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EFFECTS OF VARIATIONS IN CONTROL BACKLASH AND GAIN ON TRACKING PERFORMANCE

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FOREWORD

This report was prepared by the Psychology Branch of the Aero Medical Laboratory, Directorate of Laboratories, Wright Air Development Center, for a task under Project 7197, "Human Engineering Factors in the Design of Operator Training Equipment," with Dr. Ross L. Morgan acting as Project Scientist. The Task was 71635, "Simulation Requirements of Operator Training Equipment," with Dr. Marty R. Rockway acting as Task Scientist. The experimental data were collected in the Training Research Section laboratory of the Psychology Branch.

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ABSTRACT

Six subjects performed a simulated aircraft tracking task using each of twelve control conditions resulting from combining four levels of control backlash and three levels of gain. The experimental findings demonstrated a significant interaction between the effects of backlash and gain on system performance. That is, there was a monotonic increase in system error with increasing backlash at all levels of gain. However, the higher the gain the greater the rate of increase. The implications of these results for the design of manual control systems were discussed briefly.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

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INTRODUCTION

This report is one of a series concerned with the effects of discontinuous control system nonlinearities on tracking performance.* Discontinuous nonlinearities arise primarily as the result of friction, limiting and free-play in the system (2). They affect the system in such a way that the static relationship between system input and system output is discontinuous in the region under consideration. The present experiment was designed to investigate the effects of variations in control backlash and gain (i.e., sensitivity) on the performance of a simulated aircraft tracking task.

Backlash. A frequent source of backlash is the free-play or "slop" in the mechanical portions of a system. In an aircraft, for example, it is likely to be present to some degree as a result of unavoidable imperfections in the linkage between the pilot's control and the controlled surface. "Mechanical" backlash is conventionally represented by the hysteresis loop presented in Fig. 1. In this illustration θ_1 may be considered to represent the angular deflection of the pilot's control and θ_2 the resulting control surface deflection. Backlash is indicated by $\Delta\theta$. Backlash in the present experimental system was "nonkinesthetic" (7). That is, the effect of backlash between control and display was simulated (electronically), but it was not associated with differences in mechanical resistance or stick "feel."

A recent experiment by Senders and Bradley (7) provides data with respect to the effect of backlash on tracking proficiency at one level of control sensitivity.** Using a one-dimensional task with simulated aircraft pitch dynamics, they varied backlash through five values ranging from 0 to 1.83° of control stick movement. Their results indicated a monotonic increase in system error with increasing backlash. The relationship appeared to be linear at backlash values above .089°, and no tendency toward instability was reported for any of the conditions studied.

* Actually, the primary experimental program is aimed at the determination of the simulation requirements of Air Force training devices. Exploratory performance studies such as the present one are conducted only to aid in the selection of conditions for more extensive (and expensive) transfer of training experiments.

** The present experiment is an extension of this work.

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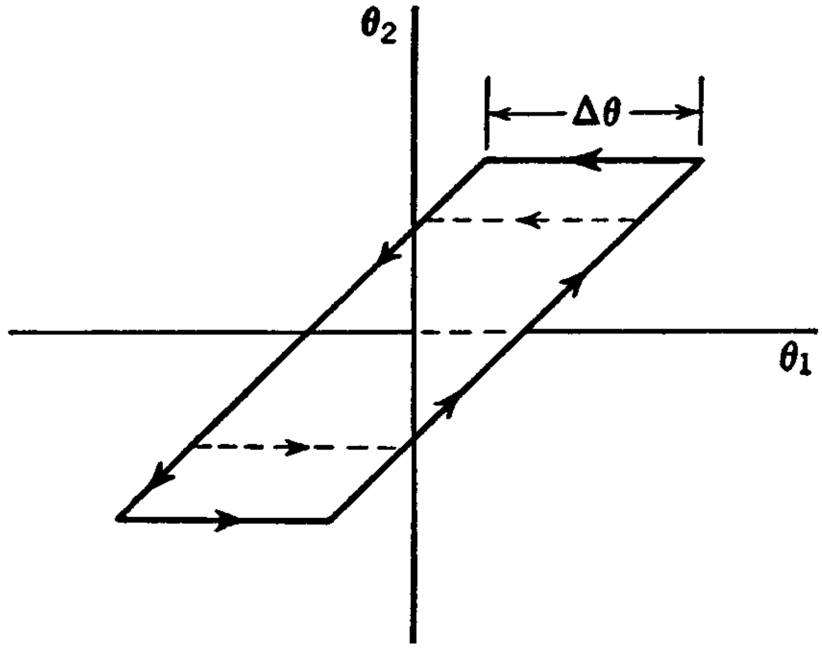

Figure 1. Graphic representation of backlash. Adapted from Johnson (1).

<u>Gain</u>. Control gain is ordinarily defined in terms of the magnitude of system output resulting from a given input. In the present system, the input was the angular deflection of a joystick control and the output the movement of the horizon bar of a simulated attitude-gyro. Disregarding the highly damped oscillatory transient, control gain in this case may be expressed in terms of the steady-state rate of display movement resulting from a 1° control deflection.

There is considerable experimental data with respect to the effect of control gain on tracking proficiency (e.g., 6). In general, the relationship appears to be "U" shaped. That is, as gain is varied from "low" to "high," system performance tends to peak at some intermediate value or range of values. However, the particular function observed in any given instance depends upon the values of the other system parameters involved.

<u>Interaction of backlash and gain</u>. The authors are not aware of any previous experiment specifically concerned with the effects of joint variations in backlash and gain. However, a recent study in this series (5) investigated the interaction of control deadspace and gain in a simple first-order compensatory tracking system. In this study six experienced subjects tracked with each of twelve control conditions generated by combining four levels of deadspace and three levels of gain. The experimental

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findings demonstrated a statistically significant interaction between the effects of deadspace and gain. Specifically, there was a systematic increase in system error with increasing deadspace at all levels of gain. However, the higher the gain the greater the rate of increase.

Although the mechanical effects of backlash and deadspace are not identical, there are some similarities. In fact, backlash might be described as a "floating," or "traveling," deadspace which is in evidence whenever the direction of control movement is reversed. This is an oversimplification, but to the extent that the two phenomena are similar one would predict that the effects of backlash and gain in the present experiment should be roughly similar to the effects of deadspace and gain in the study described above.

METHOD

Apparatus. The basic experimental system consisted of a one-dimensional compensatory tracking device with associated scoring and recording equipment.

The tracking control was a slightly loaded spring-centered joystick. The length of the stick, as measured from the pivot point to the top of the hand grip, was 20 in. Stick deflection was mechanically restricted to $\pm$ 10° from the vertical in the fore-aft plane.

The tracking display was a simulated artificial horizon bar presented on the face of a 6 in. cathode-ray tube. The stationary reference* was a 2 in. line centered on the horizontal axis of the tube face. The display was perpendicular to the subject's (S's) line of sight and at a mean viewing distance of approximately 28 in.

Incorporated in the link between the control and display was a linearized second-order simulation of the longitudinal dynamics of a jet aircraft. Since this system is described in detail elsewhere (4), it will not be elaborated here except to indicate that in the present case the natural frequency of the short period oscillatory transient was 1 cps and the damping ratio approximately .5.

The displayed problem was generated by an electro-mechanical function generator. The problem signal was the approximate sum of three equal amplitude sinusoids of 3, 5, and 11 cycles per min. (The addition was made with the 3 cycle wave displaced 180° in phase.) The maximum excursion of the simulated horizon bar when driven by the problem input was approximately ± 2 in. from the horizontal axis of the display.

* That is, the "little airplane."

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During performance of the tracking task, S attempted to keep the horizon bar superimposed upon the stationary reference at the center of the display by nulling the signal from the problem generator. Failure to compensate for the problem signal resulted in a displacement of the horizon bar from the "zero" pitch attitude. The magnitudes of these displacements were directly related to the error voltages producing them. The error voltage functions were used to obtain two measures of system performance during each tracking trial. These measures were proportional to the time integrals of the absolute error and error squared voltages, respectively. Integrated absolute error was obtained by passing the error voltage directly through an absolute value circuit (1, 3) and integrating over the 60-sec. trial period. To obtain integrated error squared, on the other hand, the error voltage was multiplied by two prior to being squared and integrated.*

Subjects. The Subjects (Ss) were six male engineering psychologists, all of whom had some pre-experimental tracking experience.

Conditions. The experimental conditions are presented in Table I. The conditions shown resulted from the use of all twelve combinations of four levels of backlash and three levels of gain. The four values of backlash were 0°, $.2^\circ$, $.6^\circ$, and 1.8° of stick deflection in total extent. These values correspond to approximately .00, .07, .21, and .63 in. of arc at the tip of the stick, respectively. The three values of gain, in order of increasing sensitivity were 0.5:1, 1.5:1, and 5.0:1. Neglecting the oscillatory transient this simplified notation is intended to indicate that each 1° of control deflection produced either a 0.5, 1.5, or 5.0 in./sec. movement of the horizon bar.

Procedure. The twelve experimental conditions were arranged in a "systematic" Latin square. The square was such that, in addition to each condition being represented once and only once in each row and column, each condition preceded and followed every other condition once and only once. Both the assignment of conditions to Latin letters and the assignment of Ss to conditions was random. In the case of Ss, assignment was to a pair of sequences, one being the reverse of the other.

Each S served for six days. On each day, S practiced for four trials with each of the twelve conditions. The order of experiencing conditions

* The error voltage was doubled to increase the relative accuracy of the squaring operation which was performed with an electronic function multiplier. The output of the multiplier in this case equalled $.04e^2$.

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TABLE I

The Conditions of the Experiment

		Backlash (Degrees) 0	.2	.6	1.8
	.5:1				
Gain	1.5:1		N=6		
	5.0:1				

on even days was the reverse of that on odd days. On each day practice was distributed approximately as follows: Three blocks of (four) trials, 10 min. rest interval, three blocks of trials, 10 min. to 3 hr. rest, three blocks of trials, 10 min. rest, and three blocks of trials. Trials were 60 sec. in length. The inter-trial rest interval was 30 sec., and the inter-block interval 2 min.

RESULTS

Two types of data were obtained in this study. The integrated error scores described previously were recorded for each subject on all trials throughout the course of the experiment. In addition, a limited number of continuous graphic records of display error and control position were obtained under each of the experimental conditions from a single highly proficient subject. Only the integrated error data were subjected to quantitative analyses. The graphic records were merely inspected visually for clues to some of the more specific differences resulting from the experimental variations.

Integrated error data. Both the error squared and the absolute error scores were subjected to analysis of variance. In general, the effects of the experimental variations were the same for both criteria. Thus, for convenience, only the absolute error data will be considered here.

The data of primary interest are those for the latter stages of practice viz., days five and six. The mean scores for all conditions on days five

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TABLE II

Mean Integrated Absolute Error Scores
(Days 5 and 6 Combined)

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	75	83	89	102
Gain	1.5:1	73	91	101	135
	5.0:1	79	112	139	213

and six combined are presented in Table II and Fig. 2.* Each mean is a measure of group performance and is the average of 48 scores, 8 for each of the 6 Ss.

The functions plotted in Fig. 2 obviously are consistent with the pre-experimental prediction concerning the interaction of backlash and gain. That is, it is apparent that tracking error tends to increase with increasing backlash for all levels of gain; and the greater the gain, the greater the rate of increase.

The analysis of variance summarized in Table III confirms the statistical significance of the general relationships revealed in Fig. 2. The significant "subjects" effect in Table III is of little interest, since it merely reflects individual differences in tracking ability. The significant interaction of subjects with control gain, while important, is a frequent finding (Cf. e.g., 5). Inspection of individual data curves reveals that the major source of significance in this case probably results from inter-individual differences in relative proficiency with the three gains under the 0 backlash condition. The non significant S x B interaction should be interpreted

* All other data are tabled in the Appendix. It should be noted that all error data are presented in raw voltage units. The basic integration rate was 1/3 volts/sec./volt and the period of integration 60 sec. Therefore, the absolute error scores are equal to $1/3\int_0^{60}|e|\,dt$ and the error squared scores to $.04/3\int_0^{60}e^2\,dt$. Given the additional information that the scope gain was 20 volts/in., it will be left as a simple exercise for the interested reader to convert the raw data to a metric, and/or statistic, which may have greater meaning for him.

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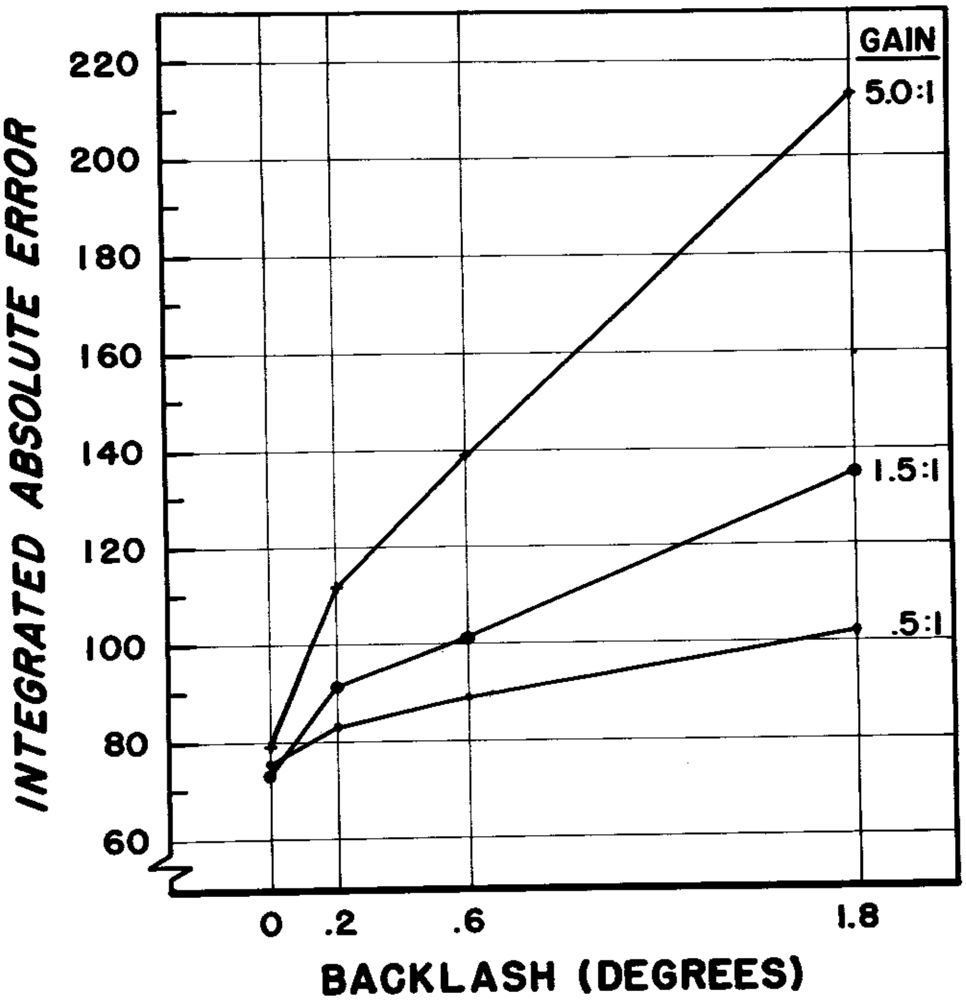

Figure 2. Mean integrated absolute error scores for days 5 and 6 combined.

with some caution, since more sensitive measures probably would reveal statistically significant* inter-individual differences in rate of degradation with increasing backlash.

Graphic records. Simultaneous recordings of display error and control position during tracking were obtained from a single highly proficient S

* Although perhaps not "practically" significant.

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TABLE III

Analysis of Variance of the Mean Integrated
Absolute Error Scores
(Days 5 and 6 Combined)

Source of Variance	df	Mean Square	F	p
Backlash (B)	3	71113.2	360.61	<.01
Gain (G)	2	60673.4	109.76*	<.01
Subjects (S)	5	21083.2	106.91	<.01
S x B	15	278.1	1.41	—
S x G	10	552.8	2.80	<.05
B x G	6	13172.0	66.79	<.01
Remainder	30	197.2		
Total	71			

*S x G mean square used as error.

following completion of the experiment proper. Sample records for each of the twelve combinations of backlash and gain as well as the open-loop problem error are reproduced in Figs. 3 to 6. The "error tracings represent the position of the horizon bar above and below the horizontal reference marker during the course of a trial. The "control" tracings represent the angular position of the joystick control during the same period.

Although visual inspection of the graphic records reveals nothing unusual concerning the effects of backlash and gain, there are a few features worth noting. For instance, inspection of the error tracings reveals no instability even under the most unfavorable combination of backlash and gain. However, the somewhat greater frequency of large amplitude oscillations about the zero-error reference is suggestive of more subject induced overshooting when tracking with high gain and backlash. Actually, the subject represented in these records was the most proficient of those tested, so his extremely good adjustment to even the poorest control condition may be somewhat atypical.

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The control position tracings reflect the effect of backlash and gain on the amplitude of control movement employed. The most obvious difference among conditions is the general increase in mean amplitude resulting from both increasing backlash and decreasing gain. It is also apparent that the amplitude increase with increasing backlash is relatively greater at higher gains.

DISCUSSION

The present experiment was not intended to establish definitive design tolerances for man-operated control systems. Indeed, the results demonstrate that any simple formulation of such tolerances for the parameters considered is difficult, if not impossible, to achieve.

It would be unreasonable to assume that the particular performance levels observed in this experiment are identical to levels to be expected in actual airborne systems. For, although the experimental tracking device incorporated simulated aircraft dynamics, the totality of demands imposed upon the experimental Ss differed in many ways from those experienced in operational situations.*

However, even though the absolute values obtained in this study may not be significant, the general relationships are. It is extremely important that interactions among system parameters be identified and taken into account for design purposes. In the case of backlash, for instance, a tolerance value sufficiently rigorous to satisfy the performance demands of a "low gain" cargo aircraft might be intolerable in a "high gain" fighter.** Thus, the design engineer should be alert to the possible hazards of across-the-board acceptance of "precise" single parameter performance functions obtained on systems, or under conditions, different from the ones of interest to him.

SUMMARY

Six subjects performed a simulated aircraft tracking task using each of twelve control conditions resulting from combining four levels of control

* For example, acceleration forces and the requirement for multi-channel (time-sharing) operation were not simulated.

** Conversely, adoption of the "high gain" system tolerance might be uneconomical when designing a "low gain" system--especially if one battles a positively accelerated cost curve while striving toward an irreducible minimum imposed by the state-of-the-art.

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backlash and three levels of gain. The experimental findings demonstrated a significant interaction between the effects of backlash and gain on system performance. That is, there was a monotonic increase in system error with increasing backlash at all levels of gain. However, the higher the gain the greater the rate of increase. The implications of these results for the design of manual control systems were discussed briefly.

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APPENDIX

TABLE IV

Mean Integrated Absolute Error Scores

Day 1

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	107	120	171	145
Gain	1.5:1	107	134	139	198
	5.0:1	128	156	201	303

Day 2

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	102	100	111	139
Gain	1.5:1	96	113	129	167
	5.0:1	116	140	170	254

Day 3

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	84	92	104	122
Gain	1.5:1	83	102	123	158
	5.0:1	89	116	158	228

Day 4

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	80	95	90	116
Gain	1.5:1	71	93	107	146
	5.0:1	81	123	151	222

Day 5

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	78	85	98	107
Gain	1.5:1	75	99	110	139
	5.0:1	79	118	147	217

Day 6

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	72	81	81	98
Gain	1.5:1	72	83	92	130
	5.0:1	79	106	114	210

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TABLE V

Mean Integrated Error Squared Scores

Day 1

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	53	71	109	107
Gain	1.5:1	60	89	95	176
	5.0:1	83	124	201	397

Day 2

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	50	64	57	87
Gain	1.5:1	44	60	76	127
	5.0:1	67	95	138	291

Day 3

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	31	39	51	68
Gain	1.5:1	35	48	72	108
	5.0:1	38	62	117	244

Day 4

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	29	41	36	59
Gain	1.5:1	30	38	53	95
	5.0:1	39	71	105	227

Day 5

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	28	34	44	51
Gain	1.5:1	26	51	56	86
	5.0:1	29	67	106	223

Day 6

		Backlash (Degrees)			
		0	.2	.6	1.8
	.5:1	23	29	29	43
Gain	1.5:1	24	31	42	76
	5.0:1	28	53	74	199

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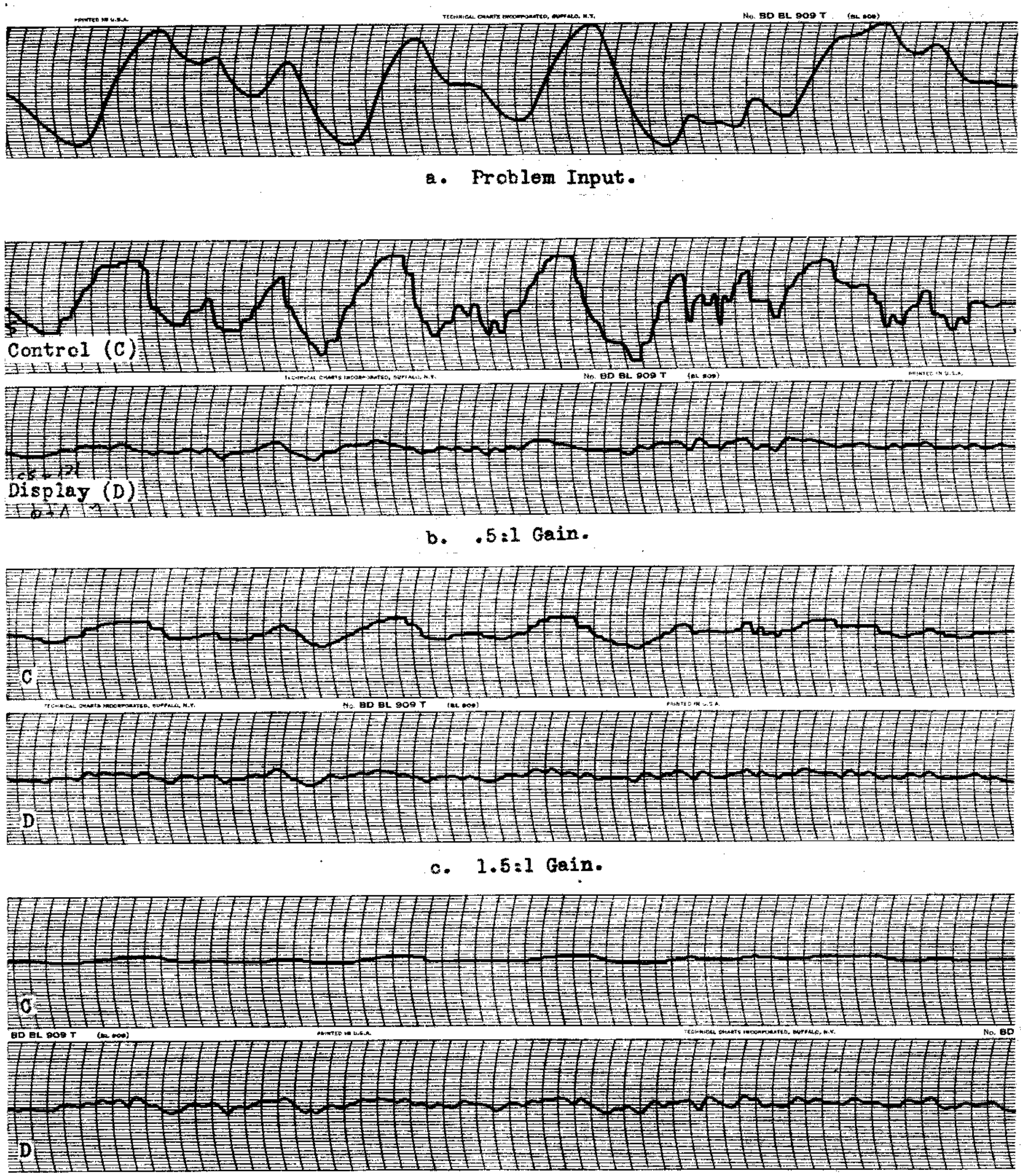

a. Problem Input.

b. .5:1 Gain.

c. 1.5:1 Gain.

d. 5.0:1 Gain.

Figure 3. Pen recordings of problem input, control stick position, and display error with 0 backlash.

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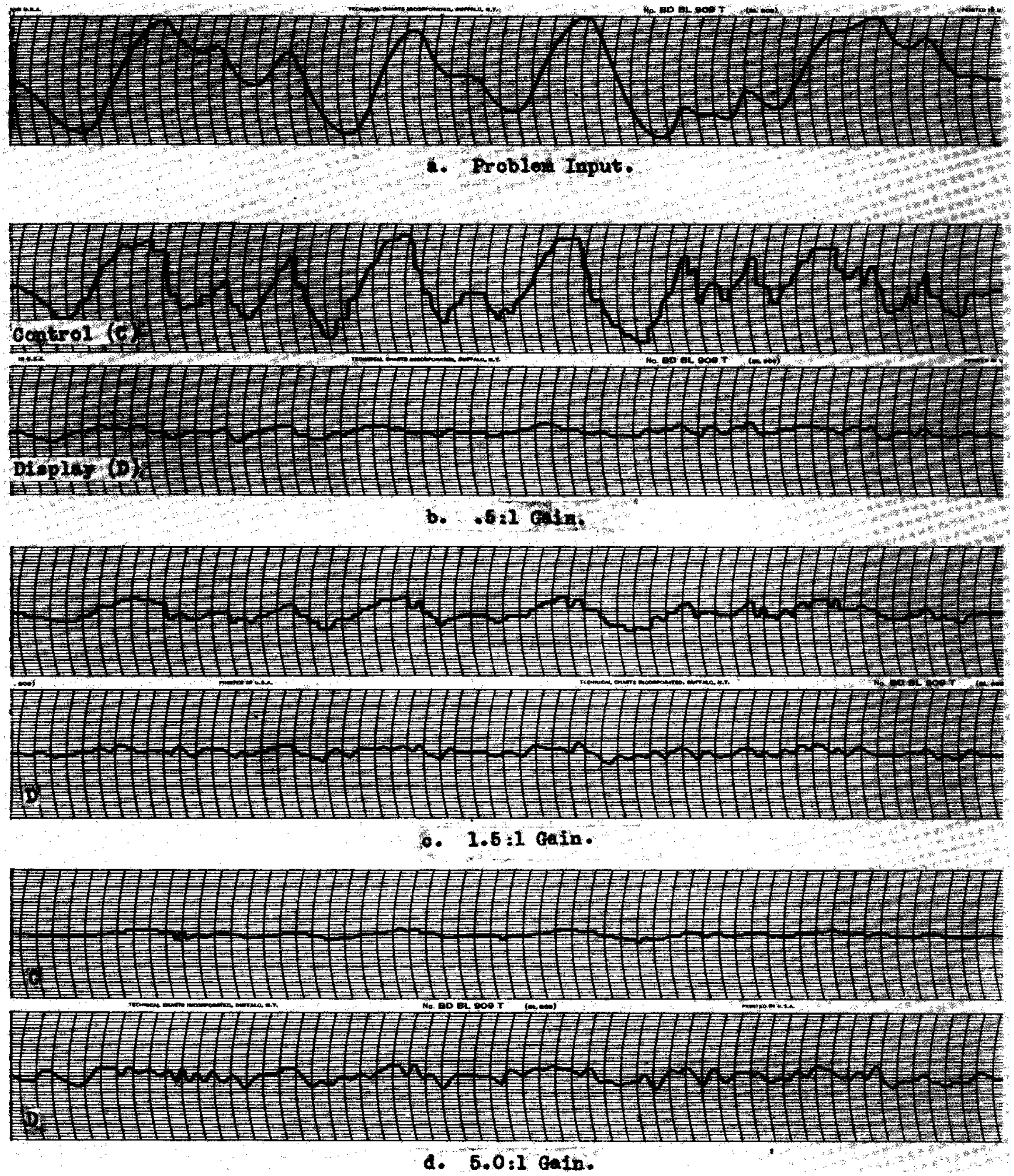

Figure 4. Pen recordings of problem input, control stick position, and display error with .2° backlash.

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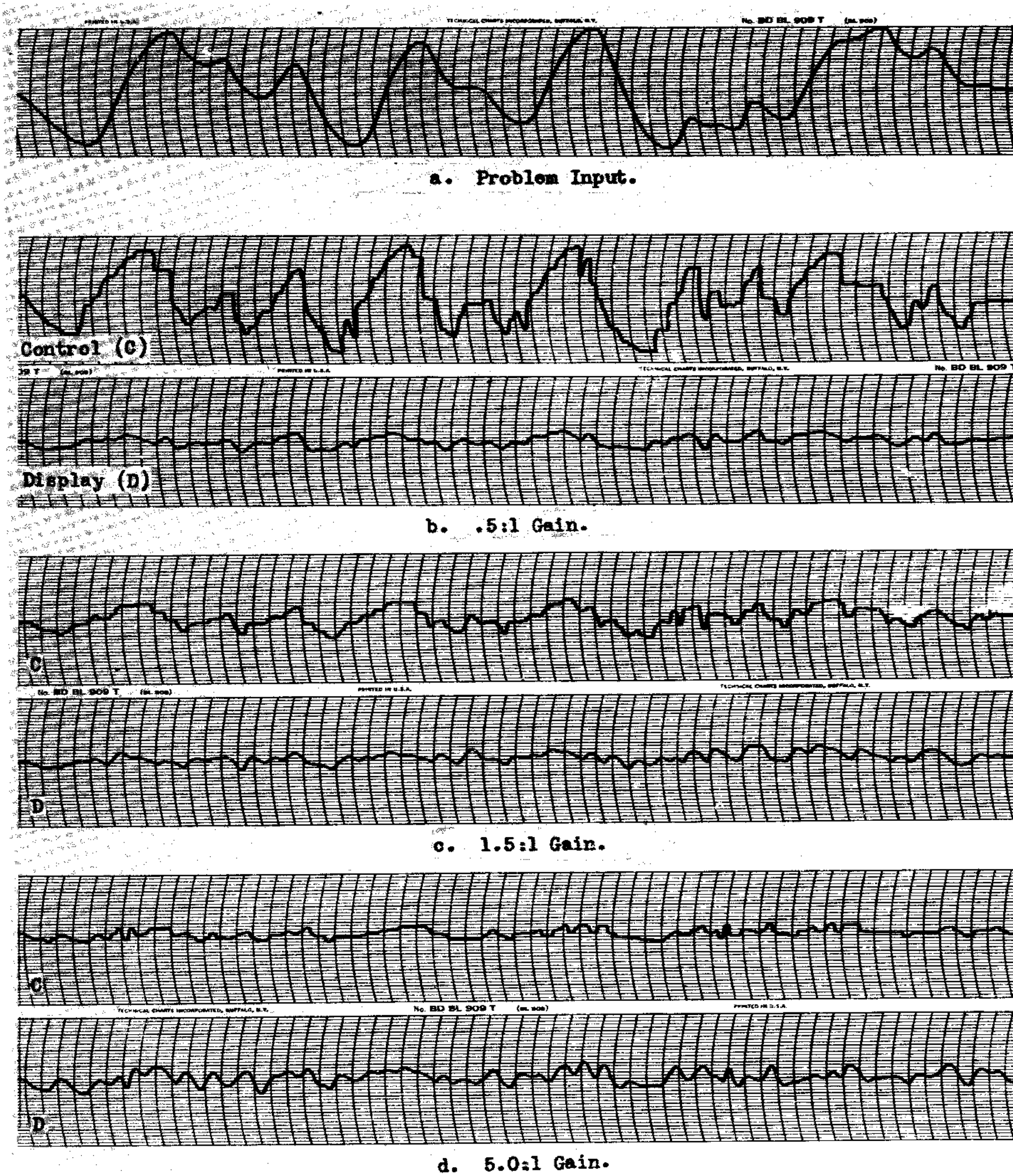

Figure 5. Pen recordings of problem input, control stick position, and display error with .6° backlash.

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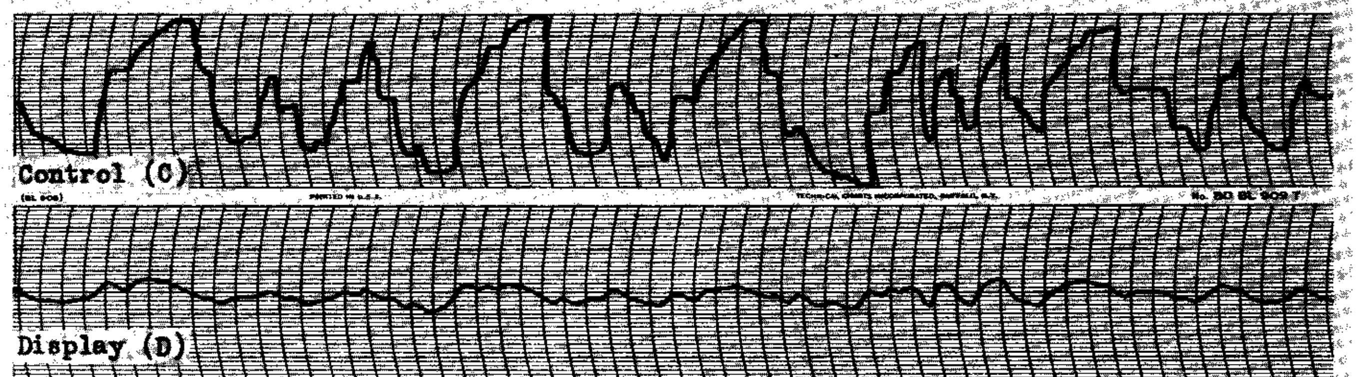
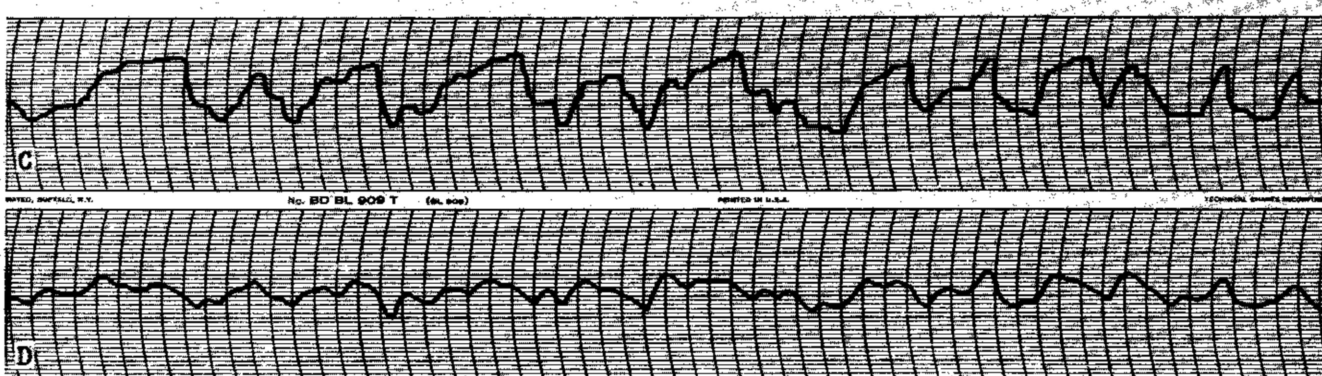
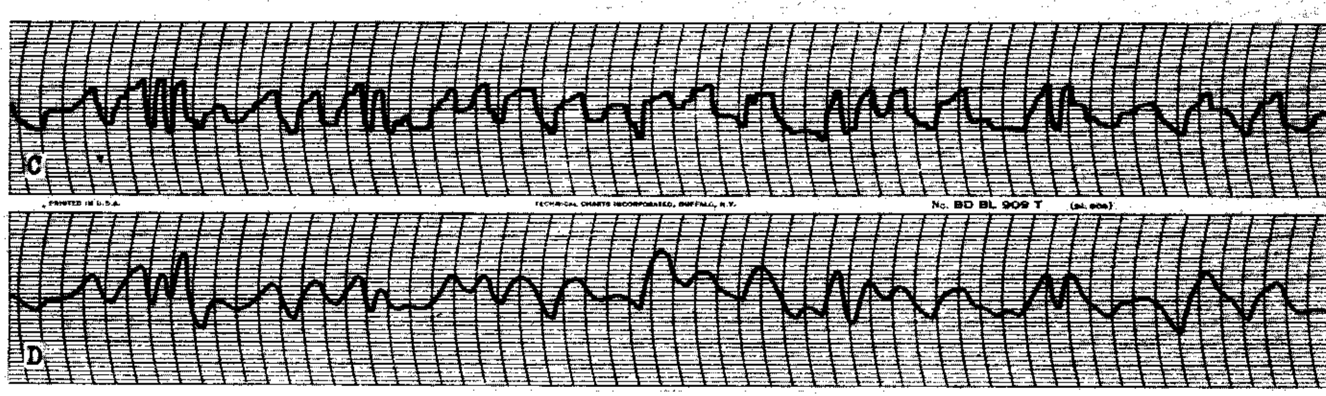
a. Problem Input.



b. .5:1 Gain.



c. 1.5:1 Gain.



d. 5.0:1 Gain.

Figure 6. Pen recordings of problem input, control stick position, and display error with 1.8° backlash.

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