621-501:621-51

Manual Control Systems Including Two or More Operators*

By Masakazu IGUCHI**

Several types of system controlled by two or three human operators were investigated to know fundamental characteristics of a manual control system including many human operators.

Controlled systems were simulated on an analog computer. Cathode-ray-tubes were used as displays, and small light handles of disk type were used in order to eliminate dynamics of handle systems.

The results showed that: In the system composed of serially connected operators, its characteristics are nearly equal to the enlarged characteristics of a unit-element. In the closed-loop system with operators connected in series, adaptive characteristics of human operators produce an undesirable influence, which can be eliminated by a minor feedback path. In the system composed of operators connected in parallel, operators' outputs tend to drift due to interaction between them. In the two-dimensional control system with strong interaction, the control by a single operator brings better results than the control by two operators.

1. Introduction

Since Tustin⁽¹⁾ succeeded in the first application of control theory to the description of a human operator in 1944, many investigators⁽²⁾ have made efforts to know human operator's characteristics by using various techniques, and have brought out many useful results. The author⁽³⁾ also has been interested in this problem, and has made several experiments to know the relation between control actions and mental strain and to know the dynamic characteristics of two-dimensional manual control systems controlled by one human operator.

Up to this time, almost all studies mentioned above have been devoted to manual control systems with single-operator. In this paper, an attempt was made to research manual control systems with multi-operators. Are the dynamic characteristics of each human operator in the manual control system with multi-operators the same as in the system with single-operator? Do they behave differently under some interaction among them? To answer these questions, several fundamental experiments were made. The results are reported in this paper.

In proceeding with discussions on the experiments, general remarks on human operators in simple tracking systems will be provided in Section 2.

2. Human operator in simple tracking system

The block diagram shown in Fig. 1 represents a human operator as a system component. Transfer characteristics of an average operator are illustrated below. The first is that the operator has an adaptability, in other words, dynamic characteristics of the operator are so determined as to adapt themselves to those of a controlled system. Therefore, they are undetermined in the case of Fig. 1.

Experimental results obtained by many investigators have proved that the operator's characteristics in simple tracking system could be described approximately in terms of a quasilinear mathematical equation. The author, at first, assumed to describe the operator by a transfer function of the form

$$H(s) = h \left\{ (\tau_{D_m} s)^m + \dots + \tau_{D_1} s + 1 + \frac{1}{\tau_{I_1} s} + \dots + \frac{1}{(\tau_{I_n} s)^n} \right\} e^{-T_s} \dots (1)$$

It was reasonably assumed by experiments that high order derivative terms were beyond the capability of an average operator and that usually there was no need for them to be included in the transfer

Fig. 1 Human operator

* Received 8th November, 1962.

** Lecturer, Faculty of Engineering, University of Tokyo, Bunkyo-ku, Tokyo.

function. The same fact was proved for high order integral terms. In consequence Eq. (1) could be reduced to the simpler form

$$H(s) = h \left(\tau_D s + 1 + \frac{1}{\tau_I s} \right) e^{-Ts} \dots \dots \dots (2)$$

This transfer function means that the operator can be approximately described in terms of dead time and the sum of proportional, derivative and integral actions in a proper ratio, as reported by Woodson⁽⁴⁾.

The combination ratio of those three actions varies according to the characteristics of a controlled system. Coefficient of derivative action τ_D increases in value as a controlled system has a long time lag in which to stabilize the system. Coefficient of integral action τ_I decreases in value to eliminate offset, when a controlled system has a short time lag and small gain constant.

Each of those three actions imposes different amounts of mental strain on the working operator. Then, the pulse-rates of working operators were measured by means of Matsuda method to estimate their mental strain. The results show that the stronger is the derivative action, the larger is the mental strain, that the mental strain imposed by the

integral action is not so heavy as that by the derivative action, and that the easiest action is proportional one with a moderate amount of dead time.

Fig. 2 shows how the pulse-rate of an operator changes as he starts on simple calculation with figures. The pulse-rate rises considerably due to the mental strain as soon as he begins to calculate.

Fig. 3 shows the aforementioned facts. The top recording shows the pulse-rate of an operator controlling some controlled systems. In this figure, the process of time is recorded from right to left. The parameter of the controlled system a was changed gradually every two minutes, as denoted in the figure. The top recording shows that the pulse-rate increases according to the decrease of a , and it was proved by other experiments that the smaller was a , the stronger was the derivative action, in order to make compensation for increased time lag of the controlled system. From these two facts, it is reasonably concluded that a strong derivative action imposes heavy mental strain on the operator.

Fig. 2 Pulse-rate and calculation with figures

Fig. 3 Relation between pulse-rate and dynamics of controlled systems, where transfer function of them is $1/s(s+a)$

3. Apparatus

Controlled system: Constructed with electronic analog computer components.

Control handle: A spring restrained handwheel, 2 inches in diameter. Operator manipulated it using his whip hand, as shown in Fig. 4.

Display: A 5-inch-cathode-ray-tube. Displacement of a spot moving horizontally on its face indicated a signal to be transmitted to the operator.

Subjects: About ten students aged 20 to 30.

Recording: Recorded by means of a six channel pen-writing recorder after a little training.

Fig. 4 Apparatus

4. Experiments and results

(1) Serial connection of human operators

At first, the two systems shown in Fig. 5 were examined as the simplest cases. In the case of Fig. 5 (a), the first operator reads the system's input from his display and manipulates his handwheel. Its angular deformation is proportionately converted to voltage. It is his output and at the same time an input to be given to the next operator. Since the system (a) has no feedback path, transfer characteristics of the operators can not be determined, as expected easily from the case of Fig. 1.

In the case of Fig. 5 (b), each operator can read not only a signal given to him, but also his own response from his display. There are two types of display in this case. One is called "compensatory display" and another is called "pursuit display", according to McRuer and Krendel⁽²⁾. The former means that an operator reads the deviation, defined as the difference between system's input and output. The latter means that an operator reads system's input and output separately from two spots moving independently of one display.

One operator component with unity feedback path is named unit-element of operator in this paper. In the unit-element the operator's integral action is considered to be very strong.

The role of the system (b) is to transmit a system's input from one operator to the next. Its

Fig. 5

Fig. 6 Gain diagram

over-all transfer characteristics are represented by the product of those of respective unit-elements. Therefore, it is reasonably considered that the characteristics of a unit-element become more and more conspicuous as the number of unit-elements increases.

To illustrate the consideration mentioned above, Figs. 6 and 8 are provided. Fig. 6 shows a gain diagram derived by means of frequency response method. Curve ① in Fig. 6 represents frequency characteristics of a unit-element of an operator. Curves ② and ③ represent those of the systems with two and three unit-elements respectively. Curve ① shows that the gain decreases according to the increase of frequency at high frequency range. Curves ② and ③ show this tendency more conspicuously.

When we gave to a unit-element the input composed of several sinusoids of equal amplitude and arbitrary phase, the following results were obtained. In one case, only the gain at low frequency range decreased as the input included a high frequency sinusoid as shown in Fig. 7 (a). In addition, McRuer and Krendel⁽⁵⁾ reported that the gain could be a positive db value under special conditions. In another case, the gain decreased uniformly in the same condition as shown in Fig. 7 (b). Usually the former is seen in a pursuit tracking and the latter in the compensatory tracking.

Those tendencies also appear markedly in systems with many unit-elements. Recordings of Fig. 8 are those examples. The top recordings show the system's input composed of three sinusoids. Following recordings show the first operator's output,

Fig. 7 Gain diagram

the second's and the third's respectively. The right recordings show that the gains decrease uniformly for any sinusoids as the number of unit-elements increases, while the middle recordings show that the gains of low frequency sinusoids decrease and only the highest frequency sinusoid tends to remain in the transmitted signal.

Considering a noise, or a remnant, produced by an operator, it has usually higher frequency components than those included in the system's input. Therefore, the noise is often enlarged gradually at every stage. The left recordings of Fig. 8 show this tendency. The noise produced by the first operator is enlarged and deforms the system's input gradually.

(2) Closed-loop system including operators connected in series

In this chapter, the system as shown in Fig. 9 is discussed. The second operator in the system reads from his display only the output of the first operator and manipulates his handwheel so as to converge that output to zero.

In this system, its stability becomes worse as the number of operators increases. Fig. 10 shows such a phenomenon. The top two recordings show the input sinusoid of circular frequency 0.18 rad/sec. The others show the system's output in various kinds of cases. The system is stable if the number of operators is less than four, but is unstable when the number increases to four.

In Fig. 11, the accuracies of two systems are

Fig. 9

compared with each other. The ordinate of this graph indicates the mean absolute error divided by the mean absolute value of input sinusoid. Then, the lower the better. Black dots and solid lines represent the results of systems with a single operator, or unit-element, while white dots and many kinds of lines represent those of systems with two operators. In consequence, the error of systems with two operators is about ten times larger than that of unit-element.

In a closed-loop system with several operators, an interesting phenomenon appeared as follows. As mentioned in Section 2, the dynamic behavior of an operator is made adaptable to that of a controlled system. In a system with multi-operators, each of the operators changes his own behavior so as to adapt it to the behaviors of the others, and it takes a longer time than in a system with a single opera-

Fig. 10 Closed-loop systems including operators connected in series

Fig. 8 Serial connection of unit-elements

tor to converge their behaviors to the adapted ones. At the same time, every operator seems to be irritated in this condition. In experiments of systems with two operators, their behaviors were determined in 1 to 10 minutes without exception. However, in systems with four operators, stabilization of the systems could not be attained in spite of many trials.

By means of a minor feedback path shown in Fig. 12, that phenomenon can be eliminated and characteristics of the system can be improved. The reason is as follows. The operator with a minor loop is insensible of the main feedback path and immediately adapts his behavior to the minor closed loop, that is to say, he forms independently a unit-element. Then another operator can make his behavior adaptable to the unit-element of which the characteristics have already been determined.

(3) Control by operators connected in series

In the system controlled by two operators as shown in Fig. 13 (a), the accuracy becomes much worse than that of a single-operator control system, as denoted in Fig. 14, so that it is impossible to

improve the characteristics of a system by dividing the control action between two operators.

The ordinate of Fig. 14 indicates a system error as well as that of Fig. 11, and the abscissa indicates several transfer functions of a controlled system. Curve (a) represents the error of the system shown in Fig. 13 (a), and Curve (c), that of a single-operator system. The latter is far superior to the former. Curve (b) represents the error of the system shown in Fig. 13 (b). It is proved that the minor feedback path provided for the second operator makes some improvement in system accuracy.

In the system including a transfer element inserted between two operators as indicated in Fig. 15, the transfer function of the last element $G_2(s)$ has a great influence on the system characteristics, even though $G_1(s) \cdot G_2(s)$ may be the same. When $G_2(s)$ includes no integration term, the system's error considerably increases. The reason is presumed as follows. When the last element $G_2(s)$ is the characteristic of proportionality, the second operator must include a strong integral action in his control action,

Fig. 11 Estimation of system's performance

Fig. 12

Fig. 13

Transfer functions of controlled systems
Fig. 14 Estimation of system's performance

Fig. 15

as he is required to hold his input to zero and to make his output proportional to the system's input. On the contrary, the integral action is done by the controlled system $G_2(s)$ instead of the second operator, when $G_2(s)$ includes integral terms. In consequence, the former has more integration terms than the latter by the terms included in the control action of the second operator, if $G_1(s) \cdot G_2(s)$ is the same in both cases.

In Fig. 16, responses of three systems, each of which has the same function of $G_1(s) \cdot G_2(s)$, are illustrated. The top recordings show the system's input, and the second recordings show the system's output. The symbols ① to ⑥ written in the record-

Fig. 16 Deterioration of system's performance due to integral action

Fig. 17

ings correspond to those of the block diagram above the figure. The recordings of the system's output show manifestly that, the larger are the integration terms of $G_2(s)$ in number, the better is the quality of the system. In Case (c), the stability of the system is nearly in critical condition.

The means to improve the system including the last element without an integration term is to provide the second operator with a minor feedback path and to make a unit-element, in order to confine undesirable effects of integral action within the unit-element.

(4) Parallel connection of the operators

A closed-loop system, composed of operators connected in parallel, was constructed. In this system, its output is the sum of three operators' outputs. The deviation of this system is indicated to each operator by his own displays on the same condition without any communications except the path denoted in Fig. 17.

The results obtained from the experiments show that their outputs are different from each other on equal condition. The most skillful operator's output tends to be the largest. When one operator stops

Fig. 18 Drifts of operator's output

controlling, the others take over the work instantaneously and smoothly without any signs.

In this system, such kinds of interactions are not observed as seen in the closed-loop system with operators connected in series. However, the zero positions of operators' handwheels drift on account of their integral actions included in their control actions, even though the handwheels may be restrained by springs. This phenomenon is conspicuous in the system without a controlled element as shown in Fig. 17, for the operator's control actions are nearly equal to pure integral actions with dead time.

The drifts are noticed in Fig. 18. The top recordings show a system's input composed of three sinusoids. The second recordings show a system's output. This output is the sum of three operators' outputs shown by the following three recordings. Observation of the fourth and fifth recordings shows that two operators' outputs are drifting in opposite directions. However, their drifts have no influence on the system's output due to their counterbalance.

(5) Control by operators connected in parallel

A two-dimensional control system with simple characteristics can be controlled with stability by one operator manipulating the two handles with his both hands. However, by dividing the control work between two operators as indicated in Fig. 19, it can be expected to reduce an operator's load given by the control work. When there is no interaction between two controlled variables, the characteristics of the system are improved by dividing the control work between two operators. On the contrary, they become worse by dividing, when there is strong interaction.

For example, Fig. 20 shows the responses of two-dimensional manual control systems. In Fig. 19, the manipulated variable of an upper controlled system is composed of the output of upper handle system and 75 percent of the output of lower system, and it is so for lower controlled system.

The right recordings of Fig. 20 illustrate responses of the system controlled by two operators, and the left recordings illustrate those of the system controlled by one operator using his both hands. The upper three recordings show responses of one closed-loop system, and the lower three show those of another closed-loop system.

Fig. 19

Though the recordings of system's input are not shown, a sinusoid of circular frequency 0.63 rad/sec is given to one closed-loop system as its input, and 1.4 rad/sec, to another. The top and bottom recordings show the absolute error of each system, that was smoothed by means of a filter with the transfer function $1/(10s+1)$. Comparison of the right recordings with the left shows that the absolute error is less in the control by a single operator than in the control by two operators, contrary to the expectation.

The reason is presumably that, while the operator makes efforts to dissolve the interaction in a two-dimensional control system with a single operator, it is entirely impossible for them to dissolve it in the system with two operators for want of direct communications between them. In order to improve the two-dimensional control systems with two operators, it is desirable to provide displays or handle systems with proper compensating elements to dissolve the interaction.

Fig. 20 Responses of two-dimensional manual control systems

5. Conclusion

From the results obtained from the experiments, it is reasonably concluded that:

In manual control systems with continuous and linear characteristics, it is desirable to reduce the number of operators as much as possible. If it is impossible, careful attention must be paid to the following facts.

(1) In the system composed of serially connected operators, its characteristics are nearly equal to the enlarged characteristics of a unit-element.

(2) In the closed-loop system with operators connected in series, adaptive characteristics of human operators produce an undesirable influence, which can be eliminated by a minor feedback path.

(3) In the system as shown in Fig. 15, integration terms should be transferred from $G_1(s)$ to $G_2(s)$.

(4) In the system composed of operators connected in parallel, operators' outputs tend to drift

due to interaction between them.

(5) In the two-dimensional control system with strong interaction, the control by a single operator brings better results than the control by two operators.

Acknowledgment

The author would like to thank Prof. S. Fujii for his encouragement and guidance, and the members of his laboratory for their assistance.

References

- (1) A. Tustin: *Jour. Inst. Elect. Engrs.*, Part II, A, 14 (1947).
- (2) Summarized in D. T. McRuer and E. S. Krendel: *Jour. Franklin Inst.*, Vol. 267, No. 5 (1959), p.381.
- (3) M. Iguchi: *Jour. Japan Soc. Mech. Engrs.*, Vol. 65, No. 517 (1961), p. 216.
- (4) W. E. Woodson: *Human engineering guide for equipment designers*, (1954), 5-27, University of California Press.
- (5) D. T. McRuer and E. S. Krendel: *Jour. Franklin Inst.*, Vol. 268, No.1 (1960), p.24.

621.547.01:621.867.8.01

Research on the Pneumatic Conveyance of Densely Concentrated Solid Particles in a Horizontal Pipe*

By Shinzo KIKKAWA**

The conveying state of concentrated particles changes sensitively according to the local concentration of the particles, namely, with an increase of the local concentration of particles the acceleration factor of particle " κ " decreases rapidly.

Firstly, the new constant denoting the concentration of particles " m " modified from the mixture ratio " μ " by taking account of the specific weights and the velocities of air stream and particle, and the distribution of particles in vertical direction, is defined.

Secondly, from the experimental results on the dispersed state of particles, the decreases of the acceleration factor κ/κ_0 are measured, where κ_0 stands for the acceleration factor for a single particle. From the above investigations, the following empirical formula is obtained.

$$\frac{\kappa}{\kappa_0} = \frac{1}{2} \left\{ \exp(-424 m) + \frac{0.00261}{0.00261 + m} \right\}$$

By using the above formula, we can presume the velocity of concentrated particles and the clogging of a pipe.

1. Introduction

The pneumatic conveyance of solid particles has been studied from the viewpoints not only of

conveyance but also of chemical technology. It is well-known that the behavior of particles changes remarkably with the mixture ratio of particles and air. The above fact can be easily observed under the condition that the mixture ratio increases gradually at constant velocity of air stream, namely, the

* Received 16th August, 1962.

** Assistant Professor, Faculty of Engineering, Doshisha University, Kamikyo-ku, Kyoto.