A Study of the Manual Control System*

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An analysis is attempted of the human operator's responses to the sinusoidal input and the random input. The human operator's characteristics in the closed loop system are represented by the Bode diagram. This diagram shows that the human operator's response to the random input containing only those frequency components lower than 4 rad/s is almost in accordance with his response to the siunsoidal input of the same frequency range.

§ 1. Introduction

In the field of human engineering, it has become one of the most important and difficult problems how to match the human operator to the machine. In the manual control system, namely, the closed loop system consisting of a human operator and a machine, the human operator may be regarded as a kind of controller, for he does the tracking task by using his eyes as the detector and his hand as the final control device, as shown in Fig. 1. This human operator as a controller often shows very interesting behaviors, and he has been the object of extensive and close investigations in automatic control.

The human operator has learning ability and is apt to adapt his behavior to various environmental conditions, and consequently his behavior cannot be free from fluctuation. This is the reason why his transfer characteristics cannot be described so definitely as those of an ordinary controller in the mechanical system. However, under certain conditions, for instance, when the input signal, the controller element, and the other environmental conditions are fixed, the human operator displays comparatively constant qualities, and his transfer characteristics in the closed loop system can be described approximately by the transfer function. And most investigators have reported the following equation as a suitable one[1]:

$$H(s) = \frac{K \exp(-\tau_d s)(T_L s + 1)}{(T_I s + 1)(T_N s + 1)},$$

where

$H(s) =$ human operator transfer function,
$K =$ gain constant,

$\tau_d =$ pure time delay, and
T_I, T_L, $T_N =$ time constant.

Those investigators who attempted to evaluate the human operator's characteristics by changing both the controlled element and the input signal variously, adopted a random signal, that is, a white noise or the sum of non-harmonic sinusoids, as the input signal in their experiments. Why did they not adopt the frequency response method in their experiments? It was because, we may consider, the human operator is apt to predict the input signal when it is a periodic one, and because this predictive action makes his response to the input signal too complex to be described by a simple linear transfer function.

However, the present authors regard the human operator's predictive action as one of his most remarkable characteristics, for in our daily life we actually do many predictive control actions. Take a driver of an automobile, for instance. He can see the curves in the road for a significant distance ahead of him. In such a case the operator does a kind of predictive control action. Many similar examples may be given. So, the present authors carried out some experiments by means of the frequency response method and examined the operator's responses to the predictable sinusoidal input. Some considerations were also attempted by comparing the results with those of other investigators.

§ 2. Method

Fig. 1 is the block diagram representing the compensatory tracking system employed in this experiment. The subject is seated in a chair, facing the 12cm-diameter cathode ray tube. There is a target line in the center of the screen. The error signal is represented by a 2cm

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bright line which moves in the vertical direction. The operator is ordered to minimize the error signal as rapidly as possible by manipulating the potentiometer. The potentiometer has no restraint and its gain constant is 30 V/rad. The gain constant of the controlled system and the display are 1 and 1 mm/V respectively.

Four men served as subjects. Data were obtained after each subject was trained and his response became stable.

§ 3. Results and Discussion

In Fig. 2, the operator's response in the form of the closed loop, $Y(j\omega) = X(j\omega)/R(j\omega)$, to the sinusoidal input is represented by the Bode diagram. The maximum frequency in which the operator can control is about 4 rad/s. Within the frequency of $\omega < 1 - 2$ rad/s, the operator's response is fairly constant, that is, the operator can try to reduce the error nearly to zero. With the increase of the input frequency, however, a more rapid control action is required of him, and the operator finds himself unable to reduce the error to zero because of his delaying control action. Consequently the operator tries to predict the coming input signal and to synchronize his response with the input. This predictive control action displays some variations according to the degree of the operator's learning. A well trained operator tries to improve his response with an on-off type control action by seeing to the amplitude and the phase of the input signal instead of trying to keep the error to zero[3]. This improving control action becomes irregular with the increase of the input frequency, and the Bode plots show some dispersions.

Fig. 3 represents the response to the random-appear (sum of 4 non-harmonic sinusoids). The maximum frequency component contained in the input signal is 5.19 rad/s, which is also the maximum frequency in the case of the sinusoidal input signal. There is almost no difference in the operator's responses between the above two types of signal.

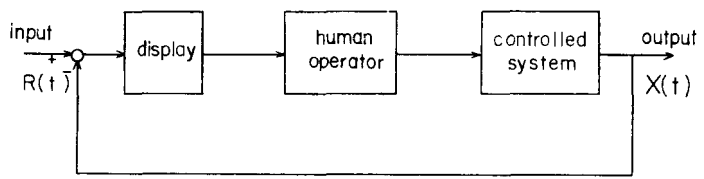Many investigators perform their experiments with the controlled systems whose dy-

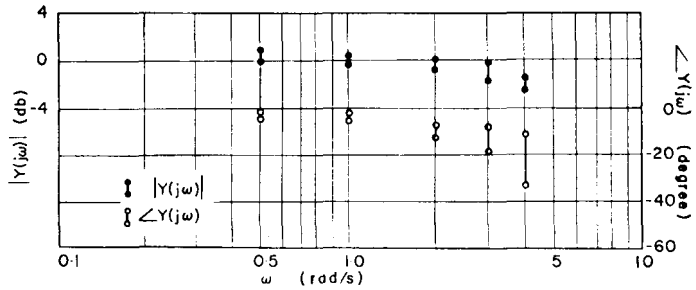Fig. 1. Block diagram of manual control system.
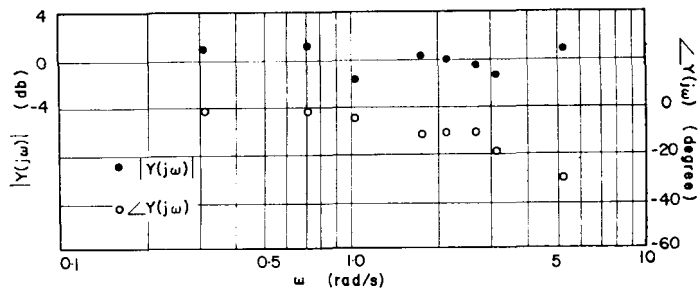

Fig. 2. Bode plots of operator's response to sinusoidal input.

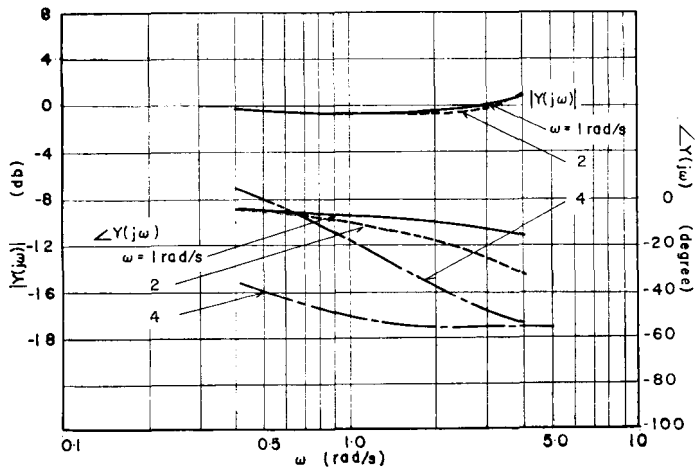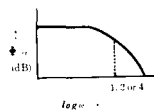Fig. 3. Bode plots of operator's response to random-appear input.

Fig. 4. Bode plots of operator's response by Franklin.

Table 1. Operator-describing functions in conpensatory tasks showing effects of forcing functions. Simple tracker, $F_p=1$, random appearing forcing function.

General control task and forcing function	'Best fit' Human Operator Transfer Function						Frequency range of human operator measurements	Average linear correlation	Investigators and remarks
Simple tracker with spring restrained aircraft control stick in aircraft cockpit mock-up (forcing function 1, below)	$$\dfrac{K exp(-\tau_d s)(T_L s+1)}{(T_1 s+1)(T_N s+1)}$$						0.4 to 4.0 rad/sec	0.7 to 0.8	Franklin, these data taken for 'lateral' control; 'longitudinal' control was exercised simultaneously
	Corner frequency	$\dfrac{1}{T_1}$	$\dfrac{1}{T_N}$	$\dfrac{1}{T_L}$	τ_d	K			
	1	0.04	1.5	0.5	0.15	100			
	2	0.11	4.55	2.0	0.20	40			
	4	0.20	11.0	3.0	0.25	1.5			
Simple tracker hand-wheel type control with no restraints (forcing function 2)	$$\dfrac{K exp(-\tau_d s)(T_L s+1)}{(T_1 s+1)(T_N s+1)}$$ $\tau_d \simeq 0.3$; T_N effect included in τ_d						Same frequencies as shown in forcing function	0.9	Russell
	Forcing function	$\dfrac{1}{T_1}$		$\dfrac{1}{T_L}$		K			
	Low speed	0.103		13.3		52.5			
	Medium speed	0.37		5.0		11.0			
	High speed	0.62		3.7		2.0			

1 White noise through third-order binomial filter giving available corner frequencies of 1, 2 and 4 rad/sec
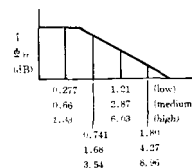
2. Superposition of four sinusoids (rad/sec)

namics are proportional gain only. Some experimental results are represented in Table 1. [1]

Figs. 4 and 5 show the human operator's characteristics calculated in the form of the closed loop, using the results in Table 1. From these figures we can know that the over-all gain decreases, the phase delaying with the maximum frequency contained in the input signal, and that the human operator's responses to the input signals not containing any frequency components higher than 4 rad/s are fairly in accordance with the frequency response in our experiment.

When the input signal consists of sinusoids, it is generally difficult to describe the operator's transfer characteristics by a simple linear ele-
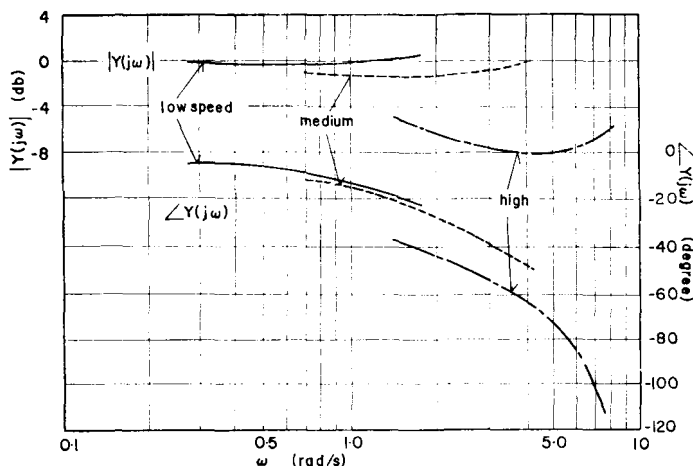

Fig. 5. Bode plots of operator's response by Russell.

ment. Even under this experimental condition, however, the operator's response is not so different from that to the random input, if the input signal does not contain any frequency

components higher than 4 rad/s.

As the human operator has a strong flexibility, his control action is greatly affected by the order given to him as can be observed in the present experiment where a simple stable element is controlled. In this experiment, the operator is told to minimize the error as rapidly as possible. A well trained operator shows a stable response under such an order, and it may be stated that the human operator's response to the random input containing any frequency lower than 4 rad/s is almost in accordance with his response to the sinusoidal input.

§ 4. Conclusion

The human operator's response to the sinusoidal input may generally be considered to be quite different from his response to the random input. From the results of this experiment, however, it can be concluded that the human operator's response to the random input is almost in accordance with his response to the sinusoidal input within the frequency range of $\omega < 4$ rad/s. Consequently, when all the frequency components of the input signal are lower than 4 rad/s the human operator in the manual control system can be characterized by the response to the sinusoidal input.

References

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2) FOGEL, L. J.: *Biotechnology: concepts and applications.* 1963, (Prentice-Hall).

3) WADA, T. & S. OHGISHI: Preprints of the 10th Annual Conference of the Japan Association of Automatic Control Engineers, 1966.