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A SIMPLIFIED METHOD FOR MEASURING HUMAN TRANSFER FUNCTIONS

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SUMMARY

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An investigation has been made with a nonmoving simulator to determine the effectiveness of a simplfied method of measuring human transfer functions. The method is based on an adaptive autopilot scheme. In this method an analog pilot, which contains three variable gains, is automatically adjusted to match the human pilot. The gains are adjusted so as to minimize the root-mean-square difference between the analog pilot and the human pilot. The dynamics that the pilot controlled were varied in this investigation.

The tests demonstrated that stable determination of the transfer-function gains could be achieved. Tests in which the adjustable analog pilot was required to match a fixed-gain analog pilot resulted in accurate determination of the gains. Tests made with human subjects resulted in gains which are in general agreement with previous studies in that the lead of the pilot is increased as the lag of the controlled dynamics is increased.

INTRODUCTION

A great deal of emphasis has been placed on obtaining data, in a form useful for engineering studies, on the operational technique of human pilots in closing a control loop. Past efforts, such as those reported in references 1 to 4, have been directed toward writing linear transfer functions. A sufficiently accurate linear transfer function could be used in designing man-machine systems.

One of the difficulties in past studies has been the lengthy and complicated computations required to go from time histories of input and output of the pilot to the transfer function. This paper presents a method for automatically obtaining the desired transfer function while the experiment is being conducted. The method is demonstrated by using a nonmoving simulator with various simulated dynamics and several test pilots as subjects.

The method is derived from an adaptive autopilot scheme described in references 5 and 6. An analog pilot, with a predetermined transfer-function form and three adjustable gains, is adjusted to match the human pilot. The gains are adjusted so as to minimize the root-mean-square difference between the analog pilot and the human pilot.

References 7, 8, and 9 describe methods which are similar to the method presented in this paper. These other methods also automatically adjust coefficients in a predetermined transfer-function form. Reference 7 states that very rapid matching of fixed-gain analog pilots has been achieved and that tests with human pilots will be made. References 8 and 9 report some results of tests made with human pilots.

SYMBOLS

D	disturbance signal, volts
H	transfer function of the controlled dynamics
K_1, K_2	computer gains
K_1'	gain
K_2'	lead time constant, sec
K_3'	delay time, sec
δ	pilot output, volts
ϵ	displayed error, volts
θ	system output, volts
τ	lag frequency break point, radians/sec

APPARATUS

A block diagram of the elements used in the tests is shown in figure 1, and the simulator and computer are shown in figure 2. The equipment consisted of an oscilloscope display for presentation of the control problem to the pilot, a single-degree-of-freedom stick controller, and an analog computer. A "random" signal, produced by a dual cam device, was introduced into the display. This random disturbance caused a horizontal line presented on the oscilloscope to move plus and minus approximately 2 inches. The pilot's stick signal was passed through various simulated mechanism dynamics before it was also entered into the display. Most of the tests were of a compensatory-type tracking task, in which the disturbance and the output of the simulated dynamics were summed before being displayed. The pilot was required to keep the moving horizontal line alined with a fixed reference point on the oscilloscope. In addition, some tests were made in which the disturbance was applied to one line of a dual beam presentation and the pilot's effort was displayed on a second line. The pilot was required to keep the two lines together. These latter tests are called pursuit tracking tests.

The random disturbance was produced by two cams running at different speeds. The output of the two cams was summed by means of a geared differential. The output spectra consisted of 12 discrete frequencies, the highest of which was approximately 1 cycle per second, with approximately equal amplitudes. This cam device is the one described in reference 1 as cam D, but in the tests reported in this paper the device was probably run at a slightly slower speed than in the tests reported in reference 1.

The controller was a lightweight center-located stick. The pivot axis of the stick was supported by two ball bearings. A linear potentiometer was attached to the stick to provide the electrical signal required in the computer. The total motion of the stick was plus and minus approximately 3 inches at the top. A centering spring, which produced approximately $2\frac{1}{2}$ pounds of force at the grip at full deflection, was also included.

An analog computer was used to determine the transfer function. The method used was derived from a scheme for an adaptive autopilot described in references 5 and 6. A derivation of the theory of operation of the adaptive scheme is given in these references. The scheme is designed to obtain the least root-mean-square error between the model and the controlled plant. In applying the scheme to the present job of determining the transfer function of a pilot, the pilot is used in place of the model, and the analog pilot, which includes three adjustable gains, is used in place of the controlled plant.

A general description of the method is as follows. The signal which serves as the input to the pilot - that is, either the disturbance or the error presented on the oscilloscope - is also used as the input to the analog pilot. The output of the analog pilot and a voltage taken from the potentiometer attached to the pilot's stick are compared, and their difference is one of the signals used to change the adjustable gains in the analog pilot. The other signal required is obtained as follows. The analog pilot has three internal signal loops which, instead of being connected through fixed gains, are brought out and used as inputs to filters. These filters are duplicates of the part of the analog pilot that exists between the summation points of the signals being considered and the output of the analog pilot, except that the gains in the filters are fixed. The output of each particular filter, then, has the characteristics of the contribution that the signal under consideration makes to the total output of the analog pilot. This filter output is multiplied by the difference between the output of the pilot and the output of the analog pilot, mentioned previously. If these two signals are in phase, in either a plus or minus sense, the product will have some finite value. This product is integrated, and the output of the integrator is used to drive a servo potentiometer which adjusts the gain of the signal so as to reduce the difference. The filter section of the computer was repeated three times to obtain three variable coefficients.

A complete diagram of the analog pilot, filters, and servo potentiometer is shown in figure 3. Note that τ occurs in three locations in the analog pilot, but only one filter was used for τ. A discussion of the formulation of the filters is given in the appendix.

It was shown in reference 1 that one form of the transfer function which could be used to describe the output of a human operator with fair accuracy is

$$\frac{K_1'\left(1 + K_2's\right)}{\left(1 + \frac{1}{\tau} s\right)^2} e^{-K_3's} \tag{1}$$

In the present study the time-delay term $e^{-K_3's}$ was omitted, and just the remaining linear portion of the transfer function was used. It was not feasible to obtain this exact form with analog computer equipment. Instead, the following form was used:

$$\frac{K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{\left(\tau + s\right)^2} \tag{2}$$

When numerical results are summarized in this report, the results are given in the following form:

$$\frac{\frac{K_1}{\tau}\left(1 + \frac{K_2}{\tau} s\right)}{\left(1 + \frac{1}{\tau} s\right)^2} \tag{3}$$

where K_1/τ is the static gain, which has the units of volts per volt in these tests, K_2/τ is the lead time constant which has the units of seconds, and $1/\tau$ is the lag time constant which has the units of seconds.

TESTS AND ANALYSIS

Initial tests were made to check the accuracy and stability of the method. Tests were made in which the adjustable-gain analog pilot was required to match a fixed-gain analog pilot which had a form identical to that of the adjustable-gain analog pilot. A variety of initial values were used for the gains in the adjustable-gain analog pilot, and a variety of input signals (random, step, and sine-wave) were used.

The nonmoving single-degree-of-freedom simulator was then used with four experienced test pilots and a research engineer as subjects. The simulated dynamics that the pilot had to control were varied and included first-order lags, a second-order oscillatory system, and a rate system with no lag (a pure integrator). The same random disturbance signal mechanism was used in all the tests. The maximum output of the control stick was adjusted so that the pilot did not have to use full stick deflection at any time.

In previous studies in which human transfer functions have been determined, the function has usually been that which relates pilot output to displayed error. In the present study the function that is determined is, in most cases, the function relating pilot output to the disturbance signal. Only in the case of the rate mechanism is the displayed error used as the input to the analog pilot. In the other cases, in which the simulated dynamics did not contain a free integrator, the disturbance signal was used as the input to the analog pilot. The different functions determined in these tests can, therefore, be compared only in a qualified sense.

A meaningful comparison can be made between the various complete closed-loop-system (pilot-plus-dynamics) responses to the disturbance. In this way a comparison can be made on the basis of the characteristics that the pilot creates in the complete system by adapting his control technique. For example, in the case of the oscillatory dynamics in which the function relating pilot output to disturbance signal is determined, the closed-loop-system response function can be derived as follows:

$$\frac{\delta}{D} = \frac{K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{(\tau + s)^2}$$

$$\frac{\theta}{\delta} = \frac{10}{s^2 + 3s + 10}$$

where

δ pilot output

D disturbance signal

θ system output

Therefore

$$\frac{\theta}{D} = \frac{10K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{(s^2 + 3s + 10)(\tau + s)^2} \tag{4}$$

In the case of the rate mechanism, in which the function relating pilot output to displayed error is determined, the closed-loop-system response function can be derived as follows:

$$\frac{\delta}{\epsilon} = \frac{K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{(\tau + s)^2}$$

$$\frac{\theta}{\delta} = \frac{2}{s}$$

$$\epsilon = D - \theta$$

where ϵ is displayed error. Therefore

$$\frac{\theta}{D} = \frac{2K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{s^3 + 2\tau s^2 + \left(\tau^2 + 2K_1K_2\right)s + 2K_1\tau} \tag{5}$$

This method is used for comparison in this report.

It is also possible to relate the function δ/D to the function δ/ϵ by the formula

$$\frac{\delta}{\epsilon} = \frac{\delta/D}{1 - \frac{\delta}{D} H} \tag{6}$$

where H is the transfer function of the controlled dynamics.

RESULTS

The method of adjusting the variable gains was checked by having the adjustable-gain analog pilot match a similar fixed-gain analog pilot. Sample results of this type of test are shown in figure 4. The fixed-gain pilot was set up with the following gain settings: $K_1 = 10$, $K_2 = 10$, and $\tau = 10$ radians/sec. The adjustable-gain analog pilot was given initial gain settings as follows: $K_1 = 5$, $K_2 = 7$, and $\tau = 5$ radians/sec. The gains K_2 and τ also appear in the filters and are not varied during a given test. The gain settings in these filter locations were the same as the initial gain settings for the analog pilot - that is, $K_2 = 7$ and $\tau = 5$ radians/sec.

Shown in figure 4 is the disturbance used, the fixed-gain-pilot response, the analog-pilot response, and the difference between the responses of the two pilots. The disturbance used in this test was produced manually rather than by the cam device mentioned previously. The difference is relatively large at first, and is reduced as the gains are adjusted to the proper values. Shown in the second part of the figure are the adjustments of the gains. Within 15 seconds an overshoot of 10 percent occurs for K_2, and τ changes from 5 to 8 radians/sec. Very little adjustment occurs in K_1 at first, but at the end of $1\frac{1}{2}$ minutes K_1 is at 90 percent of the correct value and it remains at this setting for the rest of the run. Also, at $1\frac{1}{2}$ minutes K_2 and τ have reached the correct values, and they remain at these values for the rest of the run.

These results are typical. In additional tests sinusoidal inputs with frequencies as high as 10 cycles per second and as low as 0.5 cycle per second were used, with a variety of initial gain settings and filter gain settings. Stable results were achieved in all these tests. Disturbance frequencies higher than 10 cycles per second and lower than 0.1 cycle per second sometimes produced instabilities. The tests also indicated that, in general, the closer the filter gains were set to the correct values, the more accurate the final adjustment of the analog pilot gains would be.

A computer check with no pilot is shown in figure 5. In this case K_1 adjusts to zero in 20 seconds. After this time there is no further output from the analog pilot, the difference is zero also, and K_2 and τ remain at the values that existed when K_1 became zero.

As a matter of interest, it should be pointed out that in the tests in which a fixed-gain analog pilot was matched, much more rapid gain adjustments than those just mentioned were achieved by using high gains on the gain-adjustment integrators. Changes similar to those shown in figure 4 were achieved in 2 seconds. However, in order to maintain stability in the computation of the gains when attempting to match a human pilot, it was necessary to reduce these integrator gains. The tests presented in figures 4 and 5 incorporate integrator gains that could be used when matching a human pilot. These integrator gains were 3 volts per volt-second.

A series of tests was made using experienced NASA research test pilots as subjects. The pilots operated a series of dynamics ranging from a first-order system with a short time lag (0.4 second) up to a second-order oscillatory mechanism with a natural frequency of 3.16 radians per second and a damping ratio of 0.47. These tests were all done with a compensatory tracking display and the pilots were instructed to keep the moving line as close to the reference point as possible. The disturbance used in these tests created a difficult piloting task. The pilots were given a 3-minute practice run, and records were made of their second run.

In this series of tests no pure integrator was included in the dynamics; the disturbance signal, rather than the error presented on the oscilloscope, was used as the input to the analog pilot. Attempts to use the presented error resulted in a divergent instability in the adjustable gains.

The results of these tests are summarized in table I. The computer scaling in these tests was such that a perfect tracking performance would result in a static gain of 1. It can be seen that with the short time constant $\left(\text{dynamics of } \frac{2.5}{s + 2.5}\right)$ the transfer function of the pilots does show a static gain of approximately 1. As the lag of the simulated dynamics is increased, the lead time constant is increased. In general, the static gain and the lag time constant were very nearly the same for all of the pilots for each of the dynamics. The lead time constant shows more variation among the different subjects, with one pilot choosing to employ no lead whatsoever.

Examples of the time histories from which the values shown in table I were obtained are shown in figures 6 to 9. The values used in table I are average values taken from the time histories after the necessary adjustments have been completed. In general it can be seen that the adjustable gains stabilize about some mean value after approximately 1 minute.

The fact that results could be obtained by using the disturbance as the input to the analog pilot suggests that the pilot is actually responding to the disturbance rather than the displayed error with these dynamics. Figure 6 shows that the pilot's output does closely match the disturbance when the dynamics is a short first-order lag. With this dynamics, close matching between the disturbance and the pilot's output is necessary to keep the error small. As the lag of the dynamics is increased, the correlation between the pilot's output and the disturbance disappears. It can also be seen from the figures that the difference between the pilot and the analog pilot is larger for the case of the oscillatory dynamics than for the case of the short time lag.

A wider number of variations in dynamics were investigated with a research engineer as the subject, and the results are presented as a matter of interest. These tests included a rate mechanism, or pure integrator. Pursuit tracking, as well as compensatory tracking, was also tried for all dynamics.

In the tests with the rate mechanisms it was necessary to use the display signal - that is, the difference between the disturbance and the output of the dynamics - as the input to the analog pilot, instead of the disturbance itself. Attempts to use the disturbance resulted in a divergent instability in the adjustable gains. This was true for the compensatory display, in which only the error was displayed to the pilot, and also for the pursuit display, in which both disturbance and error were presented. For the dynamics that did not include a free integrator, the disturbance was used as the input to the analog pilot for both the compensatory and the pursuit display. It was, therefore, the presence or absence of a free integrator in the dynamics that dictated which input to use for the analog pilot.

Results of these additional tests are summarized in table II. Sample time histories are shown in figures 10 to 13. The tests with the rate mechanism show a still further increase in the lead time constant over the oscillatory dynamics tests. The lag time constant is also increased.

A comparison of the compensatory and pursuit tracking can also be made. (See table II.) A large difference occurred between the transfer functions for compensatory and pursuit tracking with the oscillatory mechanism. In the pursuit tracking case the lead time constant and the lag time constant are greater than for the compensatory tracking case. In contrast, the differences are smaller for no dynamics and rate dynamics, although the lead time constant is increased for the rate-dynamics pursuit tracking.

To provide further comparison between the results obtained with the oscillatory system and the rate system, frequency-response plots for the complete closed-loop system in each of these two cases, with compensatory tracking, are shown in figure 14. The results are similar in that an amplitude ratio of approximately 0.8 exists at frequencies of 3 to 4 radians per second, falling off rapidly at higher frequencies. This type of result might be expected with the oscillatory dynamics, since the characteristics of this response are very similar to the characteristics of the oscillatory dynamics alone. However, in the case of the rate mechanism these resulting characteristics are due to either the pilot's choice or limitations.

There is no reasonable explanation for the low-frequency droop shown for the oscillatory-dynamics case. Similar results were obtained in tests reported in reference 10 in which the subjects controlled a simple mechanism (dynamics of 1).

As was stated previously, no time delay was included in the analog pilot in the tests reported in this paper. A few tests were made in which a fourth-order Padé approximation for a time delay was included, but no positive results were achieved. With a fixed delay time of 0.2 second the difference between the pilot and analog pilot was greater than the difference obtained with no time delay. A time delay of 0.1 second did not decrease the difference. Therefore, the time delay was not included in any further tests.

Results obtained with the method described in this paper demonstrate some apparent advantages over the results presented for the methods described in references 7, 8, and 9. Reference 7 describes the adjustment of only one coefficient in each separate test. The method of reference 8 provides two adjustable coefficients. The method of reference 9 provides for four adjustable parameters, but requires two iterative runs, in which the initial values of the coefficients are set at the final values obtained in the previous run, to close on a fixed-gain analog pilot. It is not as yet possible to make direct comparisons of the results of all the different methods so as to come to some conclusion as to which is the best. Further experience and tests with human subjects will be needed to arrive at any such conclusions.

CONCLUDING REMARKS

The tests reported in this paper were made to demonstrate the effectiveness of a simplified method for determining the transfer function of a human operator. The method results in a stable determination of the variable gains in the transfer function. It is therefore concluded that the method can be used satisfactorily. No analysis is made of the numbers obtained in the tests. However, it can be shown that the measured trends are in agreement with past experience in that the lead of the pilot is increased as the lag of the controlled dynamics is increased.

Further improvement on the method is needed to increase the speed with which the adjustable gains are varied. Also, it should be determined whether changing the form of the transfer function, or adding to it, will improve the fit of the analog pilot to the human pilot.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 8, 1963.

APPENDIX

FORMULATION OF THE FILTERS

Reference 5 points out that the filters are formulated by multiplying the transfer function of the plant by the inverse of the transfer function up to the summation point for the signal being considered. Thus the filters for K_1 and τ are as follows:

$$\frac{K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{(s + \tau)^2} \frac{1}{K_1} = \frac{\tau\left(1 + \frac{K_2}{\tau} s\right)}{(s + \tau)^2}$$

The K_2 filter is formulated as follows. The transfer function at the point in the analog pilot immediately following the K_2 gain is

$$\frac{K_1K_2s}{(s + \tau)^2}$$

The filter for K_2 is, then,

$$\frac{K_1\tau\left(1 + \frac{K_2}{\tau} s\right)}{(s + \tau)^2} \frac{(s + \tau)^2}{K_1K_2s} = \frac{\tau}{K_2s} + 1$$

There was some question as to whether the integrator indicated above should really be included in the K_2 filter. In some of the preliminary tests, in which the analog pilot was matched to a fixed-gain analog pilot, runs with this integrator in and out gave the same results. The integrator was therefore left in for the present tests. It was later determined that this integrator should be omitted. Further tests will be made with the integrator omitted.

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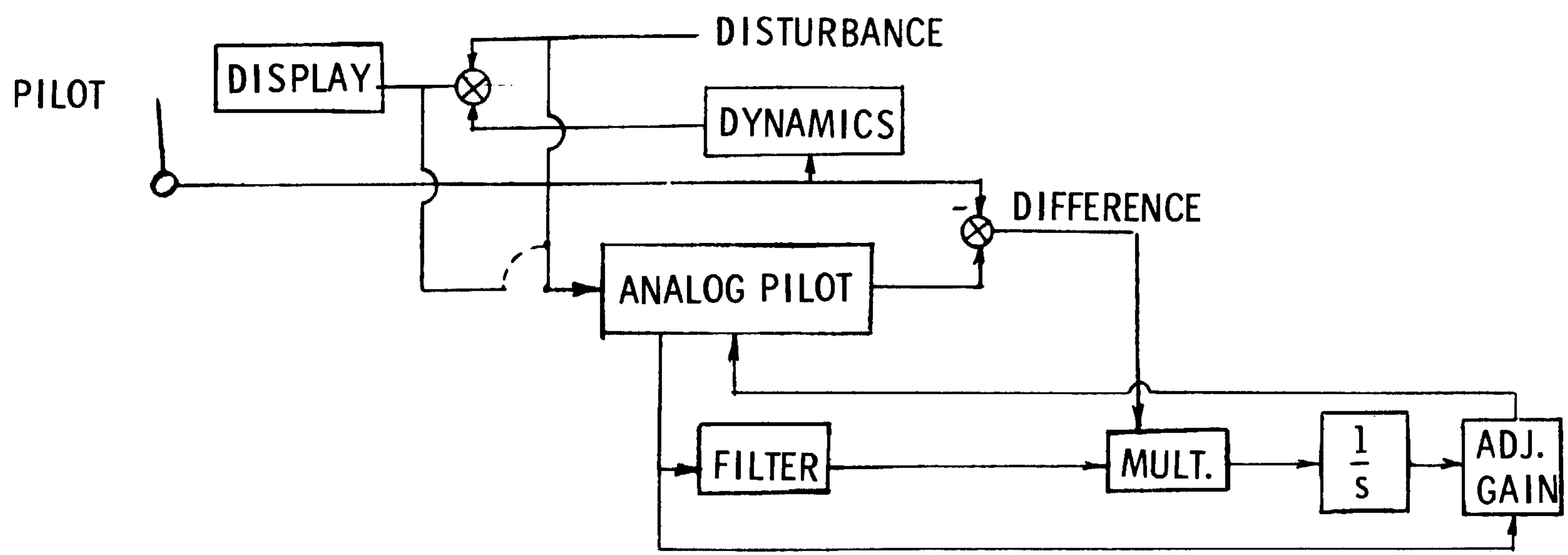
TABLE I.- SUMMARY OF TESTS MADE WITH EXPERIENCED TEST PILOTS

Dynamics	Measured transfer function for -			
	Pilot A	Pilot B	Pilot C	Pilot D
$\frac{2.5}{s + 2.5}$	$\frac{\delta}{D} = \frac{1(1 + 0.38s)}{(1 + 0.12s)^2}$	$\frac{\delta}{D} = \frac{0.91(1 + 0.18s)}{(1 + 0.091s)^2}$		
$\frac{1}{s + 1}$	$\frac{\delta}{D} = \frac{1.1(1 + 0.55s)}{(1 + 0.11s)^2}$	$\frac{\delta}{D} = \frac{1.4(1 + 0.3s)}{(1 + 0.1s)^2}$	$\frac{\delta}{D} = \frac{0.88(1 + 0.13s)}{(1 + 0.13s)^2}$	$\frac{\delta}{D} = \frac{0.5}{(1 + 0.083s)^2}$
$\frac{10}{s^2 + 3s + 10}$	$\frac{\delta}{D} = \frac{0.33(1 + 1.25s)}{(1 + 0.083s)^2}$	$\frac{\delta}{D} = \frac{0.33(1 + 0.53s)}{(1 + 0.067s)^2}$	$\frac{\delta}{D} = \frac{0.31(1 + 0.76s)}{(1 + 0.077s)^2}$	$\frac{\delta}{D} = \frac{0.5}{(1 + 0.083s)^2}$

TABLE II.- SUMMARY OF TESTS MADE WITH RESEARCH ENGINEER

Dynamics	Measured transfer function for -	
	Compensatory tracking	Pursuit tracking
1	$\frac{\delta}{D} = \frac{0.83}{(1 + 0.083s)^2}$	$\frac{\delta}{D} = \frac{0.73}{(1 + 0.09s)^2}$
$\frac{10}{s^2 + 3s + 10}$	$\frac{\delta}{D} = \frac{0.33(1 + 0.83s)}{(1 + 0.083s)^2}$	$\frac{\delta}{D} = \frac{0.25(1 + 3.0s)}{(1 + 0.25s)^2}$
$\frac{2}{s}$	$\frac{\delta}{\epsilon} = \frac{0.33(1 + 3.3s)}{(1 + 0.33s)^2}$	$\frac{\delta}{\epsilon} = \frac{0.33(1 + 4.0s)}{(1 + 0.33s)^2}$



ANALOG-PILOT FORM, $\dfrac{K_1\tau\left(1+\dfrac{K_2}{\tau}s\right)}{(\tau+s)^2}$

Figure 1.- Block diagram of test equipment.

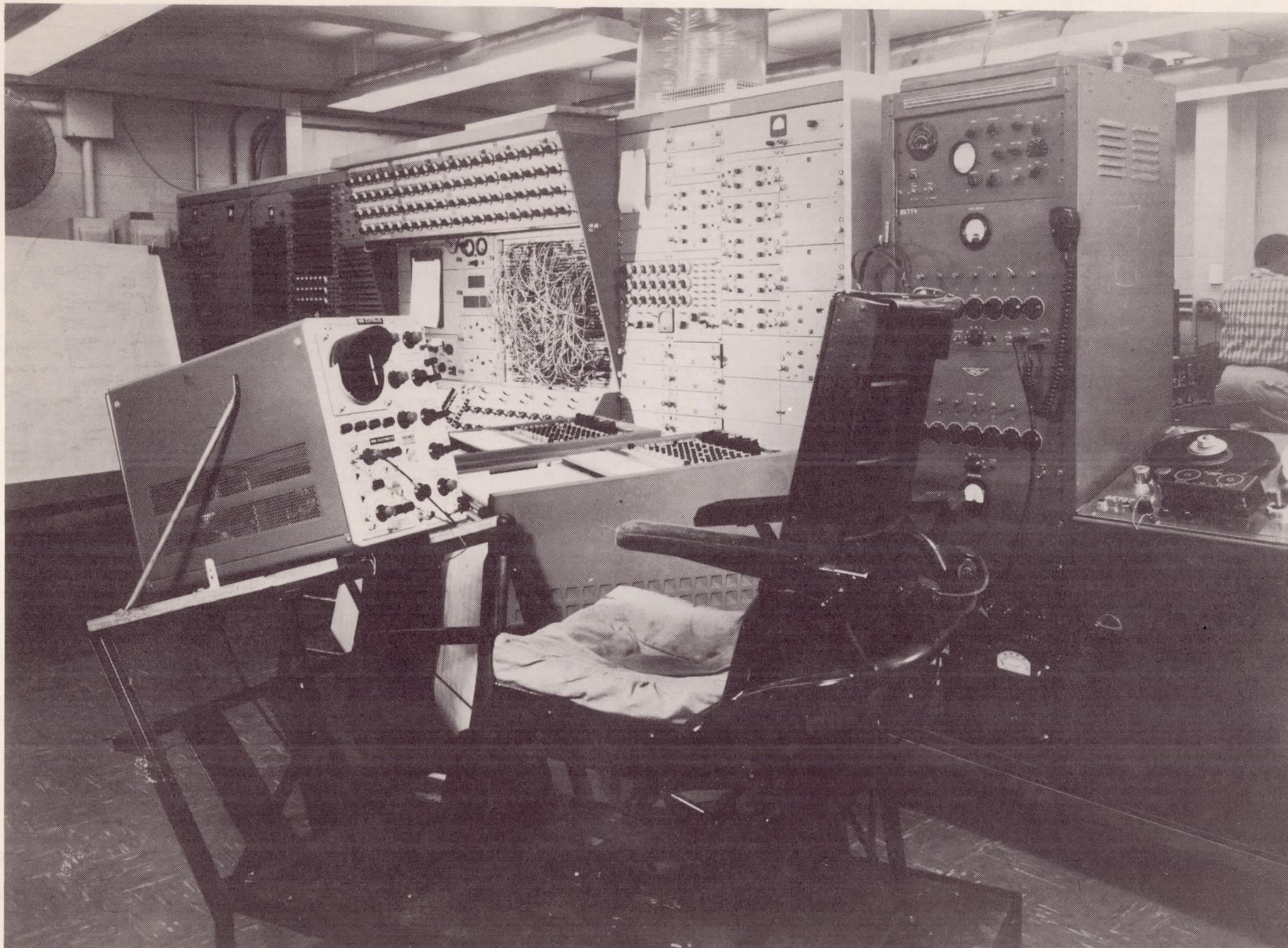


Figure 2.- Simulator and computer used in tests. L-62-7541

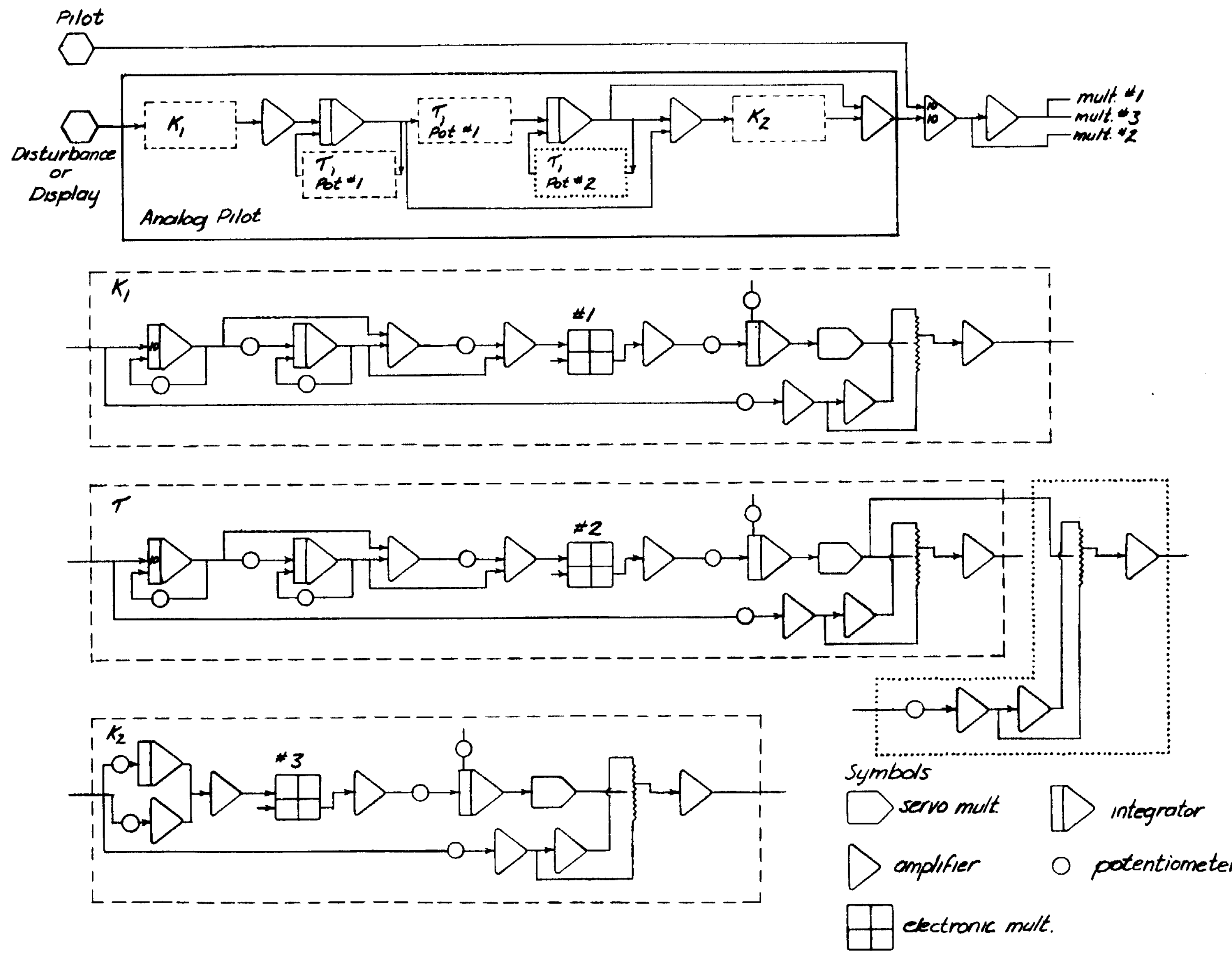


Figure 3.- Computer diagram of analog pilot, filters, and servo potentiometers.

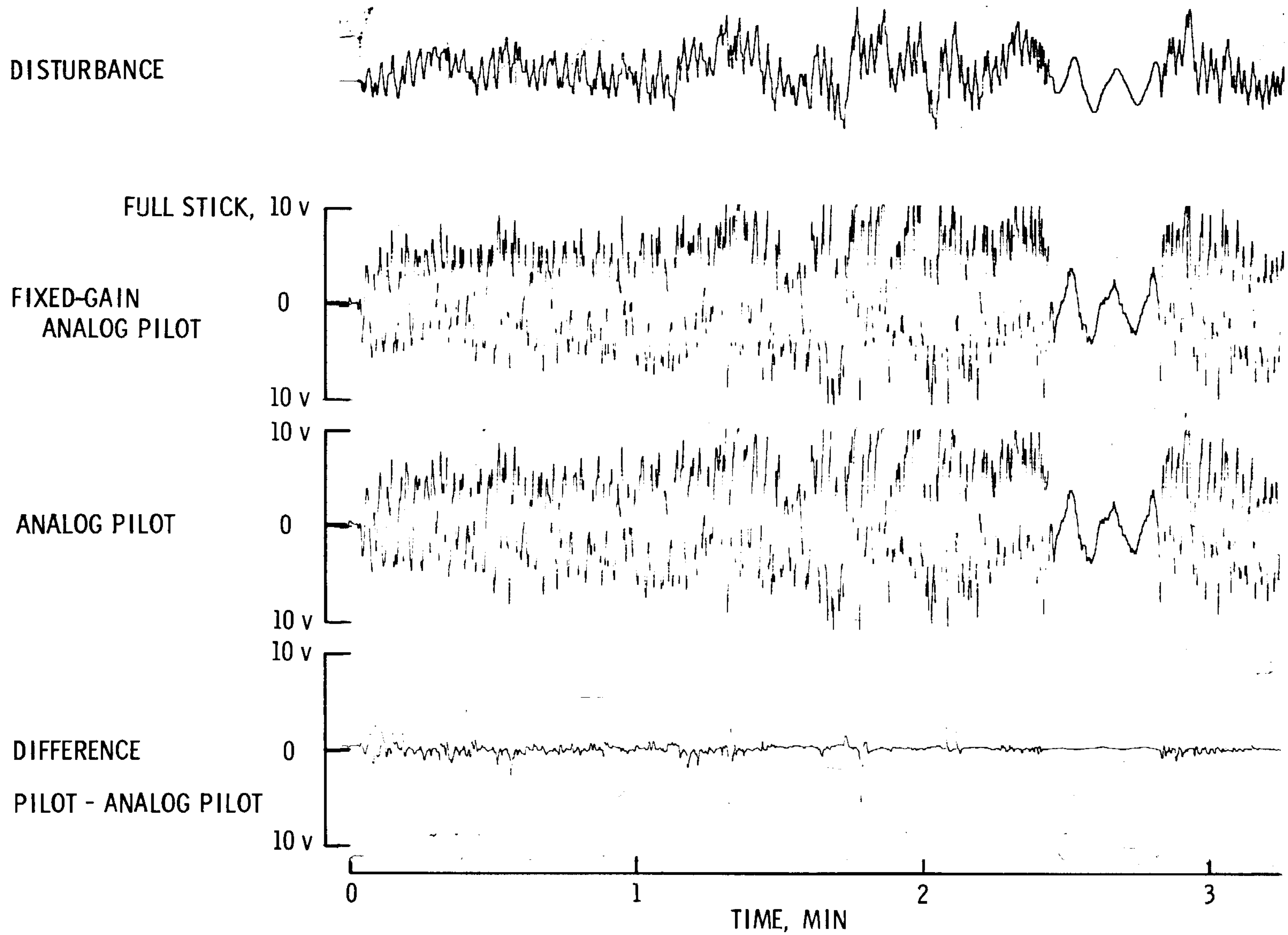


Figure 4.- Time history of test in which a fixed-gain analog pilot is matched. Fixed gains: $K_1 = 10$; $\tau = 10$ radians/sec; $K_2 = 10$.

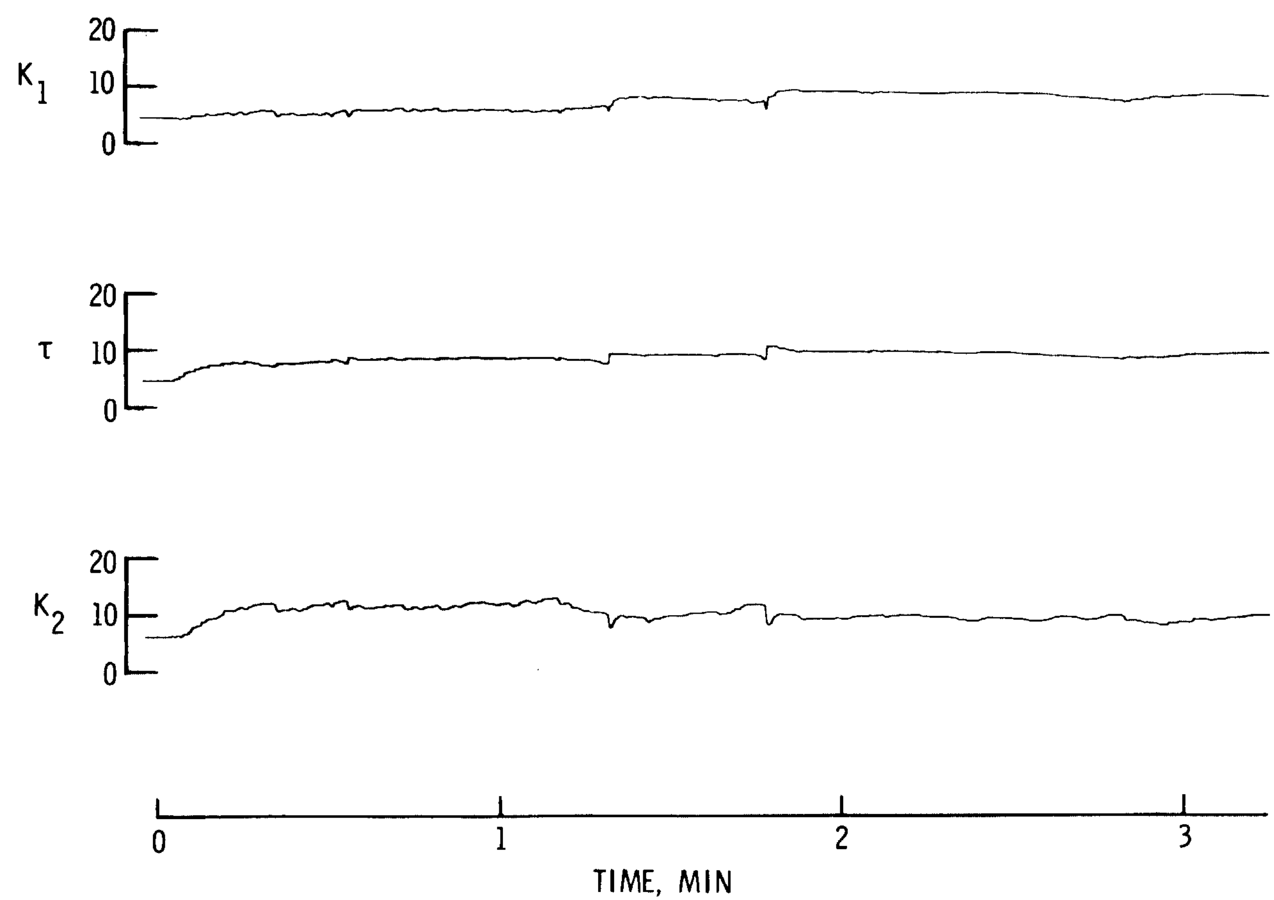


Figure 4.- Concluded.

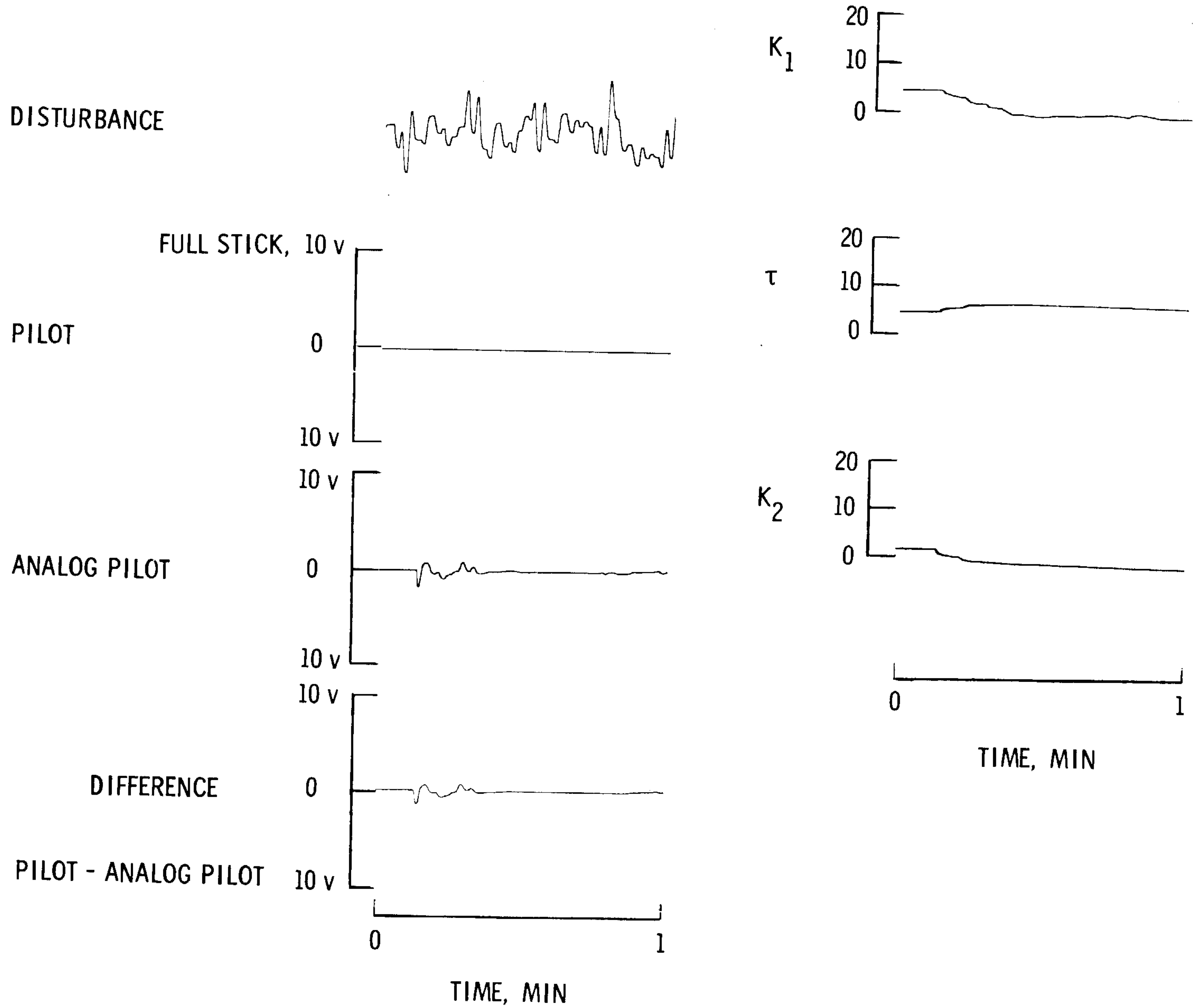


Figure 5.- Computer check with no pilot.

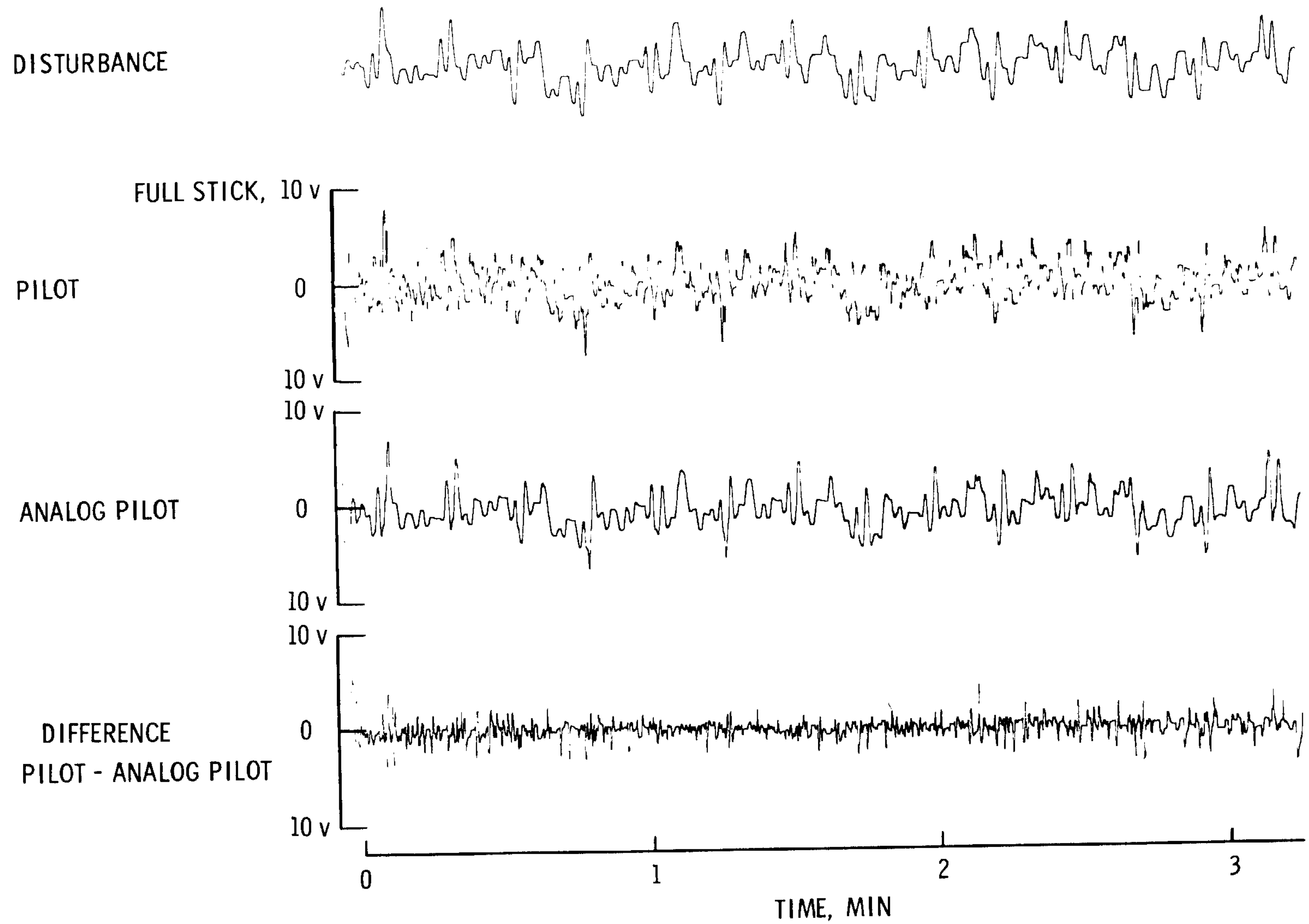


Figure 6.- Time history of test made with experienced test pilot A and dynamics of $\frac{2.5}{s + 2.5}$.

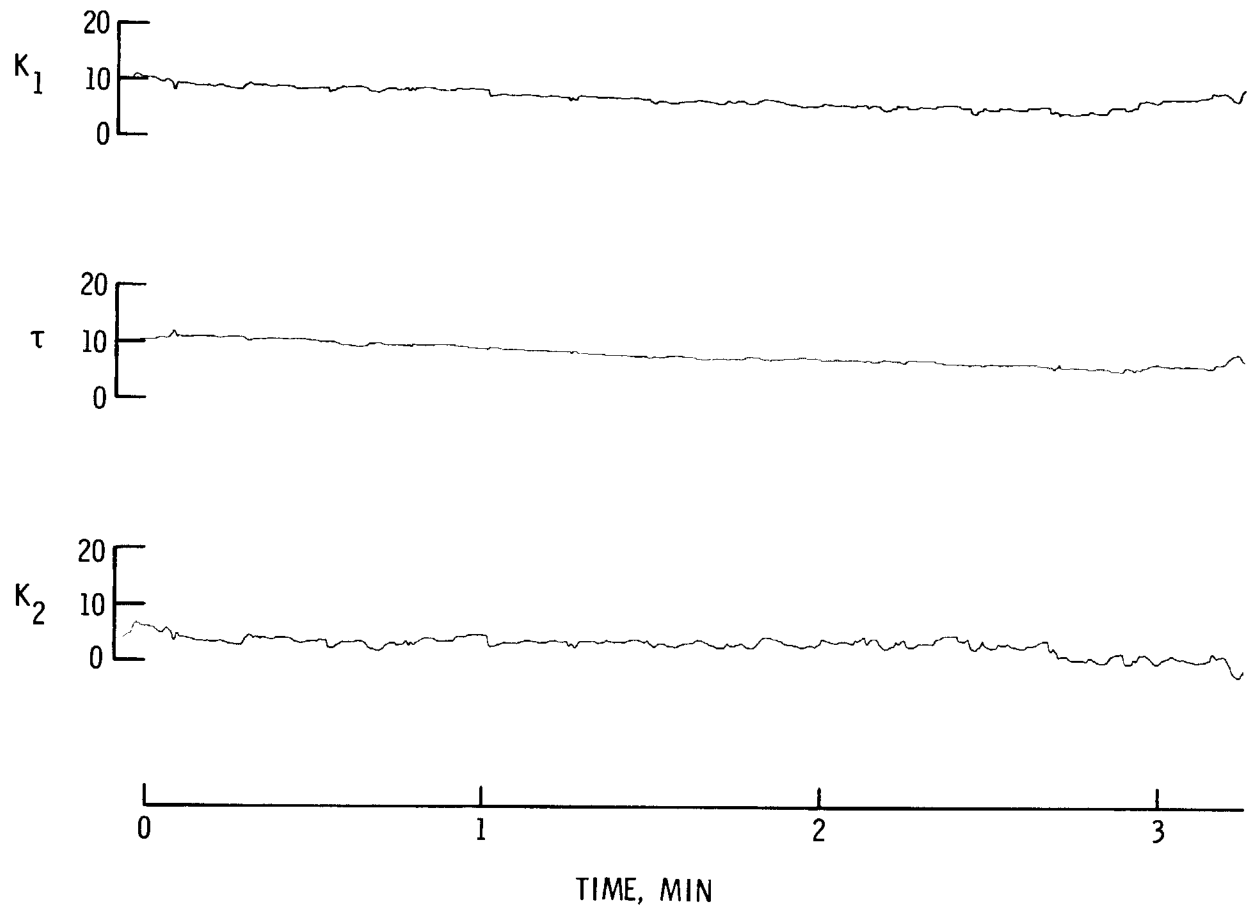


Figure 6.- Concluded.

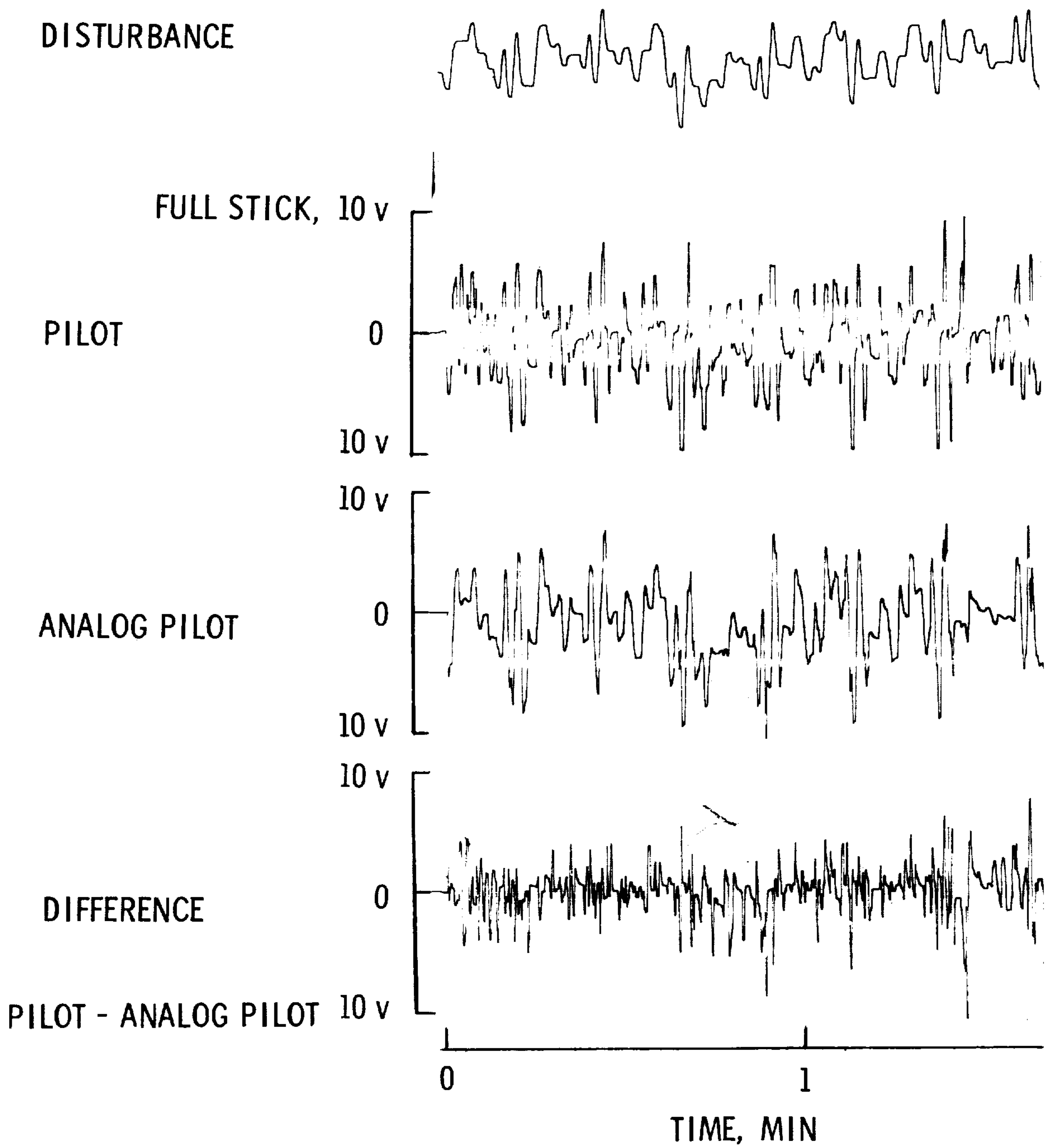


Figure 7.- Time history of test made with experienced test pilot A and dynamics of $\frac{1}{s + 1}$.

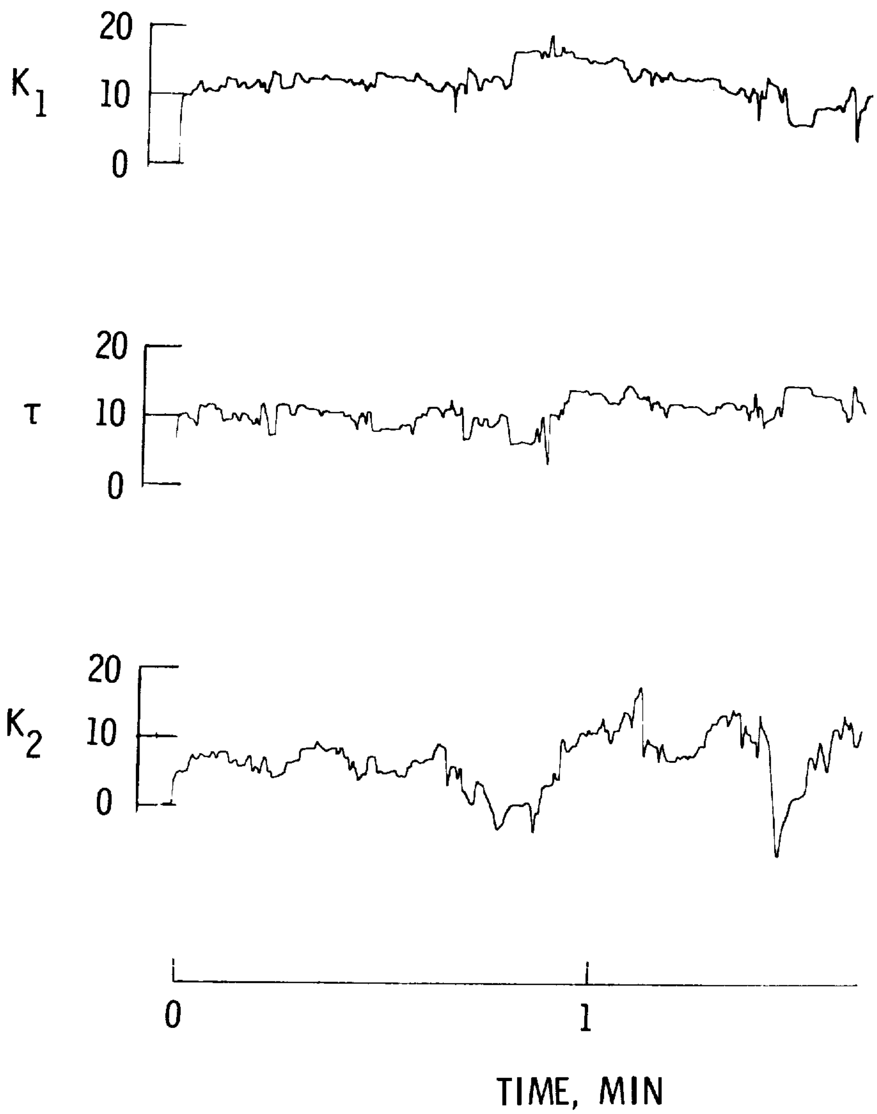


Figure 7.- Concluded.

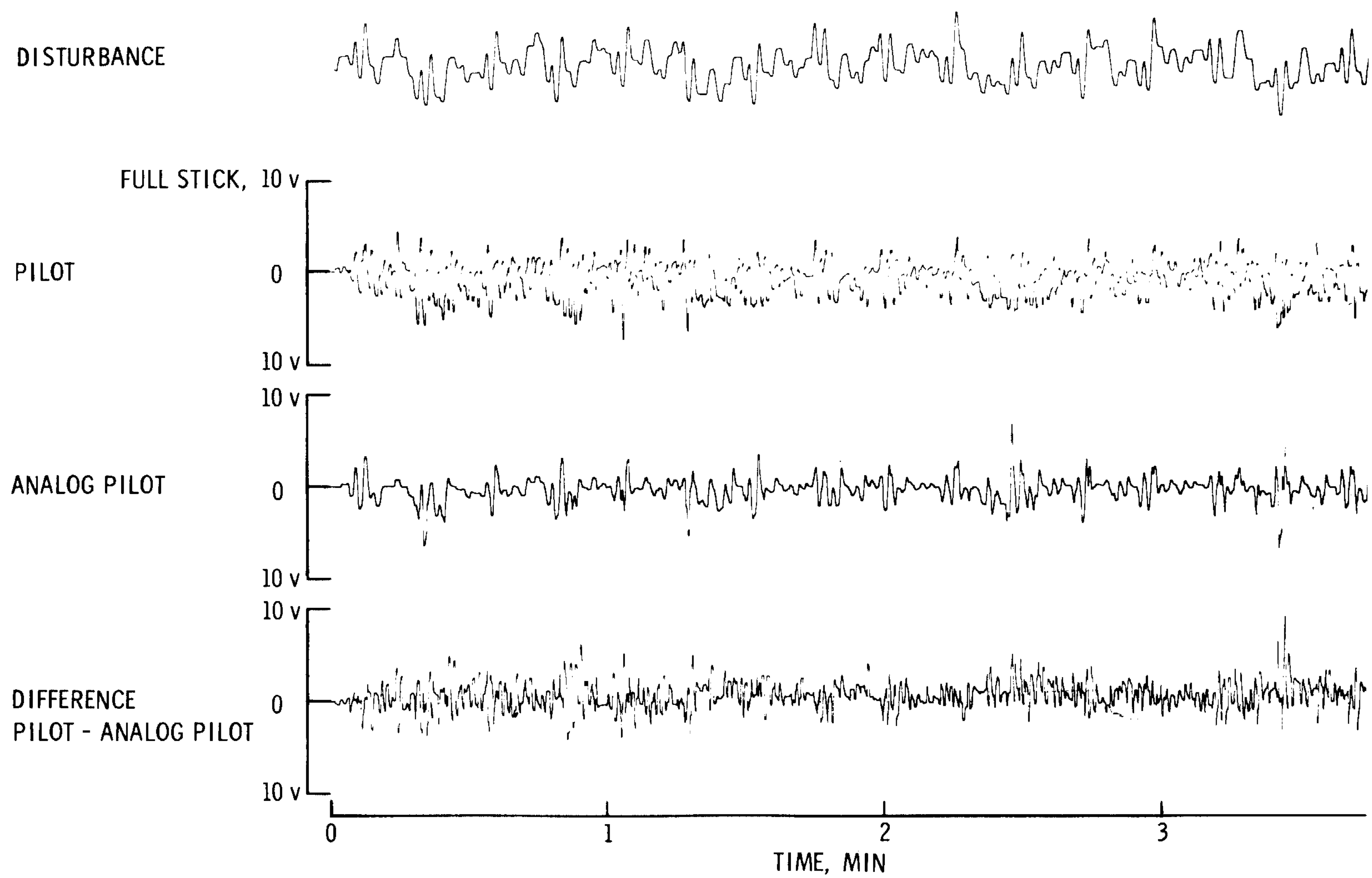


Figure 8.- Time history of test made with experienced test pilot A and dynamics of $\frac{10}{s^2 + 3s + 10}$.

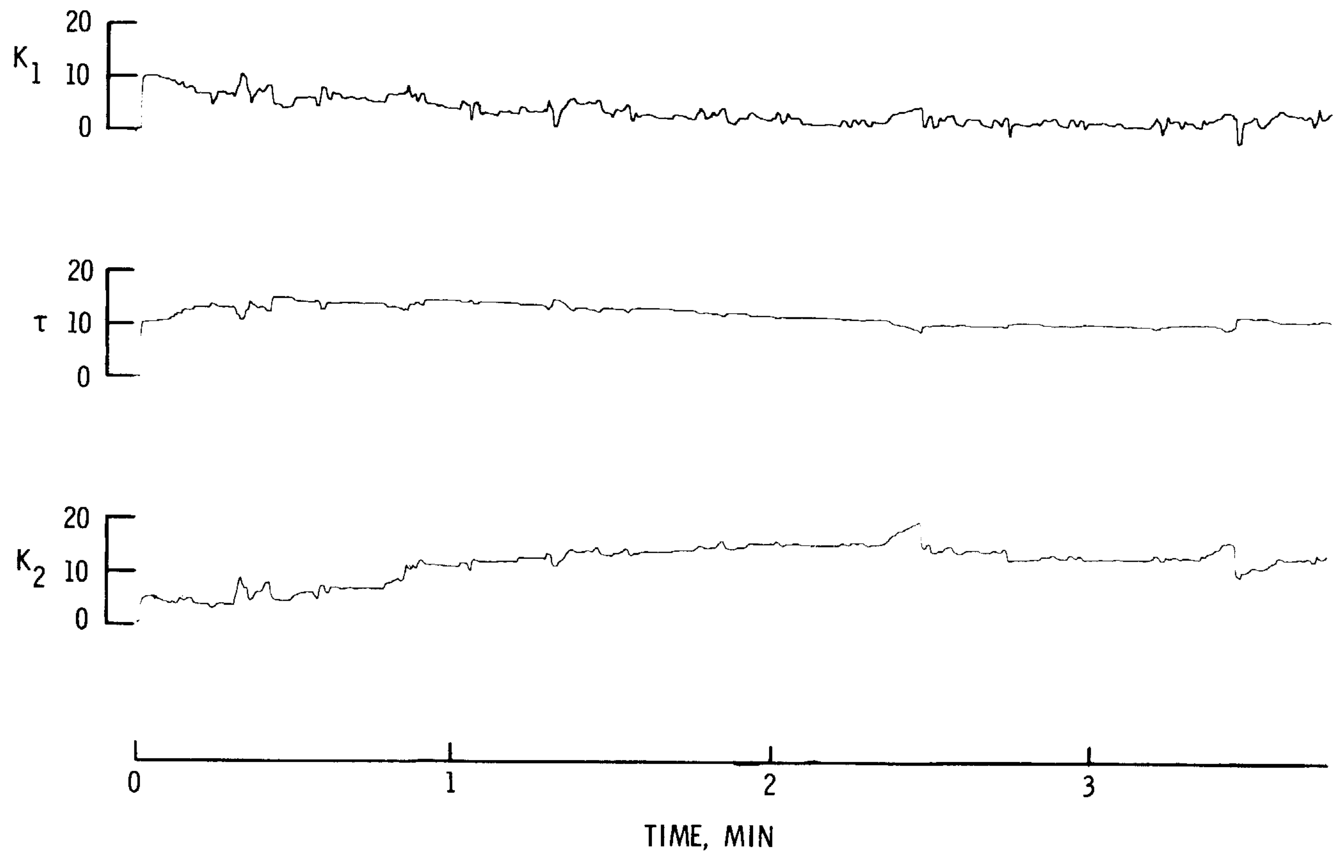


Figure 8.- Concluded.

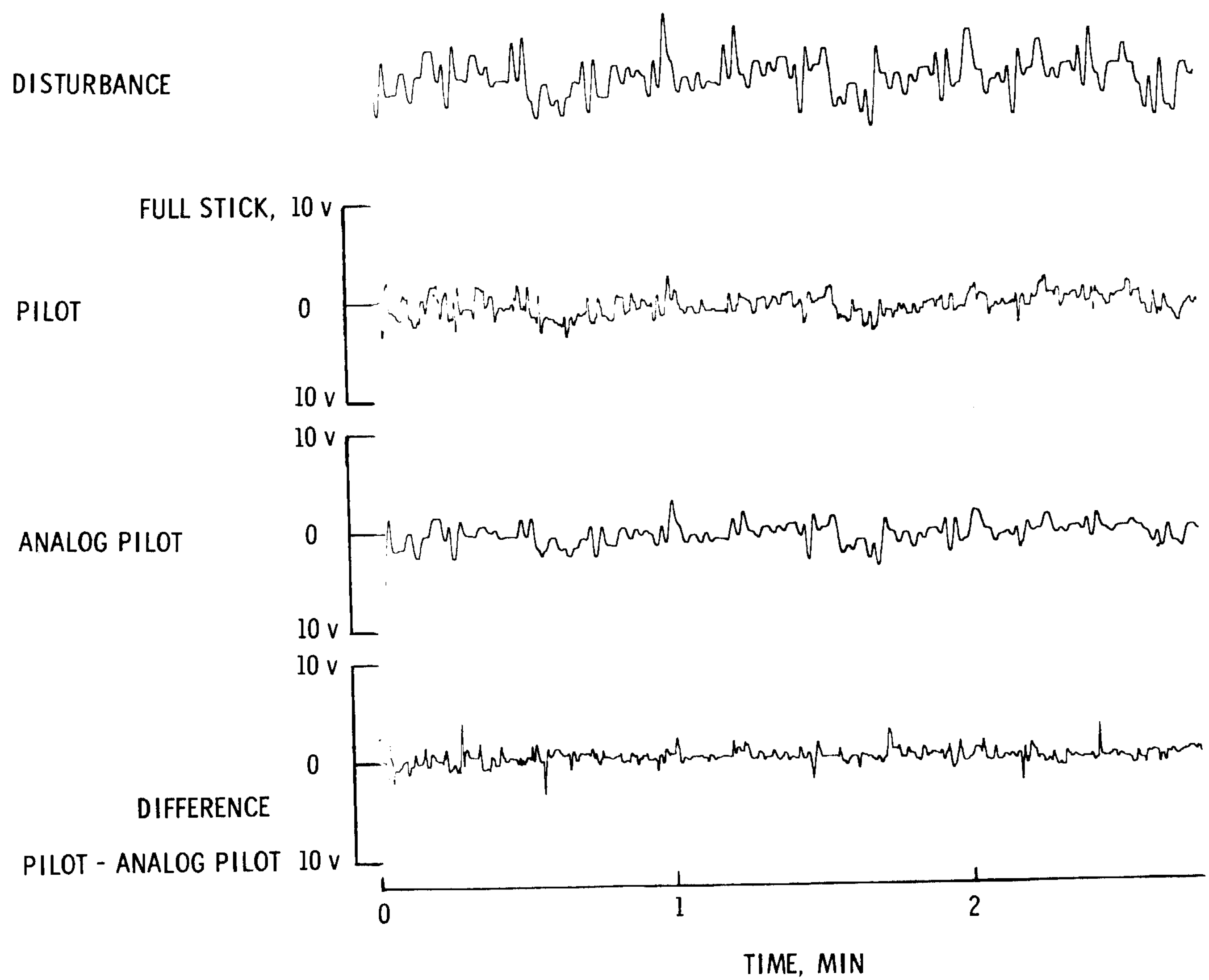


Figure 9.- Time history of test made with experienced test pilot D and dynamics of $\frac{10}{s^2 + 3s + 10}$.

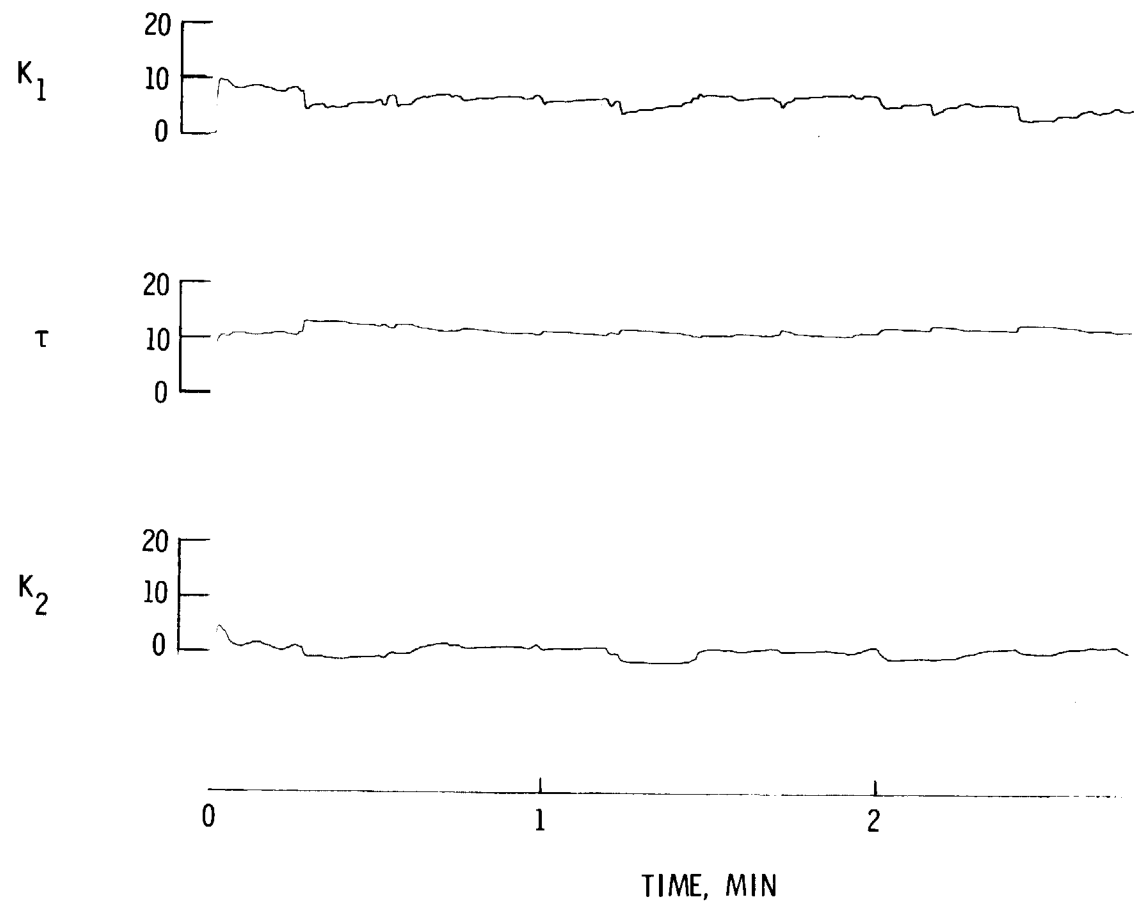


Figure 9.- Concluded.

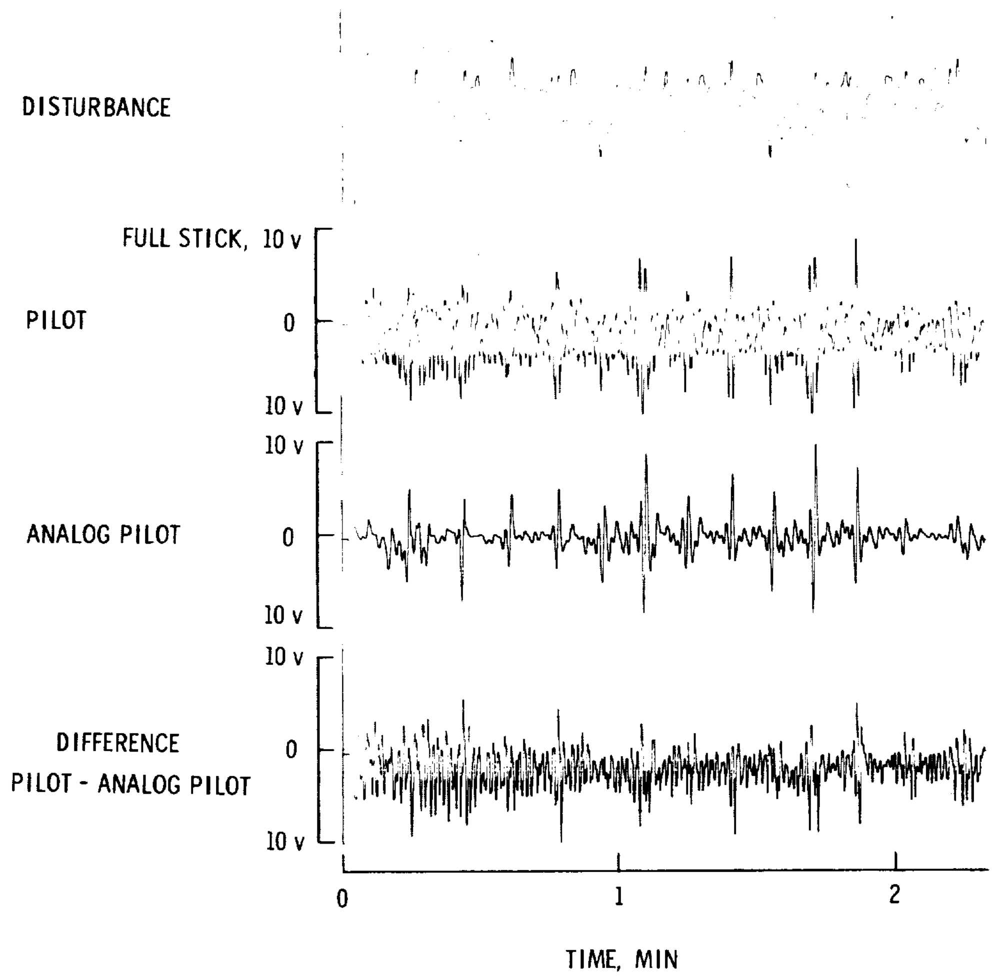


Figure 10.- Time history of test made with research engineer and dynamics of $\frac{10}{s^2 + 3s + 10}$.

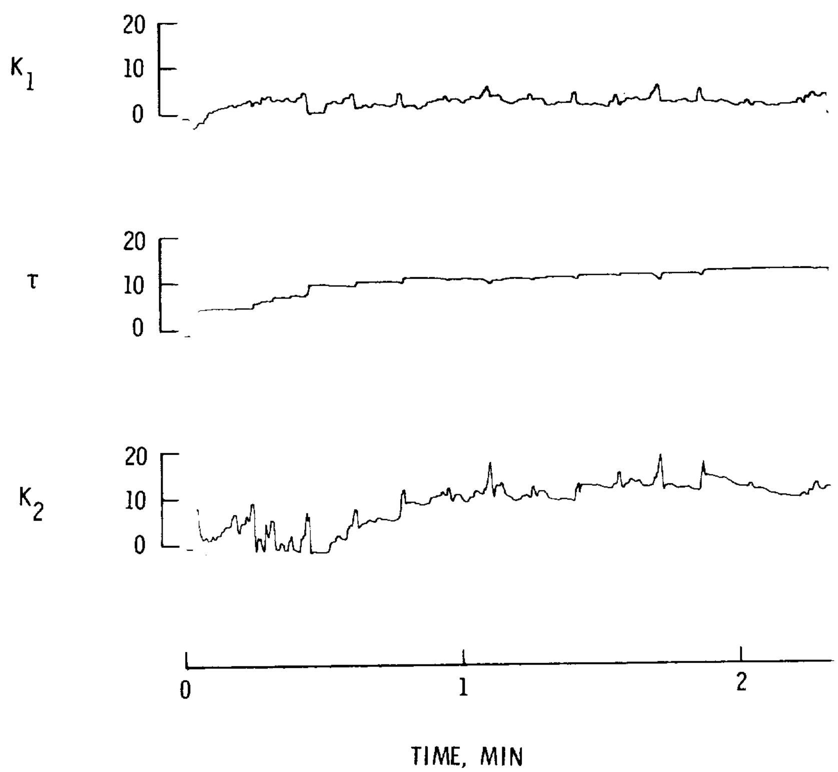


Figure 10.- Concluded.

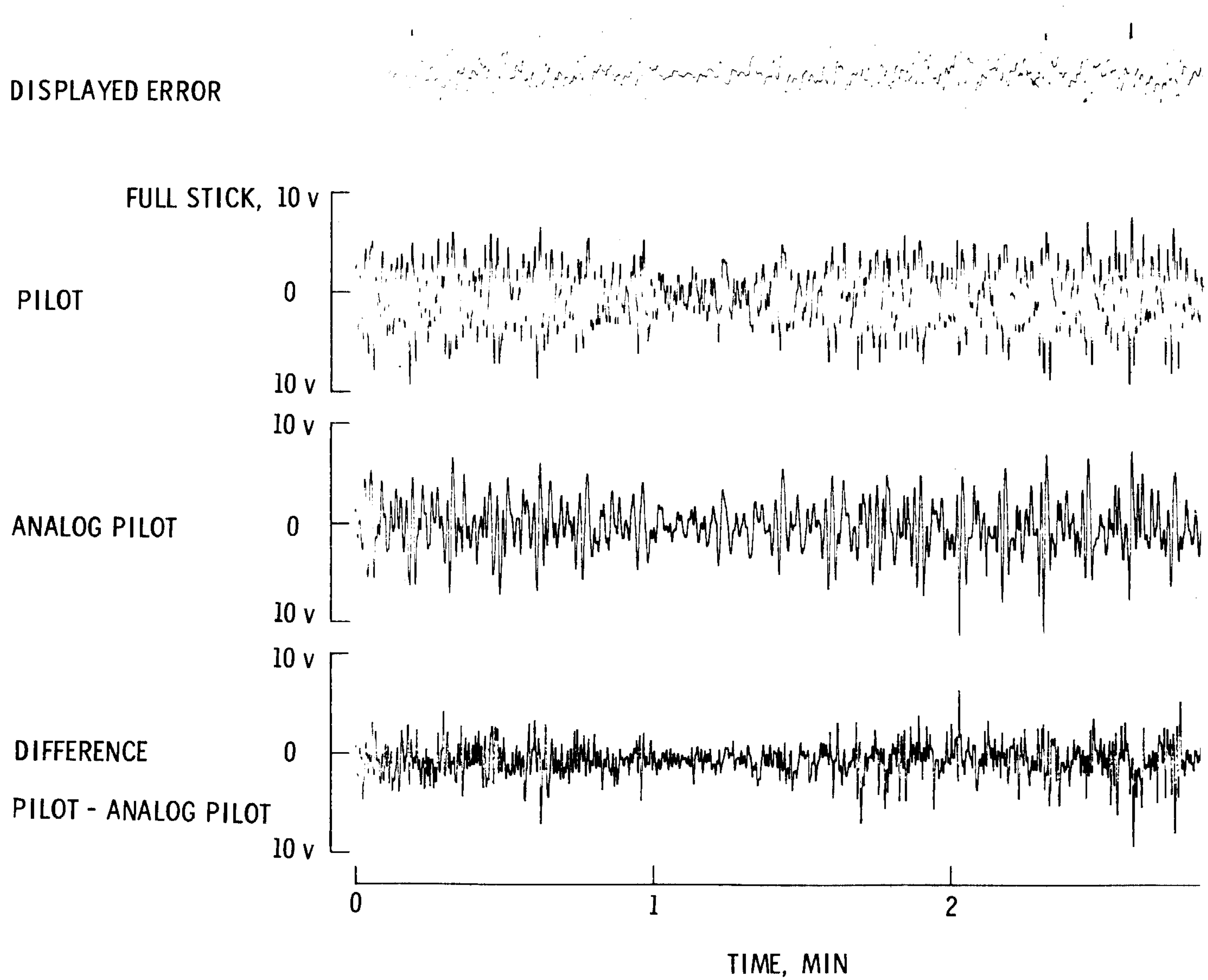


Figure 11.- Time history of test made with research engineer and dynamics of 2/s.

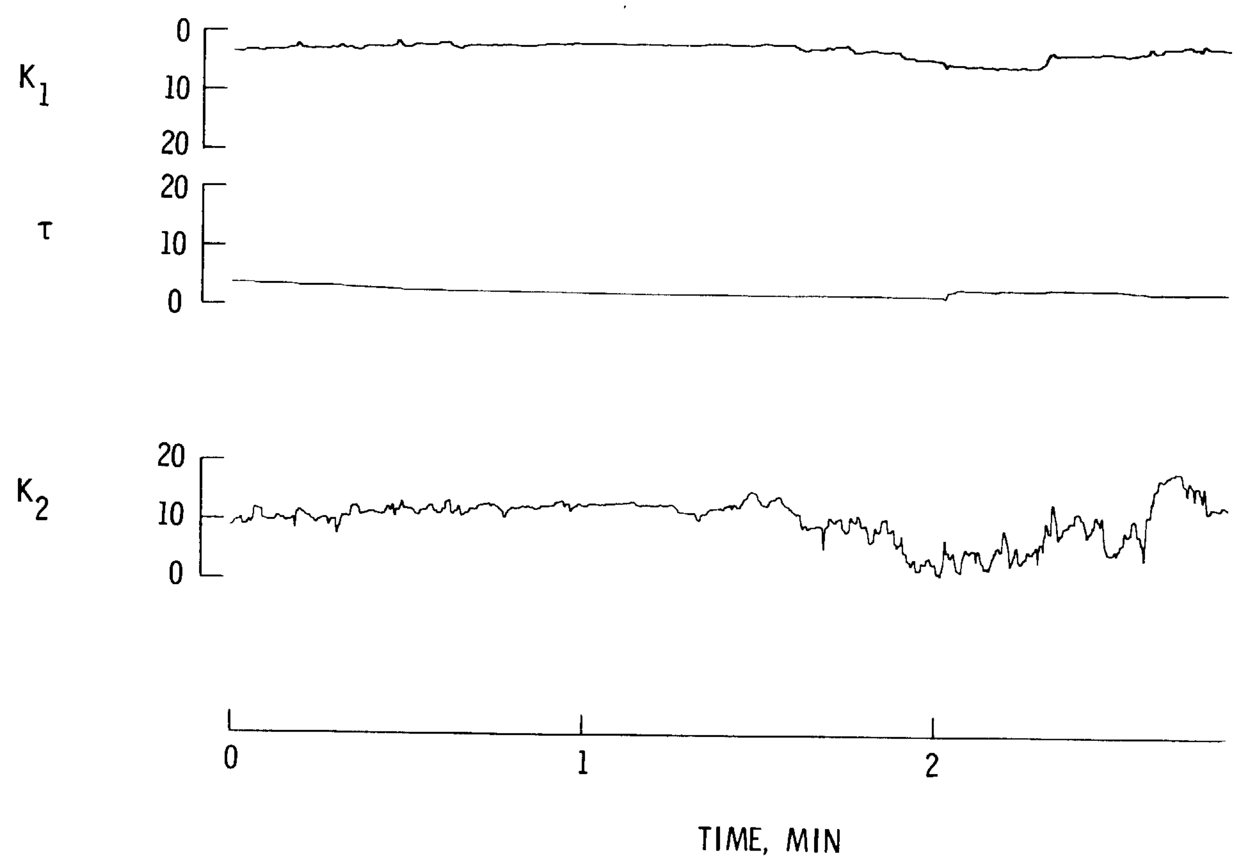


Figure 11.- Concluded.

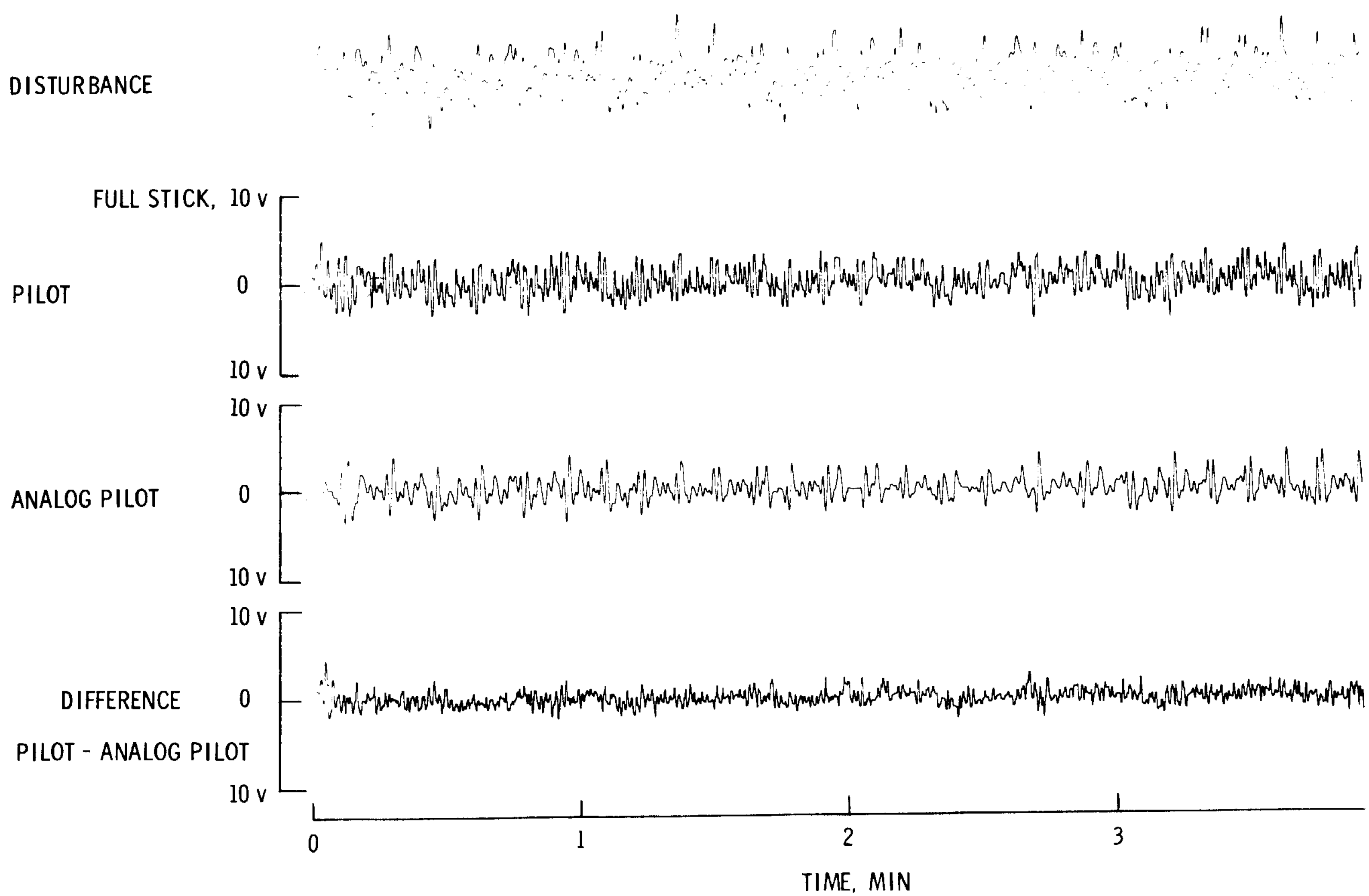


Figure 12.- Time history of test made with research engineer and dynamics of $\frac{10}{s^2 + 3s + 10}$. Pursuit tracking.

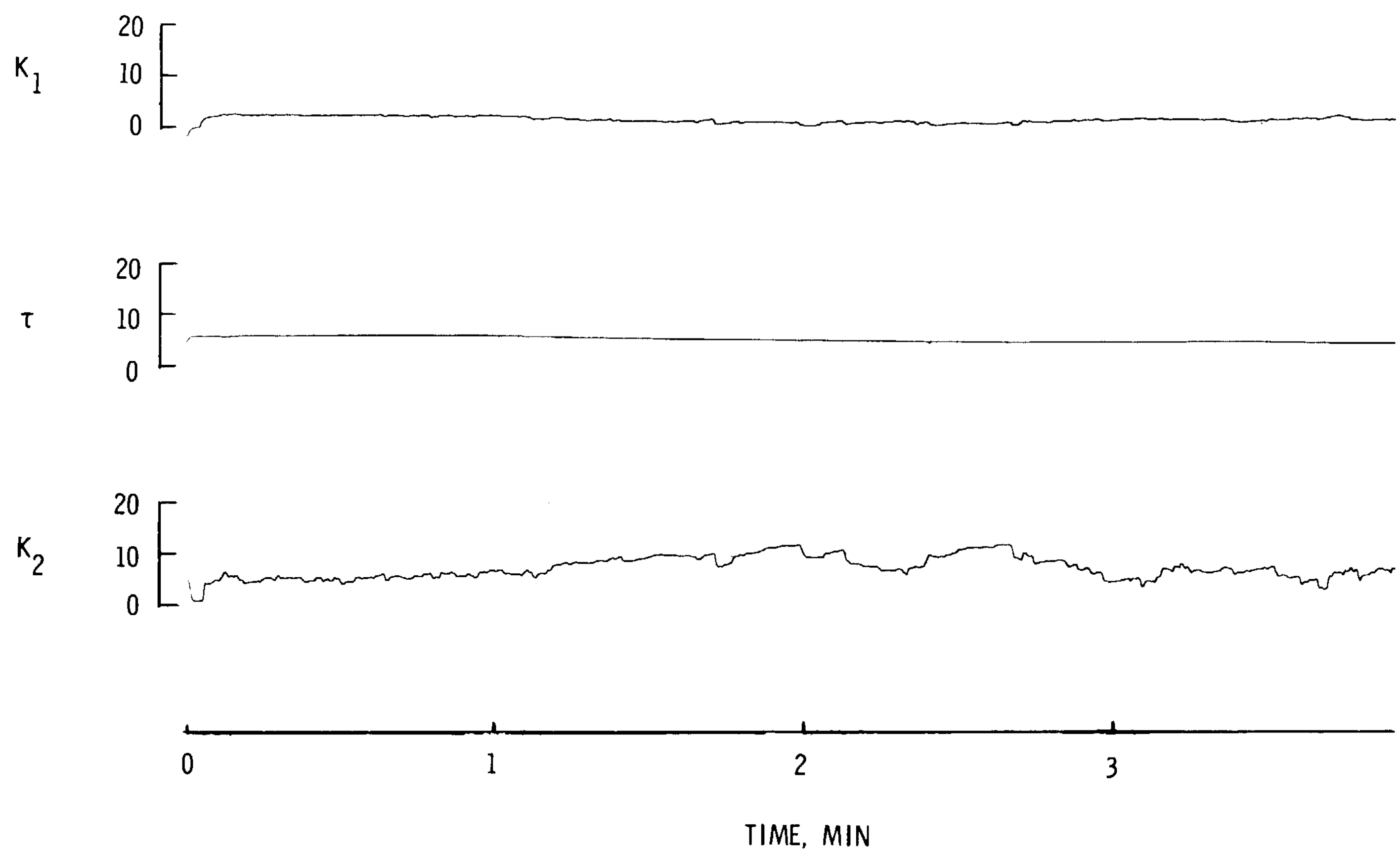


Figure 12.- Concluded.

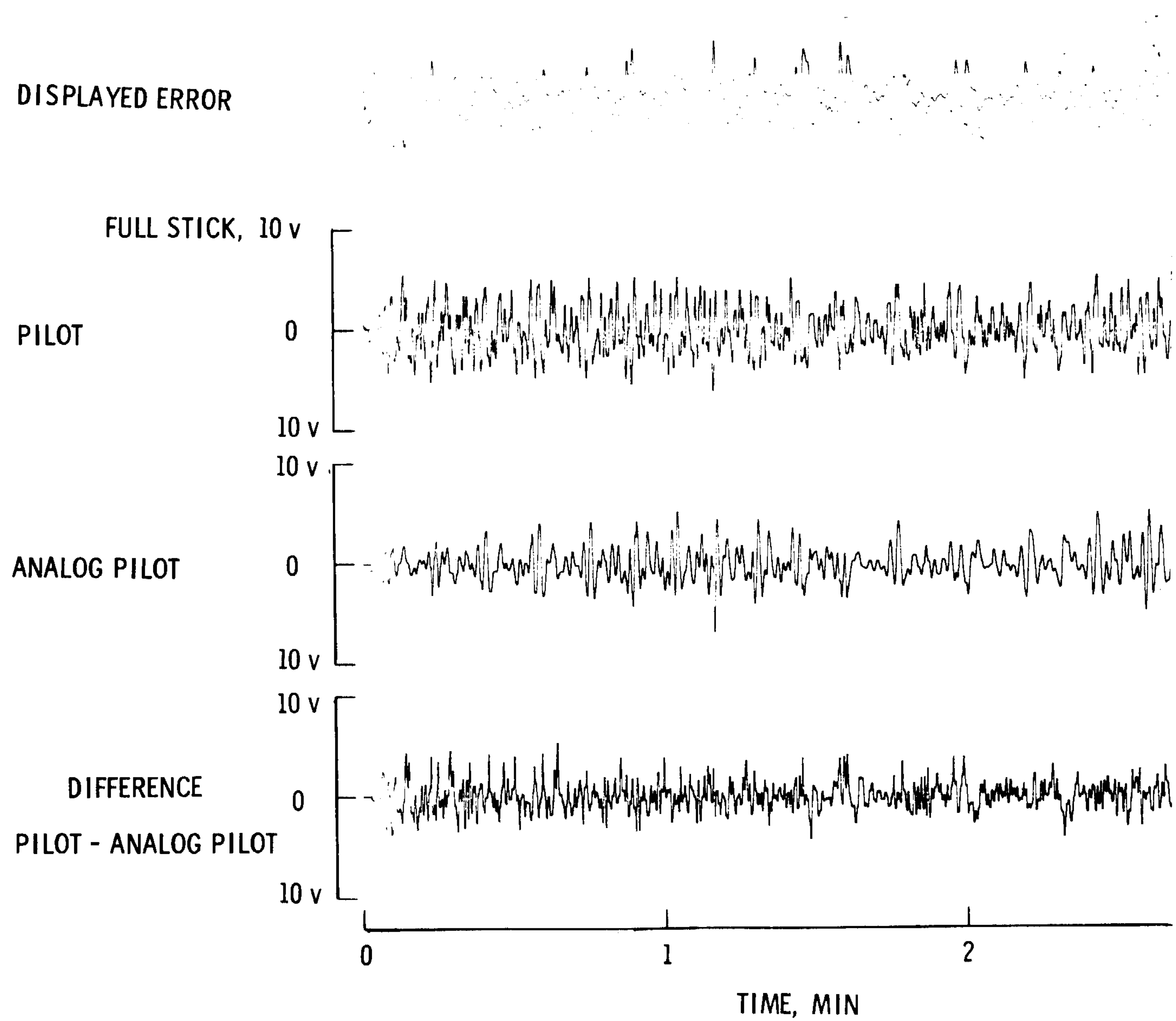


Figure 13.- Time history of test made with research engineer and dynamics of 2/s. Pursuit tracking.

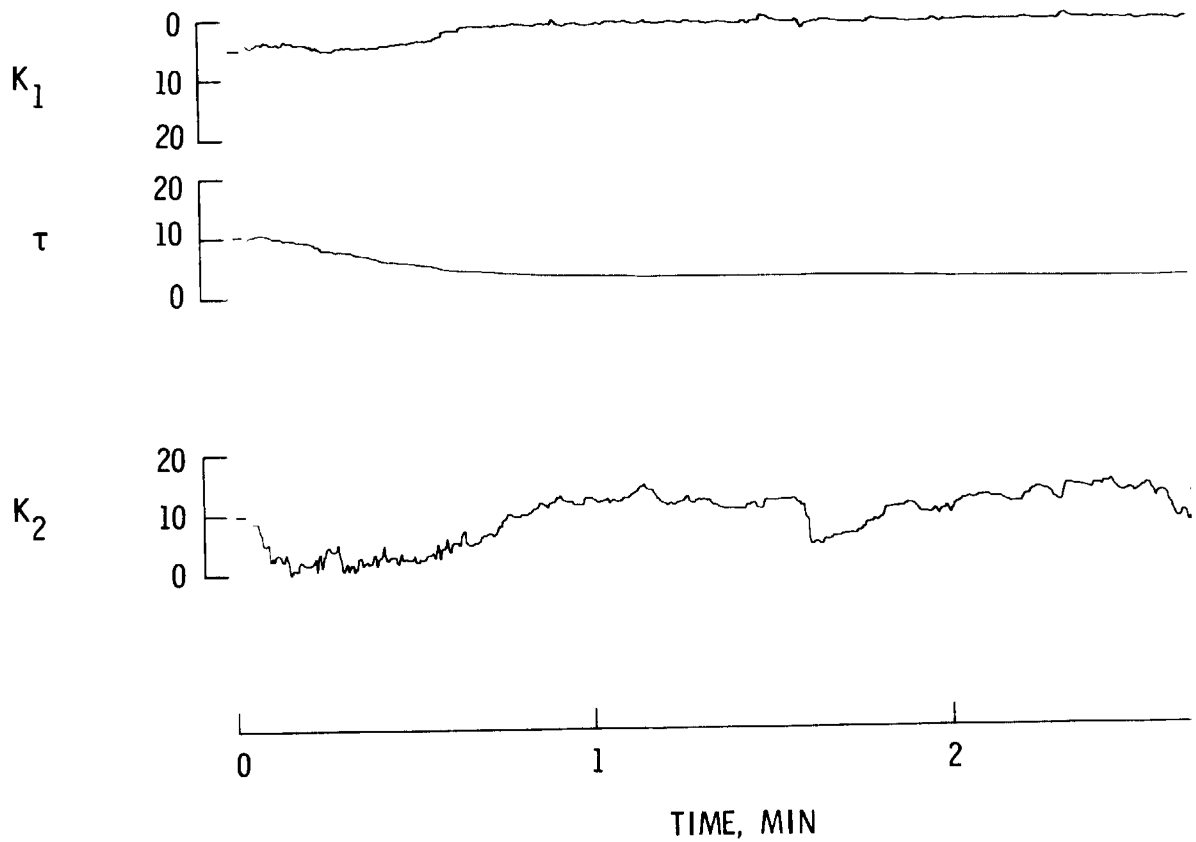


Figure 13.- Concluded.

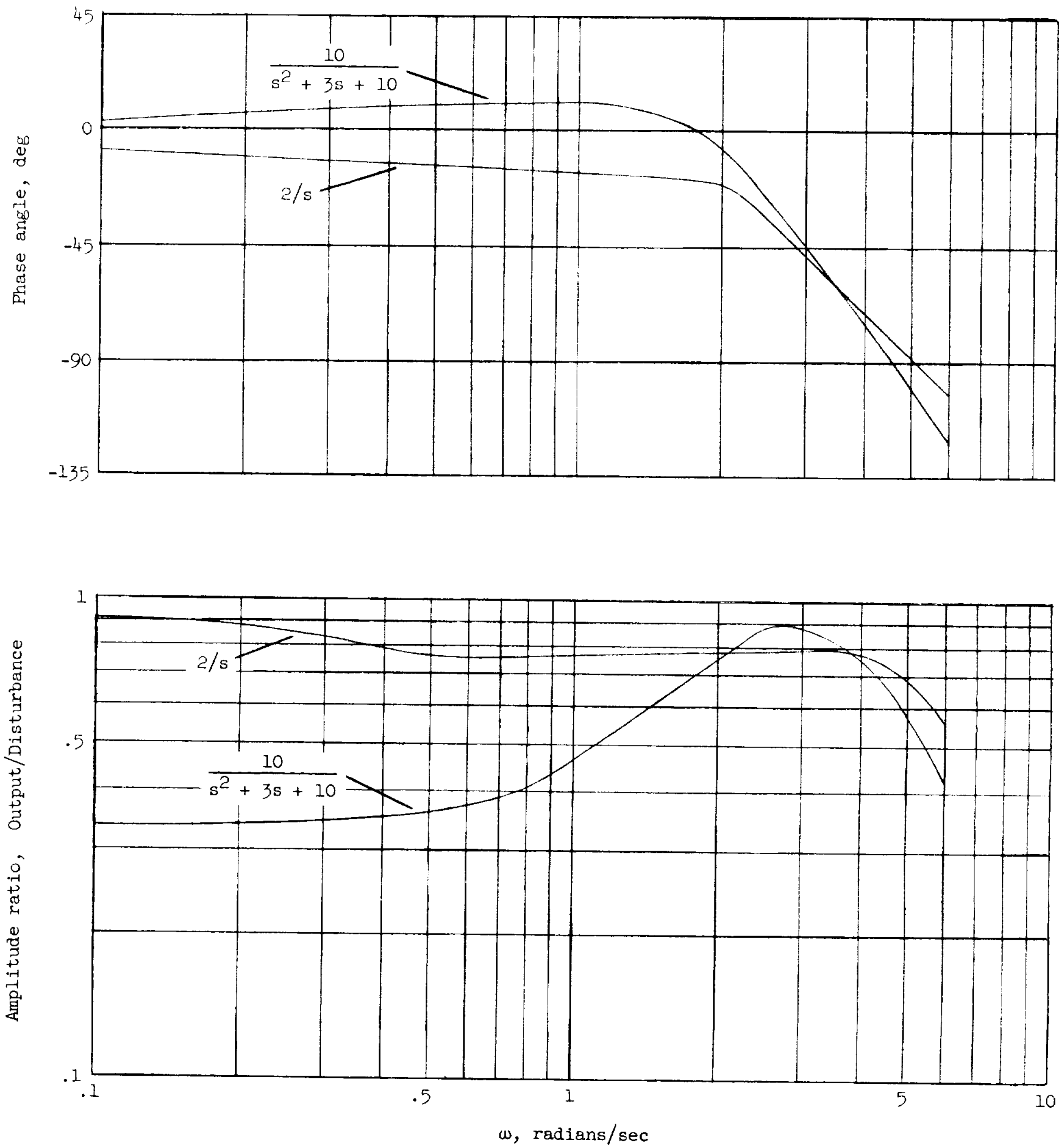


Figure 14.- Closed-loop frequency response for pilot plus dynamics, for compensatory tracking.

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