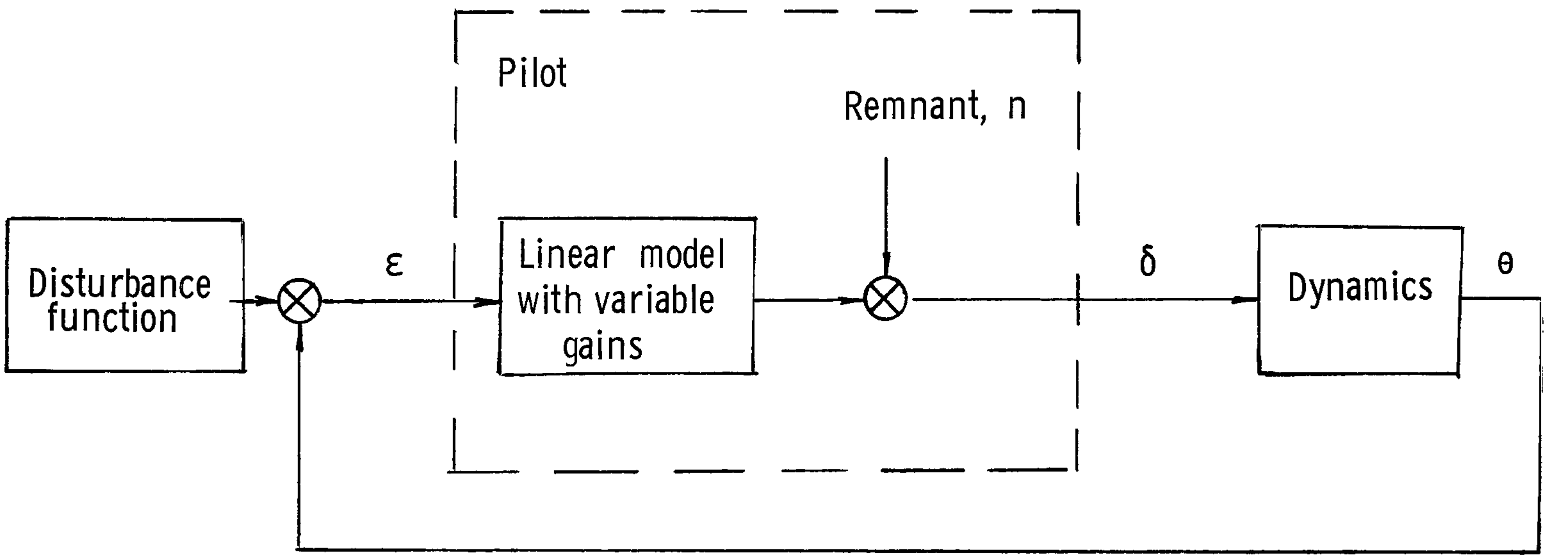
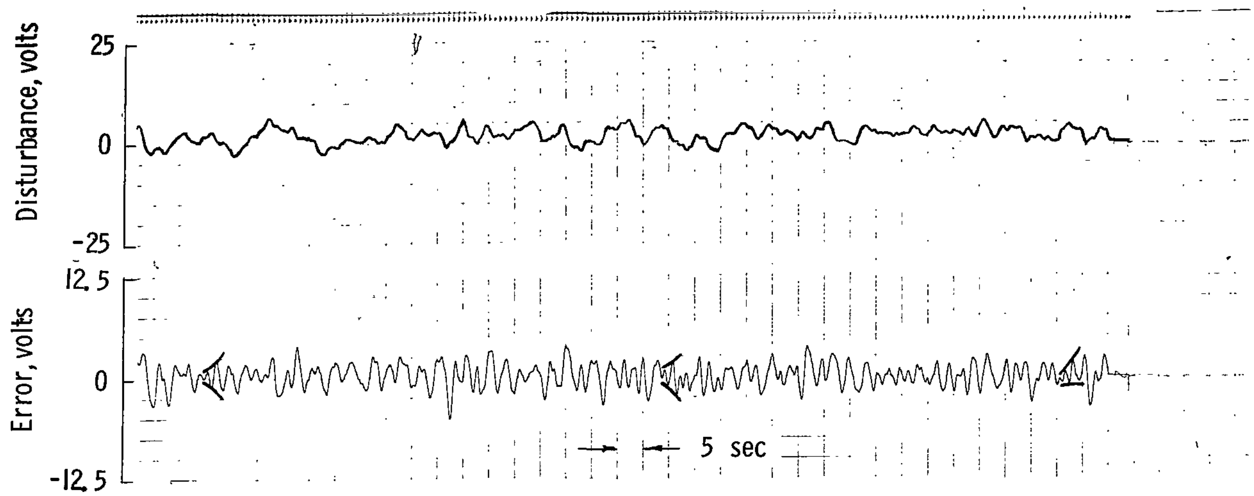
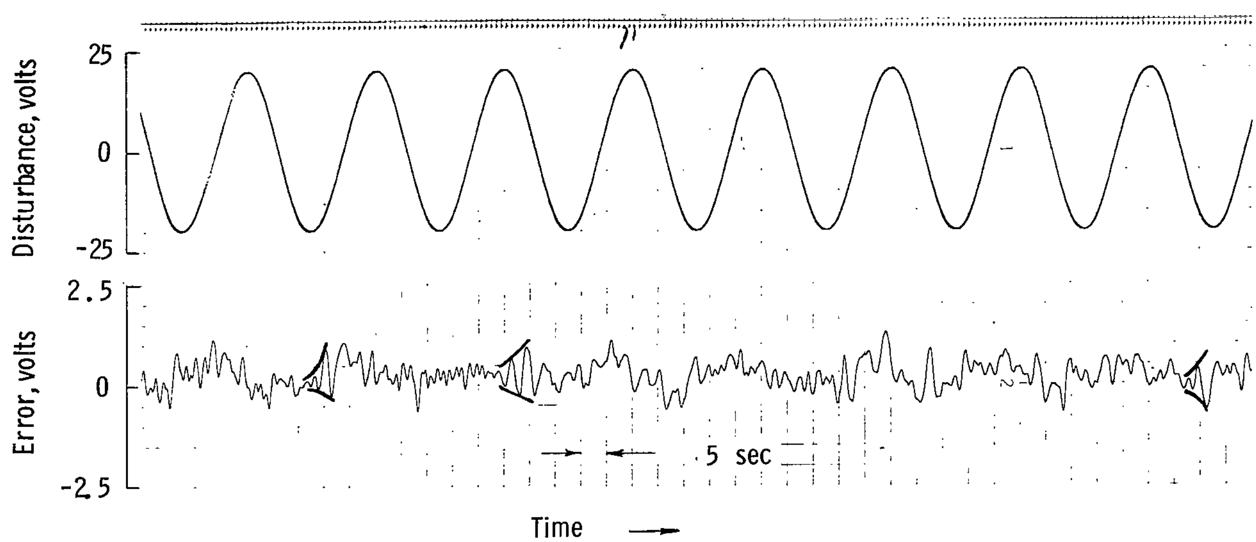


Figure 1.- Block diagram illustrating proposed pilot model in single control loop.



(a) Random disturbance.



(b) Sine-wave disturbance.

Figure 2.- Illustration of time-varying pilot response.

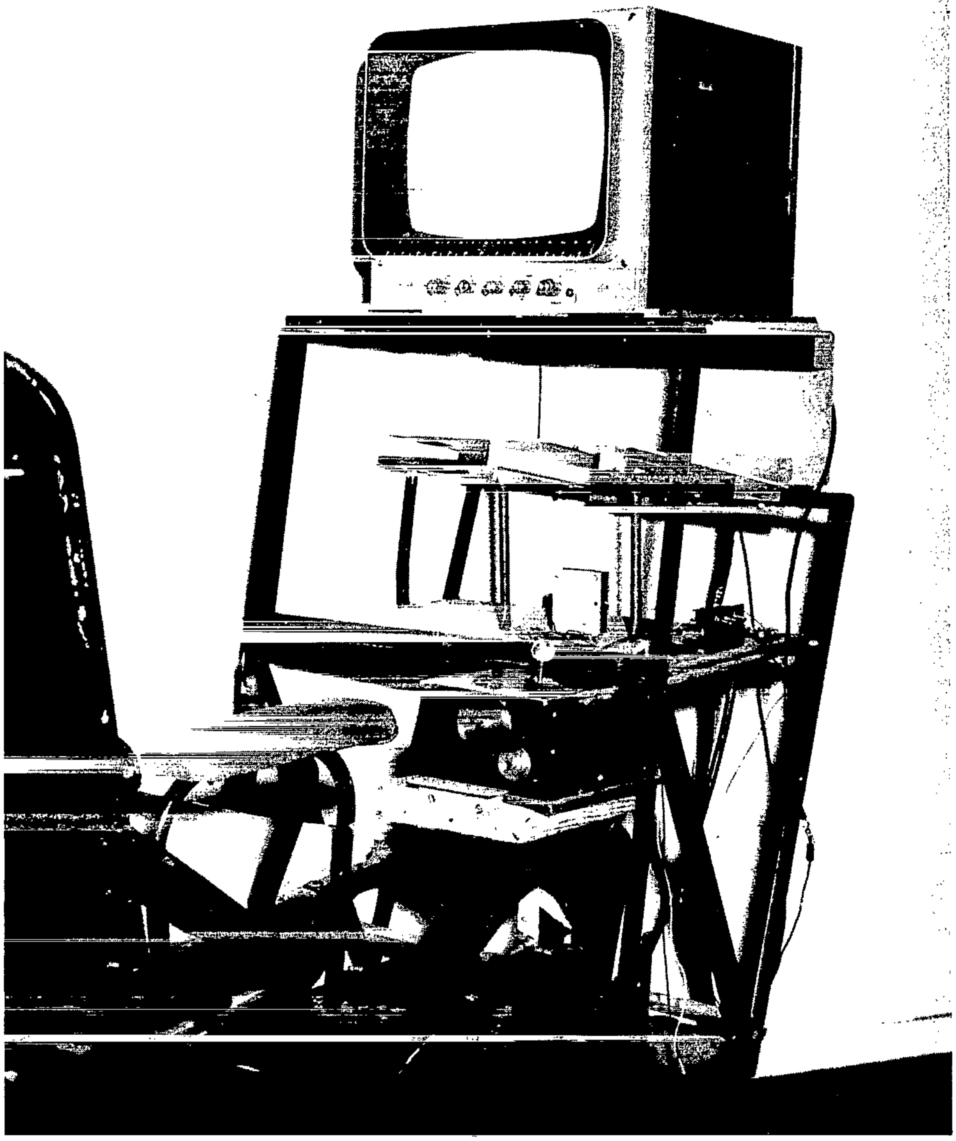


Figure 3.- Simulator used in the experiments. L-67-8201

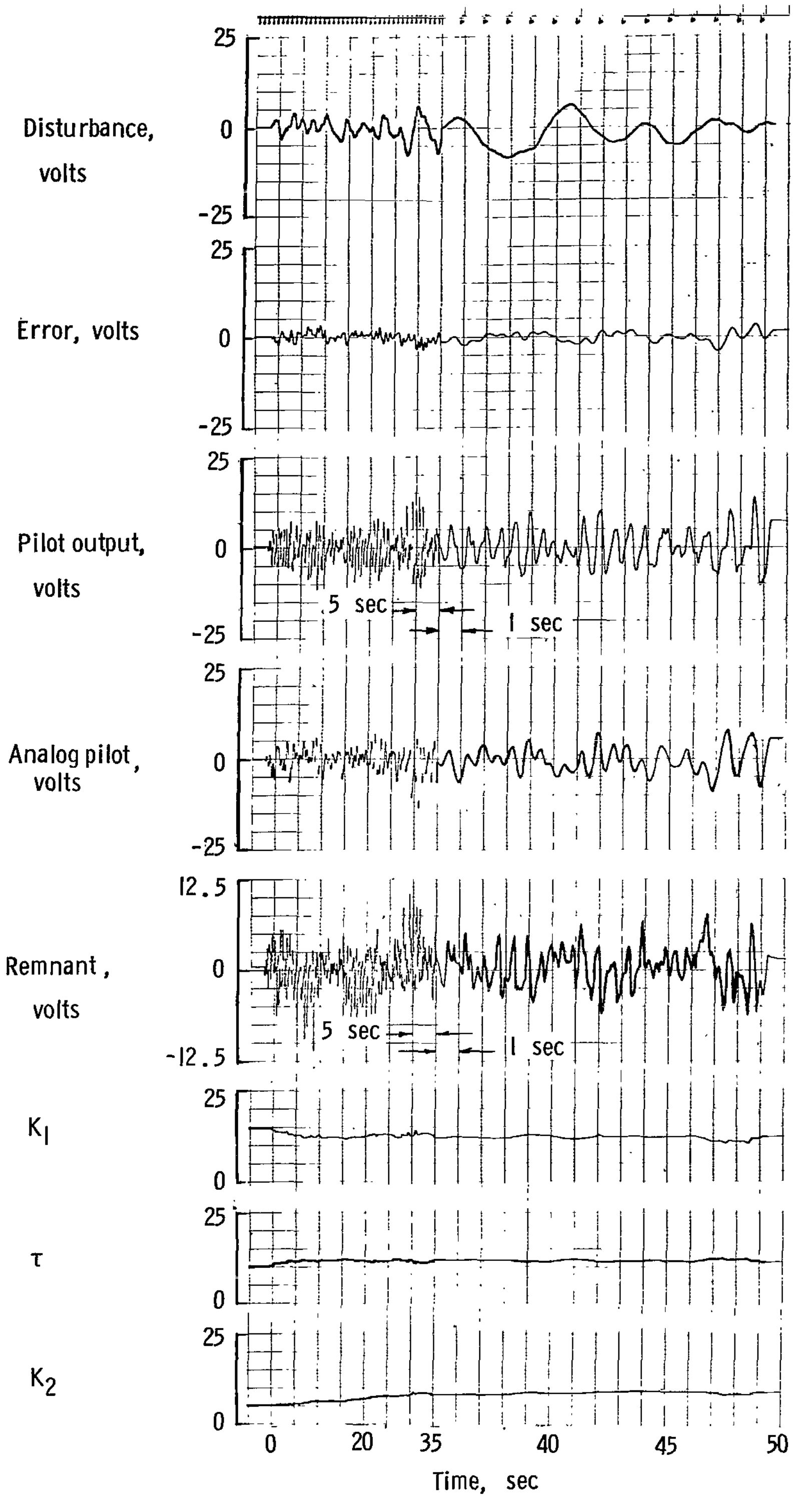


Figure 4.- Model match for subject H. Dynamics, $10/s^2$.

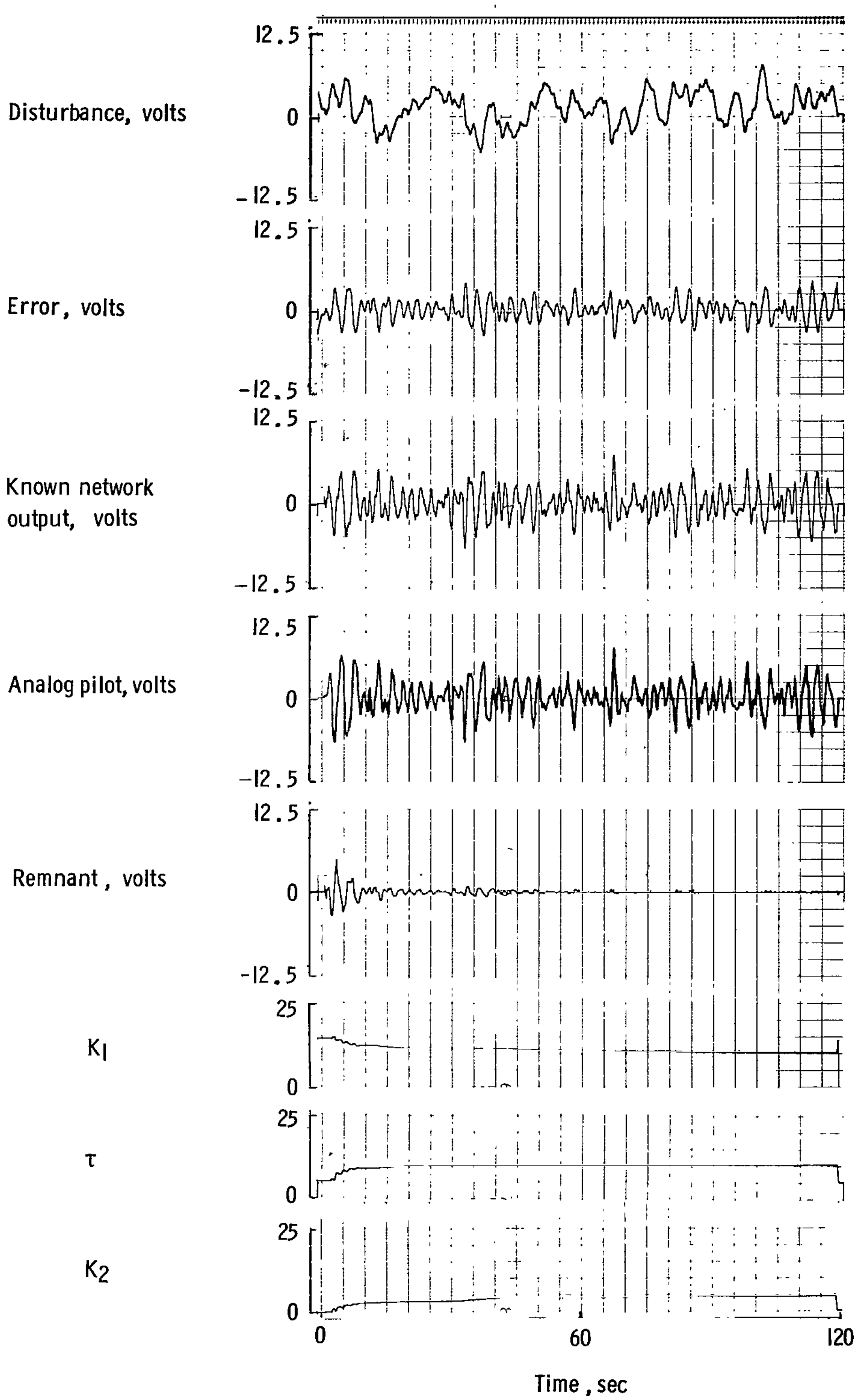


Figure 5.- Matching a known network of the same form used in the model matcher. $K_1 = 10$; $\tau = 10$; $K_2 = 5$; dynamics, $4/s^2$.

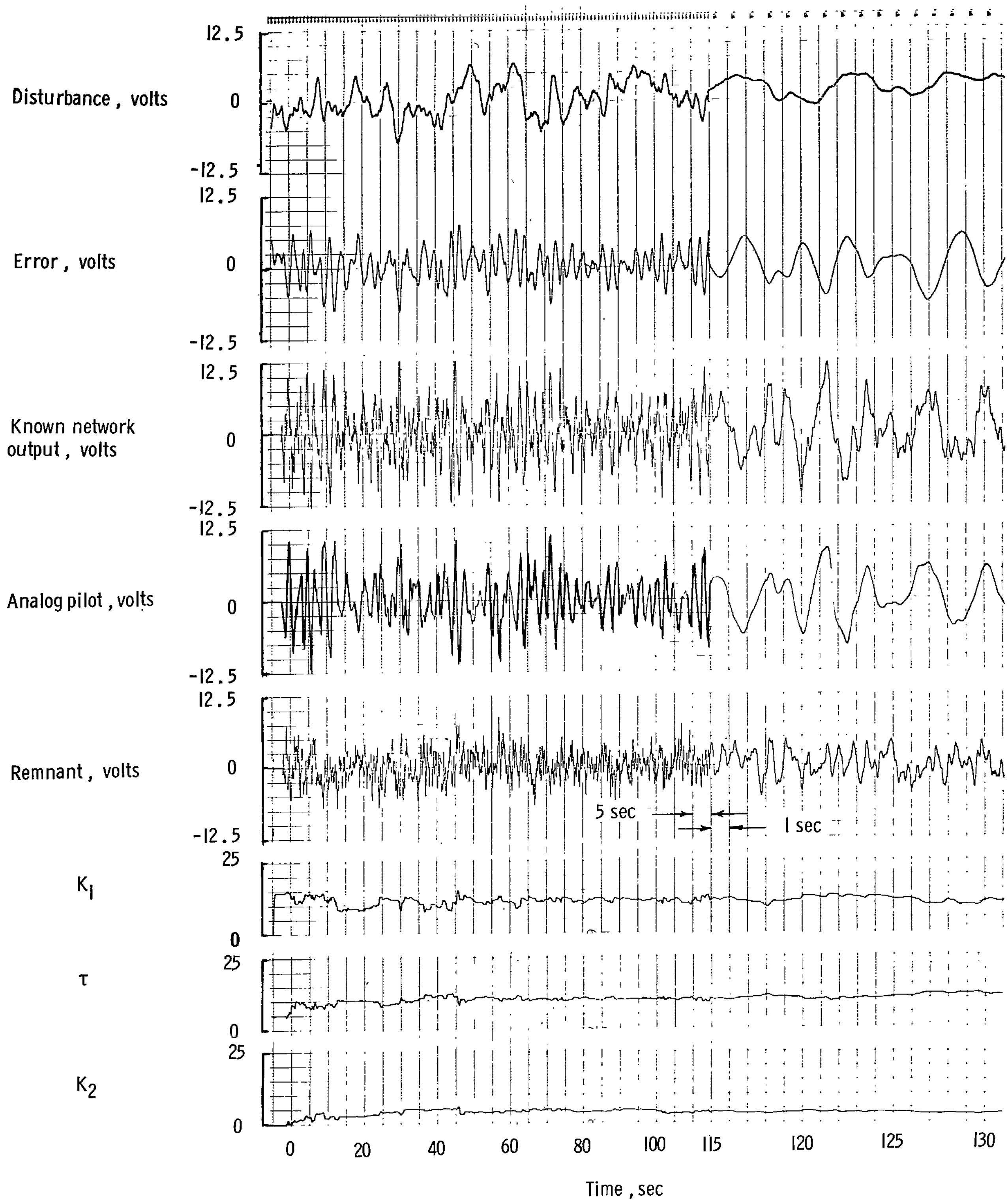


Figure 6.- Matching a known network which has a random signal added to the output. $K_1 = 10$; $\tau = 10$; $K_2 = 5$; dynamics, $4/s^2$.

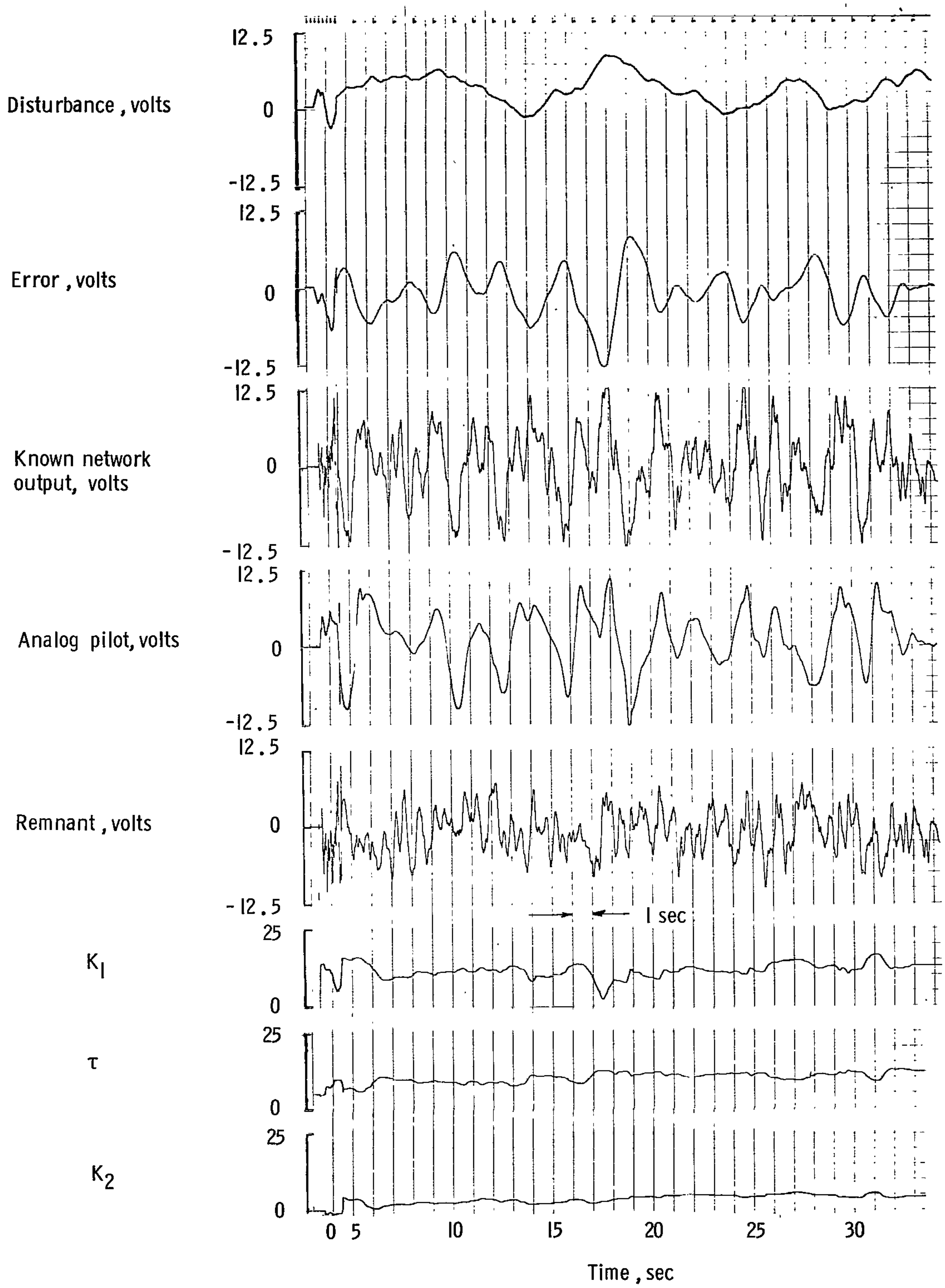


Figure 6.- Concluded.

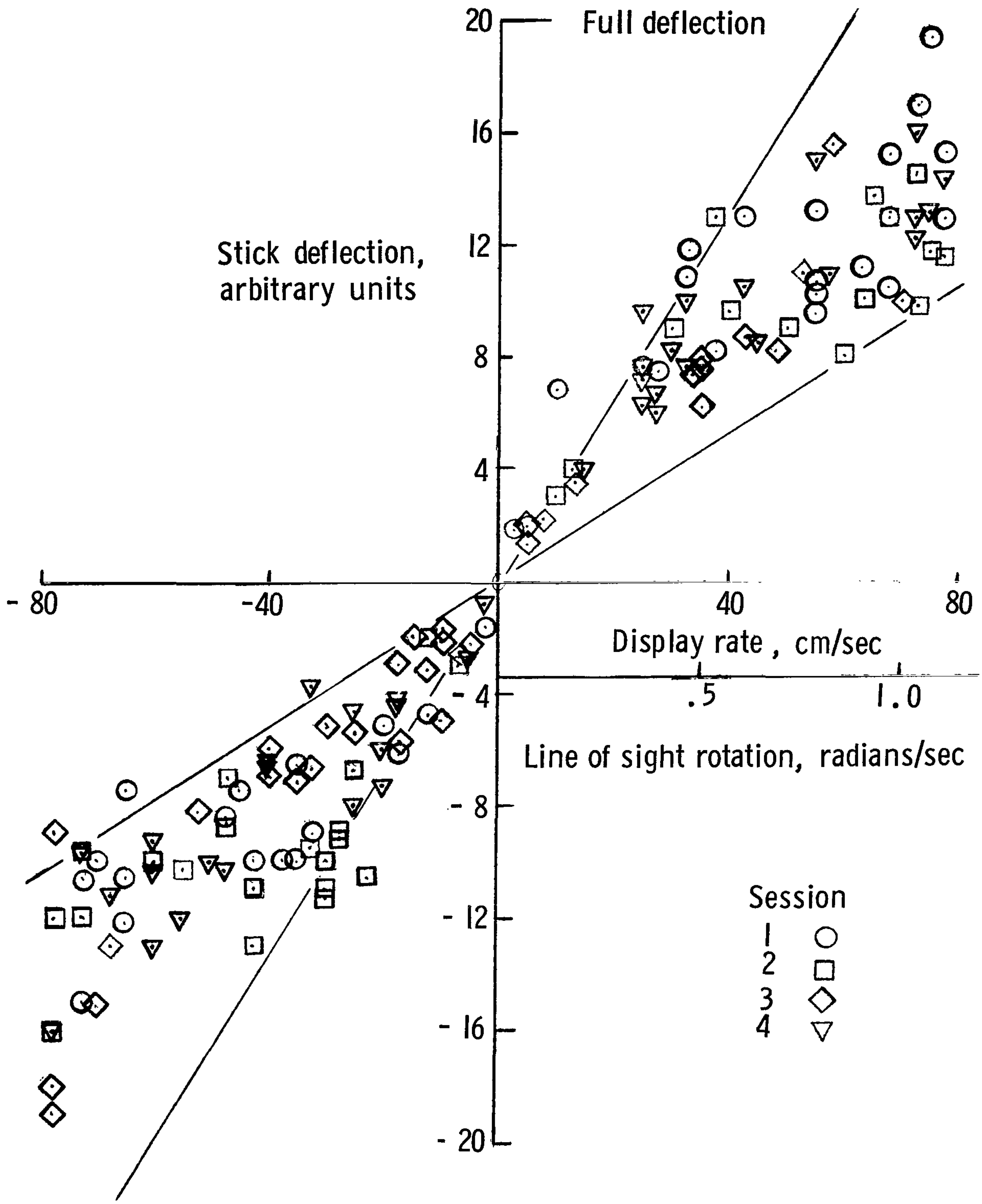
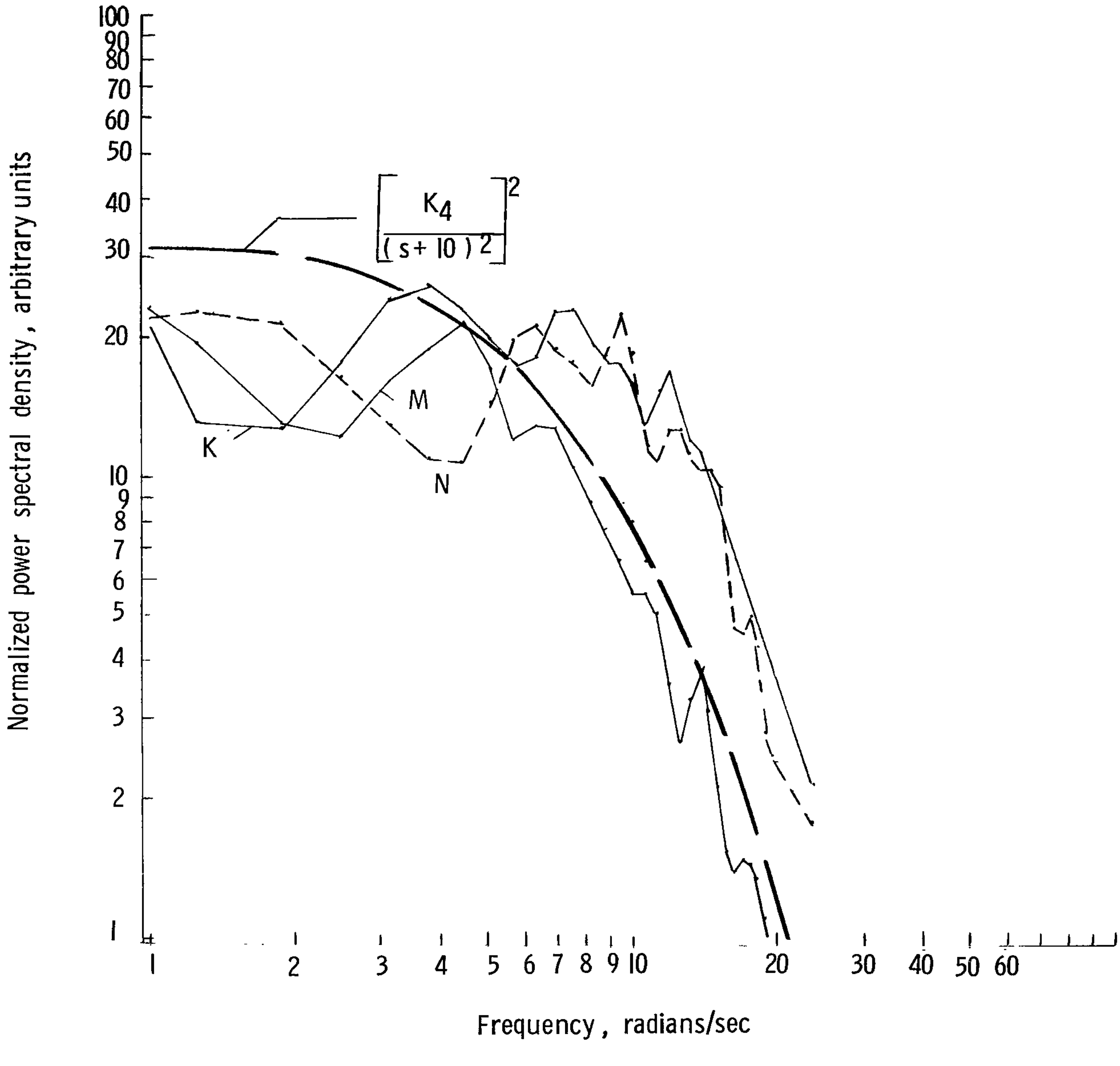
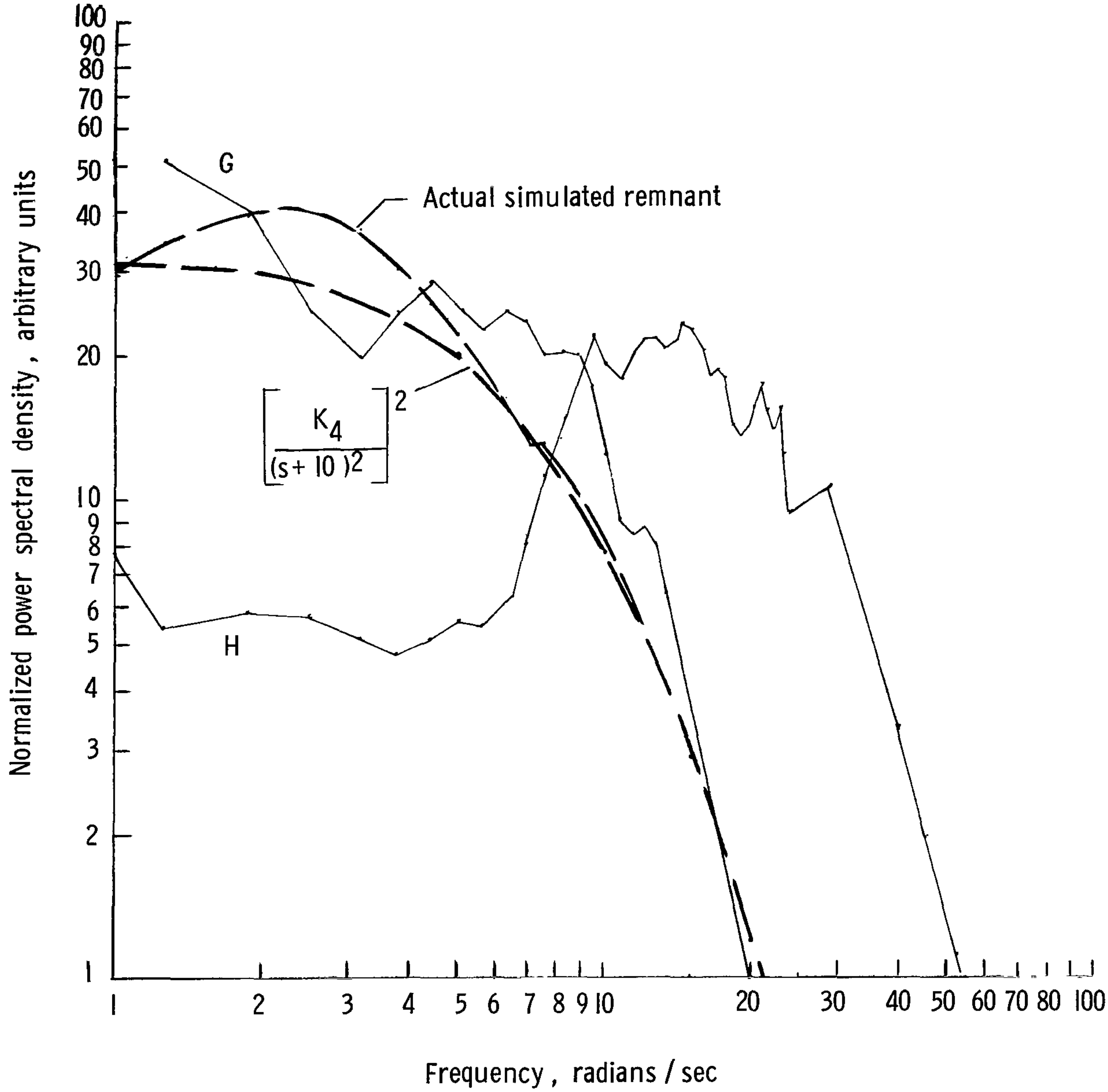


Figure 7.- Static stick deflection as a function of rate of change of display for subject M.



(a) Pilots.

Figure 8.- Power spectral density of remnant. All curves normalized to approximately the same mean-square value.



(b) Engineers.

Figure 8.- Concluded.

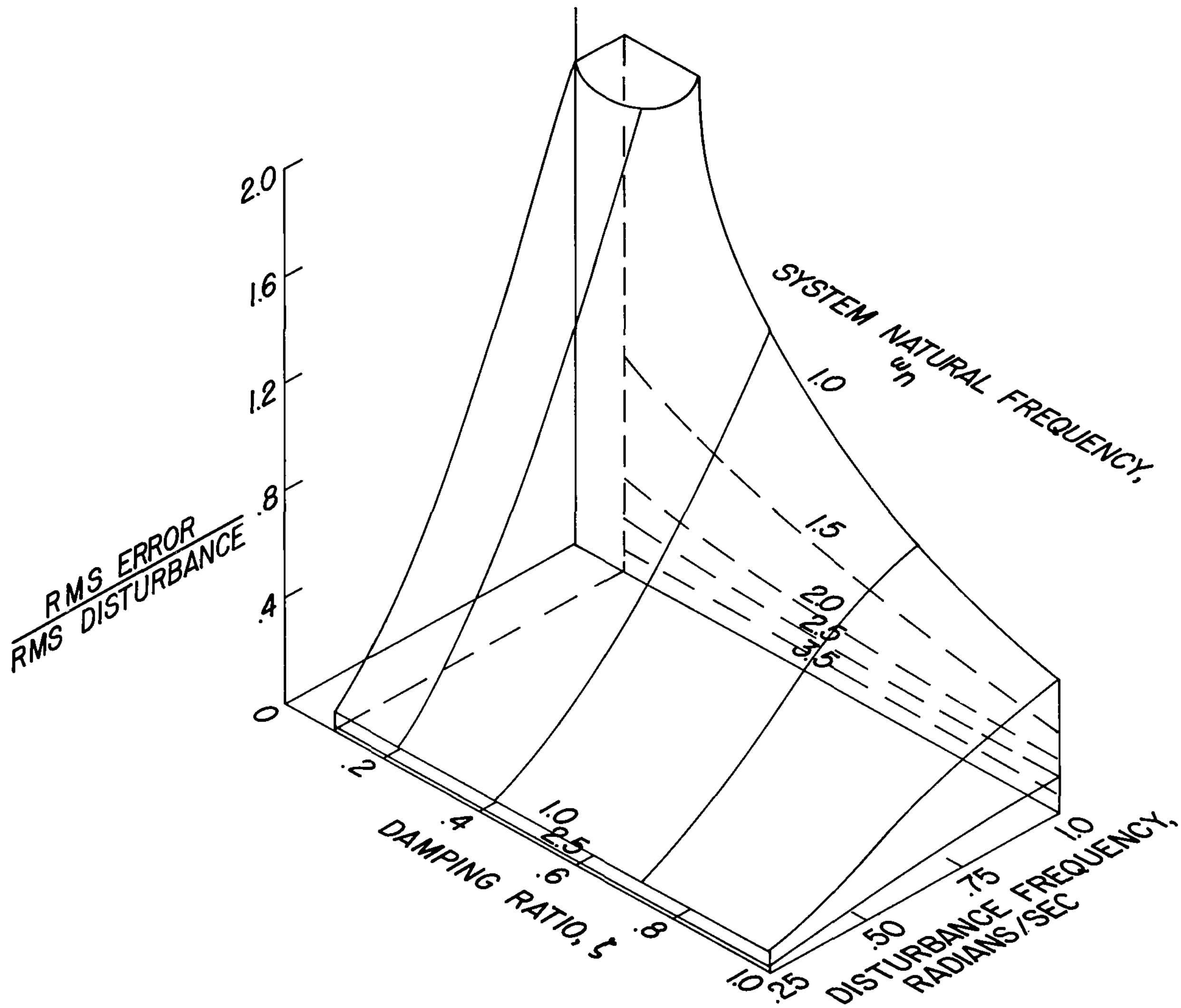
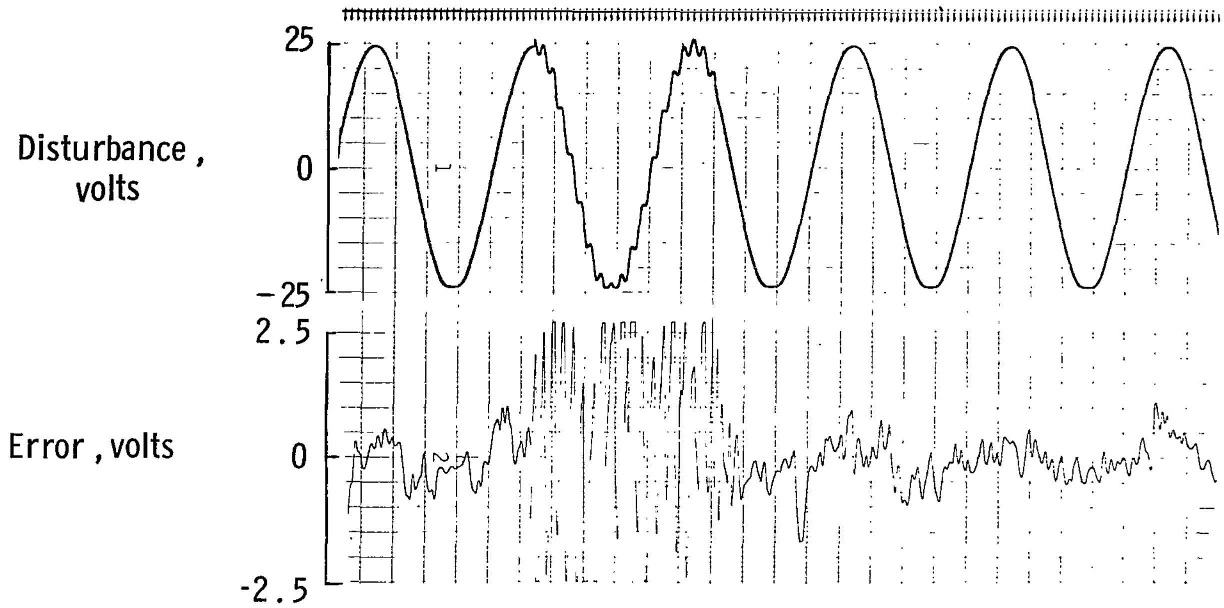
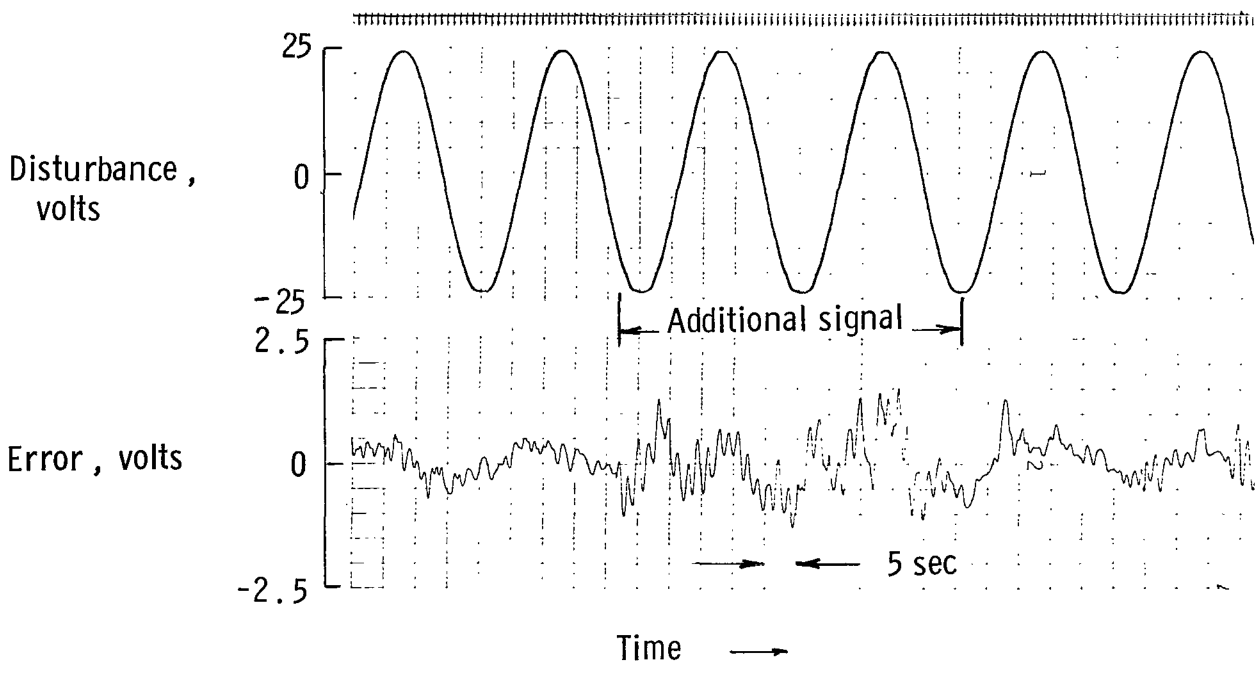


Figure 9.- Normalized system error obtained with simplified pilot model and dynamics of K/s^2 in loop. Sine-wave disturbance.

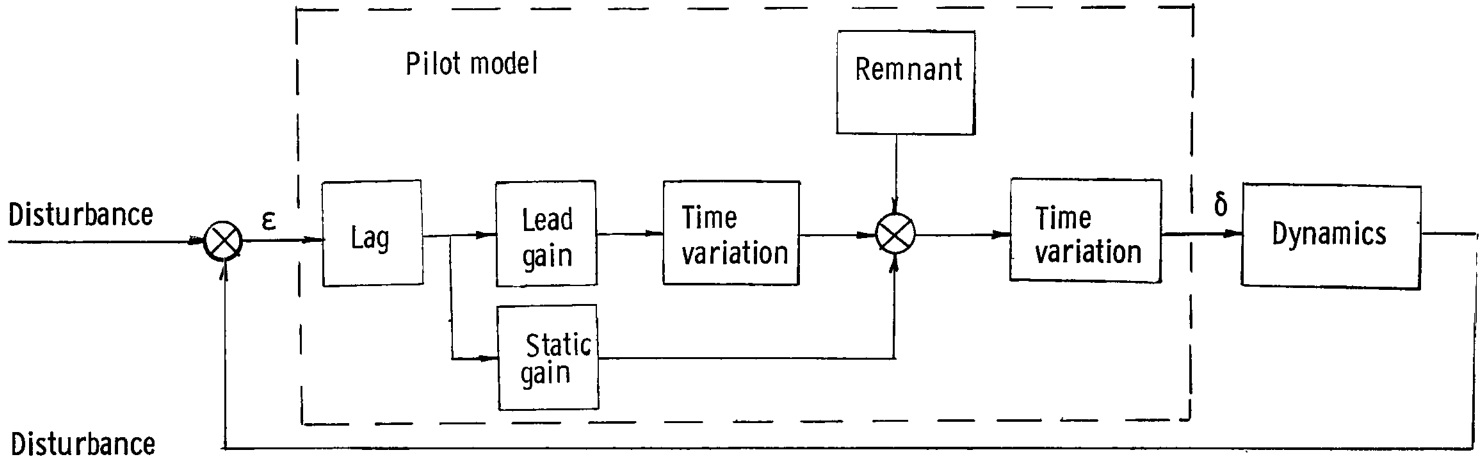


(a) D = 2 sin 4t added to D = 25 sin 0.25t.

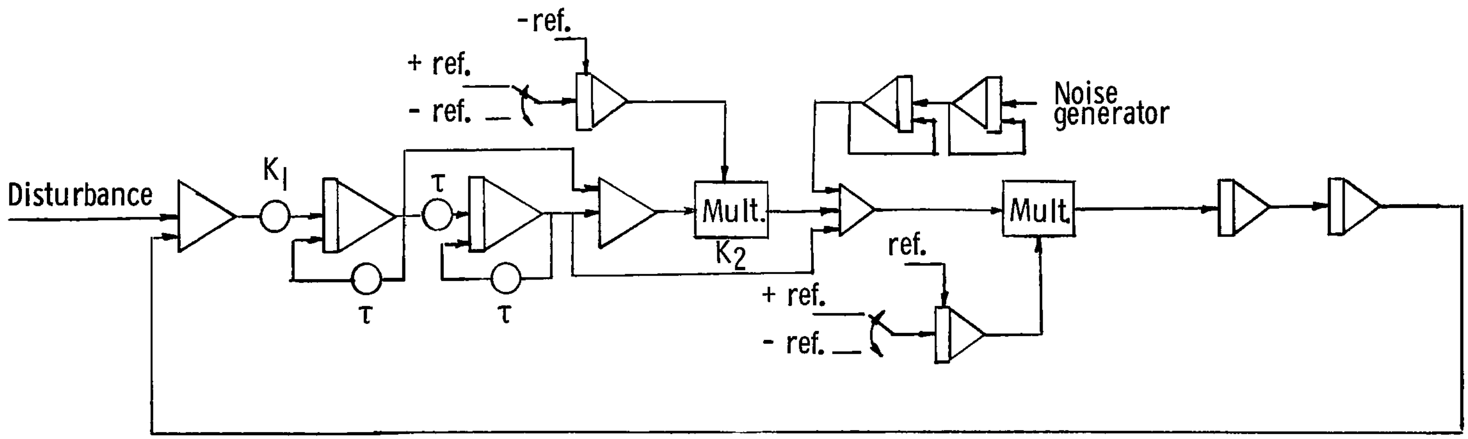


(b) D = 0.5 sin 4t added to D = 25 sin 0.25t.

Figure 10.- Illustration of effect of disturbance frequency on system error. Subject H.

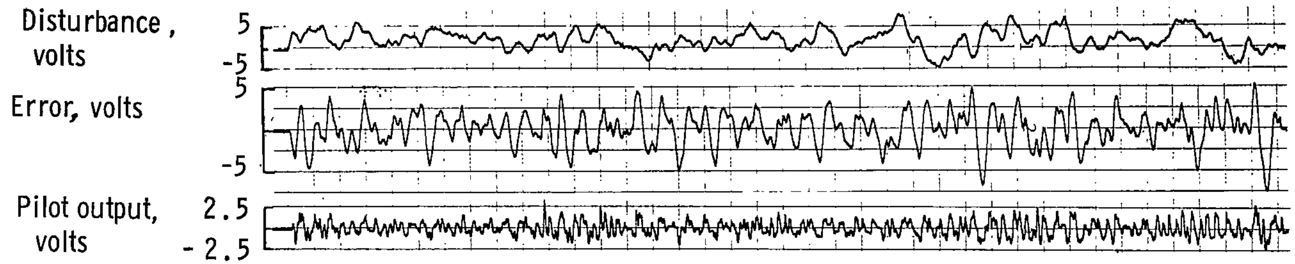


(a) Block diagram.

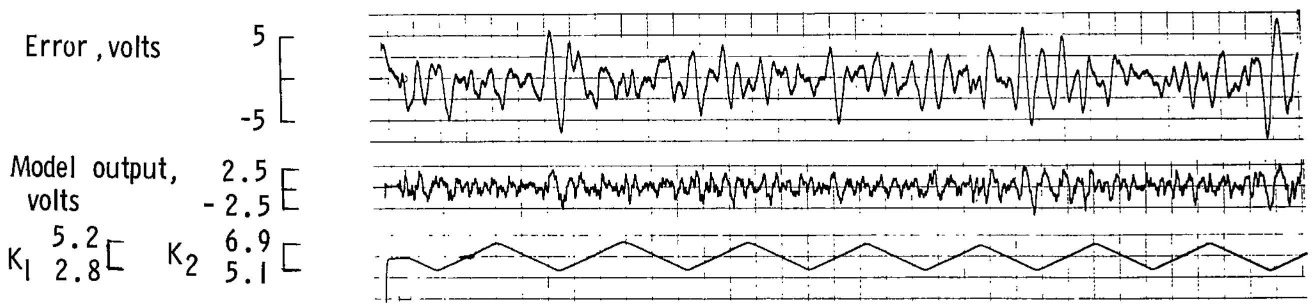


(b) Computer diagram.

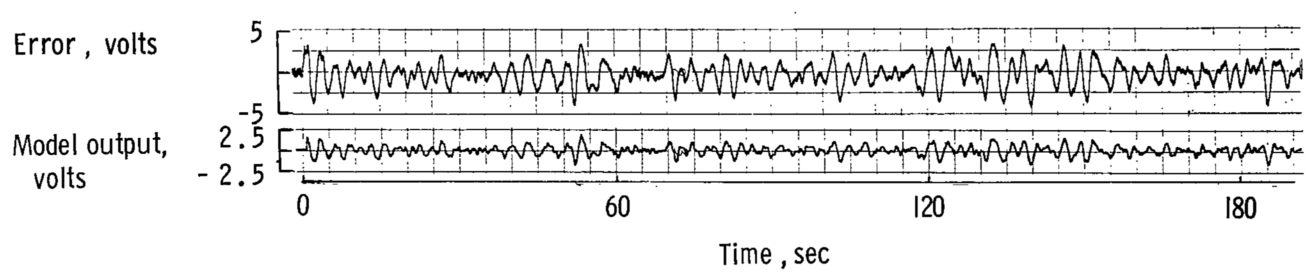
Figure 11.- Diagram of pilot model in control loop.



(a) Pilot M in control.

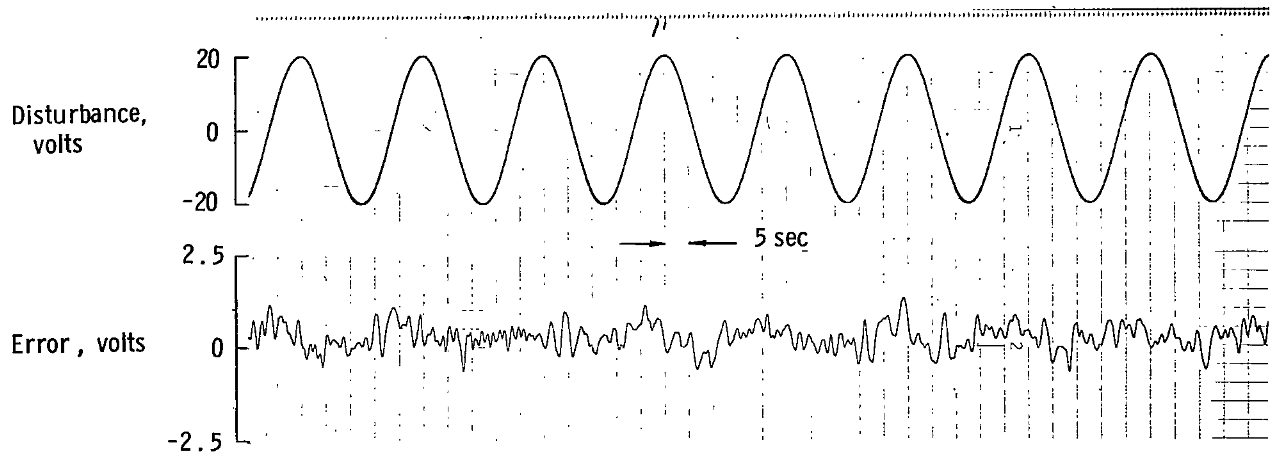


(b) Composite model in control.

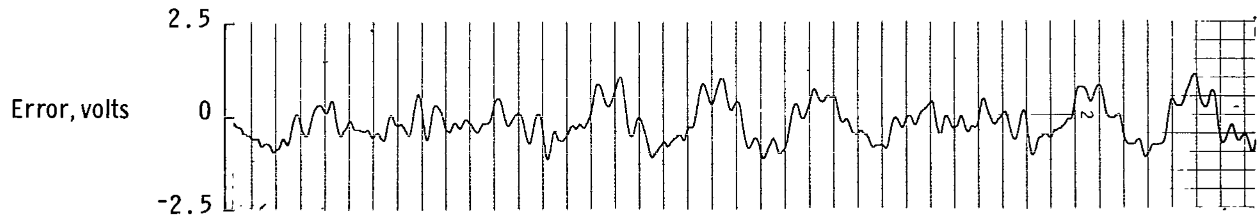


(c) Linear constant-coefficient model in control.

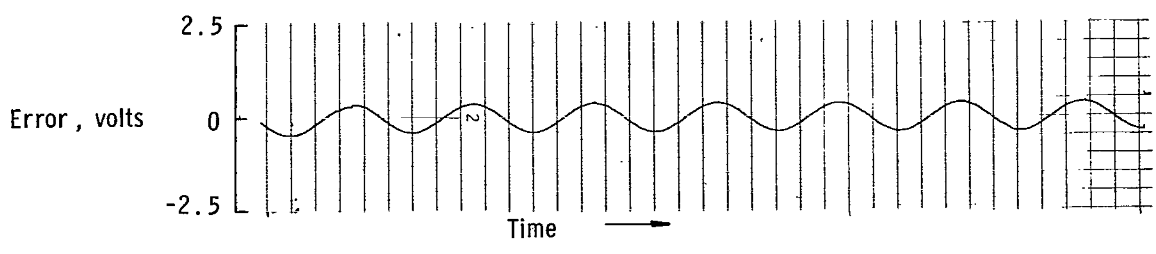
Figure 12.- System response with pilot, composite model, and linear model in control.



(a) Pilot in control.

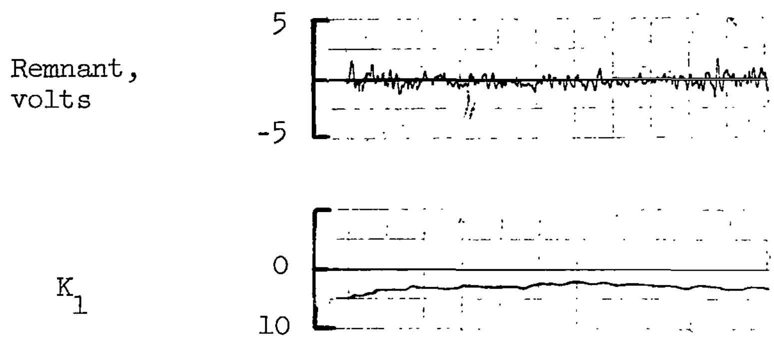


(b) Composite model in control.

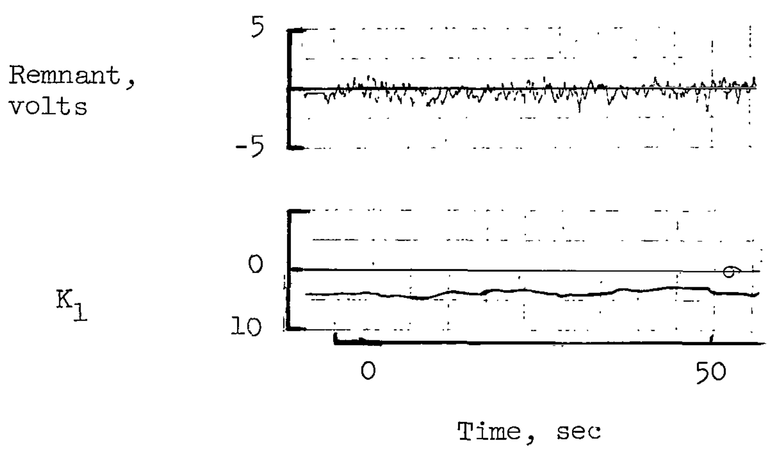


(c) Linear constant-coefficient model in control.

Figure 13.- System response with pilot, composite model, and linear model in control when disturbance is pure sine wave.

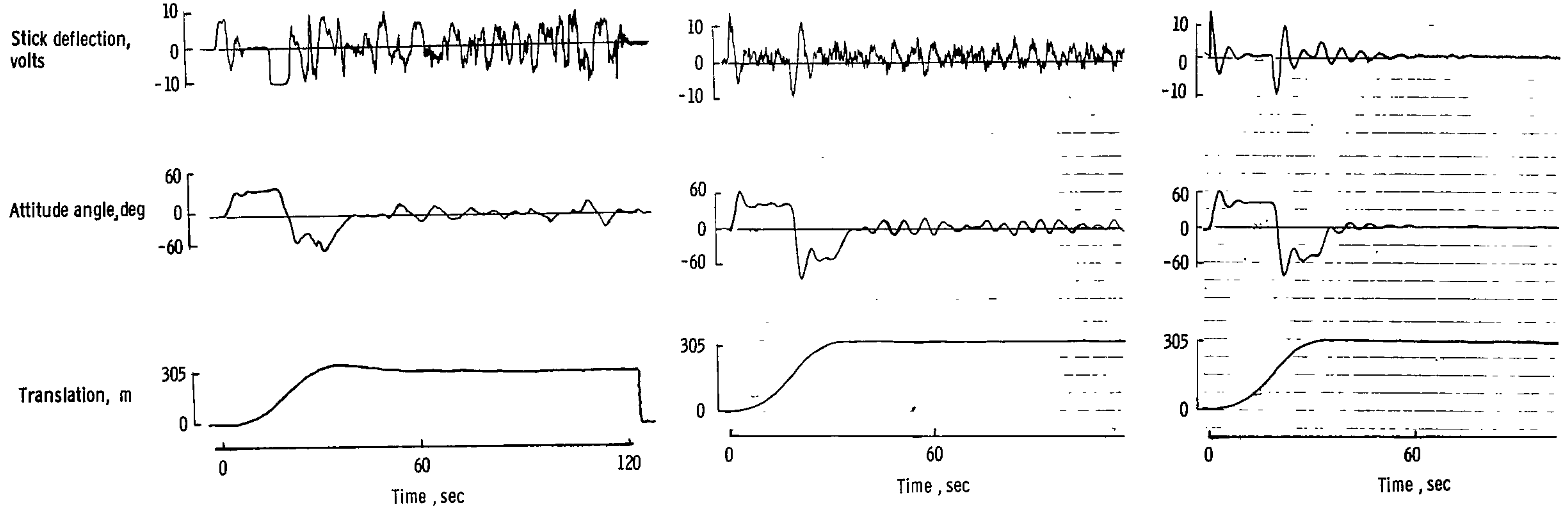


(a) Matching output of pilot.



(b) Matching output of composite model.

Figure 14.- Model match of output of pilot and of output of composite model.



(a) Pilot in control (from ref. 3).

(b) Composite model in control.

(c) Linear constant-coefficient model in control.

Figure 15.- Multiloop system response with pilot, composite model, and linear model in control. Inner-loop model: $K_1 = 16$, $\tau = 6$, $K_2 = 2.5 \pm 0.37$, plus remnant; dynamics, $\frac{0.5}{s(s + 0.5)}$. Outer-loop model: $K_1 = 0.09$, $\tau = 10$, $K_2 = 92$; dynamics, $\frac{5.36}{s^2}$.

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