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PERFORMANCE OF HUMAN OPERATORS UNDER VARIOUS SYSTEM PARAMETERS

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Abstract

The performance of human operators was investigated for varied system parameters. A practical performance index was defined, and the relation between the parameters and the performance index was found for a range of values of the parameters. Several operators with different control experience were tested, and it was found that human control capability can be represented by a hyperbolic curve in the parameter plane of gain and time constant. The result may be used in the design of man-machine systems that anticipate some unusually difficult situations which the operator may be required to deal with.

Author

INTRODUCTION

Several efforts have been made to determine the transfer function of a human controller in a linear system.[1-4] Such efforts use linear transfer functions--for various inputs to the system and for various controlled elements--to represent human controllers. Recently, efforts have been initiated to find the time-varying characteristics of human controllers, especially the adaptability of controllers to certain parameter changes of the element to be controlled.[5] These recent efforts are aimed at establishing more realistic transfer characteristics for human operators, in order to meet the demands of more stringent designs. There have also been studies of emergency conditions that may occur through failure of some part of the system.[6]

In the present study, an entirely different approach has been taken in an attempt to evaluate the performance of human controllers in a closed loop system. Instead of finding the transfer function of the operator by the data obtained from system input and output, a performance index is defined and the relation between it and the parameters of the controlled element. By varying the parameters and measuring the corresponding values of the performance index, experimental relations between these quantities are obtained. In order to make the results as general as possible, the task, the display, and the control maneuvers were made simple enough for untrained operators to comprehend and execute. The operators were required to compensate for an error signal induced by a random input to the system.

Despite the individual differences in the operators' performances, the constant-performance index curves obtained in the parameter plane of gain and time constant of the controlled element are strikingly similar in shape. This means that there is some factor common to the human operator which may be measured and evaluated. Since a comparison of operators reveals definite differences among individual operators, the method considered here may be used as an evaluation of control performance by a wider criterion, and may also be used to indicate limitations for machines to be controlled by human operators.

APPARATUS

The block diagram of the control system is shown in Fig. 1. The controlled element was simulated by an analog computer. The transfer function of the controlled element was given the following form:

$$\frac{K}{S^2(TS + 1)} \qquad (1)$$

The programming for this simulator is given in Fig. 2

The reason for selecting the third-order system is to make the system unstable in itself. If an element of the second order were placed in Fig. 1 as the controlled element, the system would be stable without any control effort. Direct connection of error signal in Fig. 1 with the controlled element would give a stable operation. If the controlled element is of the third order, however, the human operator has to stabilize the system, and for this he has to work as a compensator rather than a simple amplifier. If the controlled system operates in a stable manner, then the operator is a compensating, lead element that stabilizes the system. It should be possible to determine just what kind of compensating element the operator represents by using a performance index and the system parameters T and K.

In the experimental setup, the operator manipulates a control stick similar to the ones used in small airplanes. The maximum angle of the stick is 30° from the vertical to either the right or left. The stick is sustained by a weak spring which exerts a force of about 0.5 lb/30° at the head of the stick.

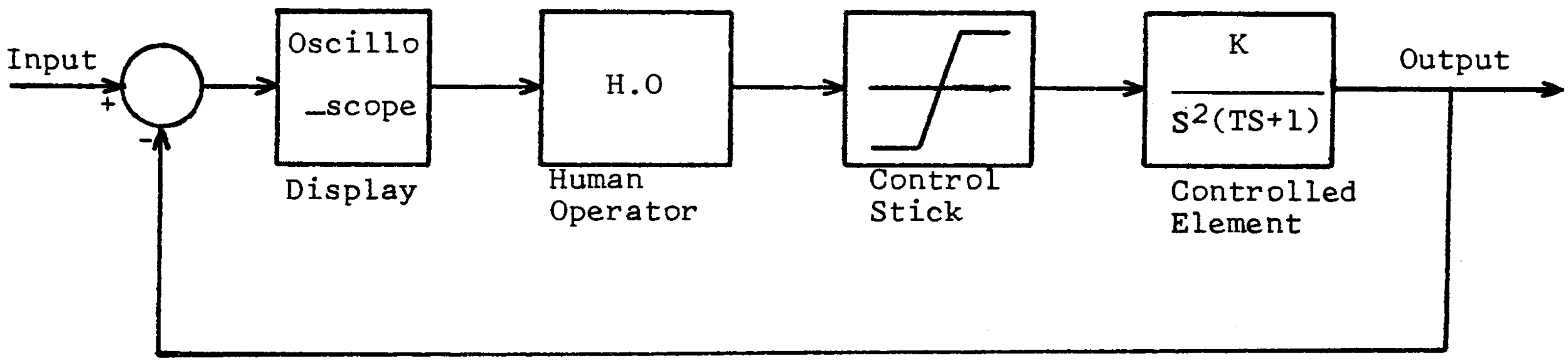


Fig. 1 Block Diagram Of The Control System

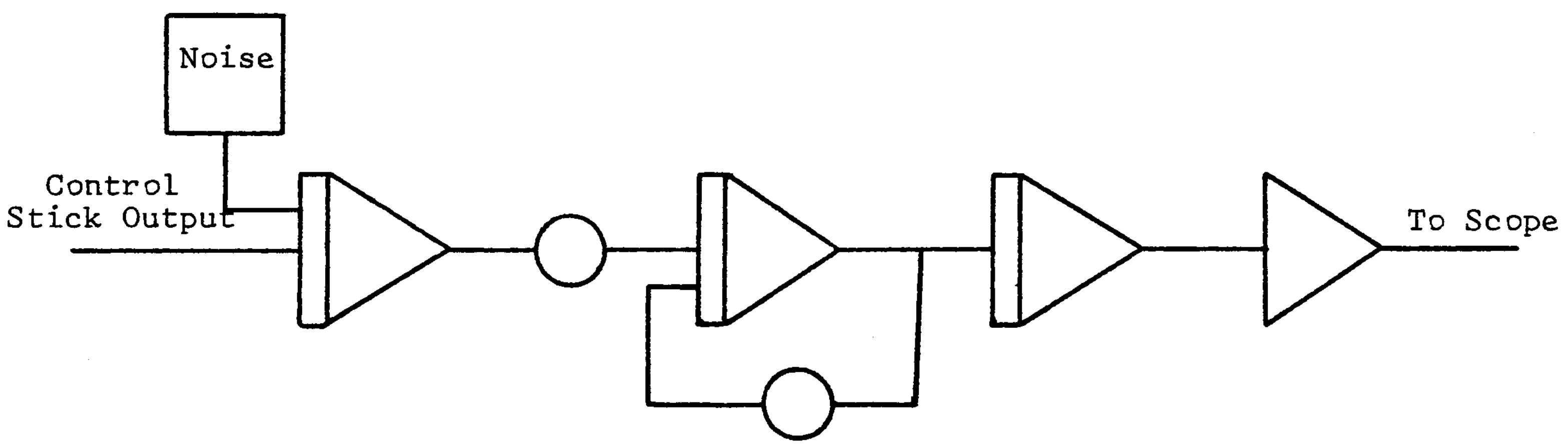


Fig. 2 Programming Of The Controlled Element

Since the movement of the control stick is limited as described, we may consider this as a saturation element, as given in the block diagram. The output of the stick is linearly converted into a voltage signal and is applied to the analog simulator of the controlled element.

The display of error is made by a cathode ray oscilloscope, on which the error signal is represented by a vertical line appearing on the screen. The degree of error is shown by the distance of this line from the reference line at the center of the scope. The function of the operator is to keep the vertical line within given limits at all times. A random input signal is applied to the system as described in the following section.

EXPERIMENTAL PROCEDURE

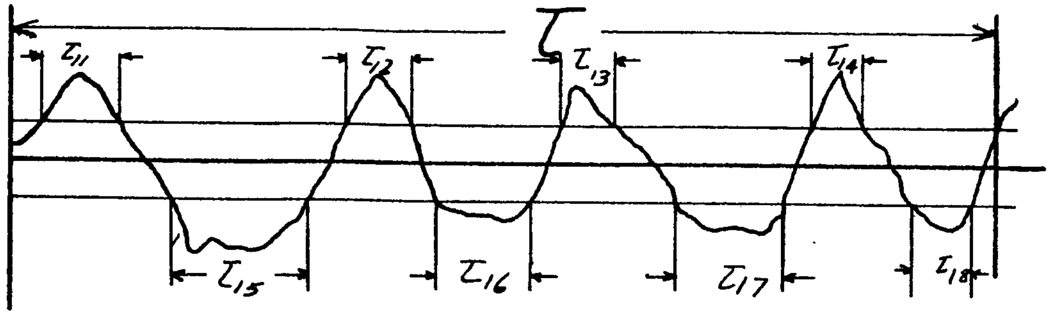
The random signal applied to the control system was approximated by the superposition of six sinusoidal functions with different frequencies. The signal, of about three minutes' duration, was stored in a magnetic tape and was fed into the system at the time of the test run. The frequencies of the composite sinusoidal signals were 0.6, 1, 1.5, 2, 2.5, and 4.2 radians per second. All were of the same relative amplitude. The random signal is similar to some used in investigations by other methods. The power level was chosen arbitrarily to make the error of the system exceed the limits specified by the performance index. A sample record is given in Fig. 23.

The performance index was chosen as follows. Let the duration time of a test be denoted by τ as shown in Fig. 3a. Let an arbitrarily chosen threshold of error be e_o. If the summation of time intervals within which error signal $|e|$ exceeds e_o is denoted by τ_1, the performance index p is defined to be

$$p = \frac{\tau_1}{\tau} \quad . \tag{2}$$

Obviously $0 \leq p \leq 1$. $p = 0$ means that the error is within the specified limits $\pm\ e_o$, whereas $p = 1$ means that the error is entirely outside the limits during the test period. Analytically, p can be expressed as follows:

$$p = \frac{1}{2\tau} \int_0^{\tau} \{ \operatorname{sgn} (|e| - e_o) + 1 \} \ dt \tag{3}$$



$$\rho = \frac{\tau_1}{\tau}, \quad \tau_1 = \Sigma\, \tau_{1i}$$

Fig. 3a Performance Index

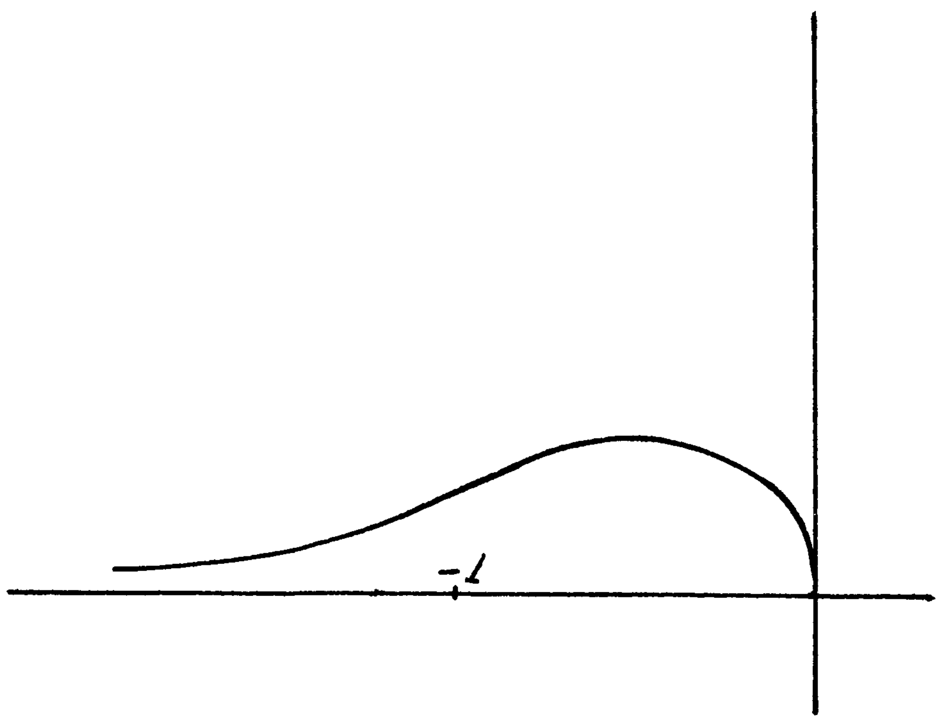


Fig. 3b Vector Diagram For a Third Order System

or

$$p = \frac{1}{T}\int_{0}^{T} \left\{ \operatorname{sgn}(e - e_o) + 1 \right\} dt =$$

$$= \frac{1}{T}\int_{0}^{T} \operatorname{sgn}(e - e_o)\, dt + 1 \qquad (4)$$

if the error is statistically symmetrical. (See Fig. 3.)

This index is practical because it represents an important factor of the performance and is nondimensional. It may be difficult to subject this performance index to analytical treatment; for the present purpose, however, it serves as a convenient measure of an operator's performance. The threshold e_o was taken to represent about 10% of the total width ($\pm$ 10 Volts) of the display oscilloscope. In the case where error is of large amplitude and the system is in a state of hunting, an estimation of the maximum error may be made by the experimental value p and the definition of the performance index. In such a case the error may be approximated by a sine function, say

$$E \sin \omega t \quad .$$

Then, by the definition of the performance index,

$$p = 1 + \frac{\omega}{2\pi}\int_{0}^{2\pi/\omega} \operatorname{sgn}(E \sin \omega t - e_o)\; dt \qquad (5)$$

If we can find the value of p from the record chart, we can evaluate the amplitude E, the maximum value of error during the hunting. It is easily seen that E is given by the following equation:

$$E = \frac{e_o}{\sin \frac{\pi}{2}\, pt} \qquad (6)$$

As previously mentioned, the transfer function of the controlled element is given the form

$$\frac{K}{S^2 (TS + 1)} \tag{7}$$

For small values of T, this is considered nearly equal to the second order element

$$\frac{K}{S^2} \tag{8}$$

For a larger value of T, the function may be approximated by

$$\frac{K}{TS^3} \tag{9}$$

The validity of these approximations depends on the frequencies, but these serve as an observation of extreme cases. For a large value of T, then, the gain of the element is small. Therefore, as has been observed in some tests, it may be easier to control an element with rather large time delay, unless K is also large. For the intermediate range of T, it is expected that the increase in T and K both enhance the difficulty of control. With these predictions, T was varied within the range of

$$T = 0.1 \sim 0.6$$

and K within the range

$$K = 0.5 \sim 8$$

The values of the parameters given above make the control of the element difficult enough for the operators that the test results give a variety of values of the performance index. This also means that the limit of controllability in terms of the parameters of the element to be controlled lies somewhere within these values, if the transfer function of the controlled element is as given in this experiment.

Operators for this test were chosen from three categories. The first, Group A (operators A_1 and A_2), contains driver-pilots, persons with both licensed flying and driving experience. The second, Group B (operators B_1 and B_2), consists of persons with average driving experience. The Third, Group C (operator C), is a non-driver. The ages of the operators range from 20 to 40.

Each operator manipulated the control stick for more than one minute, attempting to keep the error signal within the specified limits despite the disturbance that was fed in. As a rule, each operator was given 25 different combinations of T and K, within the range of the parameters mentioned earlier.

The result of the test was recorded on a paper chart and the performance index of each test run was measured on the chart. Performance was measured for one minute within the actual test run period.

EXPERIMENTAL RESULTS

First, the performance index p was plotted against K, for each value of T. Samples of such plottings are given in Figs. 4 ~ 9. An approximate curve was drawn for each T, describing the plottings on the K-p plane. The curves for some cases do not quite intersect the experimental points, which is not surprising considering that a human operator is involved in the experiment. However, the general trend is apparent and it shows the obvious fact that the higher the K the more difficult the control. Curves are not necessarily straight, and the value of p tends to level off, which is again natural because p can never exceed unity.

In the same manner, for each value of K, the performance index is plotted against T, the time constant. Here, the plotting is made from the approximation curve drawn for K-p plottings. Samples of such curves are given in Figs. 10~13. Obviously, the increasing T with K kept constant appears to make the control more difficult. As mentioned earlier, this is expected for a certain range of T.

Now, to see the relative difficulty of control due to the increase in K and T, points of the same performance index were plotted on T-K plane, with p now as a parameter. The results for three operators are shown in Figs. 14 ~16.

These may be considered as a measure of the operators' adaptability to parameter changes of the controlled element. Note that the shape of the curve is nearly the same for different operators. The comparison of the curves for three different operators is given in Fig. 17. The nearer such a curve to the origin, the better performance the operator has for this compensating task. Obviously, a driver-pilot produces a curve much nearer to the origin than an ordinary driver or a non-driver. Within the range of parameter values used in the present experiment, the increase in T and K appears to give nearly equal difficulty in the task of compensating error, because the curve is nearly symmetrical and hyperbolic of the form TK = const. Depending upon the performance index required of a system of this type and the operator, one should be able to determine the design limit of the element to be controlled.

DISCUSSIONS

Mathematically, instability corresponds to the divergence of the controlled variable. In the experiment, it is difficult to cause actual divergence and to confirm it. Besides, due to the nonlinear characteristics of the control stick and other elements, the system will never be entirely divergent. Hence, the state of hunting is what will occur eventually when the control task is "difficult." In the experiment, therefore, only the degree of stability can be determined by an index such as that used in the present experiment.

Transfer functions for the human operators have been obtained for varied conditions of controlled elements. However, even in the cases where noise is small and system parameters are constant, the operator does not necessarily operate like a linear element. One of the operators of the present experiment makes it a rule to give the stick frequent pulse motions of nearly the same magnitude and duration, changing its frequency according to the state of error. (See Fig. 18) For a swiftly varying error, the same operator gives a large constant input to the stick depending on the sign of the velocity of error. The former mode of control is similar to a pulsed, three-position, on-off control, and the latter is similar to the same with velocity input to the on-off element. These examples show that the linear transfer function for the human operator is only an equivalent linear expression of a very nonlinear element. Some other samples of similar recordings are shown in Figs. 19 ~ 22. Figs. 18 and 19 compare the control of two pilots. Fig. 18 is by an amateur pilot where Fig. 19 belongs to a professional pilot with 3000 hours' flight experience. It appears that the professional pilot resembles a linear controller. Figs. 20 and 21 show the transition from stable to unstable operations by a small change in time constant. The operator can keep $T = 0.2$ under control but not $T = 0.3$. Fig. 22 shows one by a nondriver. Here again the stick motion resembles an on-off element.

In the present experiment, the identification of the human operator is made indirectly, in terms of the parameter values of the element he controls. In the vector diagram, the controlled element represents one that is unstable as shown in Fig. 3b. The fact that the human controller keeps this system from diverging means that he provides some compensation to bring the vector locus to circumvent the point -1 if he is a linear element, or he is in effect a nonlinear element that can be given by an amplitude locus crossing the vector locus for the controlled element at some finite point. In any event, it should be possible to find a range of controlled element within which a human operator can control the system with a reasonable stability.

Referring to the controlled element used in the experiment, the modulus of the transfer function can be more simply approximated if $T\omega$ is either large or small compared to unity as previously noted. Since

$$G = \frac{K}{-\omega^2 (1 + jT\omega)}$$

the modulus of the transfer function can be approximated by

$$|G| = \frac{1}{\omega^3} \frac{K}{T} \qquad \text{if} \qquad T\omega >> 1 \qquad (10)$$

and

$$|G| = \frac{K}{\omega 2} \qquad \text{if} \qquad T <<1 \qquad (11)$$

The phase shift for either case is given by

$$\angle G = \tan^{-1}(-T\omega) \qquad (12)$$

Now, from Eq. (10), the gain constant for the case where $T\omega >> 1$ decreases as the time constant T is increased. This alone would generally make the controlled element more stable: therefore, one might expect that, depending upon the specific values of the parameters, the control of this element will become easier when T is increased. However, there is also an effect of phase shift according to Eq. (12). Thus, it is not readily apparent how the overall performance will vary as T is increased.

CONCLUSIONS

An entirely different approach from previous investigations was attempted in the present experiment. Instead of determining the transfer functions of the human operator in a control system, the relation between a performance index and the parameters of the controlled element was sought. The results of limited experiments show that the performance of operators can be represented in the parameter plane of time constant and gain by a hyperbolic curve, its distance from the origin showing the control ability of the operator and its general shape indicating the operator's adaptability to the variation of the two parameters. If we specify an allowable value of performance index, we may find the limitations on the element to be controlled. The present approach may be applied also to the controlled elements with different equations, such as

$$\frac{K}{S\ (T_1S + 1)\ (T_2S + 1)}$$

If we collect enough data on these and other cases, it would help in the design of man-controlled systems, since we then would know what parameter limits for the elements to be controlled would permit a reasonable degree of control.

The effect of changing the nature of the random noise, the display device, and the manual control mode has yet to be studied. It is hoped that the result given in this report indicates the possibility of such an approach in the design or prediction of performance of man-machine systems.

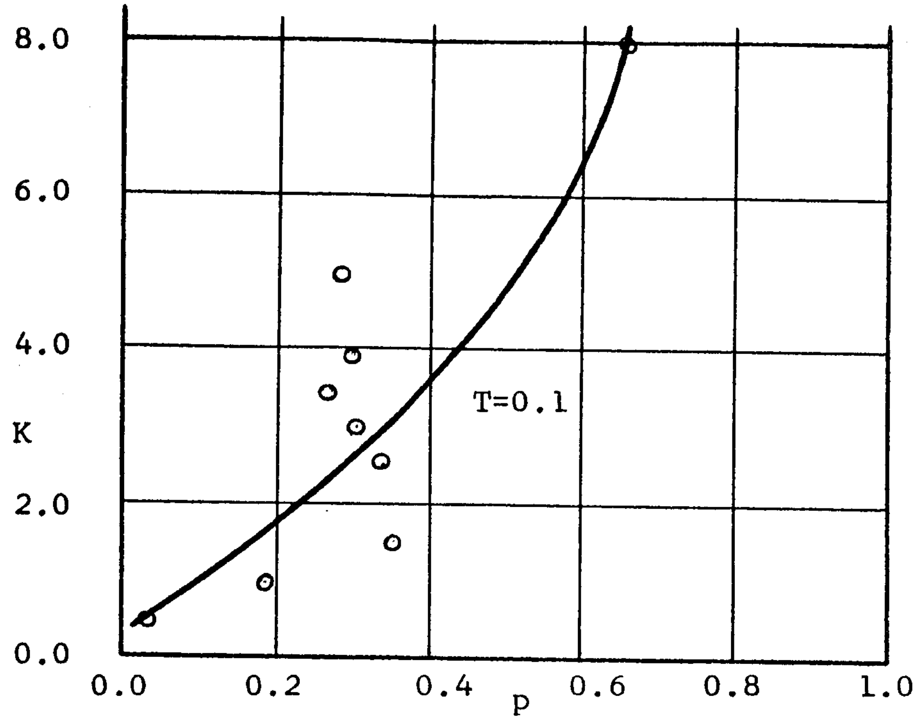


Fig. 4 Operator B_1

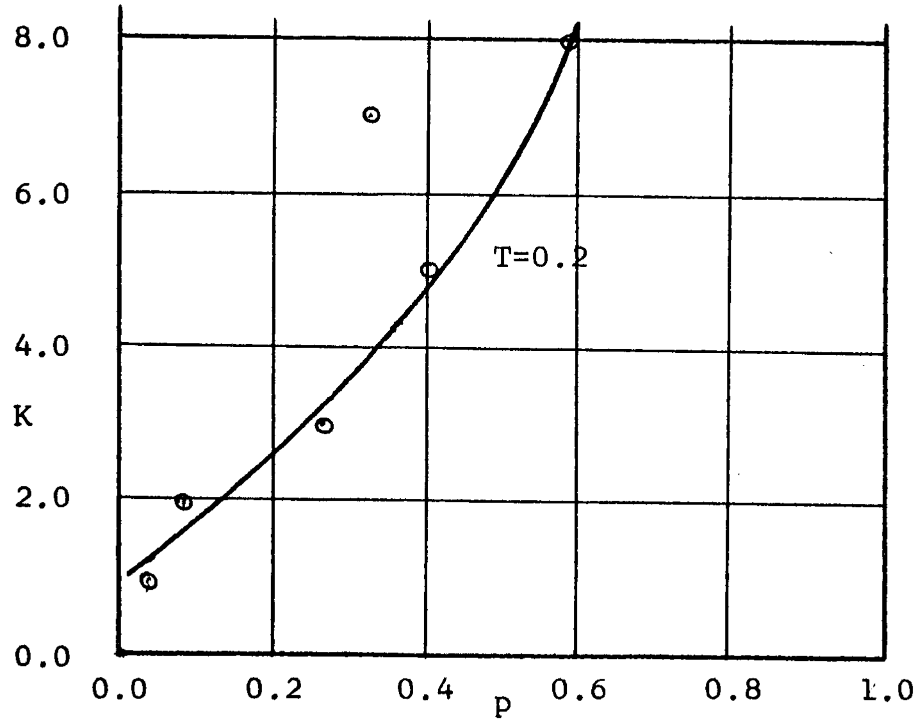


Fig. 5 Operator B_1

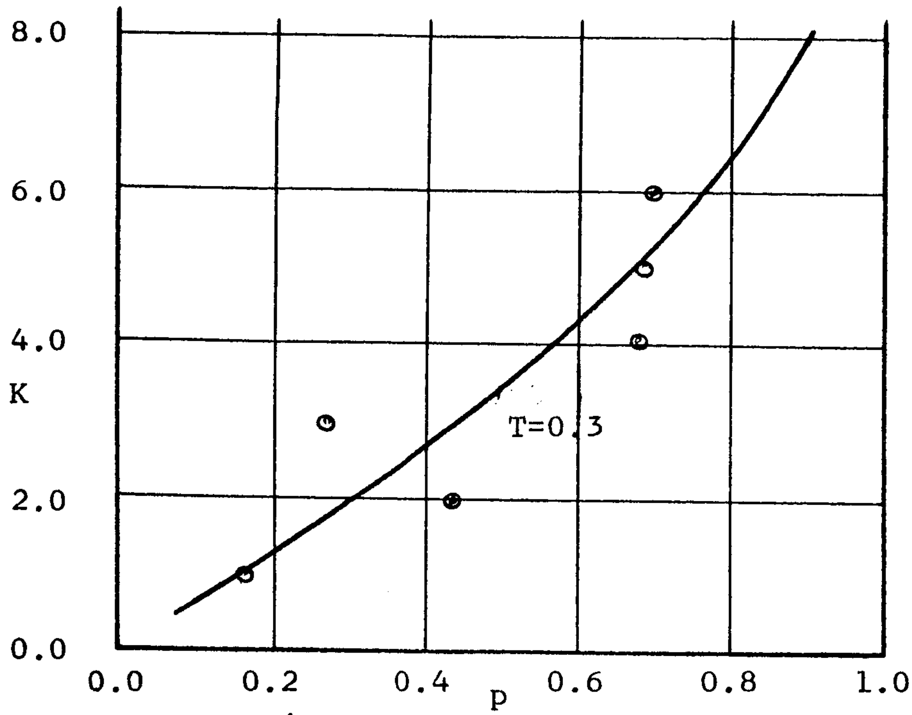


Fig. 6 Operator B_1

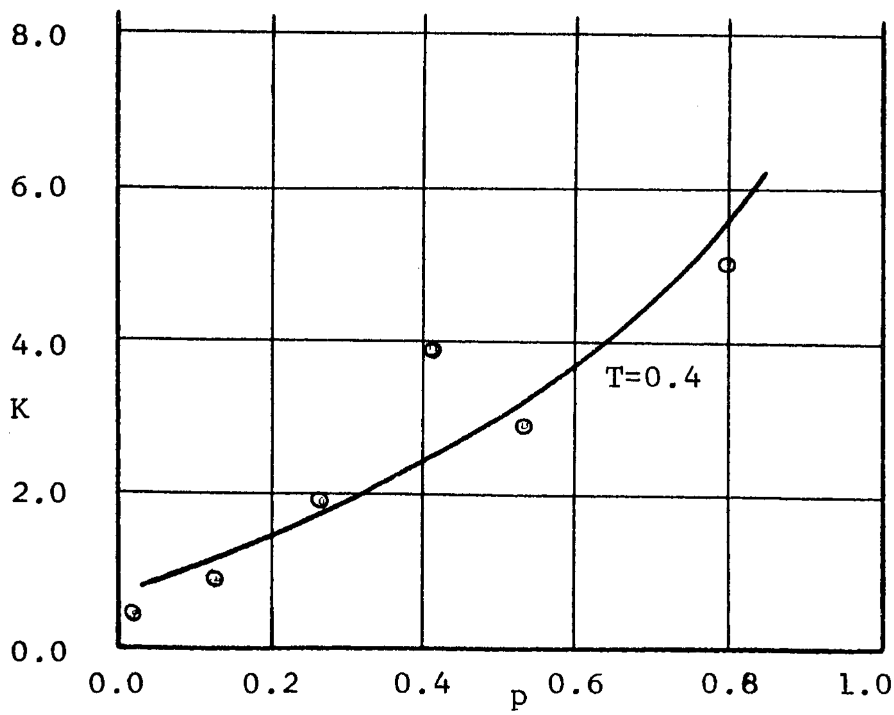


Fig. 7 Operator B_1

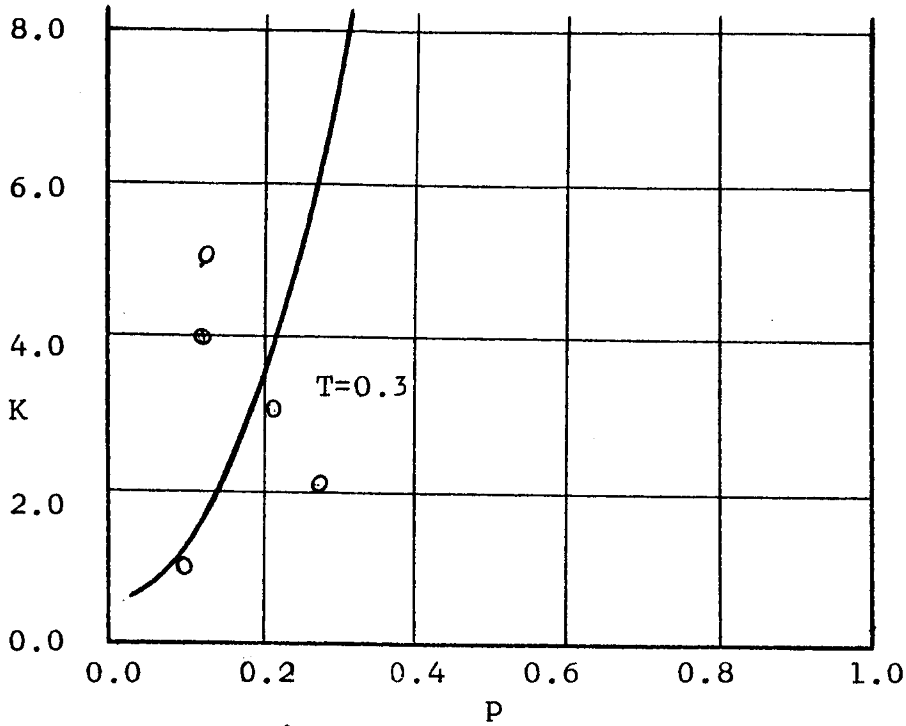


Fig. 8 Operator A_1

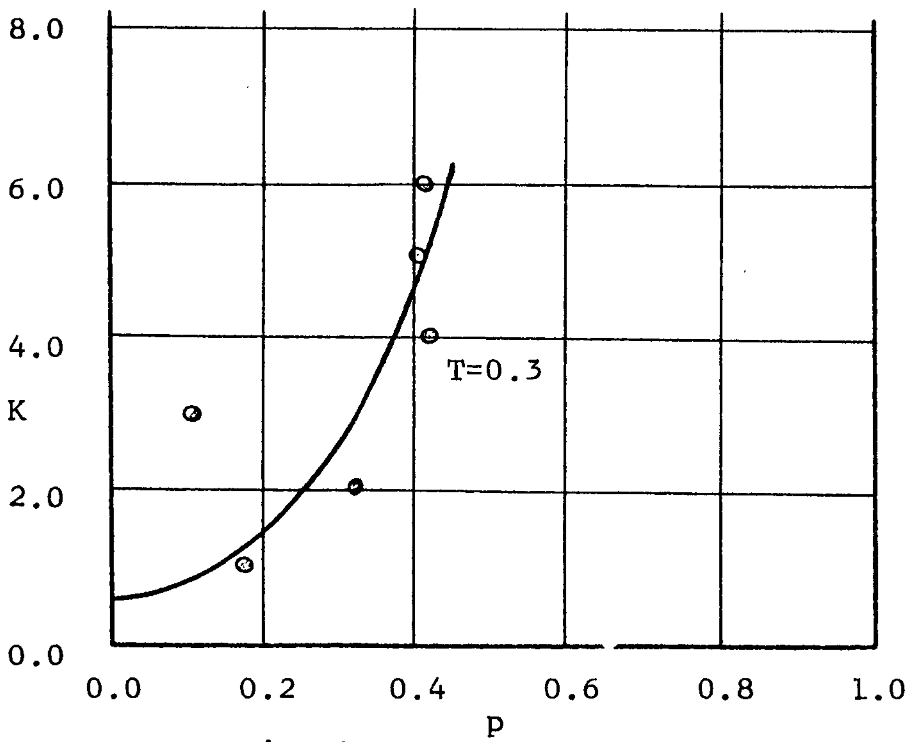


Fig. 9 Operator A_2

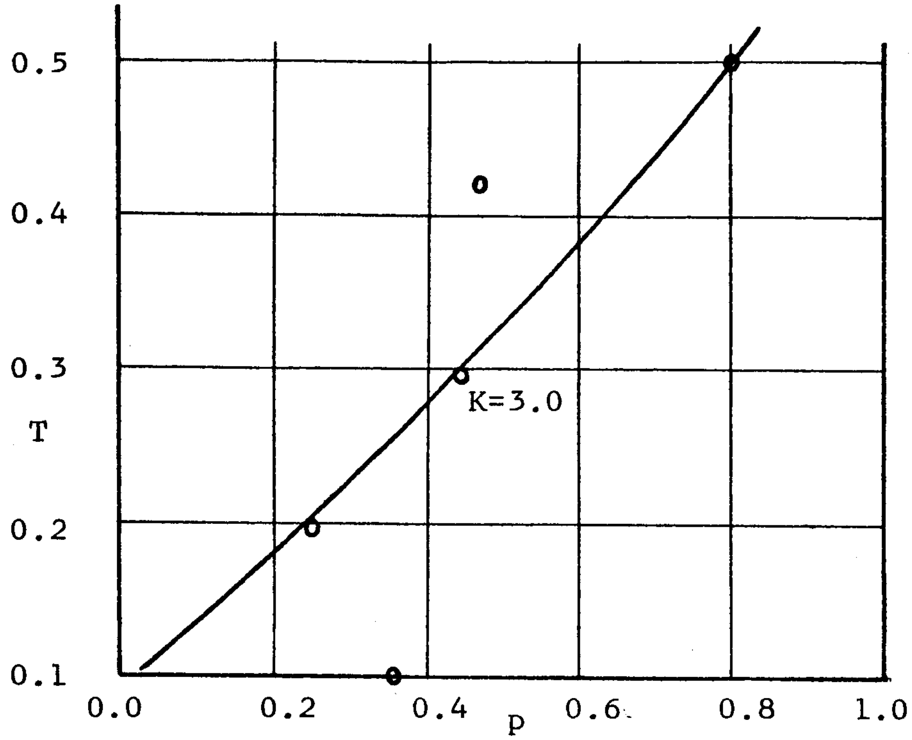


Fig. 10 Operator B1

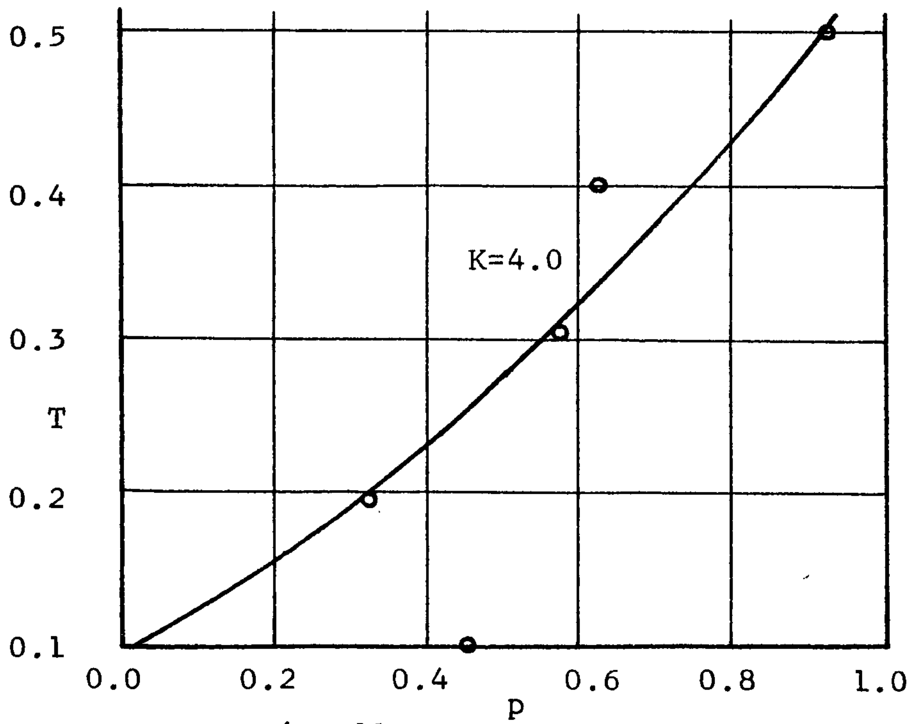


Fig. 11 Operator B_1

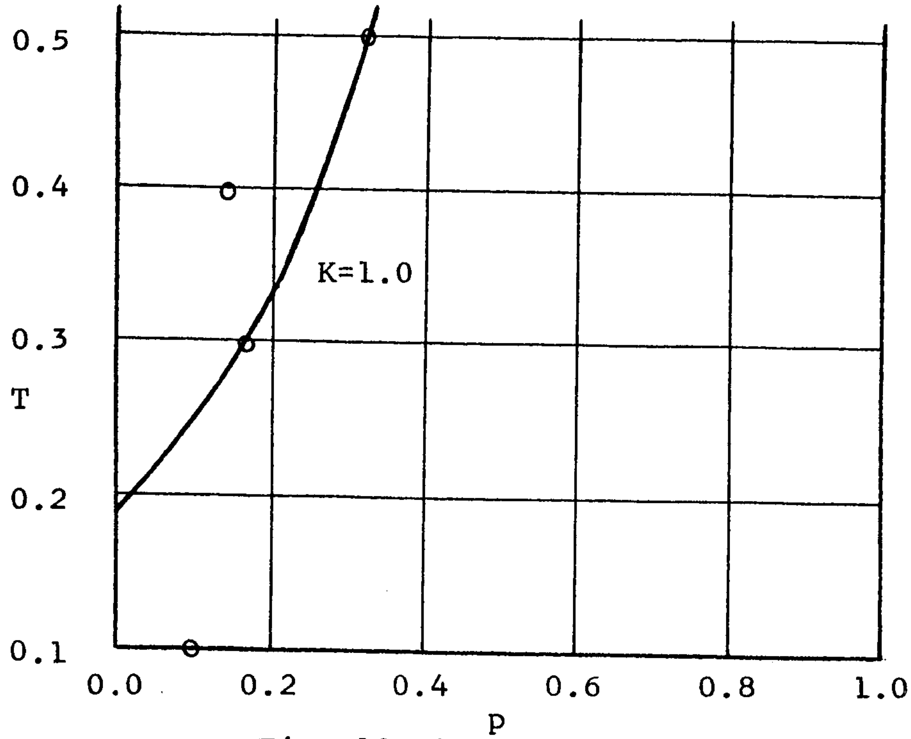


Fig. 12 Operator B1

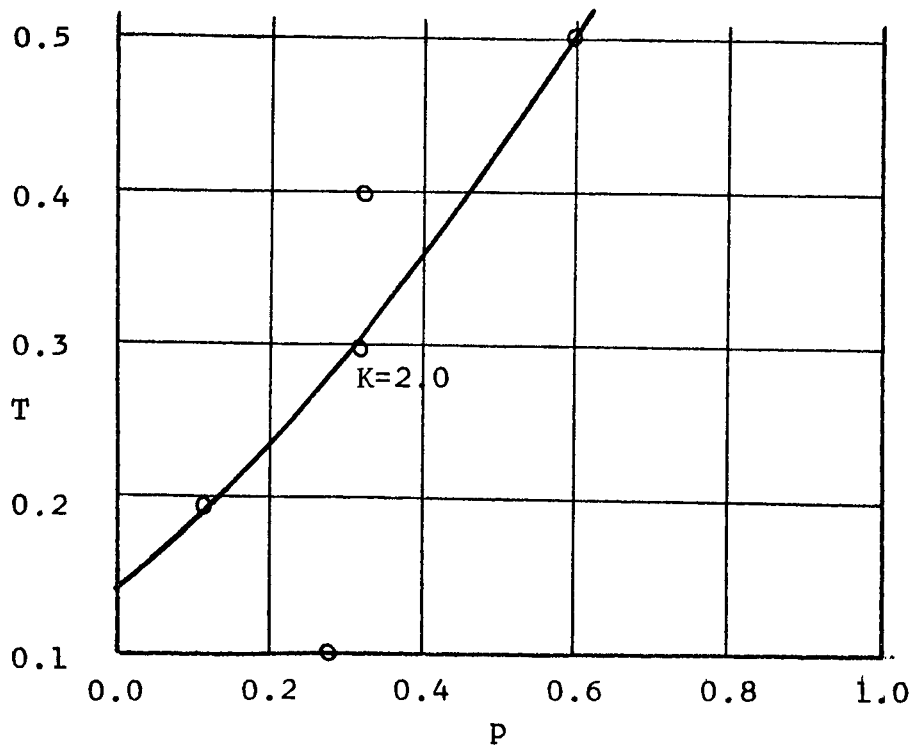


Fig. 13 Operator B1

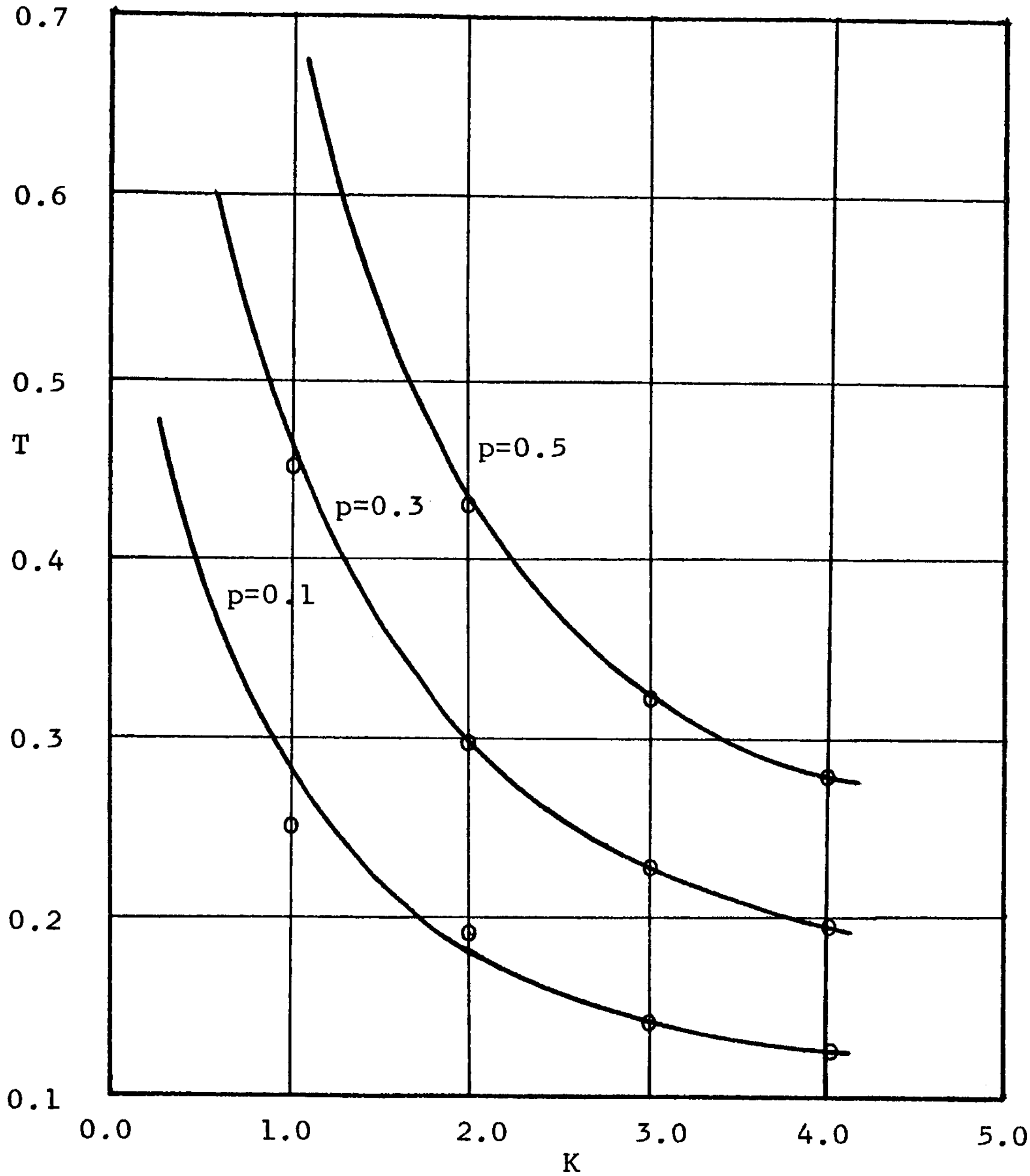


Fig. 14 Operator B_1

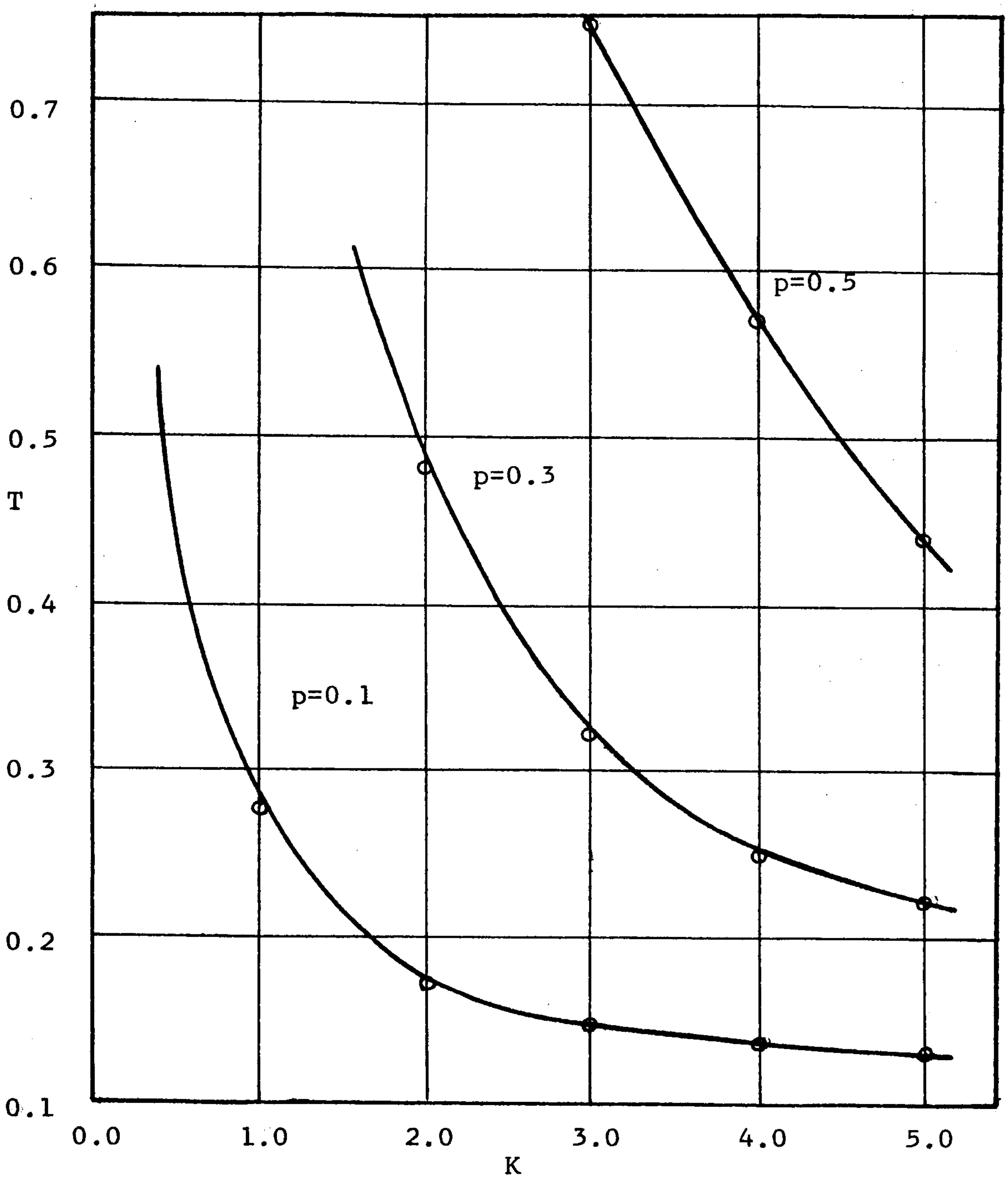


Fig. 15 Operator B_2

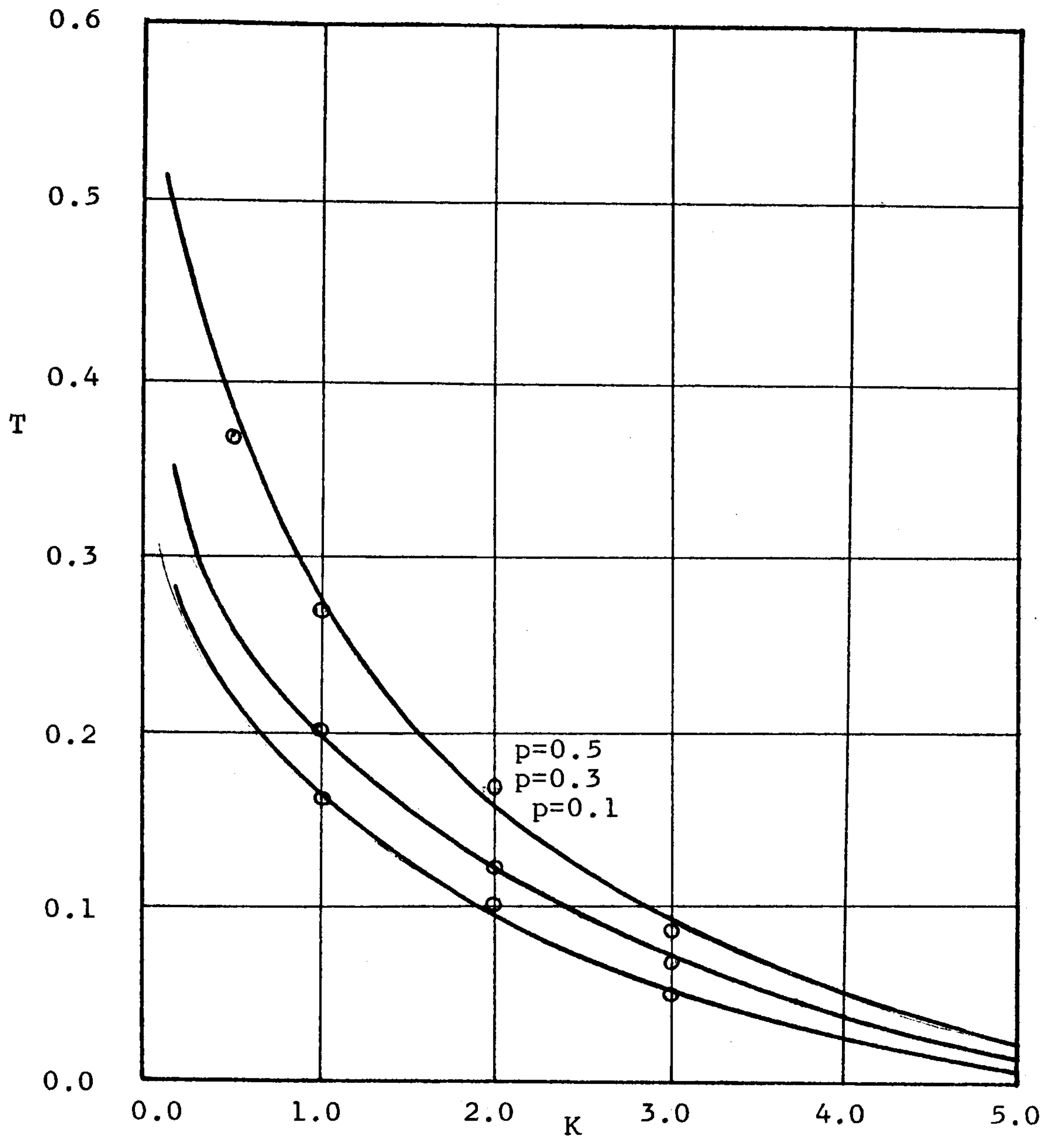


Fig. 16 Operator C

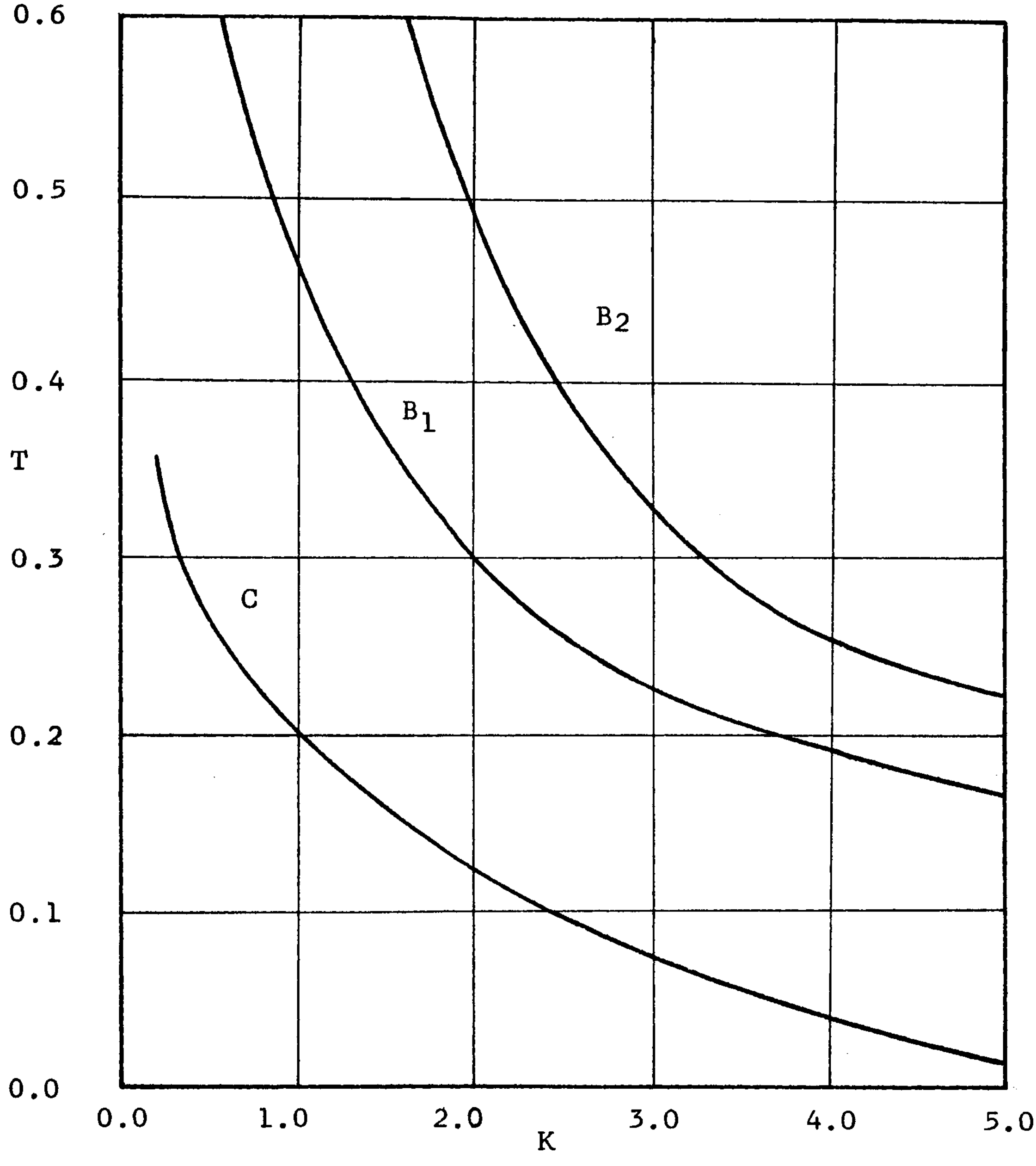


Fig. 17 Comparison For Three Different Operators

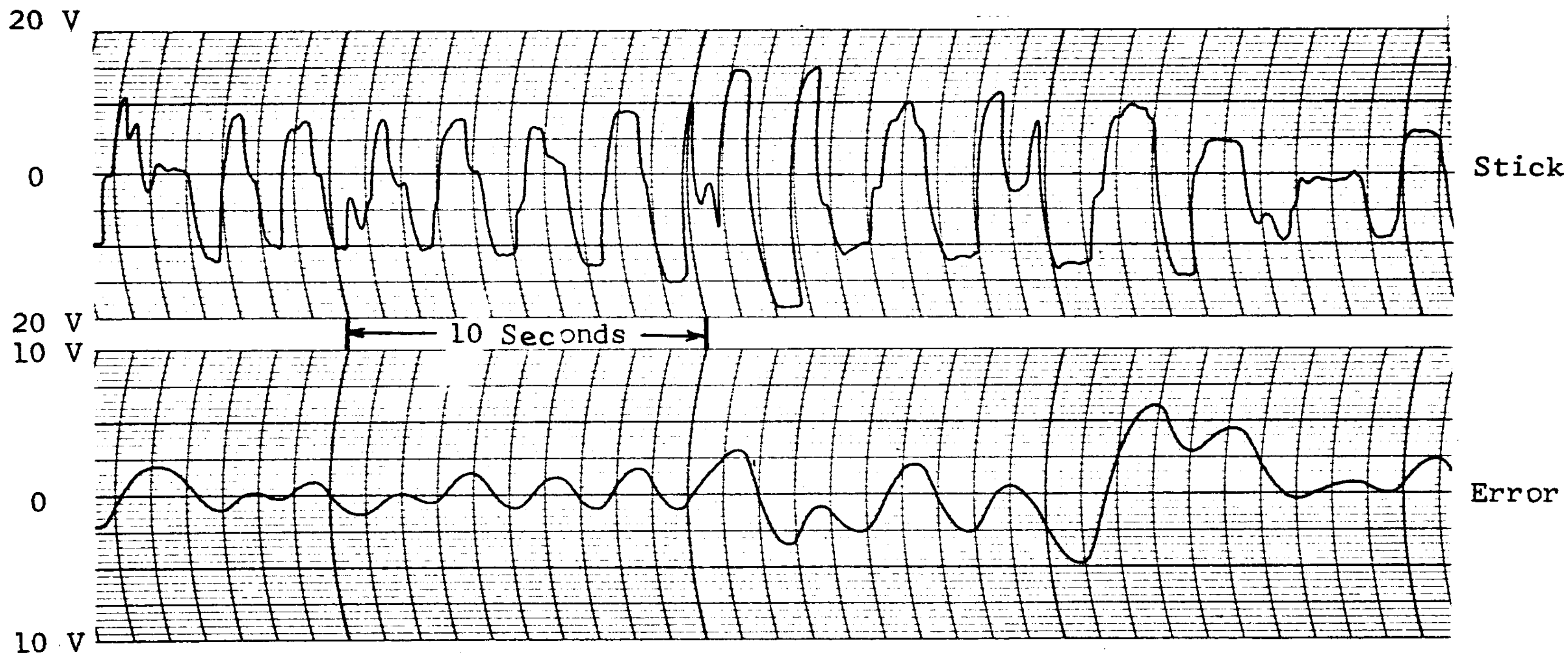


Fig. 18 Operator A2, K = 1.0   T = 0.3

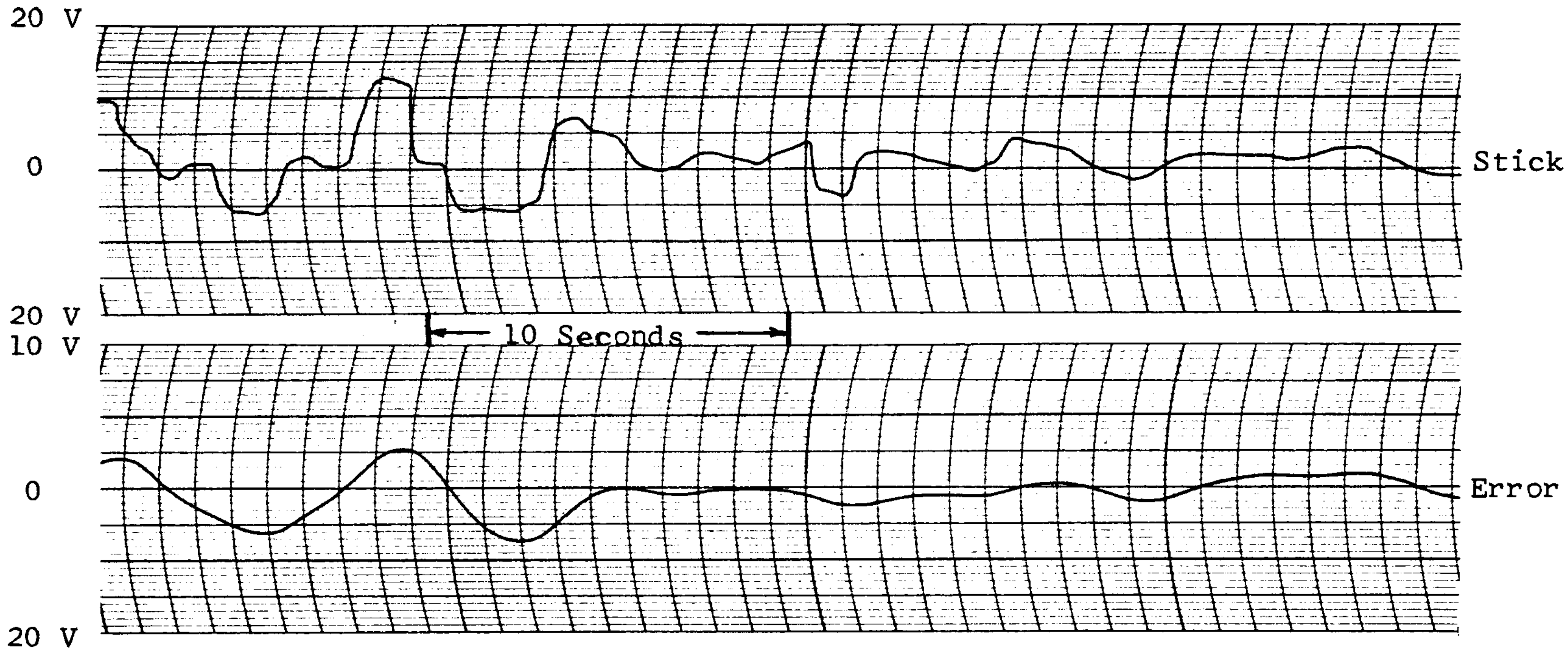


Fig. 19 Operator A_1, K = 1.0 T = 0.3

Fig. 20 Operator B_1, K = 5.0 T = 0.3

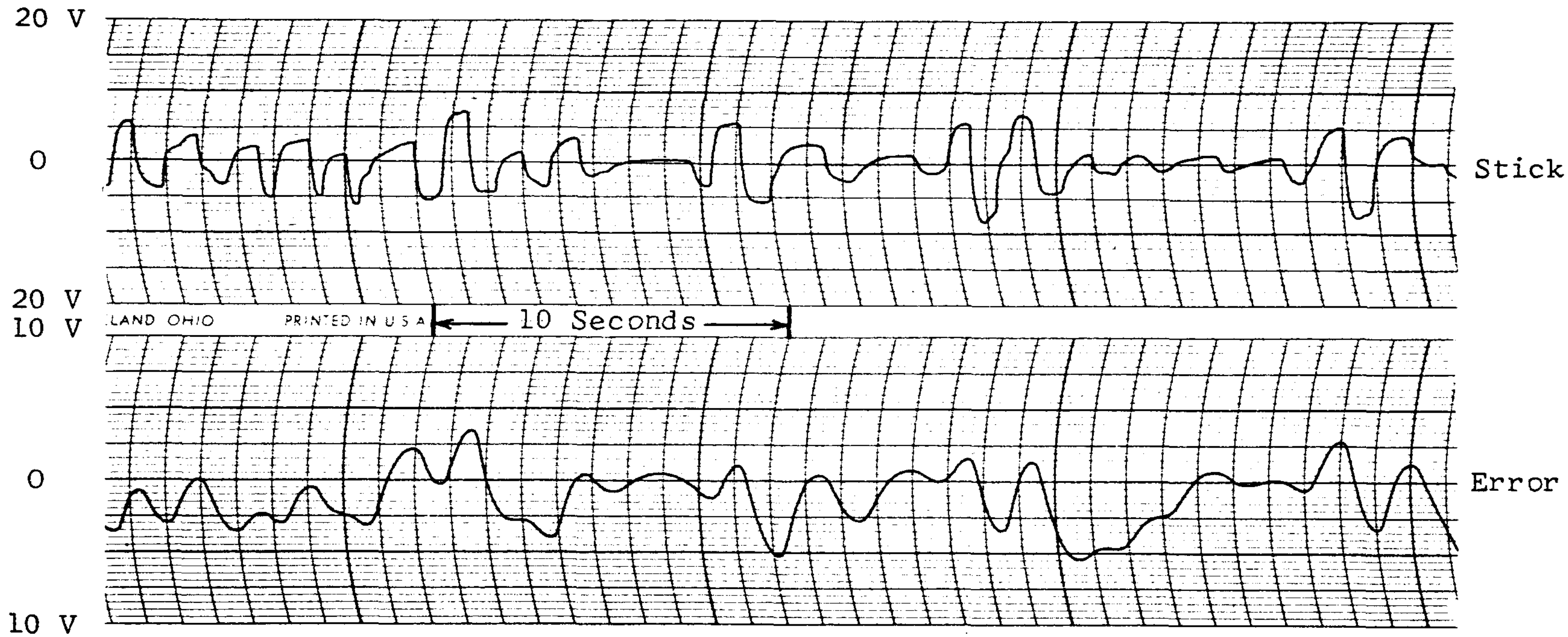


Fig. 21 Operator B_1, K = 5.0 T = 0.2

Fig. 22 Operator c, K = 2.0 T = 0.2

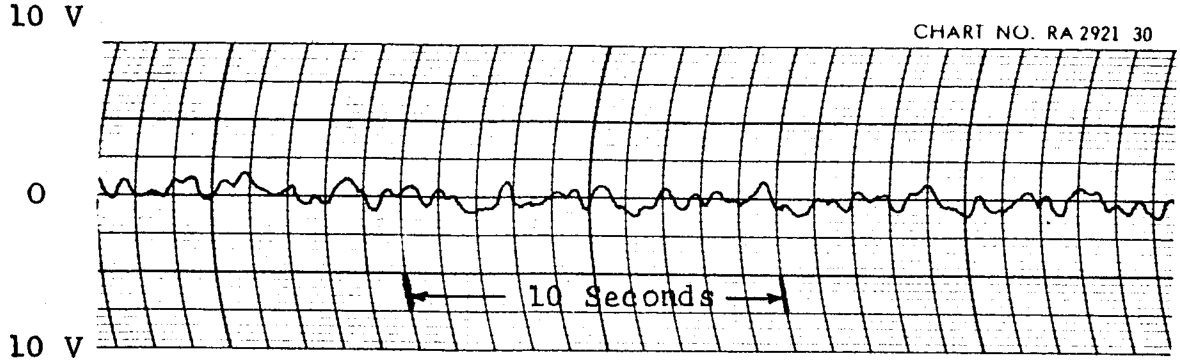


Fig. 23 Sample Of The Random Noise

REFERENCES

1. Sheridan, T. B., "The Human Operator in Control Instrumentation," Progress in Control Engineering I, Heywood & Co., London, 1962.

2. Reswick, J. B., "Determination of System Characteristics from Normal Operation Records," Trans. A.S.M.E., Vol. 78, 1956.

3. Kuehnel, H. A., "Human Pilots' Dynamic-Response Characteristics Measured in Flight and on a Nonmoving Simulator," NASA TN D-1229, March 1962.

4. Adams, J. J., "A Simplified Method for Measuring Human Transfer Functions," NASA TN D-1782, April 1963.

5. Young, L. R., et al., "The Adaptive Dynamic Response Characteristics of the Human Operator in Simple Manual Control," NASA TN D-2255, April 1964.

6. Cole, G. et al., "Study of Pilot-Controller Integration for Emergency Conditions," RTD-TDR-63-4092, Wright-Patterson Air Force Base, Ohio, January 1964.