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On the Manual Control System

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The method of the harmonic analysis of the human operator's characteristics by means of an analog computer is described. The human operator's characteristics in the closed loop system are described by vector locus. The human operator controls in response to the sine wave input so as to make constant the gain in the closed loop system. In accordance with the change of the input frequency, the operator changes his control action. Consequently the transfer function of the human operator's characteristics is too complex and difficult to be described by a linear element.

§ 1. Introduction

Recently, in the field of control, many investigators have been studying the manual control system in various ways. The present century has seen quite a remarkable progress in automation, and therefore the amout of work done by human hands has been reduced to an astonishing degree. However, human hands are still in need because machines cannot, after all, work for themselves. They have to be operated by human hands at their certain points. As machines with excellent functions are produced in great numbers, human hands that operate them should become highly functional to keep up with them. Therefore, it becomes very necessary to design the man-machine system which makes the human operation easier, more precise, and more effective, in order to accomplish the purpose of good and complete production and to prevent various disasters.

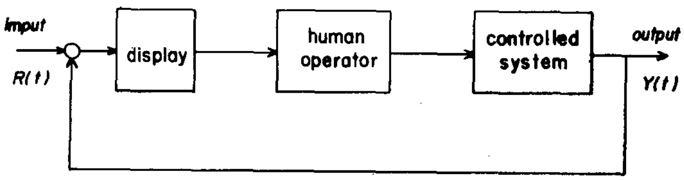
Investigations concerning the manual control system have been made by many persons, and the transfer function has been described in various forms.[1] It has been so, one might consider, because the operator's action in the control system is not so exact and constant as machine. In accordance with the change of environmental conditions and that of controlled system characteristics, the operator's control action in the given system changes, which shows that the human operator's action has adaptability. Therefore, the operator's transfer function can apply only under limited conditions where the operator controls the particular system in response to a certain input.

Random signals as the system input are often used to obtain the transfer function. In an ordinary control system, the method by frequency response is often adopted to search for the system. In the manual control system, however, this method has not been used so often. As the human operator is apt to do a predictive action when the input signal is a sine wave, the operator's response becomes too complex and difficult to be described by a simple linear transfer function.

The predictive action, however, may be considered as one of the most remarkable features of the human operator's control action. It is comparatively simple to analyze by the analog computer the human operator's response to the sine wave in the manual control system. In the present experiment, the harmonic analysis of the human operator's response was made with an analog computer.

§ 2. Human Operator's Characteristics in the Manual Control System

The manual control system is the system in which the human operator controls a certain control element by hand. In the system, the human operator performs the role of a kind of controller which detects system errors visually and performs manual movements so that the



Fig, 1. Block diagram of manual control system.

errors may be reduced.

Fig. 1 shows the block diagram of the manual control system. The human operator's characteristics in such a system may be obtained approximately only when a particular control element and the closed loop system are used. Many investigators have been studying and searching for the human operator's characteristics in the system. One example of their results may be shown by the following equation[1]:

$$H(S)=\frac{Ke^{-SD}(1+T_L s)}{(1+T_N s)(1+T_I s)} \tag{1}$$

There are many methods to describe the operator's transfer characteristics. In the above equation, however, the ratio of the power spectral density of random input signals to the cross spectral density of the operator's output signals is represented. Besides this, there is a method to obtain the operator's characteristics approximately by taking account of the operator's response to the step input or lamp input.

In an ordinary automatic control system, the method by frequency response is often used to search for the system transfer characteristics. In the manual control system, however, this method is not so often adopted. One may consider that it is so because the operator can easily predict the input signal by learning if the sine wave input is given to the system, and therefore, because the operator control action becomes too complex and difficult to be described as the operator's characteristics. However, the prediction by learning may be regarded as one of the most remarkable features of the human control action. From such a point of view should be examined the human operator's response to the sine wave in the closed loop system.

In the present experiment, when the input signal $r(t)$ was a periodic function, the output signal $y(t)$ was assumed to be also a periodic function. The harmonic analysis of the output signal to the input signal was made to know the operator's characteristics in the closed loop system, and then the human operator's characteristics were examined. The experiments by this method were made comparatively easily by using the analog computer.

In the case that the input signal to the system is the periodic function, the output signal is assumed to be a periodic function. This periodic function $y(t)$ may be expressed as follows:

$$y(t)=\sum_{i=1}^{\infty}A_i\sin(\omega_i t+\phi)=\sum_{i=1}^{\infty}a_i\sin\omega_i t+\sum_{i=1}^{\infty}b_i\cos\omega_i t. \tag{2}$$

The coefficients a_i and b_i in the above equation may be described by the Fourier Coefficients.

$$a_i=\frac{2}{T}\int_{t_0}^{t_0+T}y(t)\cos\omega_i t\,dt$$

$$b_i=\frac{2}{T}\int_{t_0}^{t_0+T}y(t)\sin\omega_i t\,dt. \tag{3}$$

In the present experiment, the system output $y(t)$ was obtained approximately by applying only the first term of the equation (2), and the ratio of the amplitude A to the amplitude of the input signal was considered to be the gain of the closed loop system. The phase of the output signal to the input signal was expressed by $\phi=\tan^{-1}b/a$. In the case that the input signal was the complex signal (the sum of 4 non-harmonic sine waves), the harmonic analysis was made of $y(t)$ to each of the 4 non-harmonic sine waves. The results were represented by vector locus.

§ 3. Experimental Apparatus

There are two types of manual control system: (a) The operator manipulates the control element after seeing input and output signals separately in the display (pursuit type), and (b) The operator manipulates the control element after seeing error signals (compensatory type). In the present experiment the latter was used. Input signals of the sine wave and complex signals conmposed of 4 non-harmonic sine waves were generated by the analog computer. Error signals were displayed by the 5 inch cathode-ray oscilloscope, and the control system was composed of the analog computer. The operator manipulated the potentiometer which had proportional characteristics. In this way, after the operator attained to a sufficiently steady state with respect to one set of environmental parameters, the experiments were made.

In the equation (3) the calculation of the multiplication term was made by the analog computer and the results were integrated by the planimeter. The characteristics of the closed loop system were represented by vector locus.

§ 4. Results and Discussion

Fig. 2 shows the vector locus of the closed system to the input signal of sine wave. Each

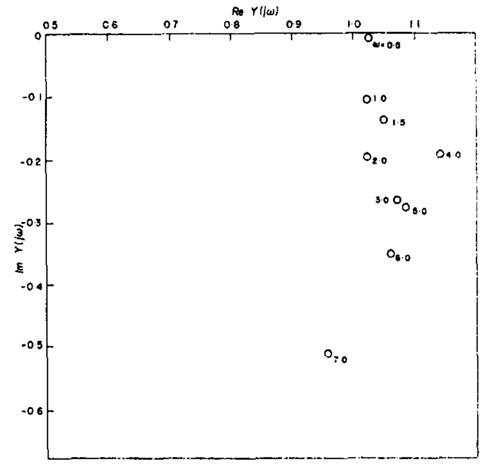


Fig. 2. Vector locus of the closed loop system.

point of vector locus is the mean value of the results obtained by the harmonic analysis of the output to the input of 10—20 cycles. With the increase of the frequency of the input signal, the operator's response becomes unstable and the vector locus at each cycle shows some dispersion. Fig. 3 shows the dispersion of the gain and phase in the Bode diagram. As shown in these figures, the open loop gain was nearly constant, but did not indicate any regularity. The phase shows a tendency towards a lag, but it is not so pronounced. The human operator can easily control the input signals within the frequency's $\omega=1.0$—2.0 rad/s. At $\omega<1.5$ rad/s, the operator can always keep the error nearly to zero. Fig. 4 shows the output and input at $\omega=1.0$ rad/s. The operator's response is nearly in agreement with the input signal. With the increase of the value of ω of the input, it becomes difficult to operate only by seeing the system error. The well-trained operator is apt to manipulate the potentiometer with an on-off type operation only by seeing to the amplitude and the phase of the input signal instead of trying to keep the error to zero (Fig. 5). Fig. 2 shows that the lag is irregular with the increase of the value of ω of the input signal.

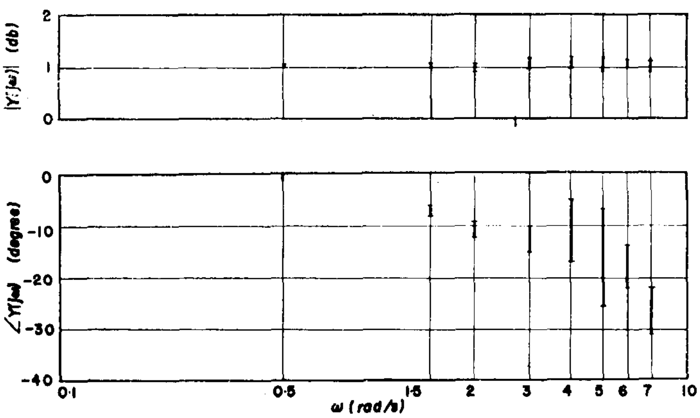


Fig. 3. Bode diagram of the closed loop system.

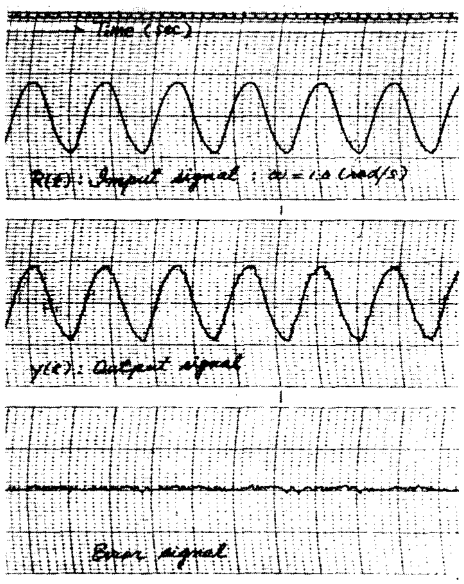


Fig. 4. Response of the operator (lower frequency).

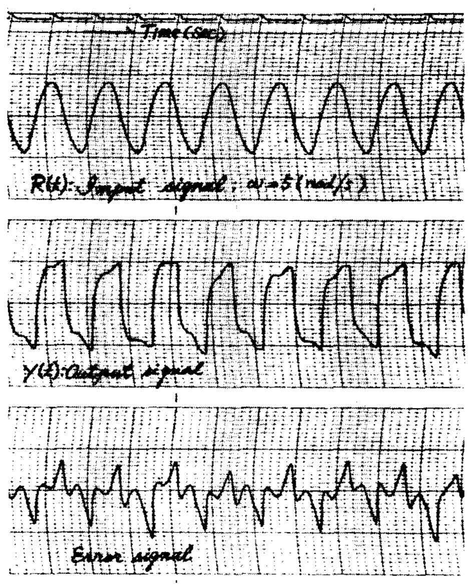


Fig. 5. Response of the operator (higher frequency).

This may have been caused by the operator's predictive action. Fig. 6 shows the results of the proportional controlled system in the case where complex signals were used as the input signal, and Fig. 7 shows the results in the case where the controlled system was of the first order lag. When the input signal is complex and difficult for the operator to predict, the operator's on-off action tends to decrease and the phase lag becomes rather regular with the increase of the value of ω of the input.

When there is a first order lag element in the system, the operator is required to do a derivative action, and such an action requires the extreme effort and carefulness. Thus, the controlled system is difficult to operate and the operator's response becomes complex and shows no constant responses.

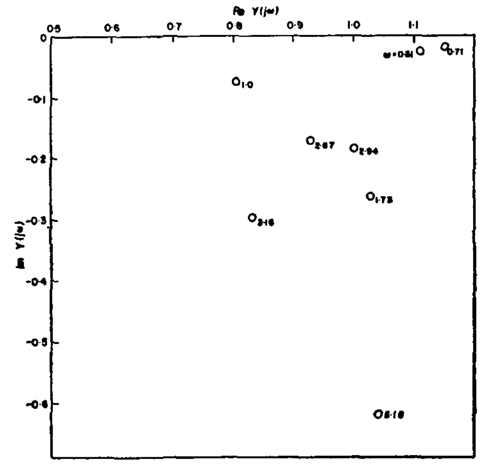


Fig. 6. Vector locus of the closed loop system: the input signal is complex and controlled system is proportional.

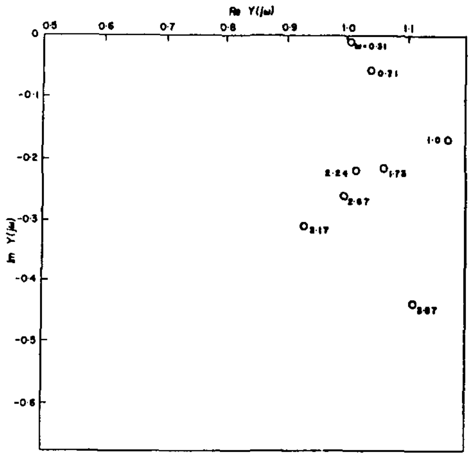


Fig. 7. Vector locus of the closed loop system: the input signal is complex and controlled system is the first order lag.

§ 5. Conclusions

(1) The harmonic analysis of the operator's response in the manual control system by the analog computer was described.

(2) In accordance with the change of the controlled system, the operator changes his control action.

(3) The frequency which the operator can easily control is within $\omega = 1.0$—2.0 rad/s. The operator's response shows a predictive action to the sine wave inputs of $\omega > 3.0$ rad/s.

There is a kind of complexity as well as a certain nonlinearity in the operator's control action, and sometimes the system output shows the signal unrelated to the input signal. This may be so, one might consider, because the operator's control action is greatly affected by learning. Therefore, this point should be further studied in order to understand the relation between learning and adaptability.

References

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