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HARDIMAN I ARM TEST

HARDIMAN I PROTOTYPE PROJECT

Prepared by

Specialty Materials Handling Products Operation
General Electric Company
Schenectady, New York 12305

December 31, 1969

Supported Jointly by

Engineering Psychology Programs Office
Office of Naval Research
Washington, D.C. 20360

Naval Air Systems Command
Washington, D.C. 20360

Army Mobility Equipment Research and Development Center
Fort Belvoir, Virginia 22060
United States Army Project No. IM62410105072

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ONR Contract Number N00014-66-C0051

Work Unit Number NR 196-049

S-70-1019

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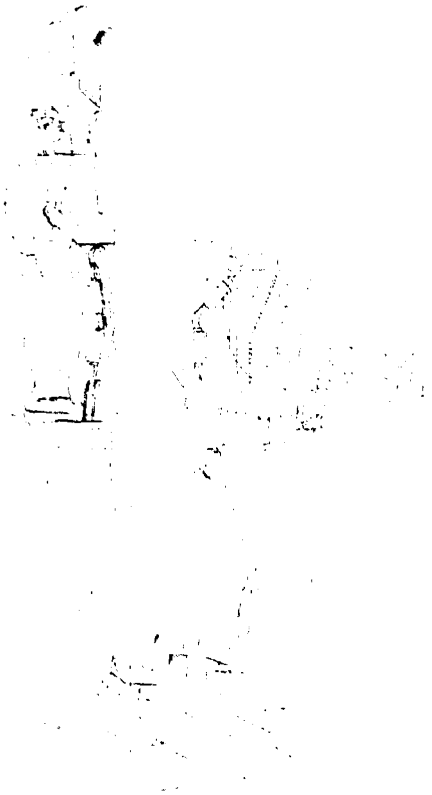

THE POWERED EXOSKELETON PROJECT

The Powered Exoskeleton concept is that of a material handling machine under intimate control of the operator.

"Worn as an outer mechanical garment, the exoskeletal structure will be powered to dramatically amplify the wearer's strength and endurance by a factor of approximately 25 to 1, i.e., when the exoskeleton wearer lifts 25 pounds, he will 'feel' as if he is lifting only one pound. The device will provide him with a set of 'mechanical muscles' that enables him to lift and handle loads in excess of 1000 pounds. The human operator will 'feel' the objects and forces he is working with almost as if he were in direct body and muscle contact. This feature, called force feedback, will provide the operator with sensitive control of the structure and will act as a safeguard against the application of excessive force.

"The exoskeleton, called 'Hardiman,' mimics the movements of its wearer, presenting a literal union of man and machine. Thus, the human's flexibility, intellect, and versatility are combined with the machine's strength and endurance."*

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*Naval Research Reviews, July 1967

FOREWORD

A prototype having the capability to implement the powered exoskeleton concept has been defined and reduced to engineering drawings suitable for part fabrication and assembly.

Fabrication and assembly of the complete leg and girdle system to demonstrate the walking capability is underway.

This report is a description of the test and evaluation of the left arm assembly.

The Appendices of this report contain performance and design data on the electronic circuits and servo system.

ACKNOWLEDGEMENTS

The Government scientific officers and project monitors who have directed this program and provided constructive guidance during the period covered by this report are:

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SECTION I

INTRODUCTION

The test and evaluations of the Hardiman I arm system marked the first time in the program that bilateral servo joints had been operated in series. Previous tests on the single joint simulator and the unilateral leg system gave promising results, but were not nearly as meaningful as was the successful operation of the arm system.

With the main objective being stable operation under full load, the test and evaluation was carried out with an awareness of the following possible problem areas:

1. Individual joint instability.

2. Joints-in-Series instability.

3. Kinematic interactions between tickler inputs.

4. Mechanical interferences and limitations.

5. Inability of the operator to control the system.

6. Excessive moment applied to the operator due to differences in lengths of master and slave hands.

7. Fatigue of operator due to lack of master counterweighting.

Although each of these problems were observed during the evaluation, none were so difficult or troublesome that a solution consistent with meeting the objectives could not be accomplished within the test plans. With minor exceptions, there were no changes in the mechanical configuration and servo parameters from those presented in Report S-69-1116, dated July 1, 1969.

SECTION II

EQUIPMENT DESCRIPTION AND THEORY OF OPERATION

The Hardiman I arm system, Figure 1, is a master-slave system containing eight powered joints. Six of the joints are bilateral servo controlled. These joints are: wrist flex, forearm rotate, elbow flex, upper arm rotate, shoulder flex, and back flex. The thumb tip and thumb flex joints are rate controlled utilizing a velocity valve.

The operator makes contact with the master structure at three points -- the hand, the wrist, and the upper forearm. These latter two contact points are required because the six joints form an unconstrained system. That is to say, the operator cannot define the articulation of the master with only one input.

When the operator places the master in a particular configuration, the desynchronization error between the master and slave is measured at each joint by a tickler mechanism. These errors are converted to electrical signals by transducers and then conditioned and amplified by electronic amplifiers. These signals are then transmitted to appropriate electrohydraulic servo valves which produce differential pressure proportional to the electrical signal. This pressure is applied to the slave actuator for the corresponding joint and causes the joint to move in the same direction as the master. The slave continues to move until the desynchronization error is reduced to a level that will maintain the system in equilibrium. The differential pressure is also applied to the force feedback actuator at each joint. These actuators are designed so that the operator will feel a force, 1/[illegible]th of that applied to the slave and in the same directional sense.

Hydraulic power was supplied by a 30 GPM laboratory supply. The supply pressure was regulated at 3000 psi, and the flow restricted to 10 GPM. An electric solenoid dump valve was used for quick shut down and locking in case of emergency.

Figure 1. Hardiman I Arm System.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

The successful completion of the arm test gave new confidence in the design and analysis of servo joints-in-series. The model used for simulating the servo system has been found to be very accurate in representing the dynamics of the system.

The human factors involved in controlling the six motions, although complex in nature, did not present any unforeseen problems. With spatial correspondence and force reflection, it was possible to operate the machine satisfactorily with a minimum amount of experience.

The arm system test was not only valuable because it substantiated basic design decisions in these two fields, but it was also useful for investigating problem areas and finding solutions. The following recommendations have resulted:

- A minimum leakage rate across the pilot piston should be specified when purchasing the pilot operated lock valves.
- When determining maximum flow rates for servovalves, a greater margin should be applied to compensate for unforeseen actuator leakages.
- Servovalves with very good dynamic response should be used even when they have larger flow capacities than is required.
- Sliding parts such as the rectangular splines in the forearm and upper arm rotate ticklers should be flash coated to prevent galling.
- The thumb joint input system should be modified so that the operator can control it more easily. The possibility of using on-off without force reflection rather than velocity control should be investigated.
- Counterweighting of the master should be provided if operation for any considerable duration is to be accomplished.
- If lifting of 1500 pounds is to be done very often, then the level of force reflection should be reduced 25%.

SECTION IV

TEST AND EVALUATION LOG

Throughout the test and evaluation of the arm system, a daily test log was maintained. This log was not only valuable as an aid in defining problems and thus solutions, but at this point in time also serves as the basis for narrative descriptions of the evaluation and the difficulties encountered in attaining the objective of stable operation at full load. The format for this narrative which follows will be to present selected excerpts from the test log and then expand upon the event or problem in greater detail. Before beginning, it will be useful to discuss the checkout sequence used in making the arm system operational.

1) Electronics Checkout

The electronics amplifiers for each joint were evaluated by obtaining the following data:

a. Calibration curve of gain versus pot setting for each of the signal channels.

b. Input-output curve at nominal gain for the position channel to check linearity.

c. Frequency response of all compensation networks.

2) Open Loop Operation

With the electronics connected but the control signals shorted, a dc signal was applied across the servovalve coil. Hydraulic power was applied to the system, and slave actuators were driven to one stop or the other, depending on the polarity of the dc signal. Each joint was exercised in this manner, and the following checks made.

a. Check for hydraulic leaks.

b. Check for mechanical interferences.

c. Check polarity of the force feedback.

d. Record the polarity of the dc signal and the corresponding direction of motion.

3) Individual Joint Start-up

The servo-controlled motions were started one at a time, beginning with the wrist and proceeding through to the back flex. Before hydraulic power was applied, the polarity of each transducer was recorded and then compared to that of the servovalves obtained previously. From this comparison, the transducers were then connected to the amplifiers to give the proper servo-loop polarity.

TEST LOG

8/8/69 - "Operated all the joints with dc signal, ... With all the actuators against the stops, an excessive amount of flow can be heard going through the system."

Based on this observation, a flow meter was placed in the hydraulic supply line and flow measurements made with different combinations of joints connected to the supply. These measurements indicated that the flow was highest in those joints which had a pilot-operated locking valve, shown schematically in Figure 2. The function of this valve is to hydraulically lock the power actuator when the supply pressure drops below a nominal value of 2000 psi. When the specifications for this valve were made, a minimum leakage rate across the locking piston was specified but not for the pilot piston. Calculations based on manufacturing tolerances for the piston clearance indicated that the flow rates measured could be realized as leakage from supply to return across the pilot piston.

The hydraulic power supply being used at this time had a capacity of 9.8 GPM, and the total standby for all of the joints together was measured at 6.85 GPM. Therefore, the remaining flow available would not be enough to operate all the joints together. To solve the problem, the system was connected to a laboratory power supply with much larger capacity. Although this was a valid solution to the problem in the case of the arm system, it will not be sufficient when more joints of the machine are added. The added number of locking valves, as well as increased flow requirements, will make it imperative that these leakage rates be reduced. (This problem has been solved by tightening the specifications on valves.)

8/13/69 - "Operated the wrist ...... The joint is unstable at nominal gain settings but stable operation can be obtained at lower gain."

The wrist is the most difficult joint to stabilize. The large variations in inertia between the loaded and unloaded conditions make it difficult to determine a set of servo parameters that will give stable operations in all conditions. Furthermore, the structural stiffness of the other joints seemed to have a strong influence on the stability of the wrist joint. The compliance at the gain settings for stable operation was seven percent. Although this does not meet the requirement of three percent, it was decided to bypass this problem for the moment and go on. (This problem and its solution are discussed later.)

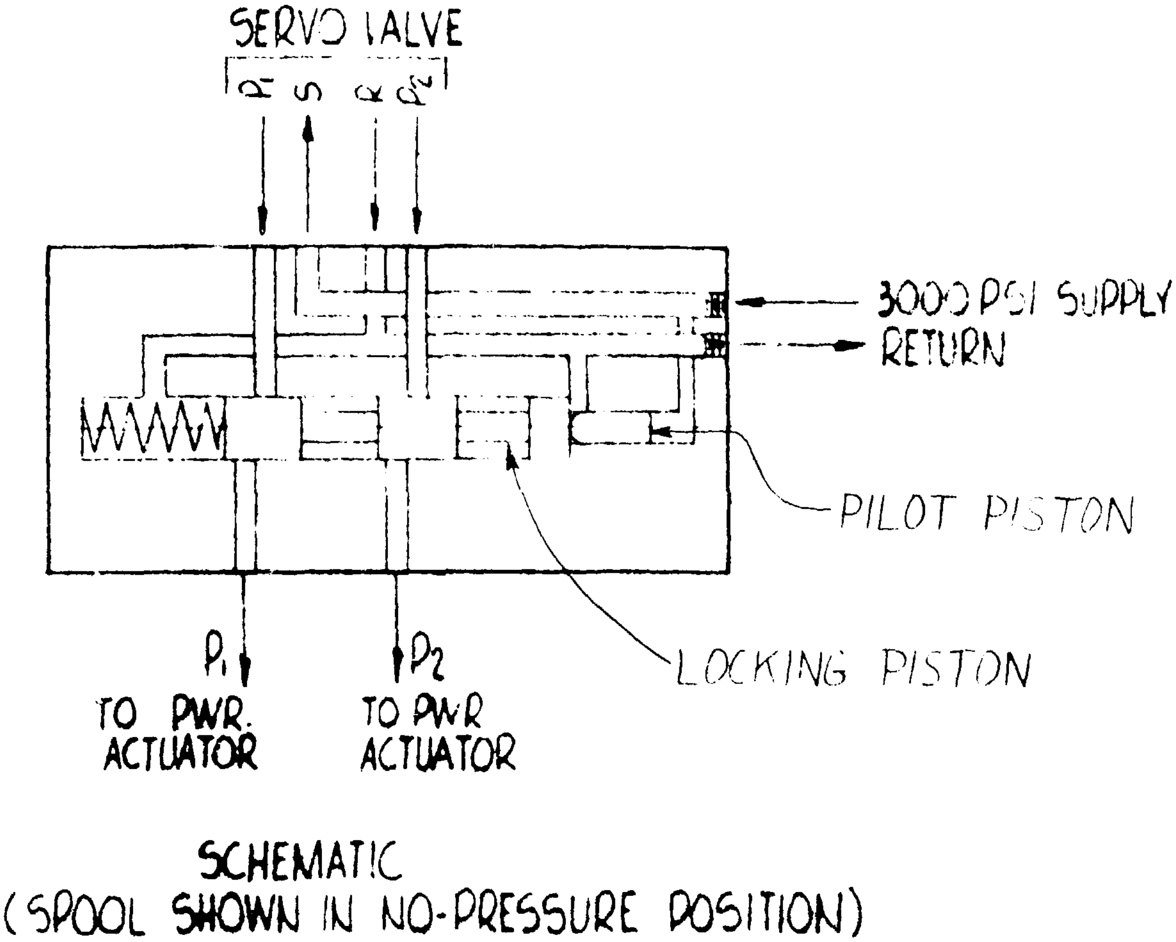


Figure 2. Hydraulic Locking Valve

8/18/69 - "Obtained stable operation of the forearm rotate but found some positions where the force needed to move the joint is excessive."

The response of the system did not seem as crisp as would be expected for the loop gain measured. The amount of desynchronization to move the slave or slew error was quite large, and at times, the master made contact with the slave. When this occurred, the operator was pushing directly against the slave causing the excessive forces mentioned in the log.

The cause of the problem was found to be flow saturation of the servovalve. The reasons for this saturation were:

1. The slave actuator used is a rotary vane type and is susceptable to internal leakage in particular positions.

2. The servovalve flow capacity was set at 2.0 cubic inches per second. Although this was probably enough capacity for normal actuator velocities, it was not sufficient to supply velocity as well as leakage flows.

The solution of the problem was to replace the servovalve with one with a maximum flow rate of seven cis. When this was done, the response of the joint was as expected.

8/21/69 - "Operated the elbow, and had to reduce the gain to get stable operation. When restarted, the wrist joint lurched and was uncontrollable."

The problem was discovered to be an underdesigned snap ring-pin connection in the wrist tickler mechanism, Figure 3. The sudden input that was applied at start-up caused the tickler linkage to come apart and subsequent loss of control. Furthermore, a mechanical interference was discovered in the elbow mechanism. The channel section, Figure 4, which transmits the master signal to the elbow tickler was damaged because of contact with the slave hand.

The wrist tickler mechanism was redesigned and repaired. The connecting pin was made larger, and a dowel pin and groove rather than a snap ring was used to hold the linkage together. The damaged channel section was repaired and reshaped so it would not interfere with the slave wrist. The changes to the shape are shown as dashed lines in Figure 5. (The elbow servo gain was increased to nominal value with stable operation later in the test program.)

9/2/69 - "When the upper arm rotate was operated, three basic problems were encountered."

1. Tickler linkage kept slipping.

2. Joint was unstable.

3. When the elbow joint was closed, the upper arm rotated counterclockwise and vice versa.

Figure 3. Wrist Tickler

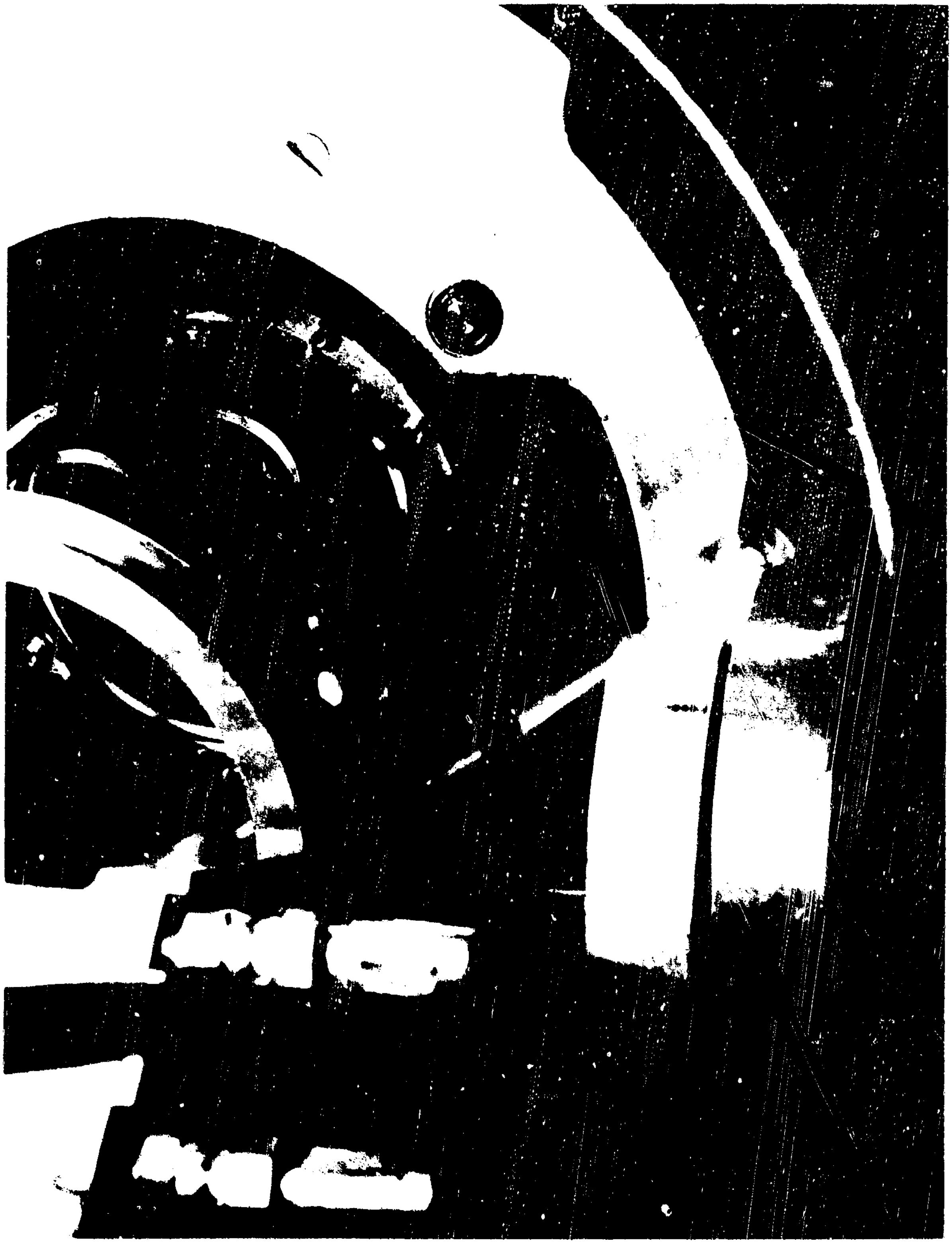


Figure 4. Elbow Channel Section

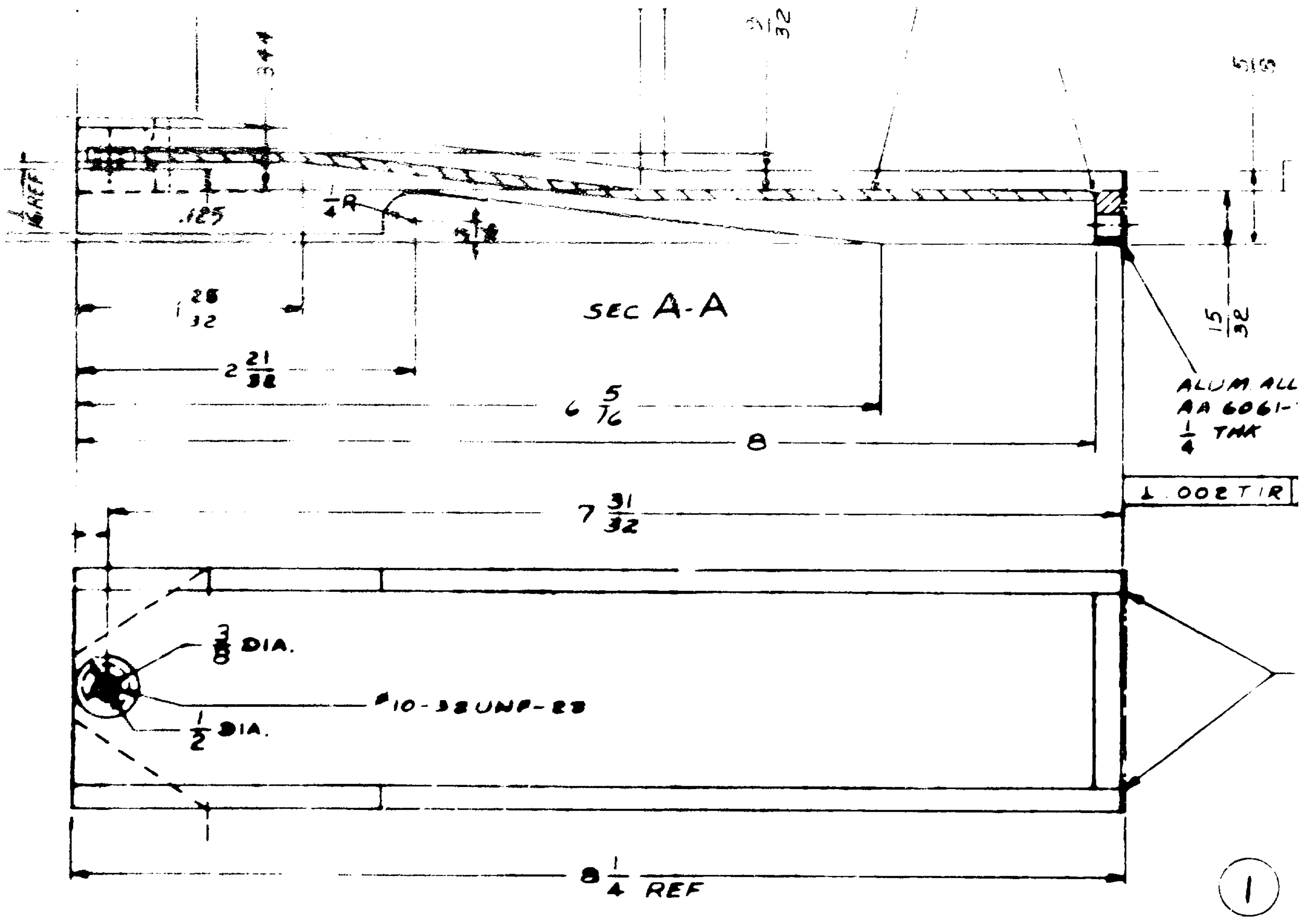


Figure 5. Elbow Channel Section

The tickler was slipping due to the failure of the set screws in the boss at the tickler attachment point to the master. When the part was removed, there was found to be oblong indentations caused by the set screws slipping. It was the design intention that these set screws be replaced by a pin after assembly, but this had not been done. When the set screws were replaced by pins, the shaft did not slip.

The instability was high frequency and, therefore, the master velocity loop was suspected. The oscillations were less severe when the velocity gain was turned down. A recalculation of velocity gain showed that the range of gain stipulated in the electronics design specification was too high. As a temporary repair, the signal from the master velocity transducer was shorted out. (Although this eliminated the instability, it would not be desirable to lift loads without the velocity signal; therefore, electronics changes were made a short time later.)

The amount of interaction between the elbow and the upper arm rotate was very sensitive to the null position of each joint. (Null position is the point of alignment of the master and slave at which the joint is in equilibrium.) When the two joints were adjusted so that the null position corresponded to the position where the master and slave centers of rotation were concentric, the interaction was very much reduced. This problem was not only a kinematic problem but also one of human factors. When the operator thought he was putting a pure elbow motion into the master, he was also moving the upper arm rotate.

9/4/69 - "When turned on power to operate the shoulder joint, the arm lurched and the elbow would not operate."

Throughout the evaluation problem, care had to be taken when turning on a servo for the first time. Each time that trouble occurred, the master had not been properly constrained from sudden movements. The problem in the elbow joint was discovered to be a long cantilevered pin, Figure 6, that had been bent. This pin acted as a pivot point for the elbow linkage and caused binding in the linkage when it was bent. Since the forces encountered were not to be expected under normal operating conditions, the pin was not redesigned but merely a new one made.

While the new piece was being made, the electronics were changed to reflect the new specifications for the upper arm rotate referred to earlier. Simultaneously, the shoulder and back joints were checked out and underwent limited operation. A meaningful evaluation could not be carried out without the elbow and upper arm rotate joints operational.

9/15/69 - "Reassembled elbow tickler and ran all the joints together. The shoulder joint null position seemed to have changed."

The operation of the shoulder and back joints is very dependent upon the proper null position for each joint. In this instance, the shoulder tickler linkage was slipping. The cause was the same as in the upper arm rotate joint. The set screws had not been replaced by a pin. When the pin was installed, and the shoulder and back ticklers properly nulled, the performance of the system with all the joints operating was quite satisfactory.

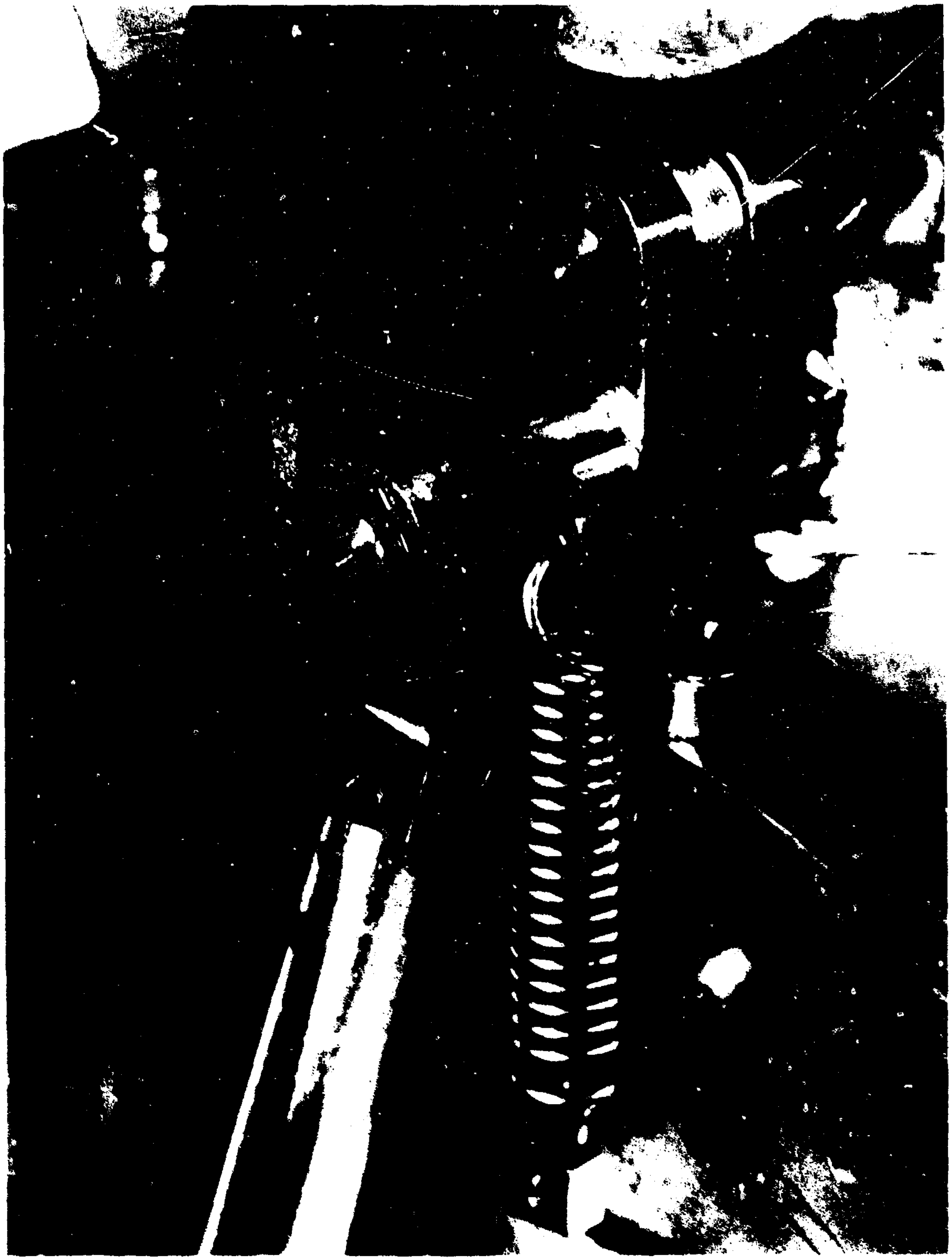


Figure 6. Elbow Cantilevered Pin

9/16/69 - "Operated the arm system with all the joints powered but could not move the shoulder or back."

The problem was caused by the upper arm rotate tickler. Part of the mechanism consists of mating female and male rectangular shafts, Figure 7. These shafts are designed to be rigid in torsion to transmit the upper arm rotate signal to the tickler, but slide one within the other to allow motion of the master shoulder and back. During the testing, galling had occurred on the male piece, and this caused the two pieces to become stuck. The upper arm master was thus grounded to the slave and no input could be transmitted to the shoulder and back ticklers.

For the arm tests, the problem was eliminated by maintaining proper lubrication between the two sliding parts. For a long term solution, a flash coating will have to be applied to one of the pieces to prevent galling.

9/22/69 - "Made a movie of the operation of the arm system. The major part of the movies showed the different motions, the excursions of the motions, and master-slave correspondence. Also tried some demonstrations: e.g., pouring liquid from a container and holding a light bulb. These are not valid tasks for the machine and therefore did not work too well."

9/25/69 - "Tried optimizing the servo parameters for all the joints. The wrist joint was unstable at maximum gain."

The gains in all of the joints were optimized to give maximum performance and stable operation. The gain values obtained met the design specifications in all but the wrist joint. It was observed that the wrist was most unstable when it was placed in series with the upper arm rotate and then the upper arm rotate grounded. There were two causes contributing to the problem, and thus two solutions. First, the servovalve used in the wrist joint was known to exhibit poorer dynamic response than those in other joints and was thus replaced. Secondly, the upper arm rotate position transducer was set up such that when the slave was grounded, a saturation condition of the electronics was obtained. By repositioning the transducer to give a more balanced signal in each direction, the problem was eliminated. (Although the wrist was never operated at maximum gain, later tests while lifting weights demonstrated that the amount of gain obtained in the wrist joint was sufficient.)

The complete system could only be operated continuously for a period of three to five minutes, depending on the range of motion. The operator could not continue for longer periods because he became very fatigued. This was caused by the weight of the master and the reflected weight of the slave. If operation for a longer duration is required, then counterweighting of the master must be provided.

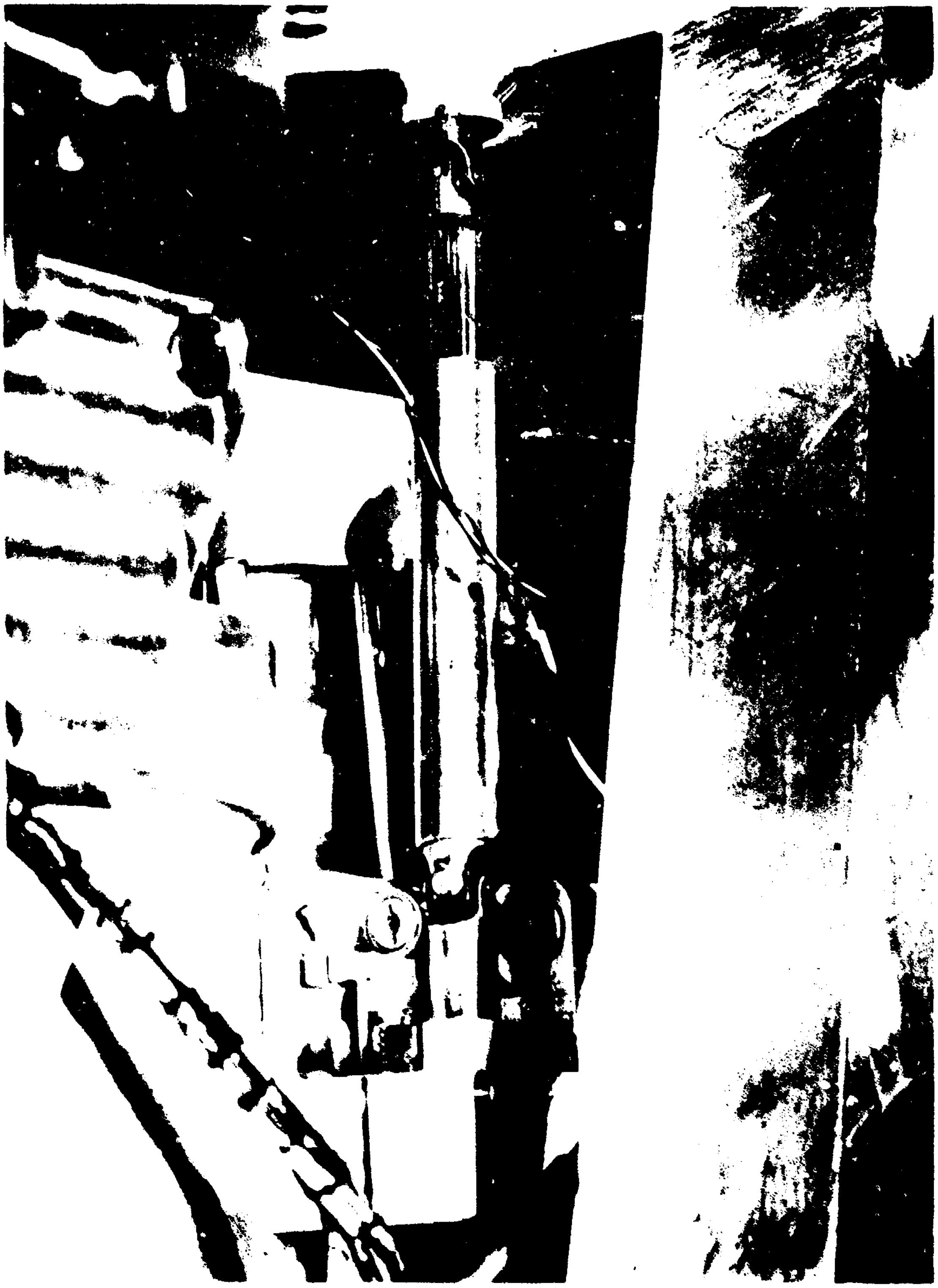


Figure 7. Upper Arm Rotate Spline

10/3/69 - "Operated the machine while lifting 125 pounds. The following observations were recorded.

1. The machine responds to inputs differently under load and seems jerky.

2. Uncomfortable contact forces at the wrist and upper forearm.

3. The grip required to close the thumb tip and thumb flex affects the performance of the other joints."

The first comment has to do with the fact that the machine responds to an input in the direction of gravity faster than against gravity. This is to be expected and is not much different from human response when lifting weights. After the operator practiced for a few minutes, he became familiar with the response of the system, and the operation was much smoother.

The discomfort due to the high contact forces was eliminated by using a leather arm pad shown in Figure 8. This is similar to the ring-pads discussed in Report S-67-1011, Page 18.

The problem with the grip was that when the operator applied the forces required to close the thumb joints, his wrist and forearm muscles became tight, and he could not apply full excursions into the master. This problem was also reduced as the operator gained experience, and although it did not limit the performance, the hand grip configuration will be studied for possible modifications.

10/7/69 - "Lifted 250 pound weight using 'A' frame and tether system."

Figure 9 shows the arm system lifting the 200 pound weight plus 50 pounds of rigging. The frame work in the background is used to support a hoist which acts as a tether and also handles the weights. The operator is wearing the hard hat as normal operating procedure when overhead equipment is being used.

The weight was raised to a height of six feet and in general was handled easily. The operator was able to hold the weight for a period of about one and one half minutes. This was limited because the operator was bending over and reaching out when lifting the weight and therefore exerted a great deal of energy. When the leg system is added, much of this will be eliminated as the legs will do most of the lifting, and the operator will be able to keep the weight in closer to his body.

10/10/69 -"Lifted the 750 pound test weight and also worked the 100 pound weight untethered."

Figure 10 shows the weight used in the 750 pound test. During testing, the machine was able to lift the weight about a foot and a half above the position in the picture. The limiting factor in lifting the weight higher was not the machine but rather the strength of the man. Again, some of the problem can be attributed to the fact that the legs are not being used, but in this case, it seemed that the force reflected to the operator was too great for him to overcome.

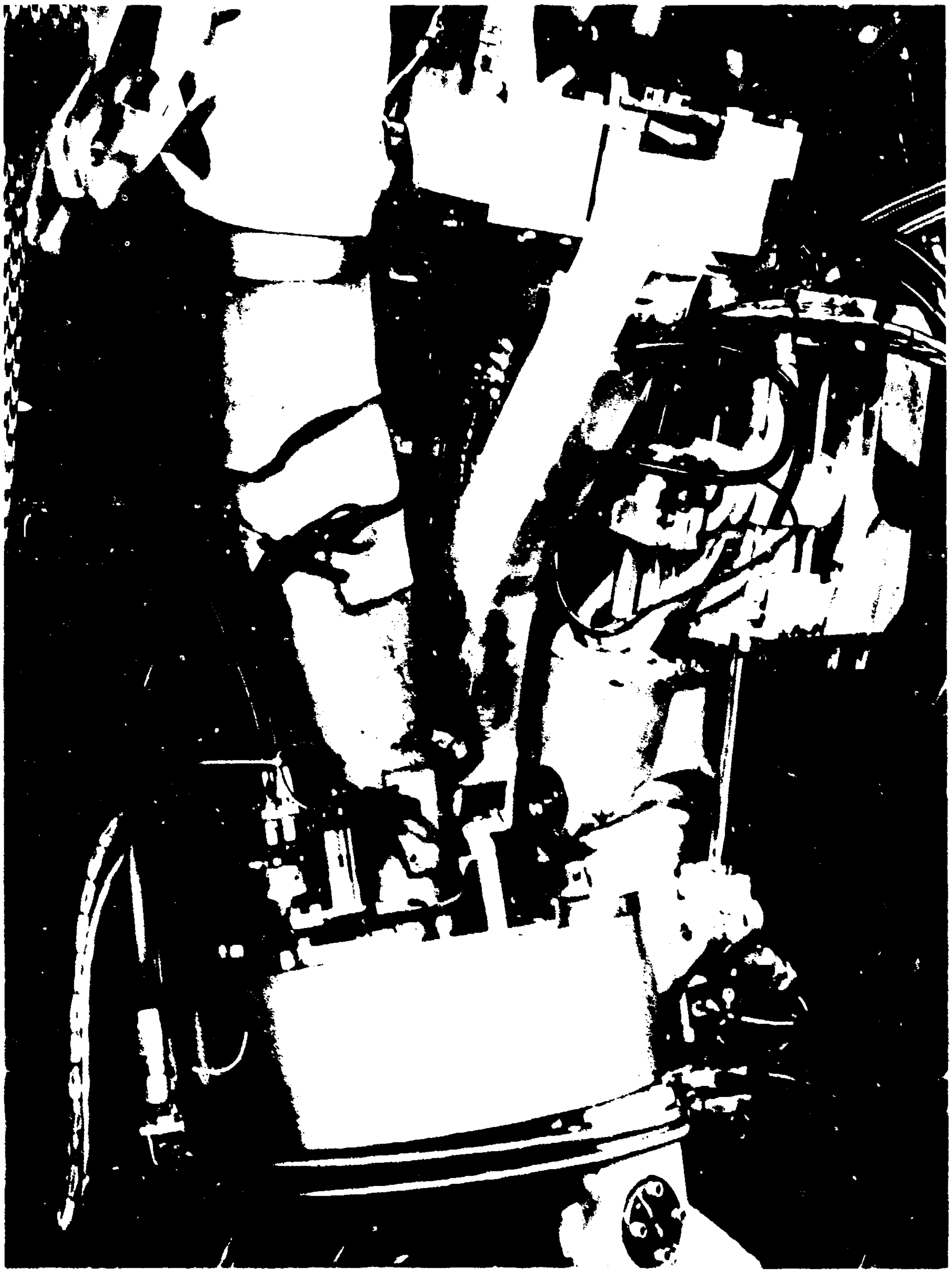


Figure 8. Arm Pad

Figure 9. Arm System Lifting 250 Pounds

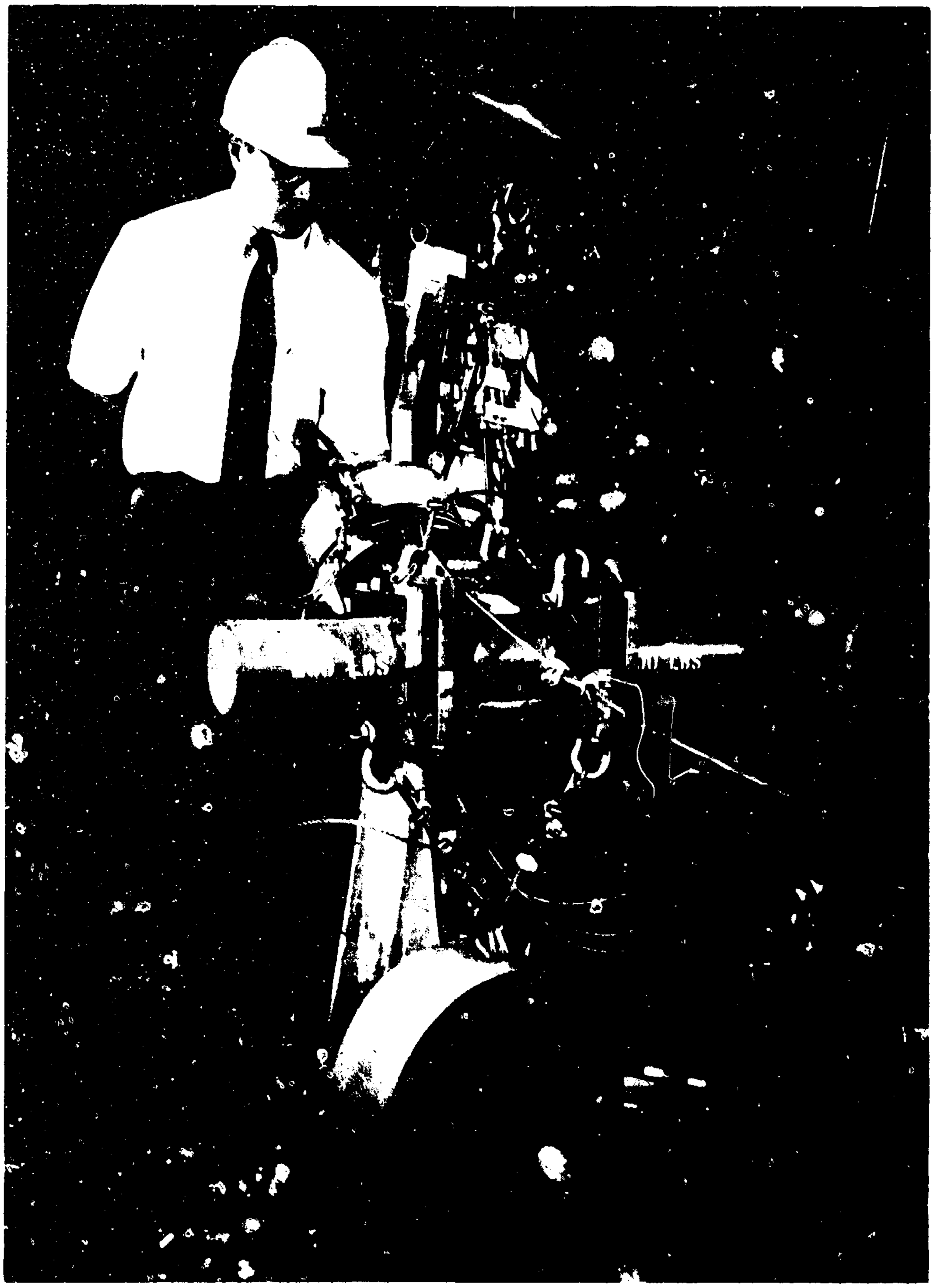


Figure 10. Arm System with 750 Pounds

In Figure 11, the machine is shown lifting the 100 pound weight without the tether. In this position, the gripping force of the thumb is strong enough to support the load. During this test, the weight was removed from a hook, held in the vertical position, rotated 90° to a horizontal position, rotated again to the vertical position, and then placed in a circular tube.

10/16/69- "Made a movie of the operation showing the machine lifting the 100 pound weight untethered, the 250 pound weight and 750 pound weight."

Figure 11. Lifting 100 Pounds Untethered

APPENDIX I

APPENDIX I

ELECTRONIC CIRCUITS

The electronic control package is shown in Figures 12 and 13. The package for the arm system was located separate from the arm assembly and connected by means of three electrical cables. The control signals were generated at the transducer on the arm assembly, transmitted through the cable to the amplifiers, and then the amplified signal transmitted back to the servovalves on the arm.

The two instruments on top of the electronics package in Figure 12 are the dc power supply and dither generator. The calibrated dials are connected to potentiometers for adjusting amplifier gains.

Figure 14 is an electrical schematic of the standard control circuit for each joint. Each circuit contains one SVD-100 printed circuit card for driving the servovalve, 1/2 a FET 200 printed circuit card for frequency compensation, and attenuator networks for properly scaling the electronic gains. For each of the four signals (tickler velocity, tickler position, master velocity, and servovalve drive), a variable resistor (potentiometer) was used to adjust the gain. Figures 15 through 38 are calibration curves of gain versus potentiometer position for each signal.

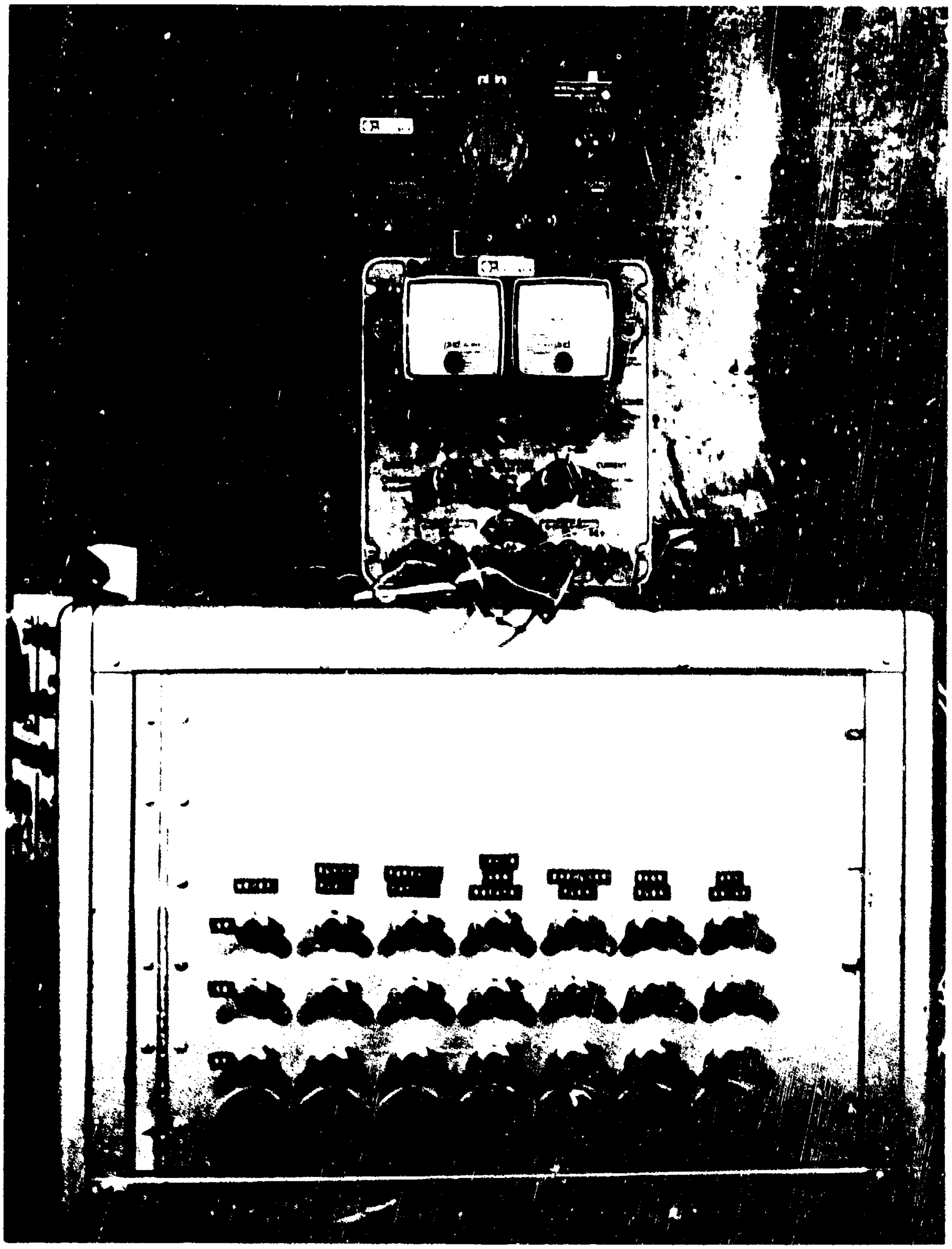


Figure 12. Electronics Package

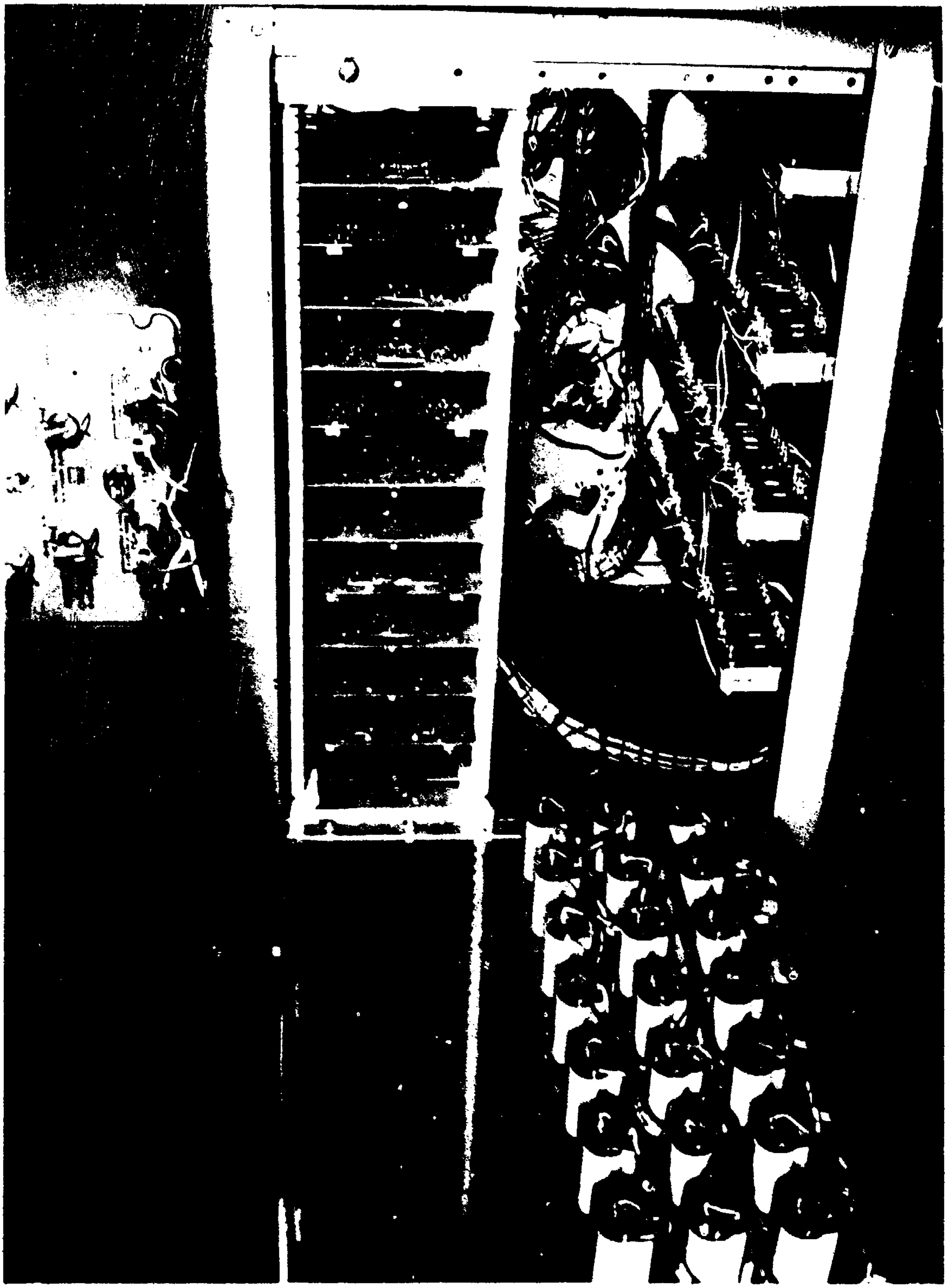


Figure 13. Electronic Circuits

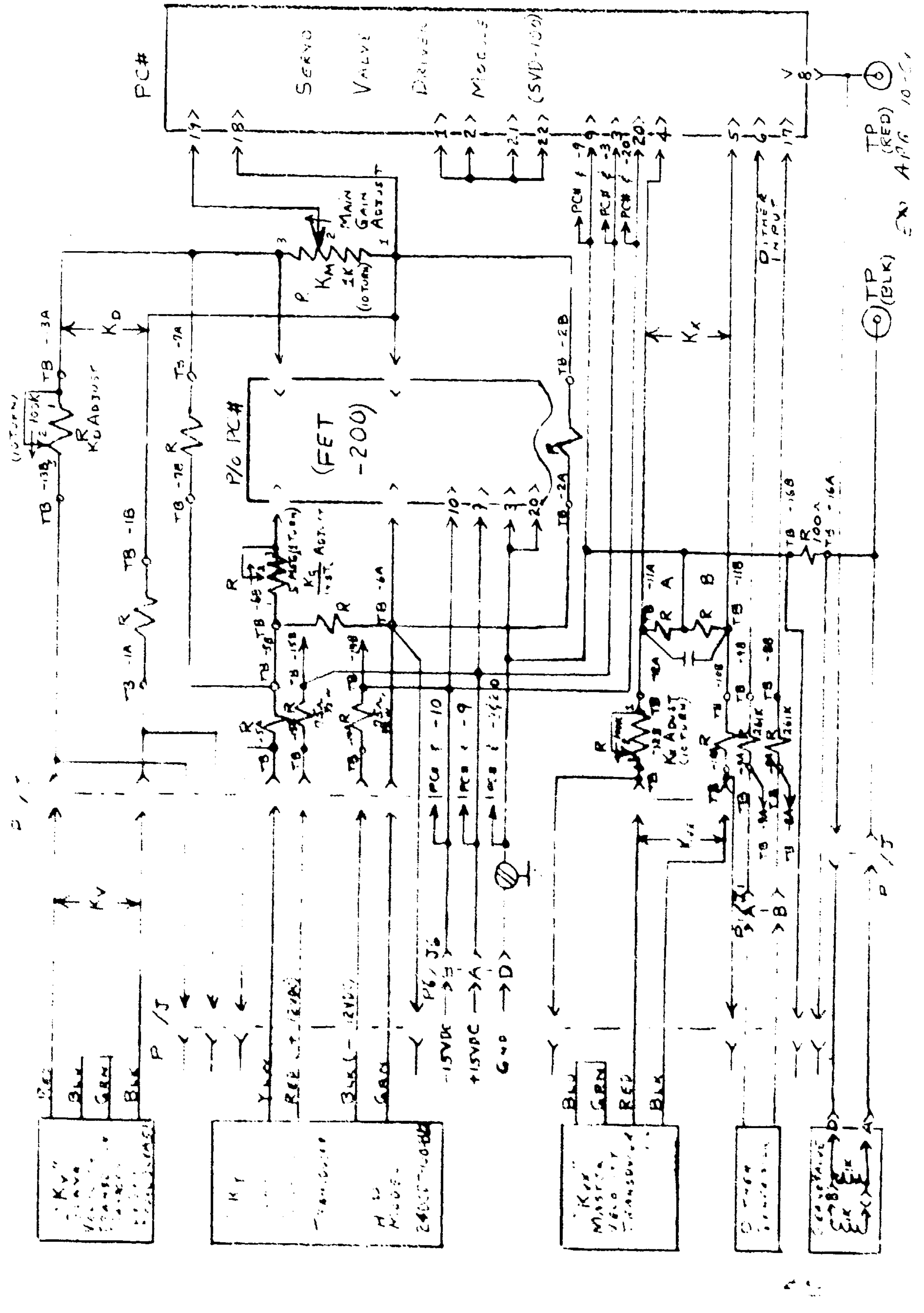
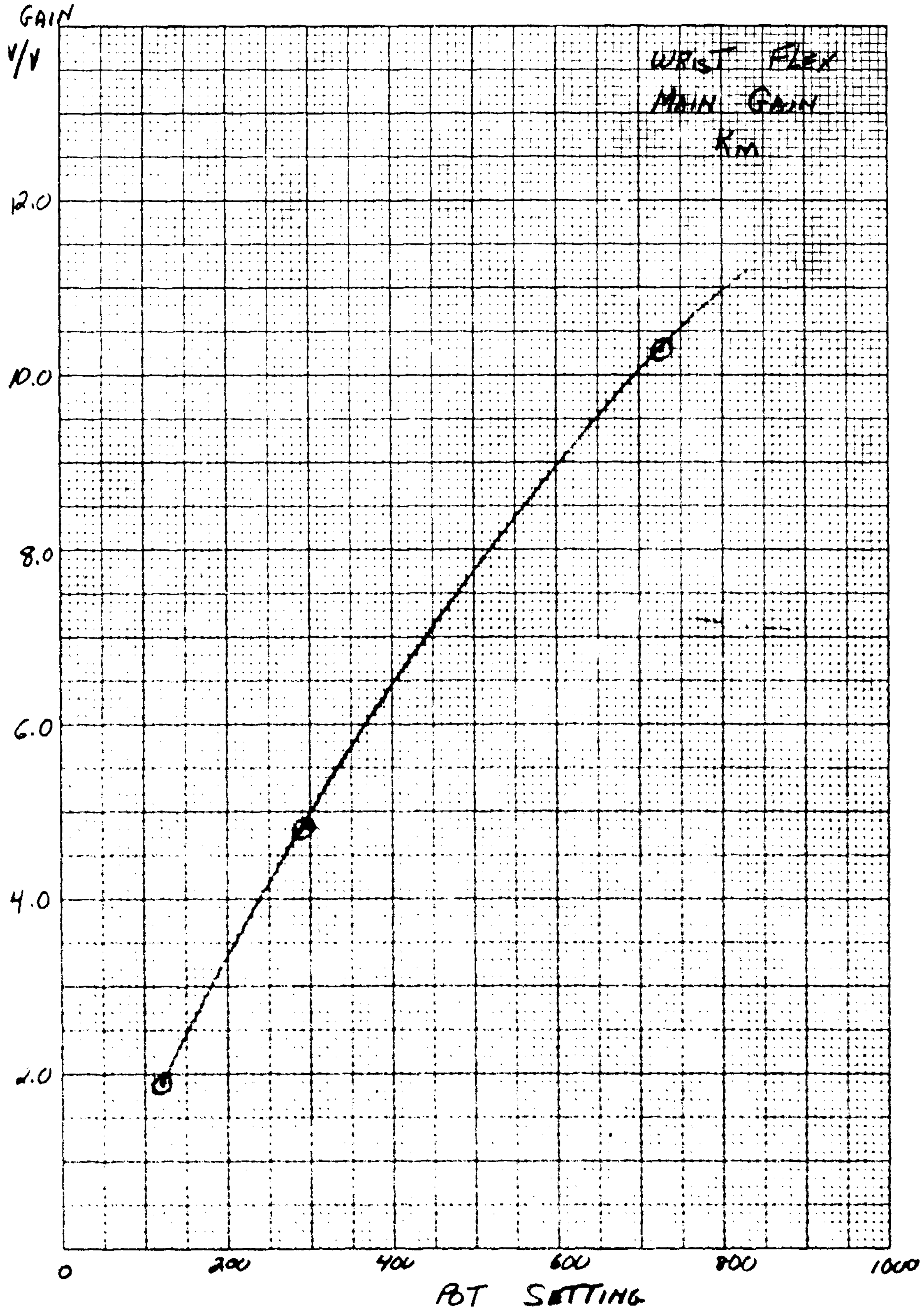


Figure 13. Electronic Circuit Schematic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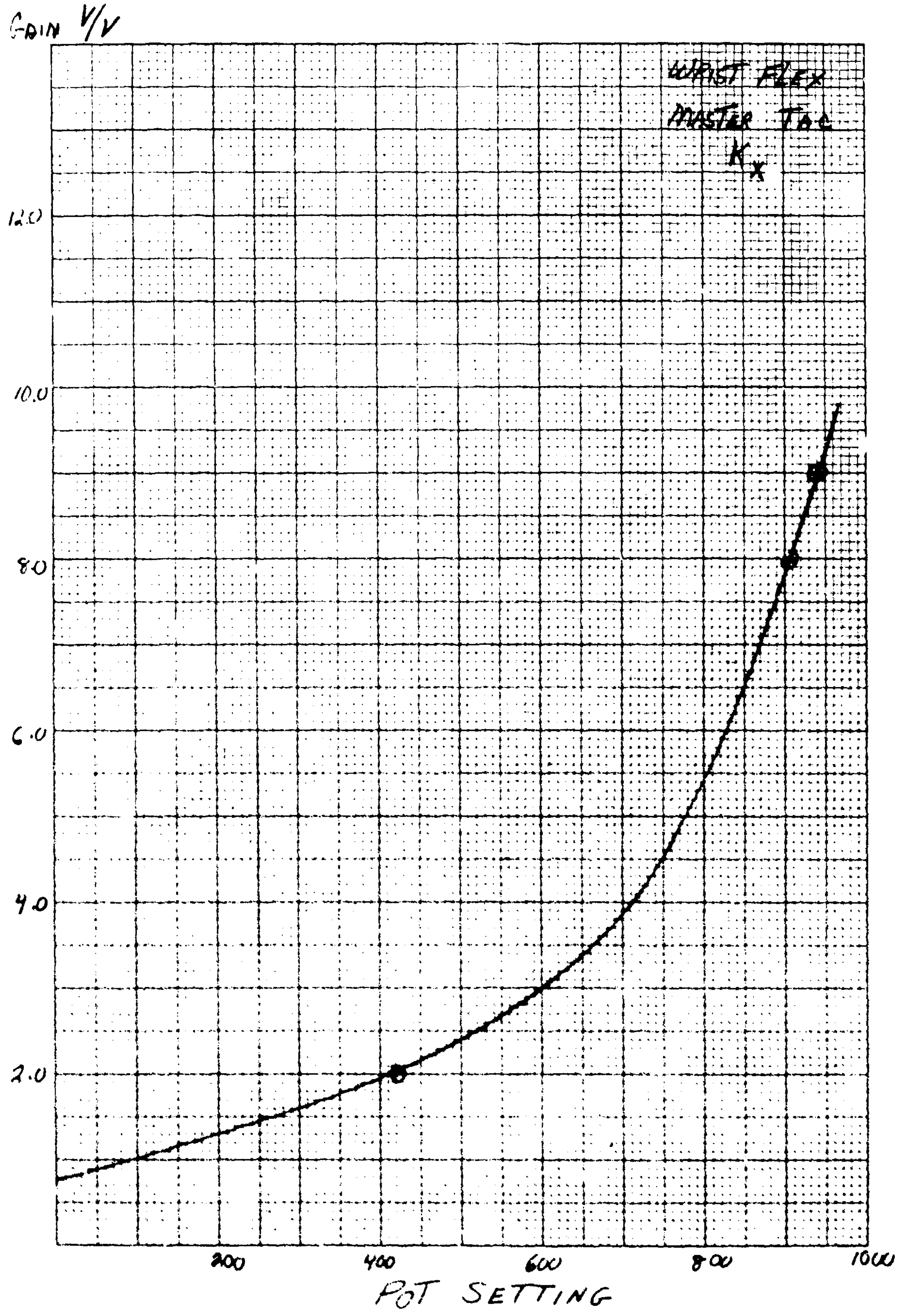
POT SETTING

Figure 15.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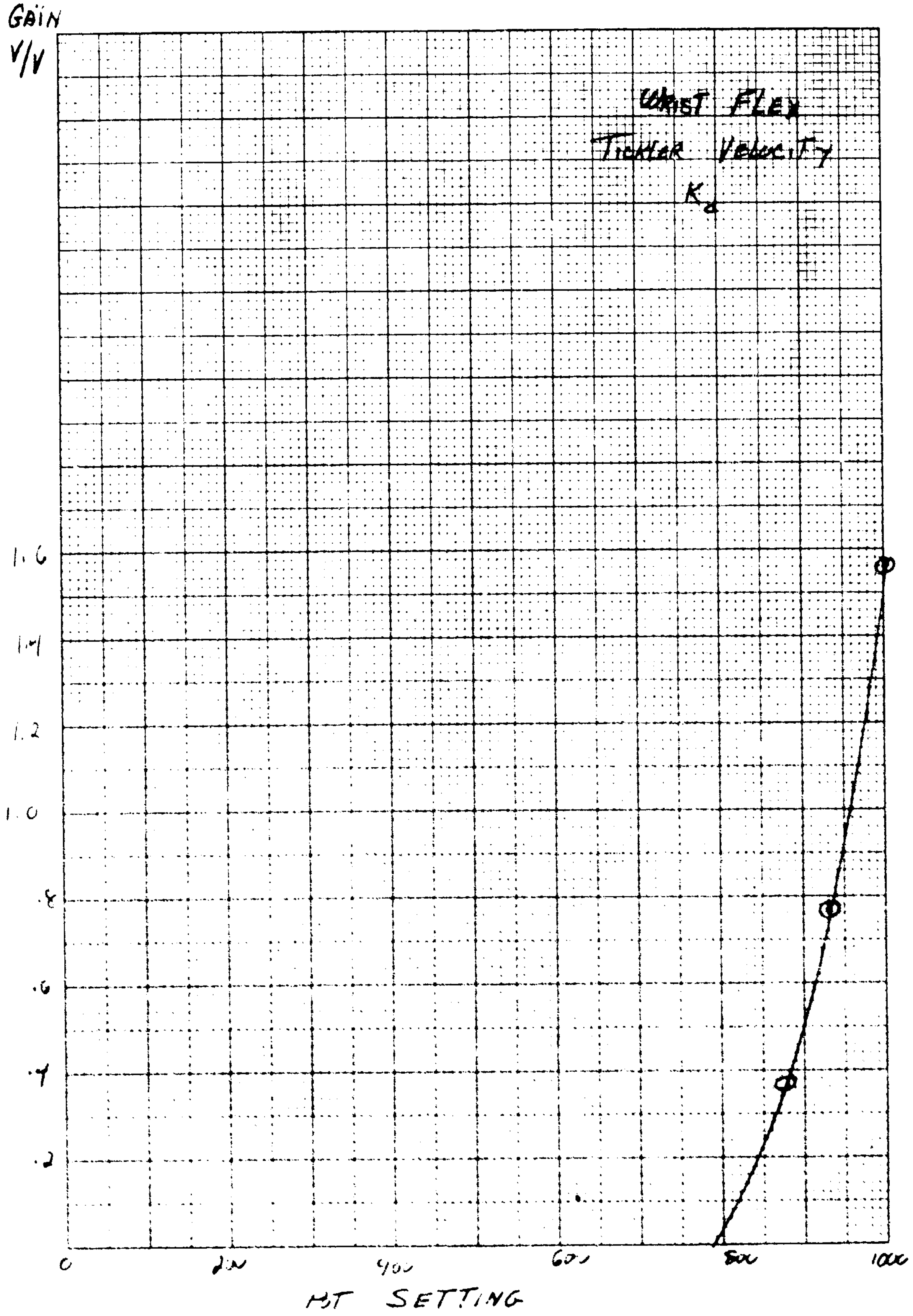
POT SETTING

Figure 16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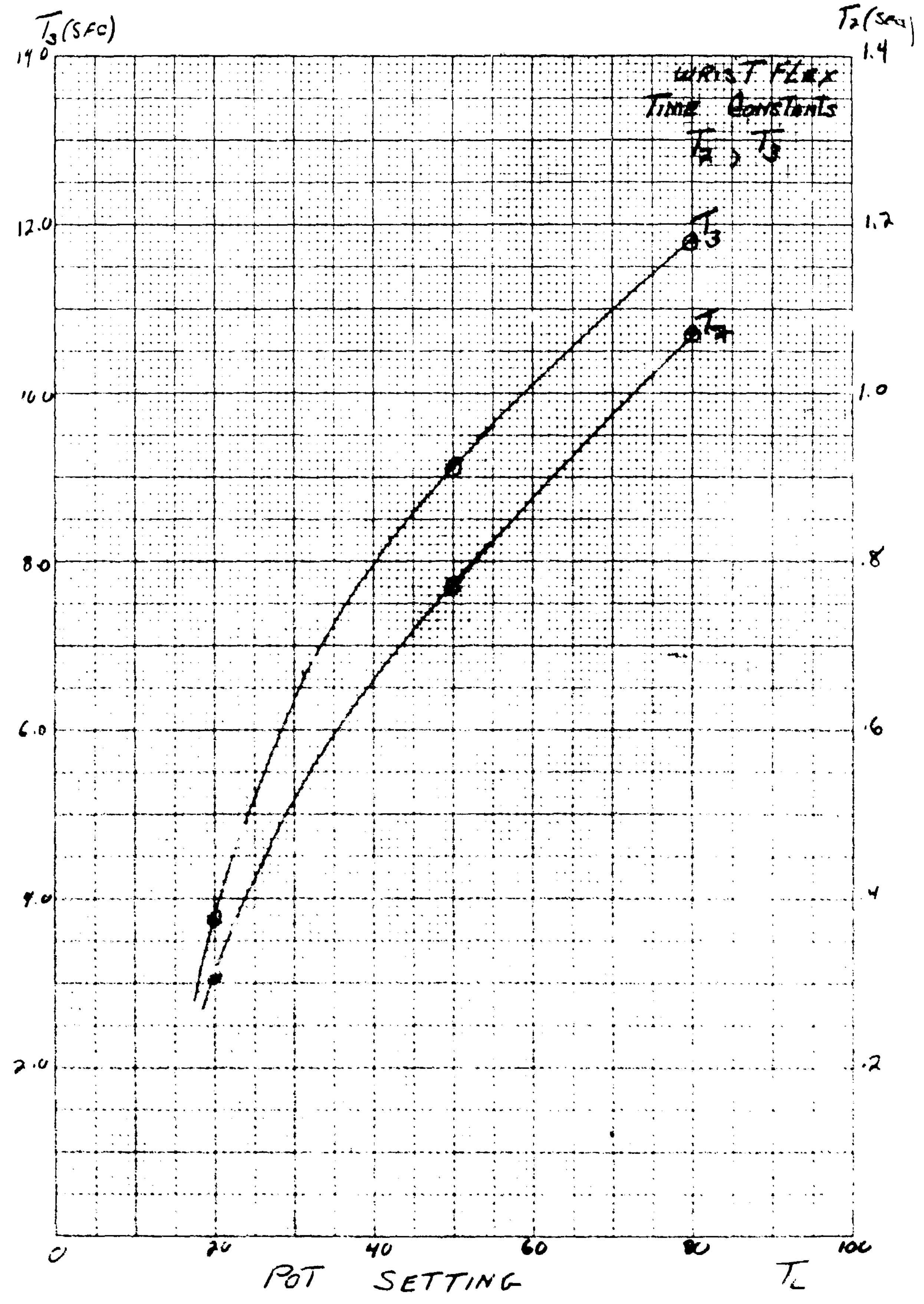
POT SETTING

Figure 17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POT SETTING
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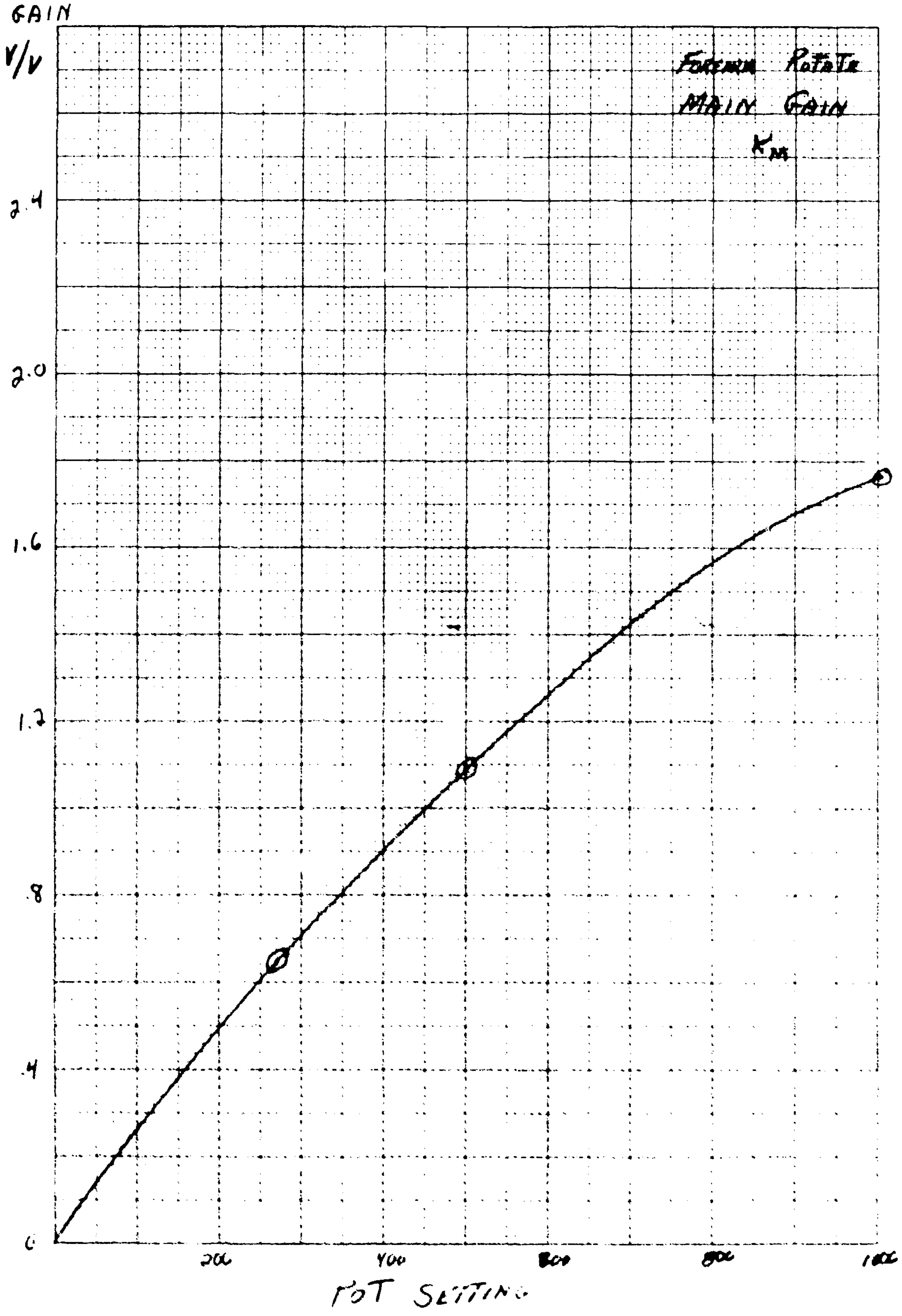
Figure 13

GAIN
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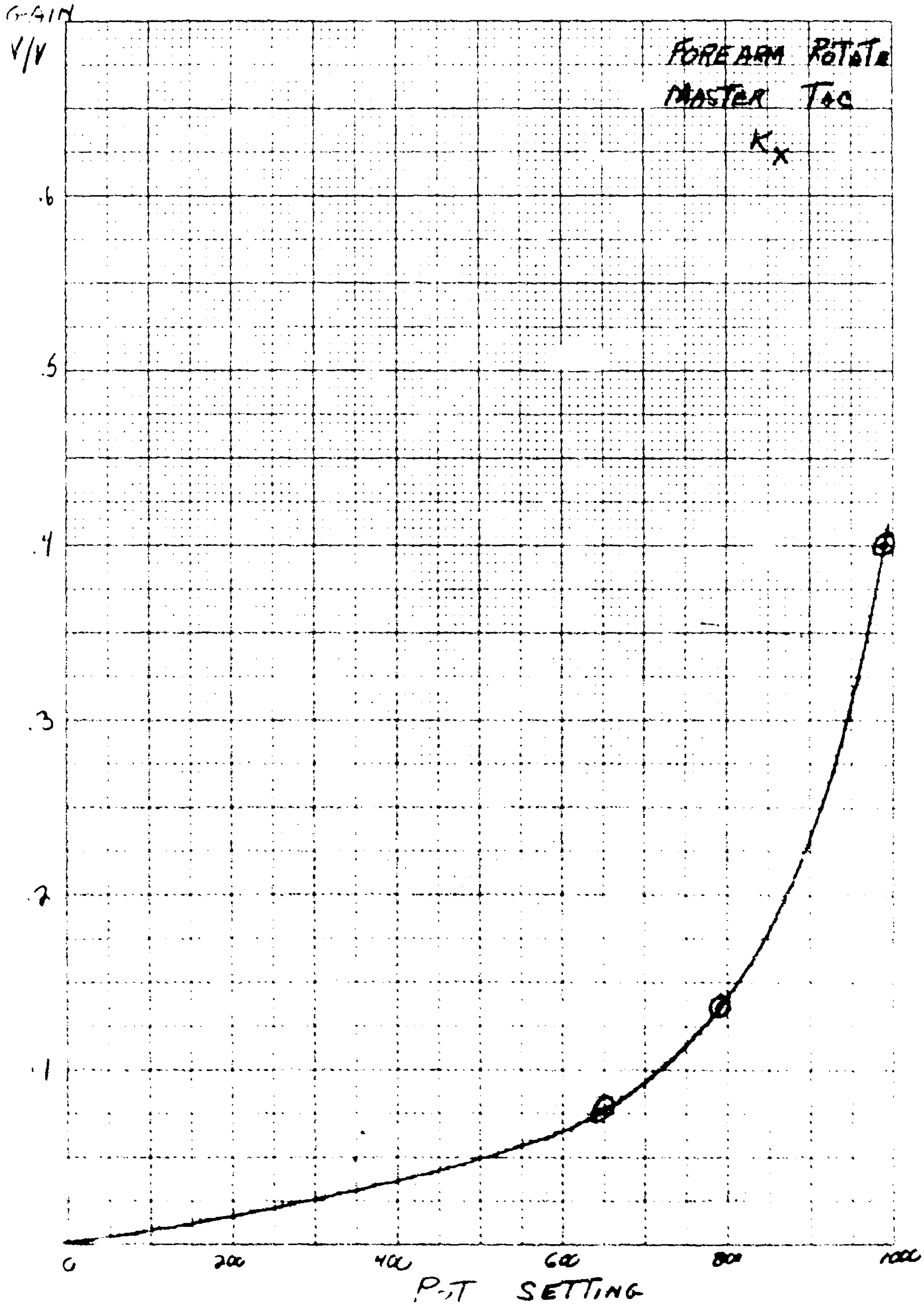
POT SETTING

Figure 19


GAIN
V/V
FOREARM ROTATE
MASTER TAC
K_X
.6
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.2
.1
0
200
400
600
800
1000
POT SETTING

Figure 20

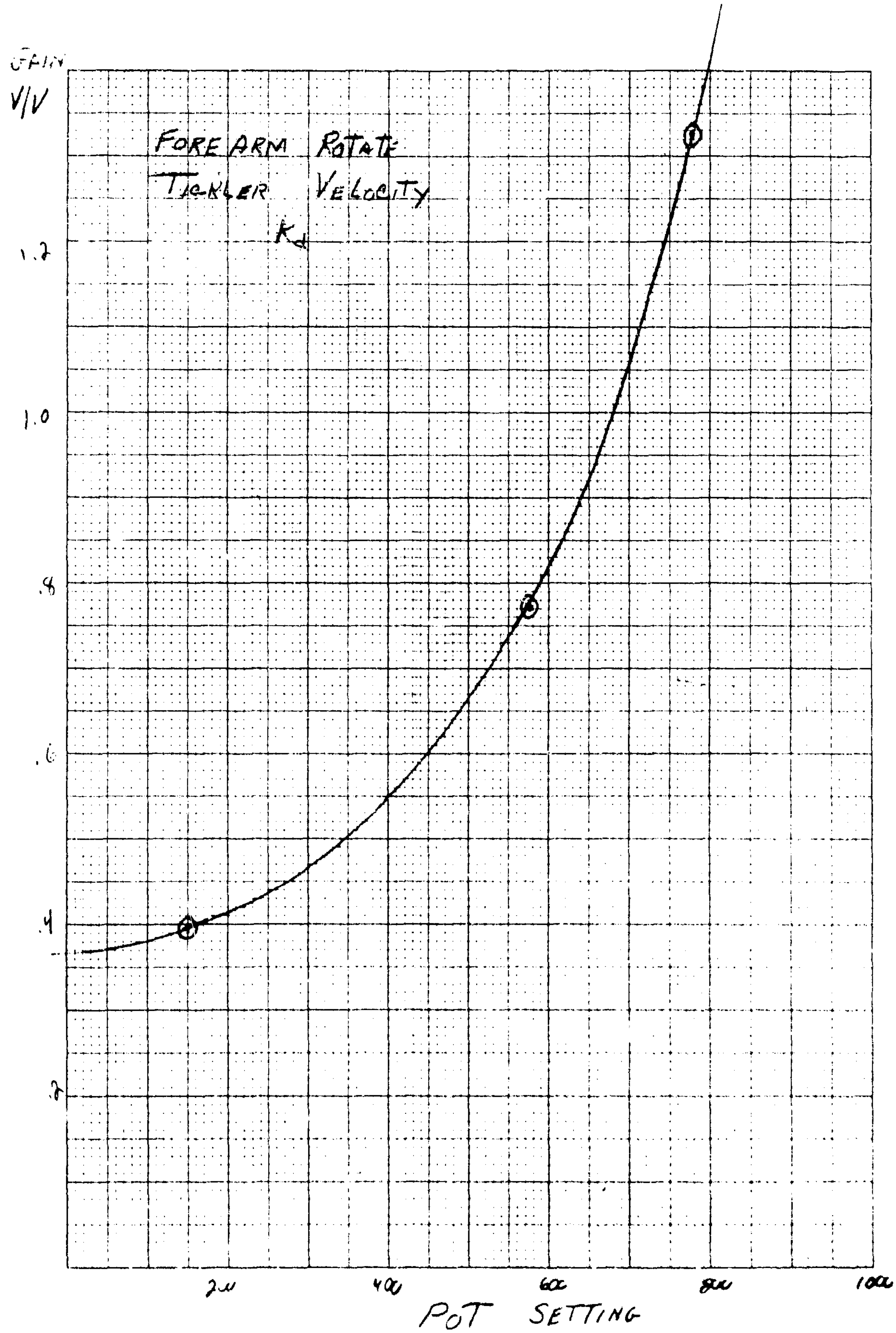

GAIN
V/V
FORE ARM ROTATE
TICKLER VELOCITY
K_d
1.2
1.0
.8
.6
.4
.2
200
400
600
800
1000
POT SETTING

Figure 21

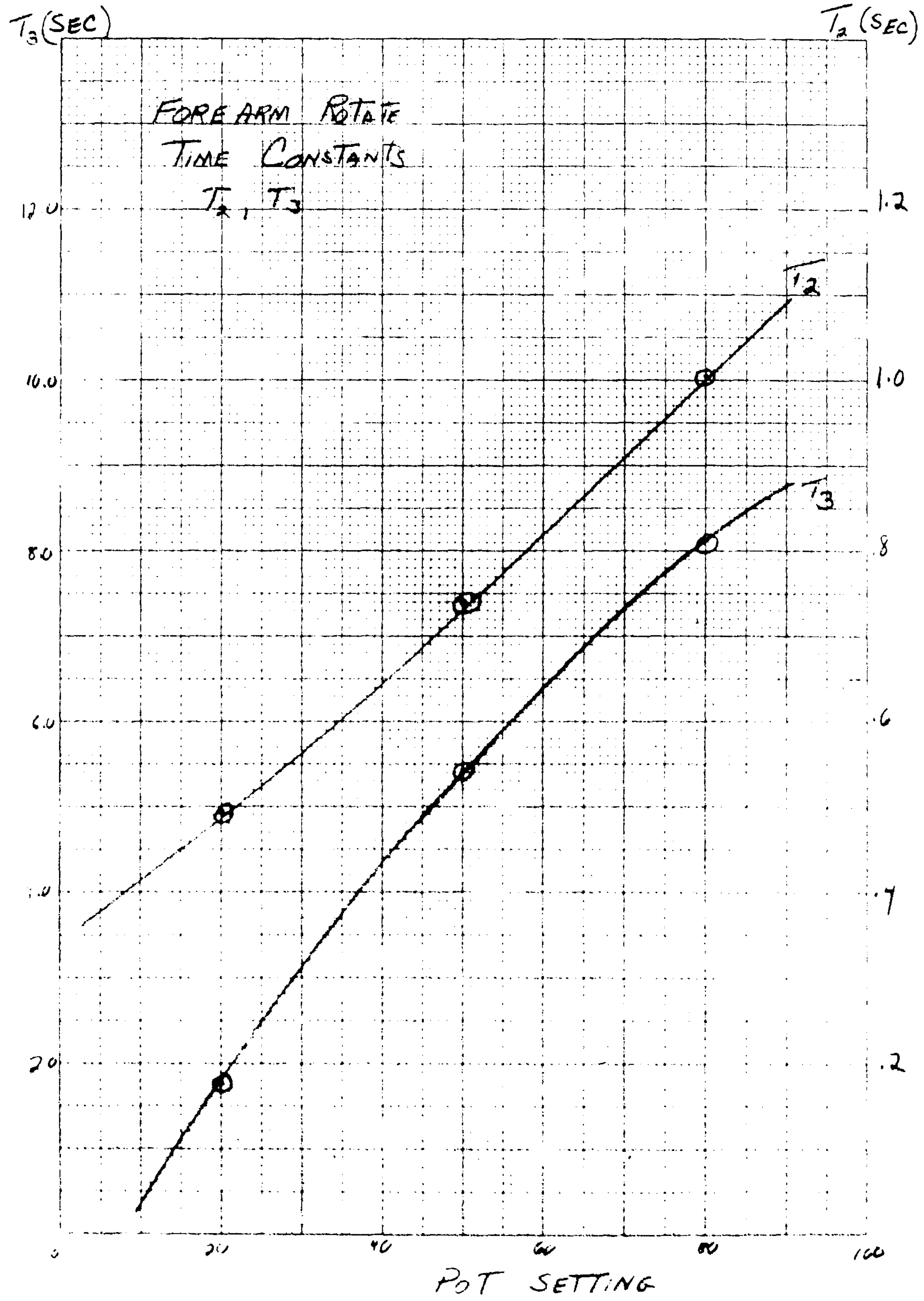

T_3(SEC)
T_2 (SEC)
FORE ARM ROTATE
TIME CONSTANTS
T_2, T_3
12.0
10.0
8.0
6.0
4.0
2.0
1.2
1.0
.8
.6
.4
.2
T_2
T_3
0
20
40
60
80
100
POT SETTING

Figure 22

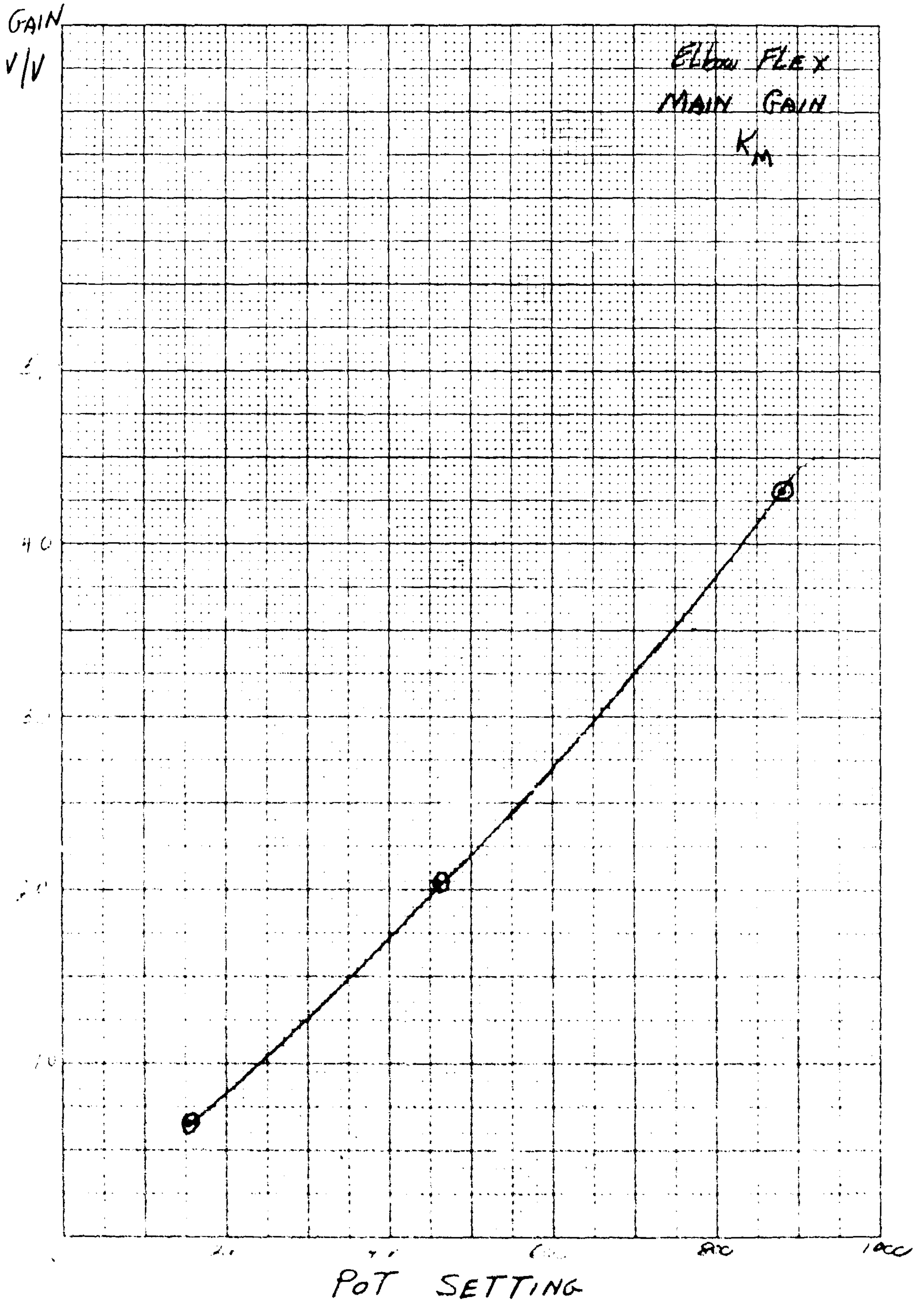

GAIN
V/V
Elbow FLEX
MAIN GAIN
K_M
50
40
30
20
10
20
40
60
80
100
POT SETTING

Figure 23

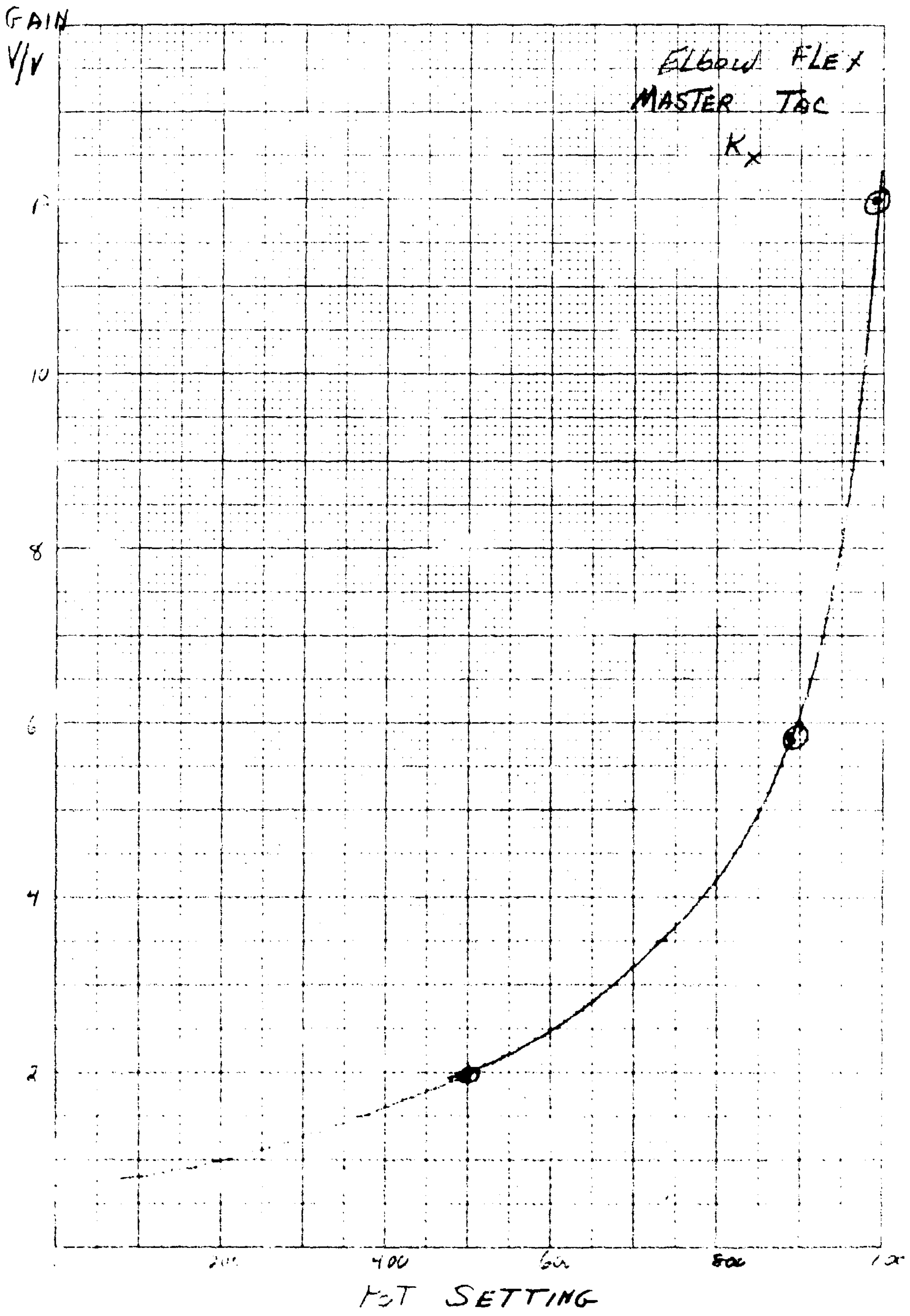

GAIN V/V
Elbow FLEX
MASTER TAC
K_x
12
10
8
6
4
2
200
400
600
800
1000
POT SETTING

Figure 24

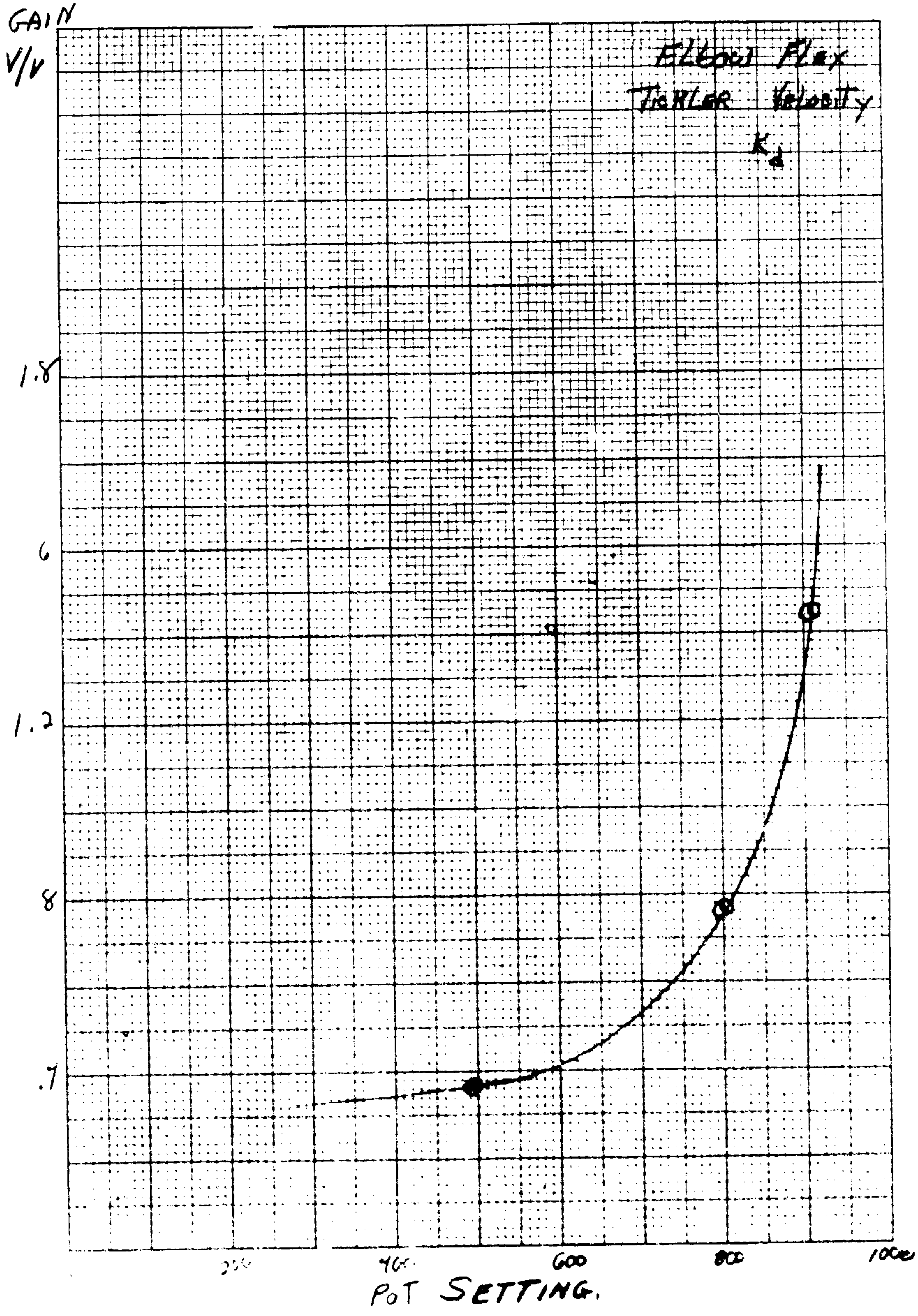

GAIN
V/V
ELBOW FLEX
TICKLER VELOCITY
K_d
1.8
6
1.2
8
.7
200
400
600
800
1000
POT SETTING.

Figure 25

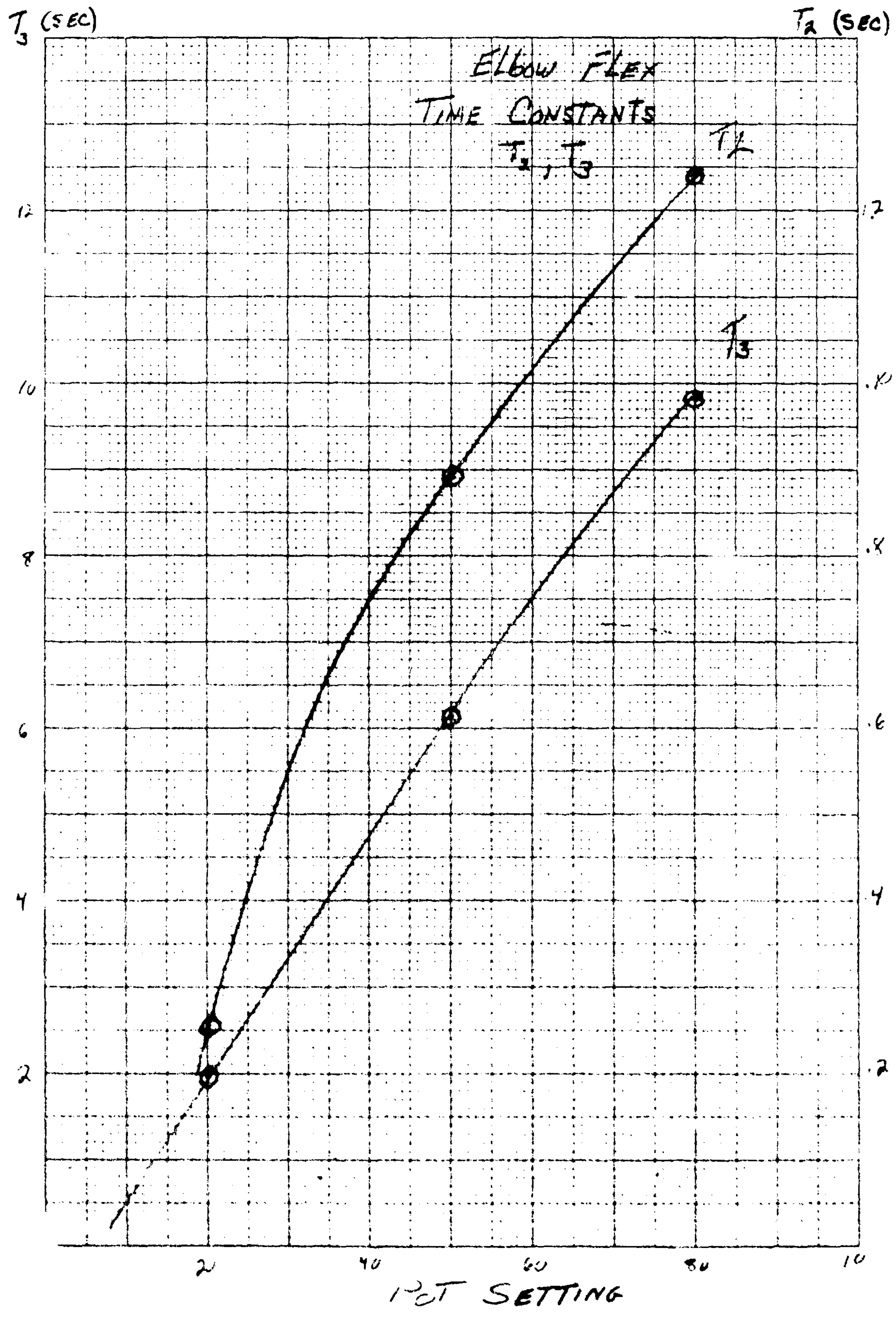

T_3 (SEC)
T_2 (SEC)
ELBOW FLEX
TIME CONSTANTS
T_2, T_3
T_2
T_3
12
10
8
6
4
2
1.2
1.0
.8
.6
.4
.2
20
40
60
80
10
POT SETTING

Figure 26

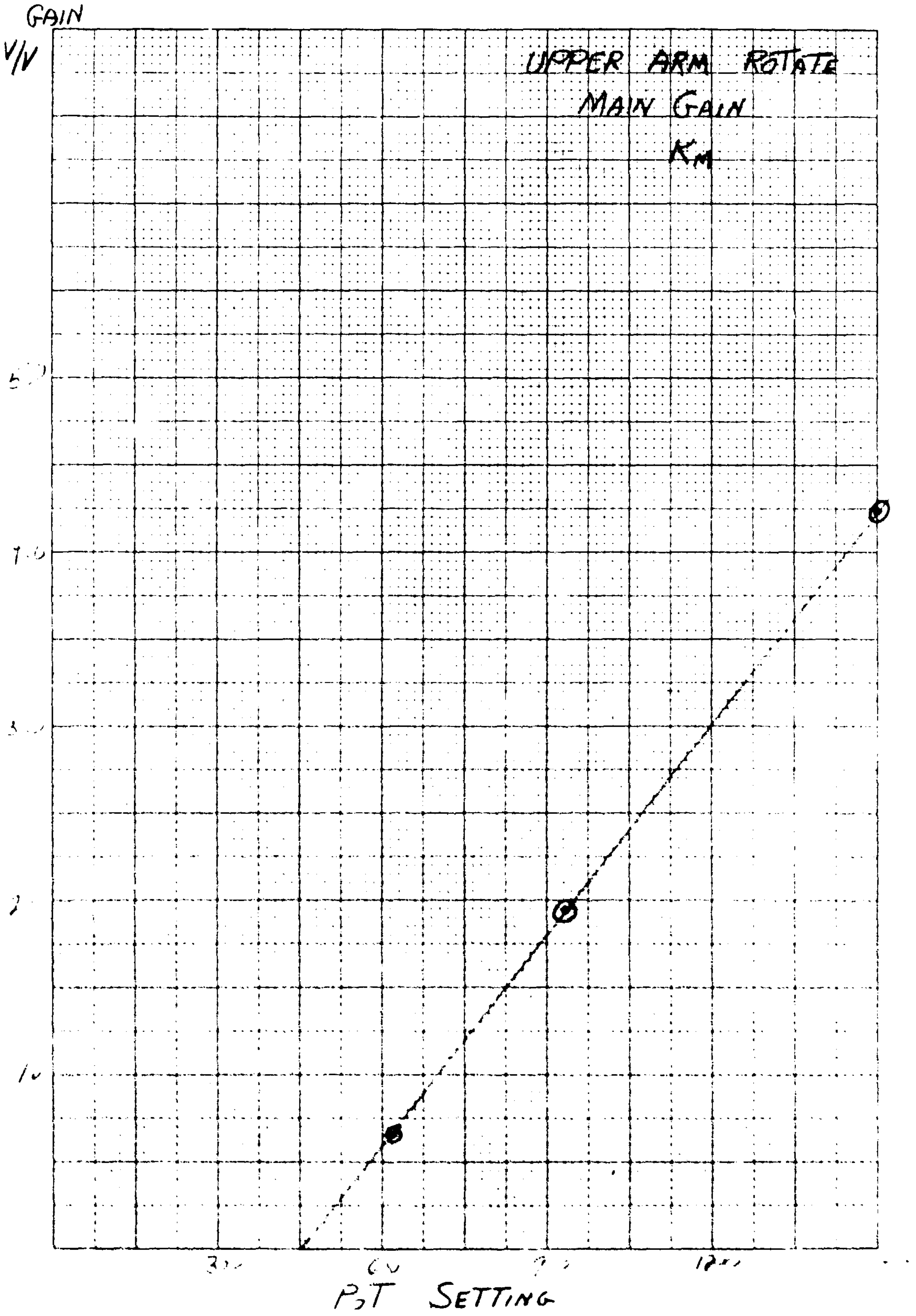

GAIN
V/V
UPPER ARM ROTATE
MAIN GAIN
K_M
50
40
30
20
10
300
600
900
1200
POT SETTING

Figure 27

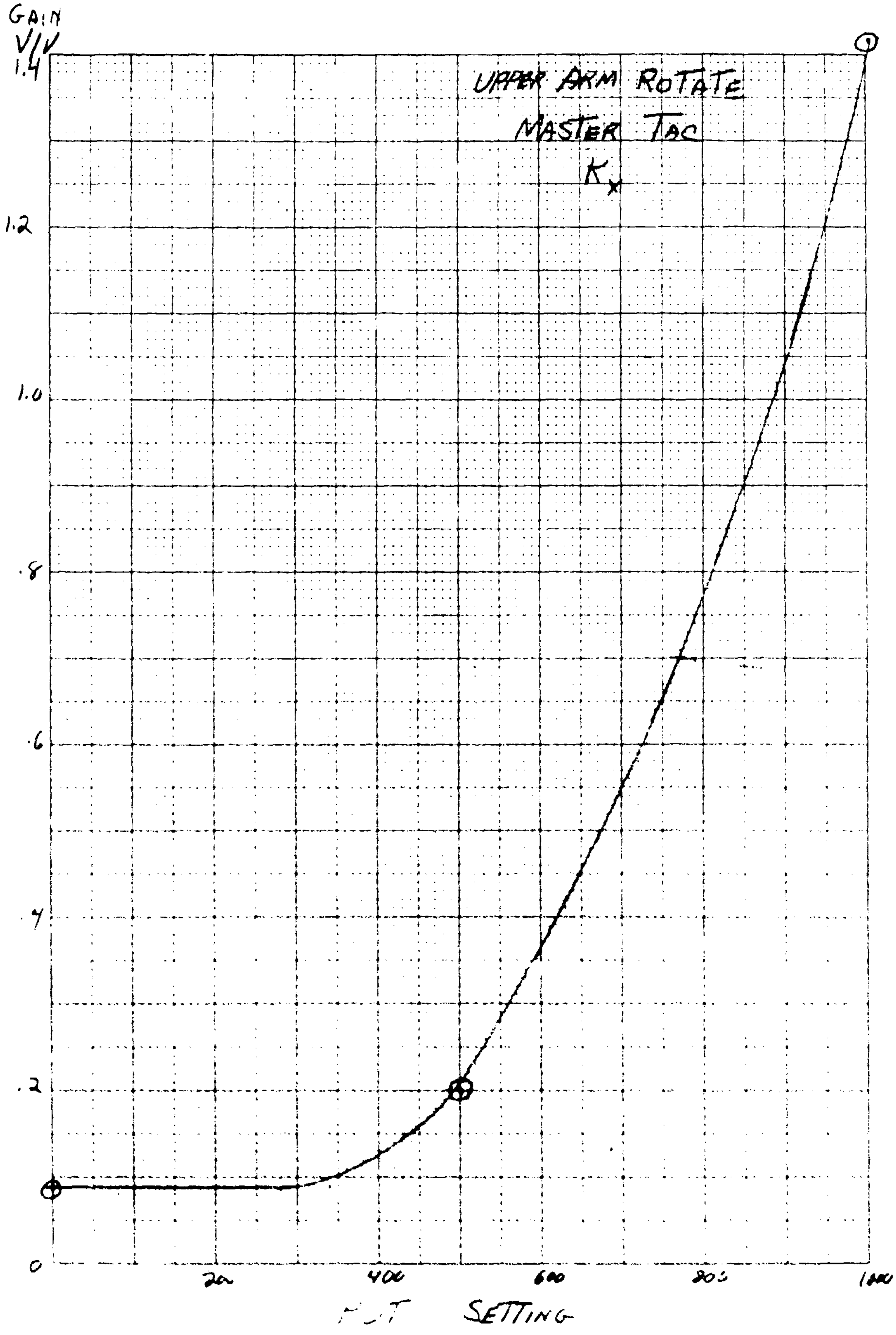

GAIN
V/V
1.4
1.2
1.0
.8
.6
.4
.2
0
200
400
600
800
1000
POT SETTING
UPPER ARM ROTATE
MASTER TAC
K_x

Figure 28

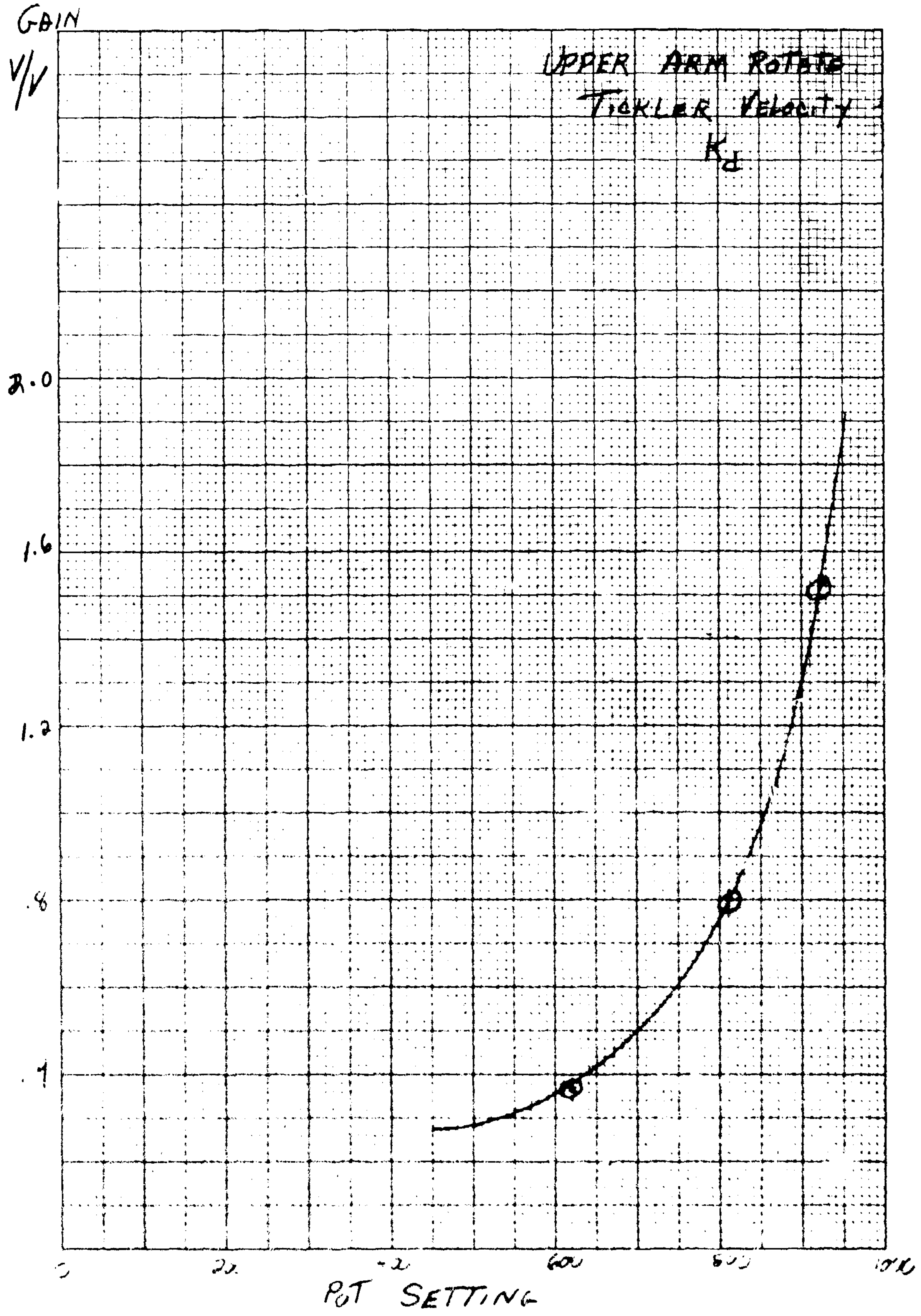

GAIN
V/V
UPPER ARM ROTATE
TICKLER VELOCITY
K_d
2.0
1.6
1.2
.8
.4
0
200
400
600
800
1000
POT SETTING

Figure 29

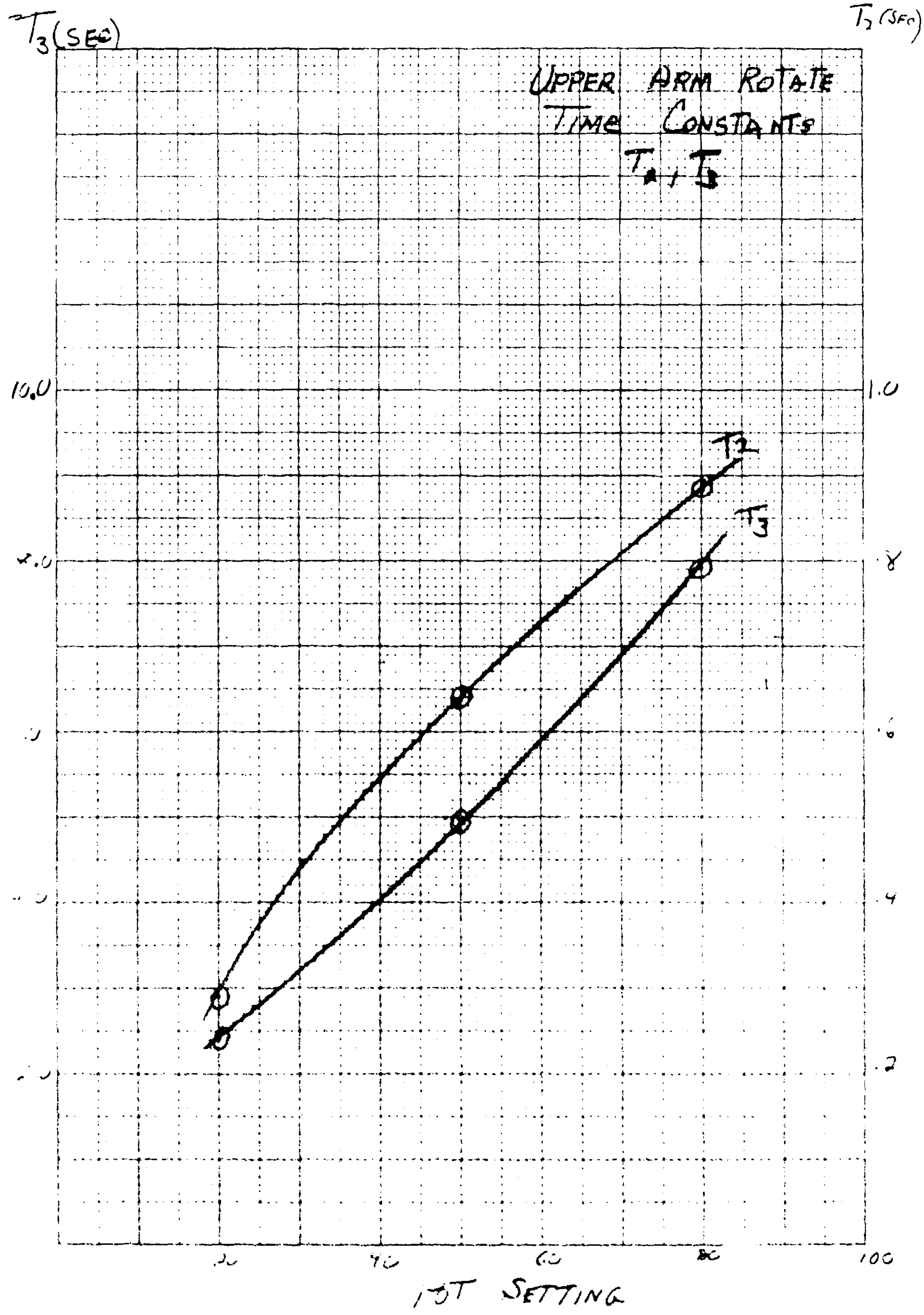

T3 (SEC)
T2 (SEC)
UPPER ARM ROTATE
TIME CONSTANTS
T2, T3
10.0
8.0
6.0
4.0
2.0
1.0
.8
.6
.4
.2
T2
T3
20
40
60
80
100
POT SETTING

Figure 30

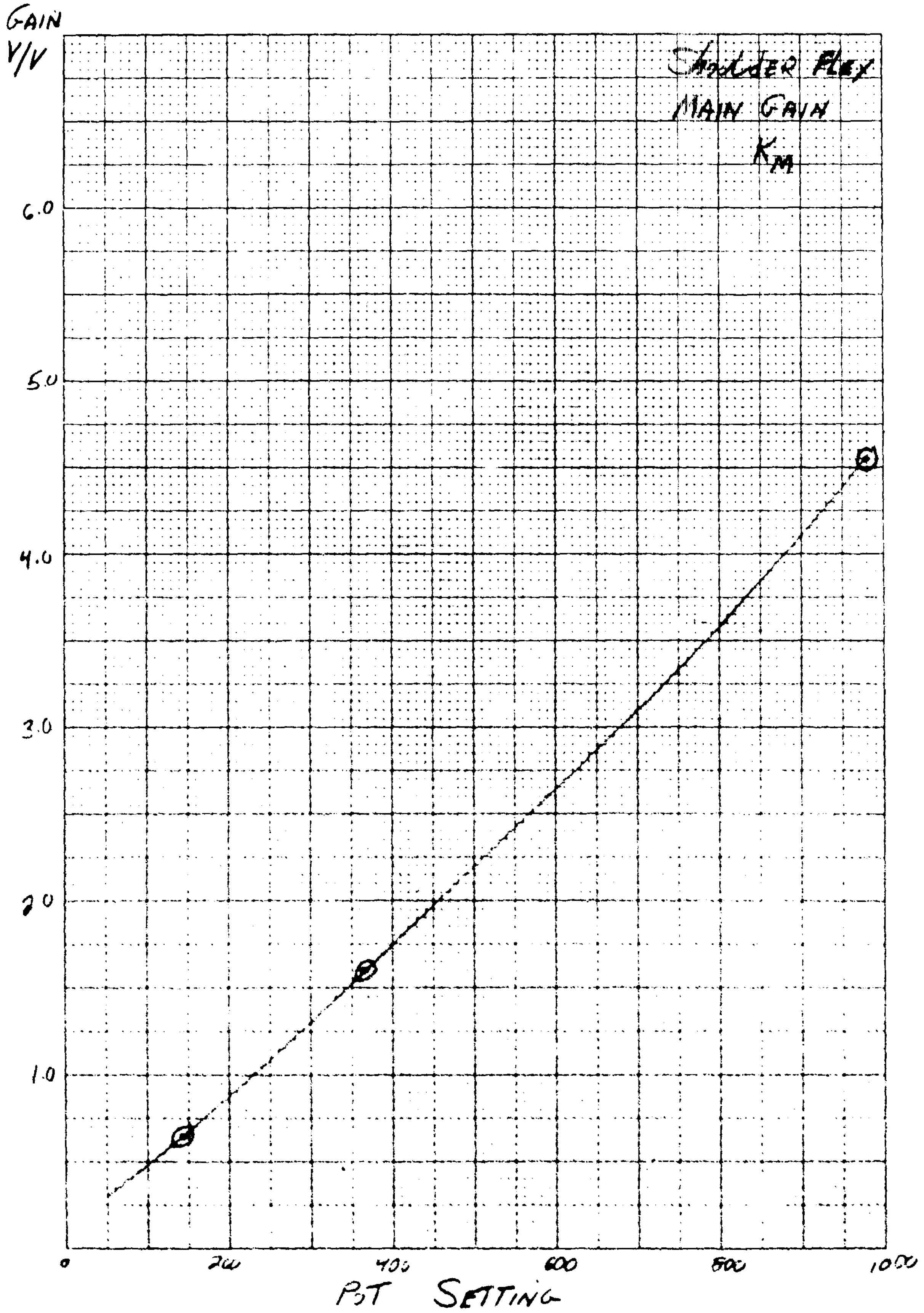

GAIN
V/V
Shoulder Flex
MAIN GAIN
K_M
6.0
5.0
4.0
3.0
2.0
1.0
0
200
400
600
800
1000
POT SETTING

Figure 31

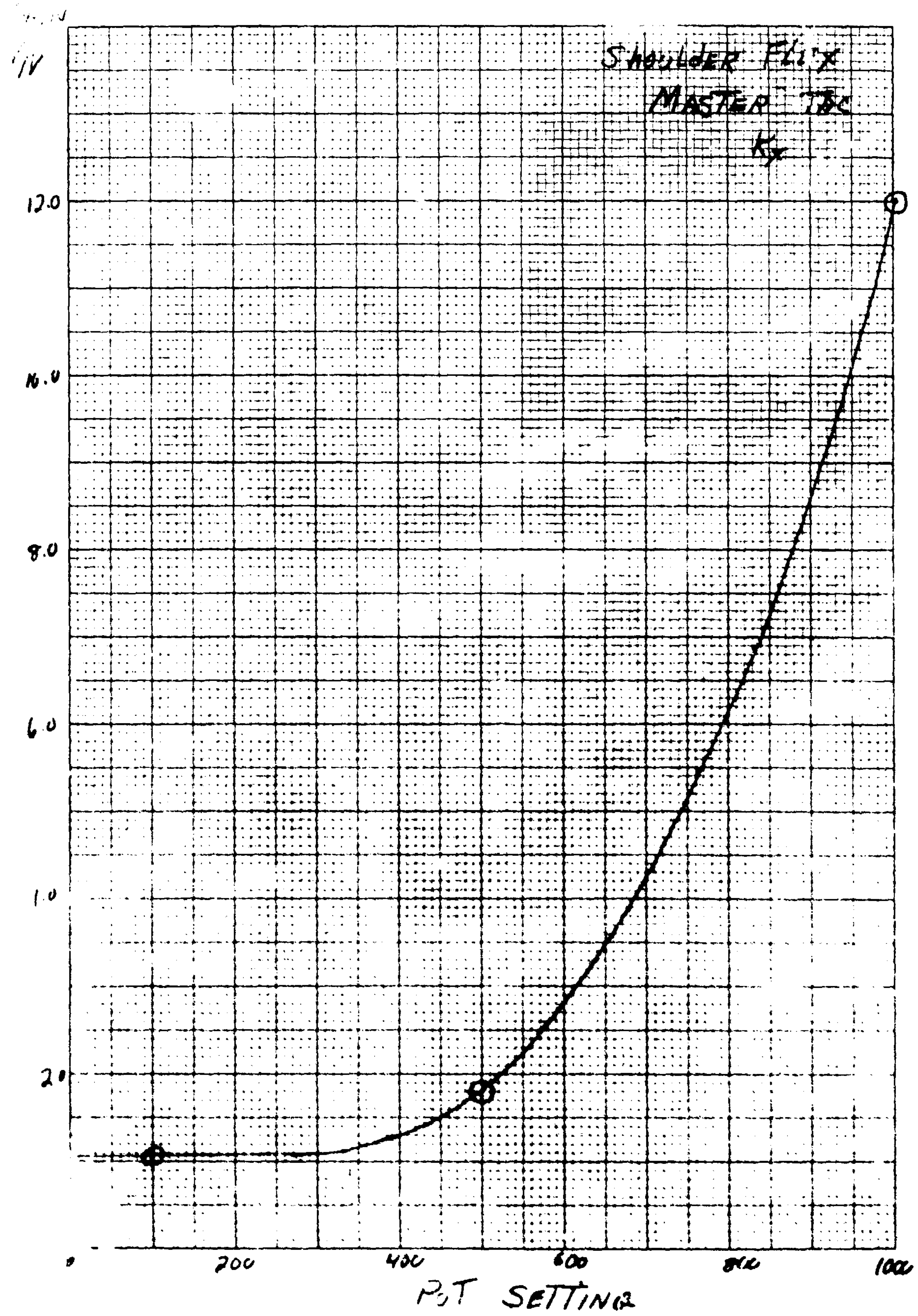
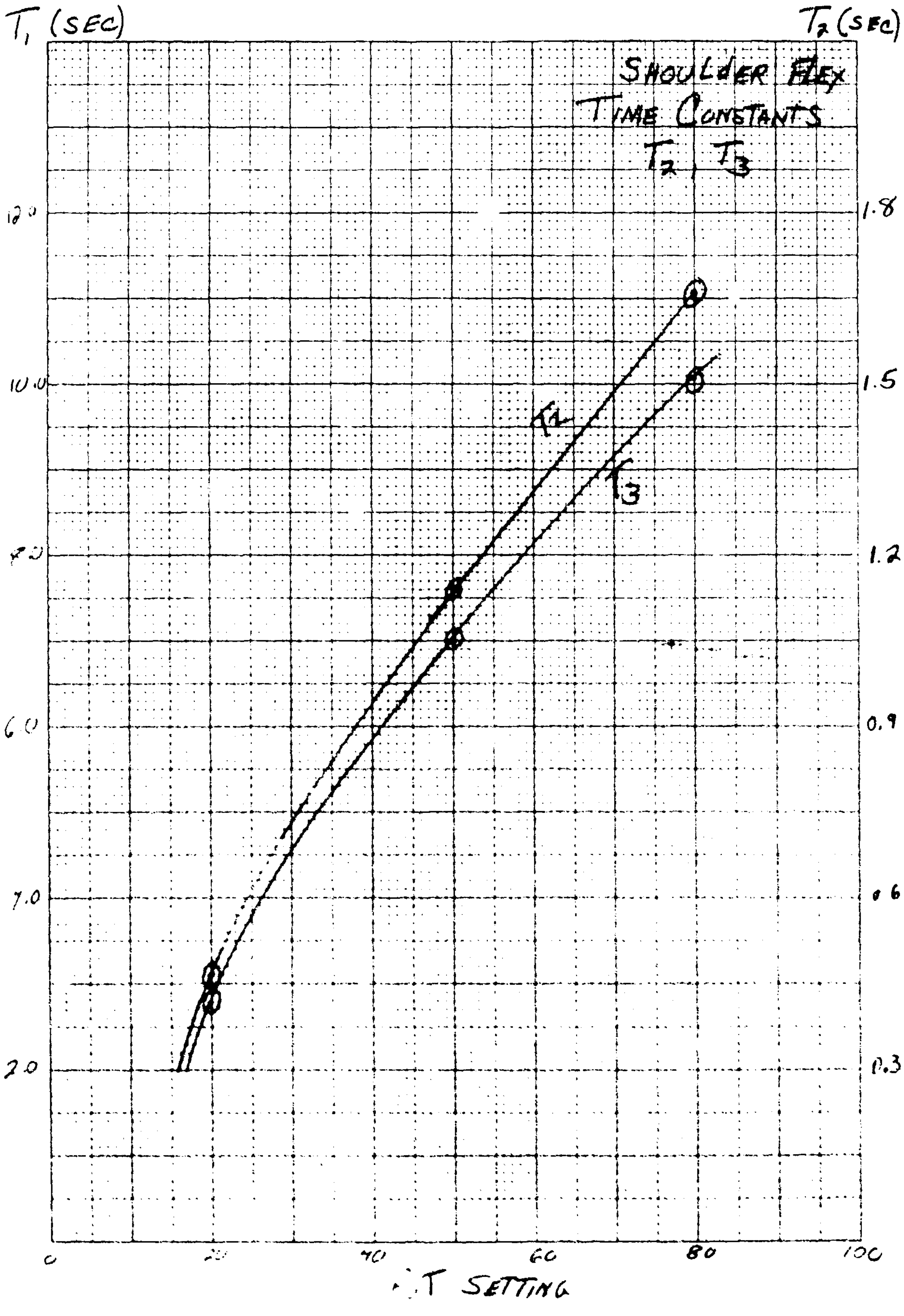

SHOULDER FLEX
MASTER TBC
Kx
/V
12.0
10.0
8.0
6.0
4.0
2.0
0
200
400
600
800
1000
POT SETTING

Figure 32



T1 (SEC)
T2 (SEC)
SHOULDER FLEX
TIME CONSTANTS
T2 , T3
12.0
10.0
8.0
6.0
4.0
2.0
1.8
1.5
1.2
0.9
0.6
0.3
T2
T3
0
20
40
60
80
100
T SETTING

Figure 33

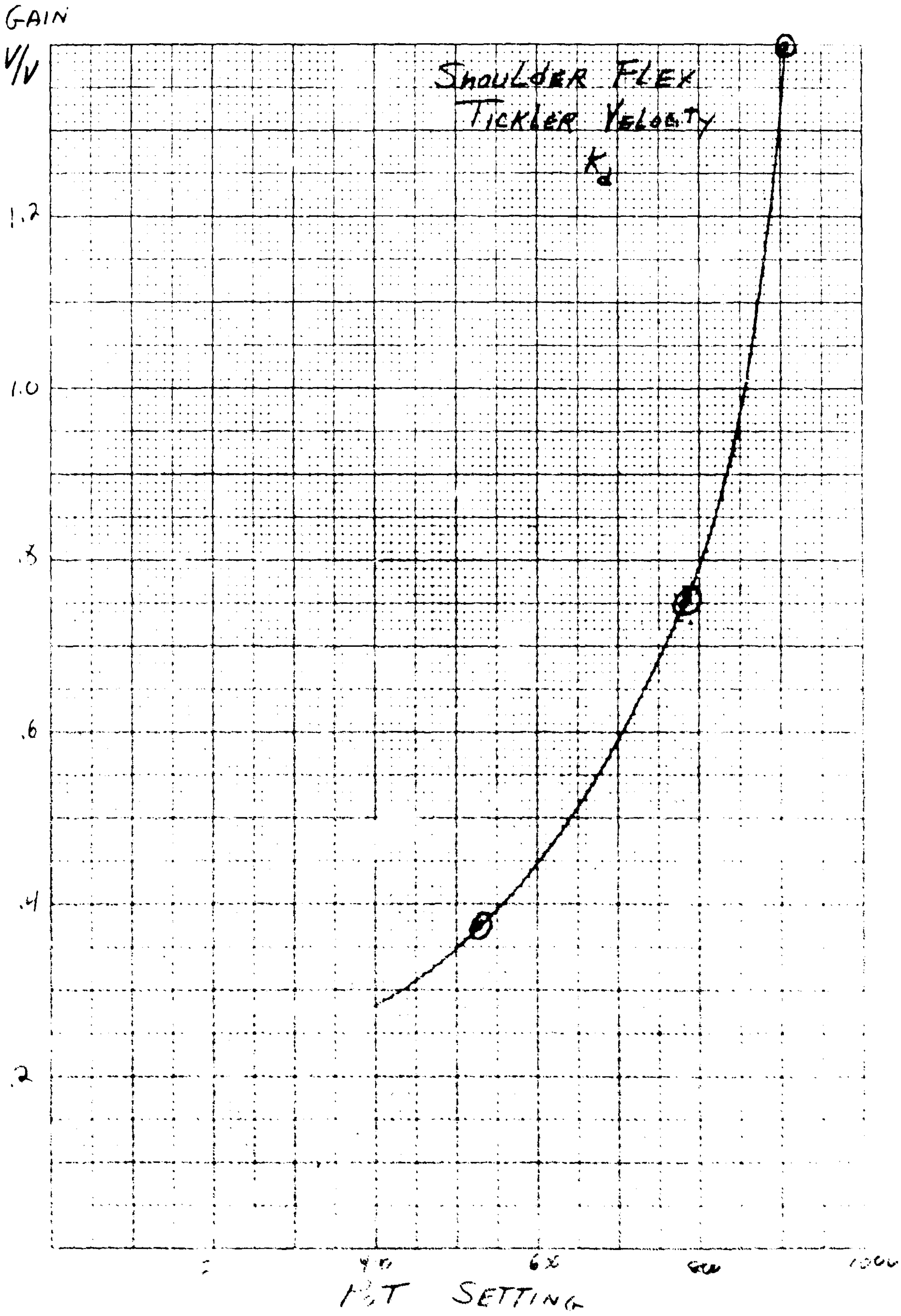

SHOULDER FLEX
TICKLER VELOCITY
K_d
GAIN V/V
1.2
1.0
.8
.6
.4
.2
200
400
600
800
1000
POT SETTING

Figure 34

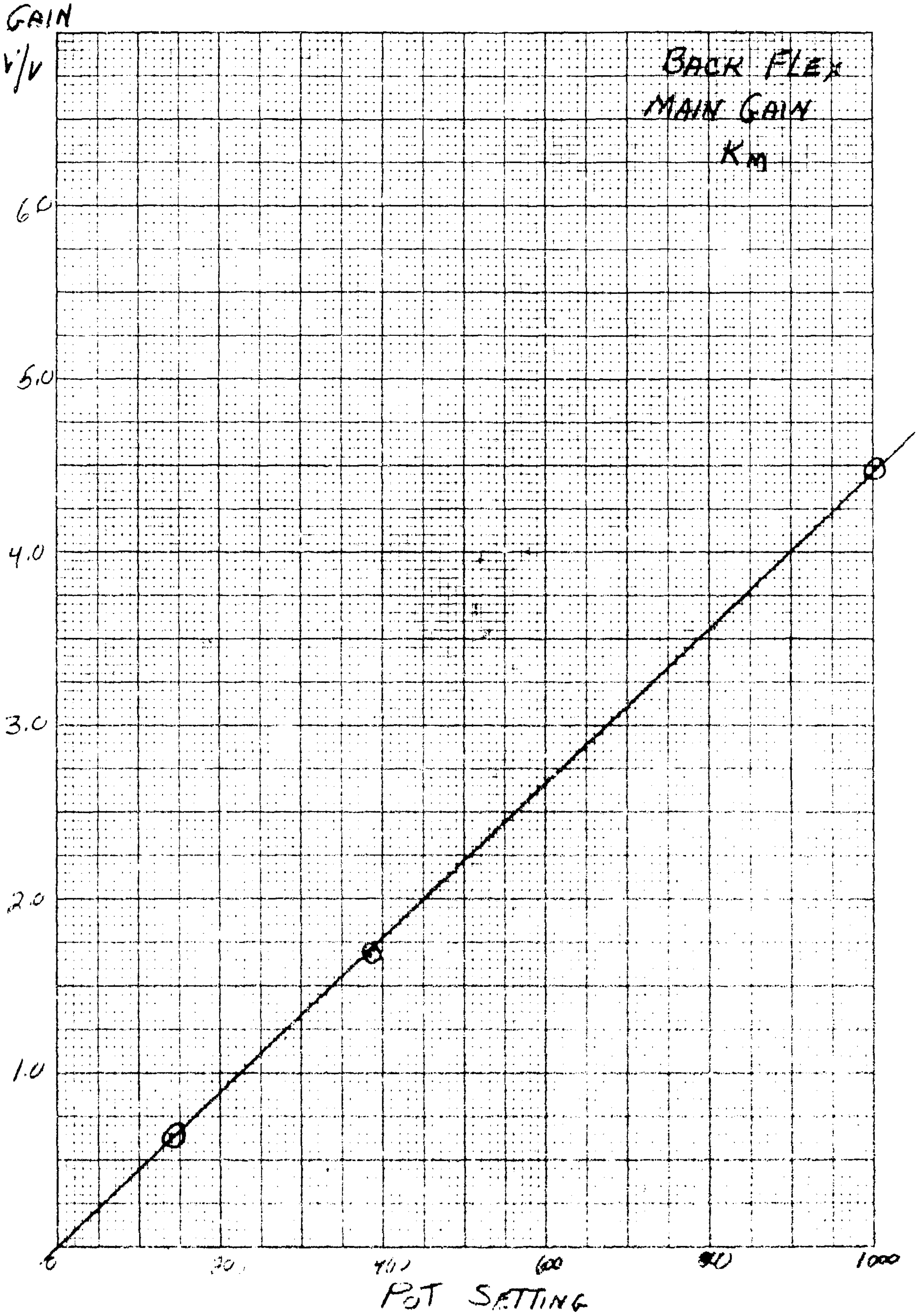

GAIN
V/V
BACK FLEX
MAIN GAIN
K_M
6.0
5.0
4.0
3.0
2.0
1.0
0
200
400
600
800
1000
POT SETTING

Figure 35

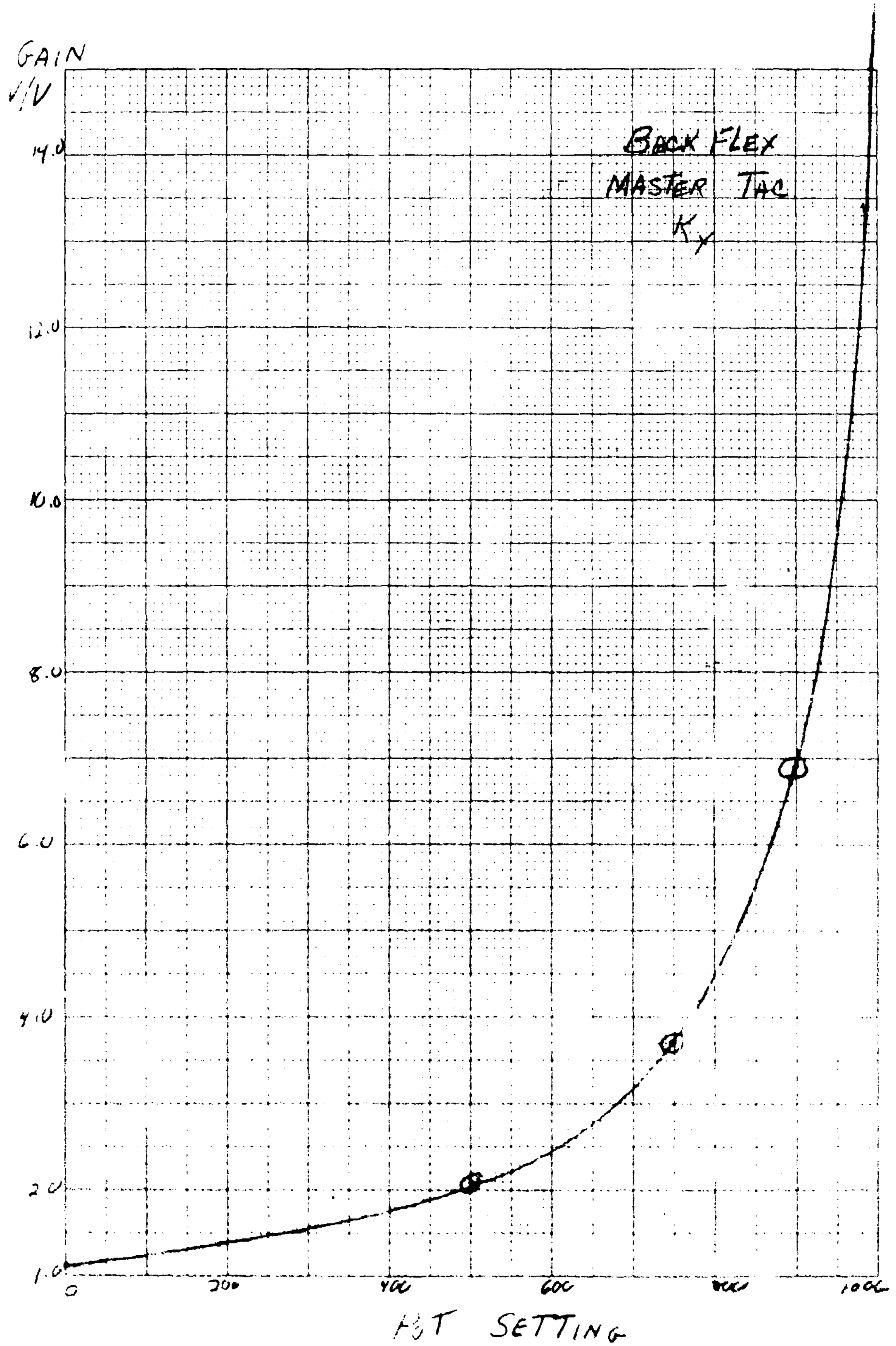

GAIN
V/V
14.0
12.0
10.0
8.0
6.0
4.0
2.0
1.0
0
200
400
600
800
1000
B/T SETTING
BACK FLEX
MASTER TAC
K_x

Figure 36

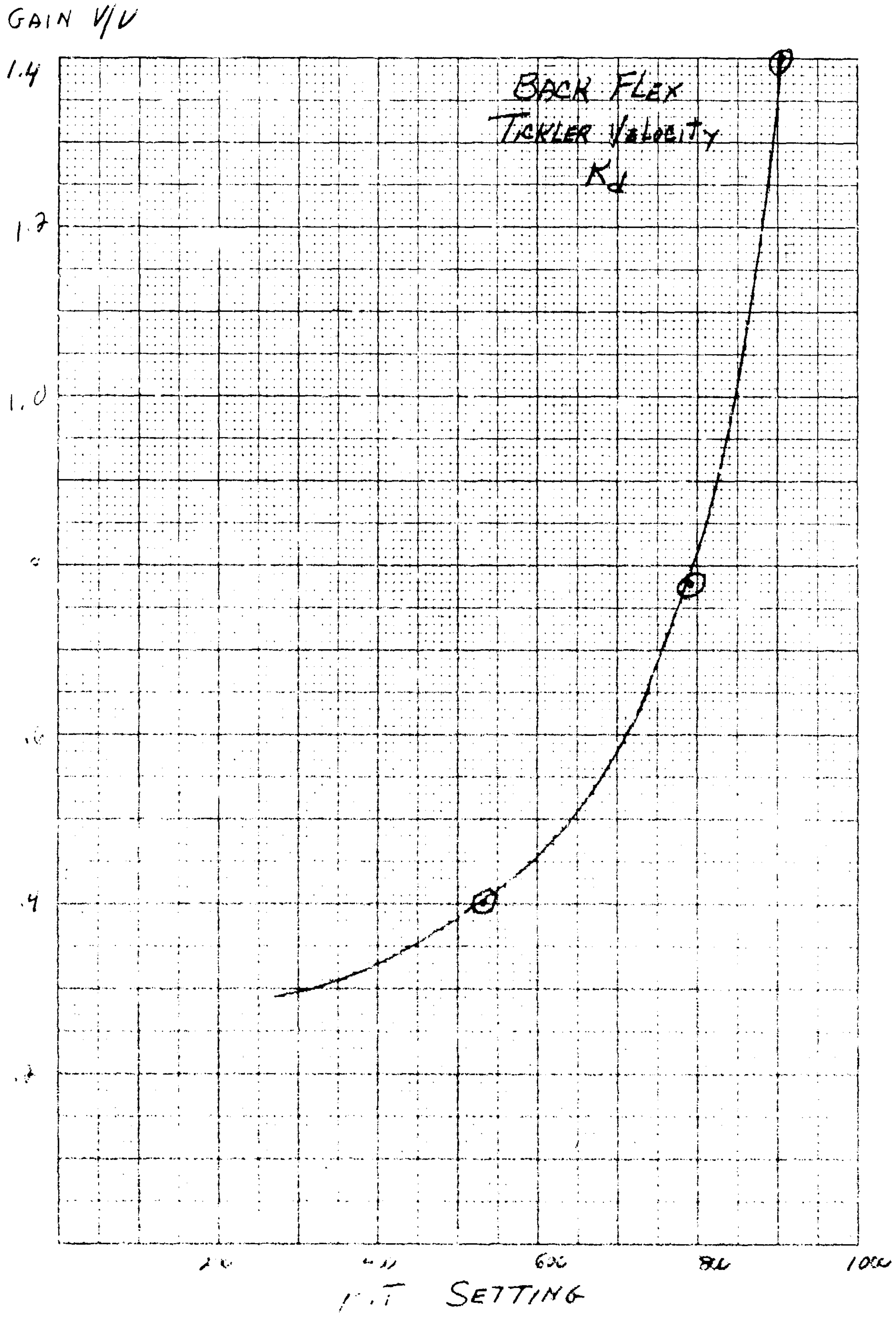

GAIN V/V
1.4
1.2
1.0
.8
.6
.4
.2
BACK FLEX
TICKLER VELOCITY
K_d
200
400
600
800
1000
P.T SETTING

Figure 37

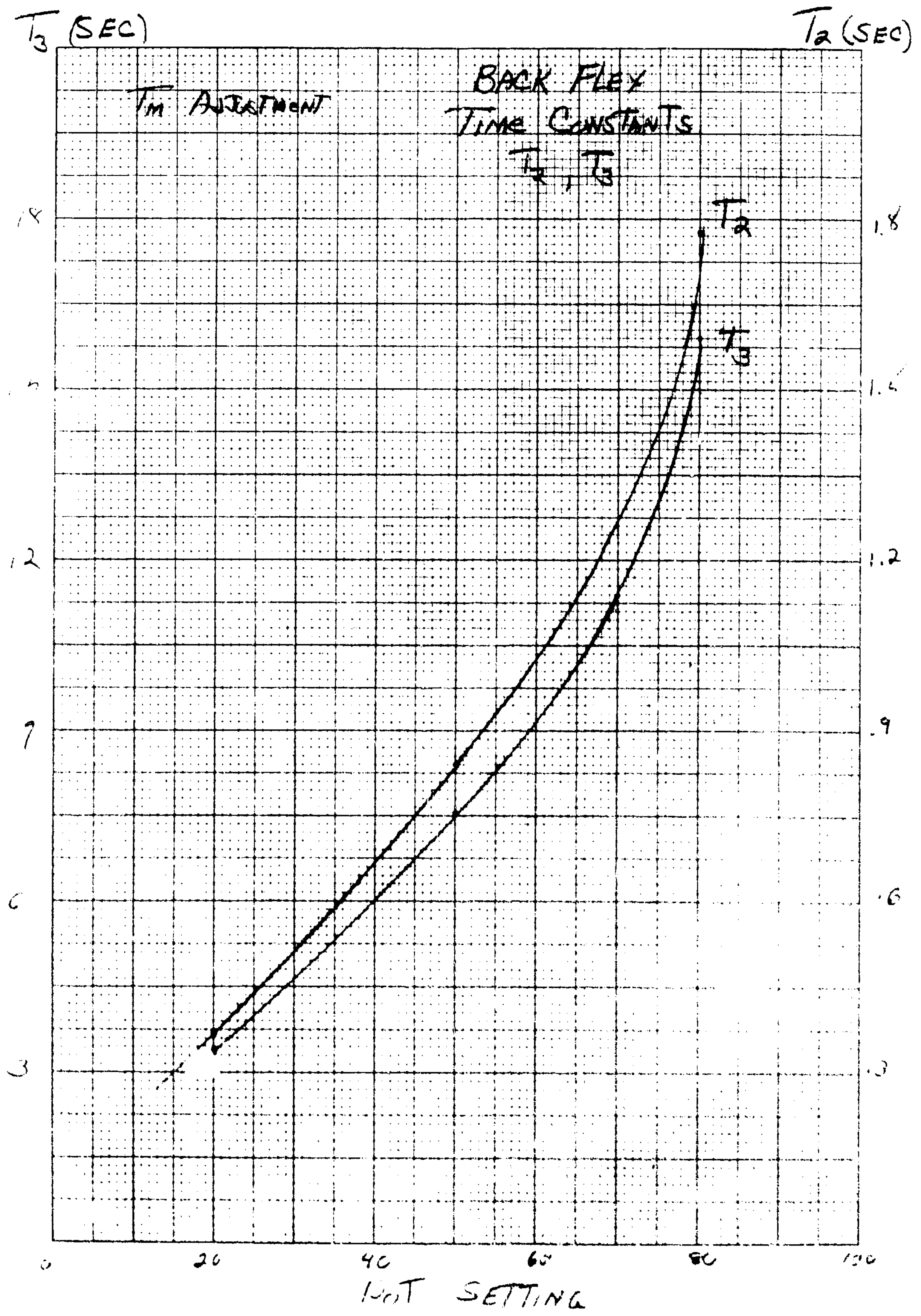

T3 (SEC)
T2 (SEC)
Tm ADJUSTMENT
BACK FLEX
TIME CONSTANTS
T2, T3
T2
T3
18
12
9
6
3
1.8
1.5
1.2
.9
.6
.3
0
20
40
60
80
100
POT SETTING

Figure 33

APPENDIX II

APPENDIX II

SERVO PARAMETERS AND CHARACTERISTICS

The configuration for the servo control system is the same as was discussed in Section 6 of Report No. S-69-1116 dated July 1, 1969. The values of the servo parameters which resulted from adjusting the electronic gains to optimize the system are given in Table I. The servo performance in terms of slew error and compliance is given in Table II. Figures 39 through 44 are computed Bode plots based on measured electrical gains.

TABLE I

EXO ARM TEST

ELECTRONIC SERVO PARAMETERS

Joint Parameter	Wrist Flex	Elbow Flex	Forearm Rotate	Upper Arm Rotate	Shoulder Flex	Back Flex
K_m (V/V)	2.55	2.45	1.09	1.75	1.96	2.00
K_d (V/V)	.90	0	0	1.70	0	0
K_x (V/V)	7.50	6.00	.30	.80	2.85	2.45
T_2 (sec)	.79	.65	.50	1.00	1.21	.85
T_3 (sec)	9.20	4.00	1.75	10.00	7.50	7.50
K_y (V/in)	69.60	69.60	69.60	69.60	69.60	69.60

TABLE II

SERVO PERFORMANCE PARAMETERS

Joint	Performance	
	% Compliance	% Slew Error
Wrist	-4.33	+.772
Elbow	-2.83	+.594
Forearm Rotate	-2.37	+.237
Upper Arm Rotate	-2.53	+.840
Shoulder Flex	-1.82	+.715
Back Flex	-1.96	+.843

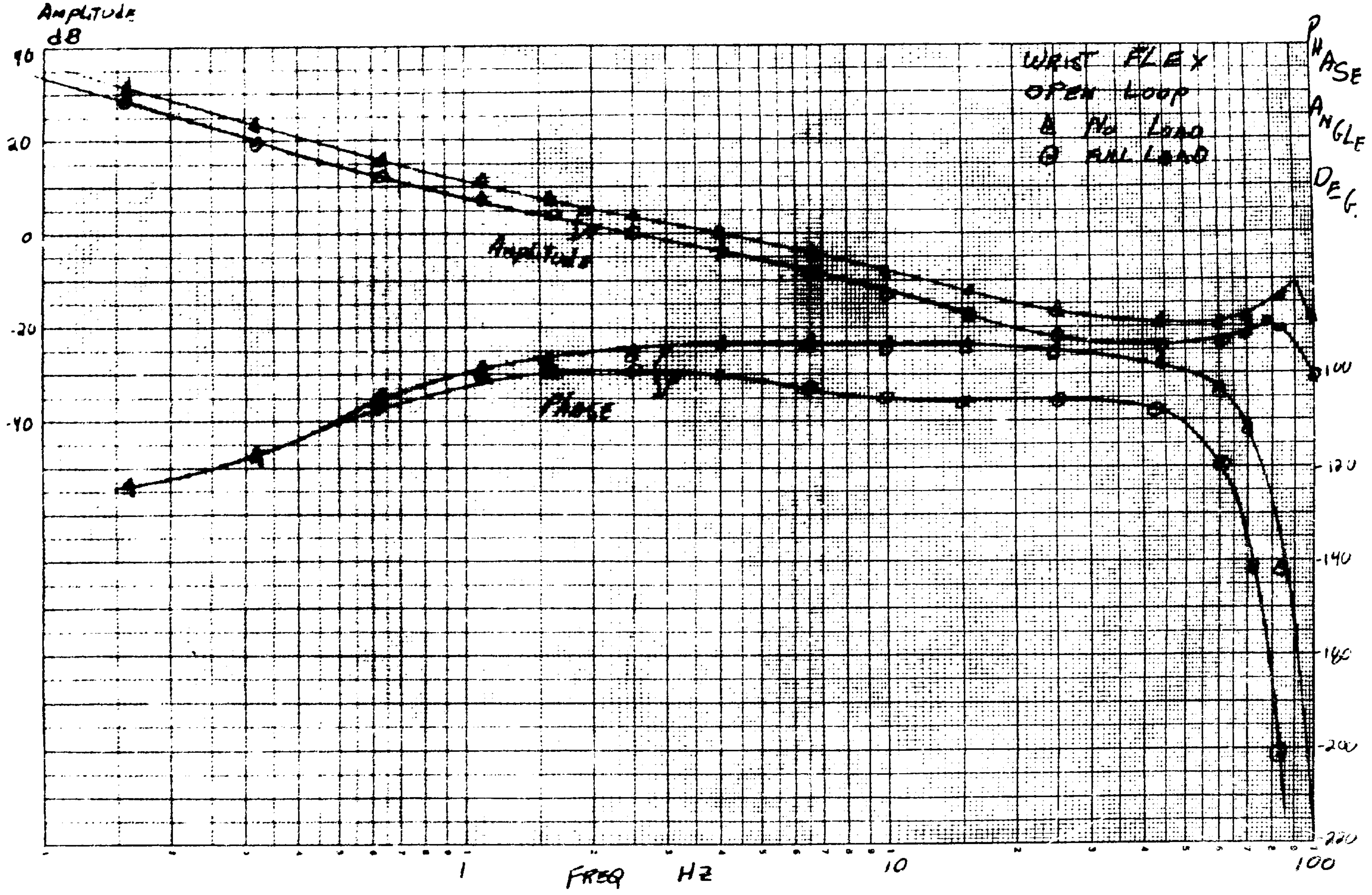

AMPLITUDE dB
40
20
0
-20
-40
PHASE ANGLE DEG.
-100
-120
-140
-160
-200
-220
WRIST FLEX
OPEN LOOP
△ NO LOAD
○ FULL LOAD
Amplitude
PHASE
1
10
100
FREQ HZ

Figure 39

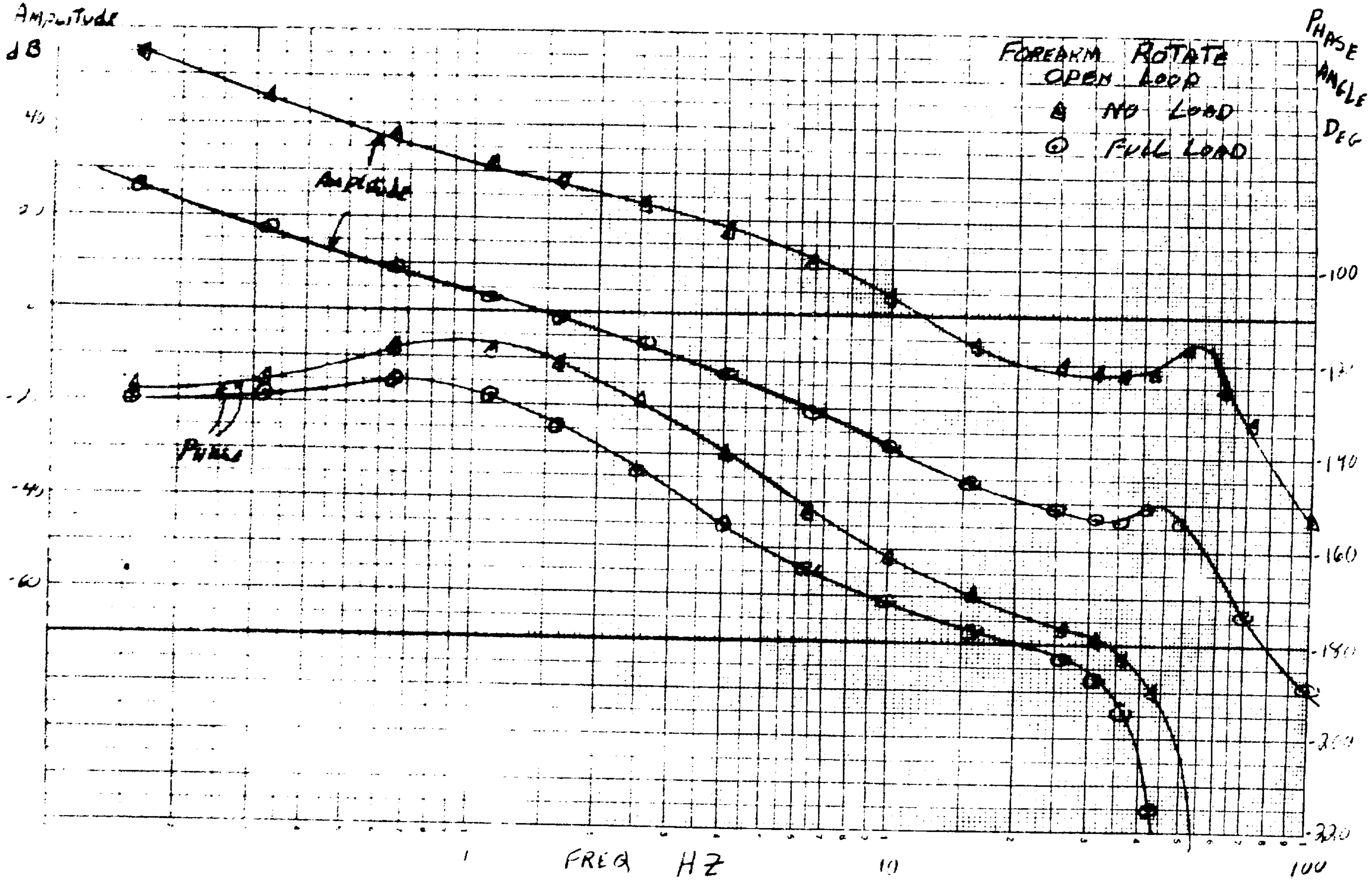

AMPLITUDE
dB
40
20
0
-20
-40
-60
PHASE
ANGLE
DEG
-100
-120
-140
-160
-180
-200
-220
FOREARM ROTATE
OPEN LOOP
△ NO LOAD
⊙ FULL LOAD
AMPLITUDE
PHASE
1
10
100
FREQ HZ

Figure 40

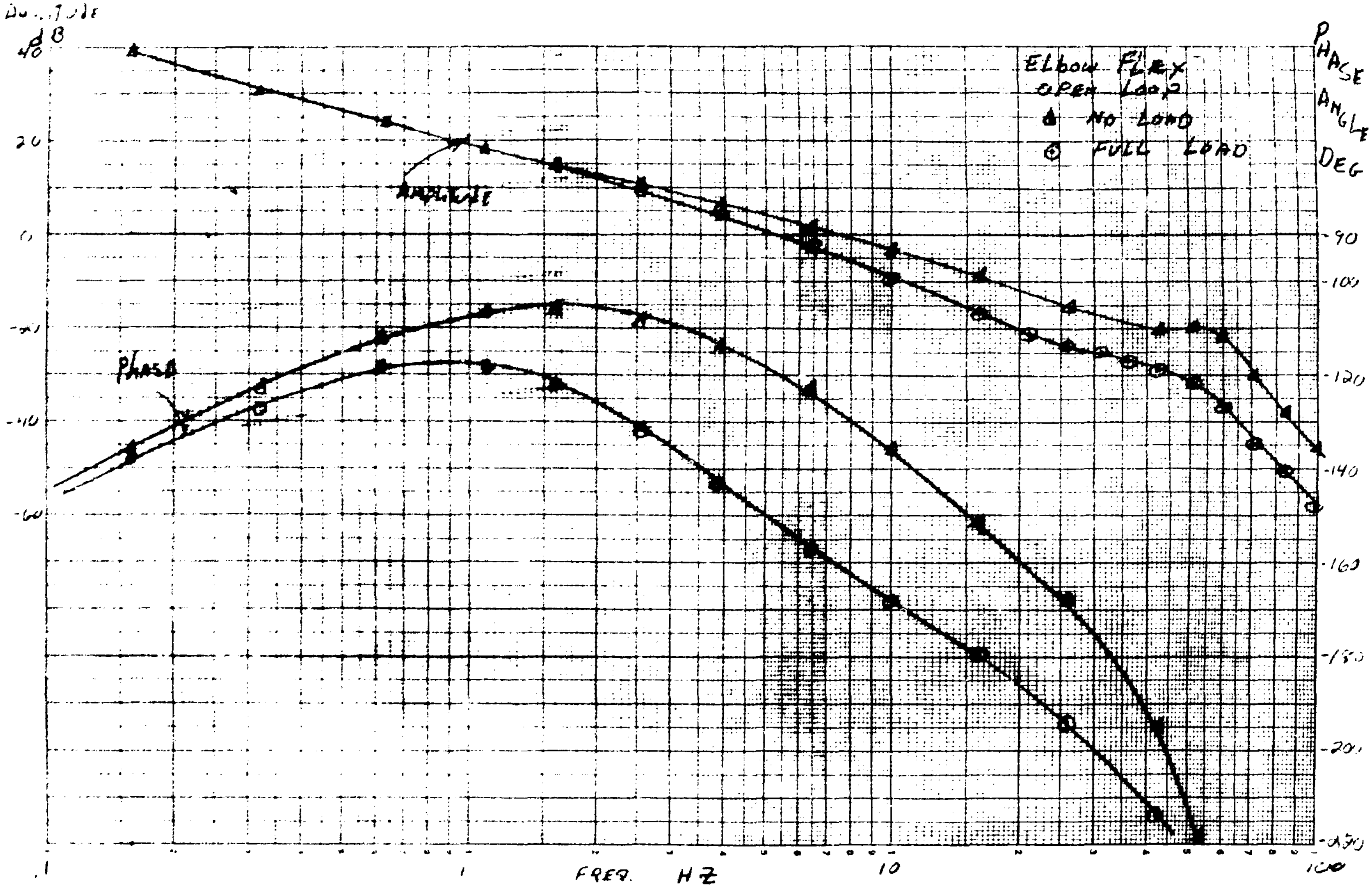

AMPLITUDE dB
40
20
0
-20
-40
-60
PHASE ANGLE DEG
-90
-100
-120
-140
-160
-180
-200
-220
ELbow FLEX
OPEN LOOP
▲ NO LOAD
⊙ FULL LOAD
AMPLITUDE
PHASE
.1
1
10
100
FREQ. HZ

Figure 41

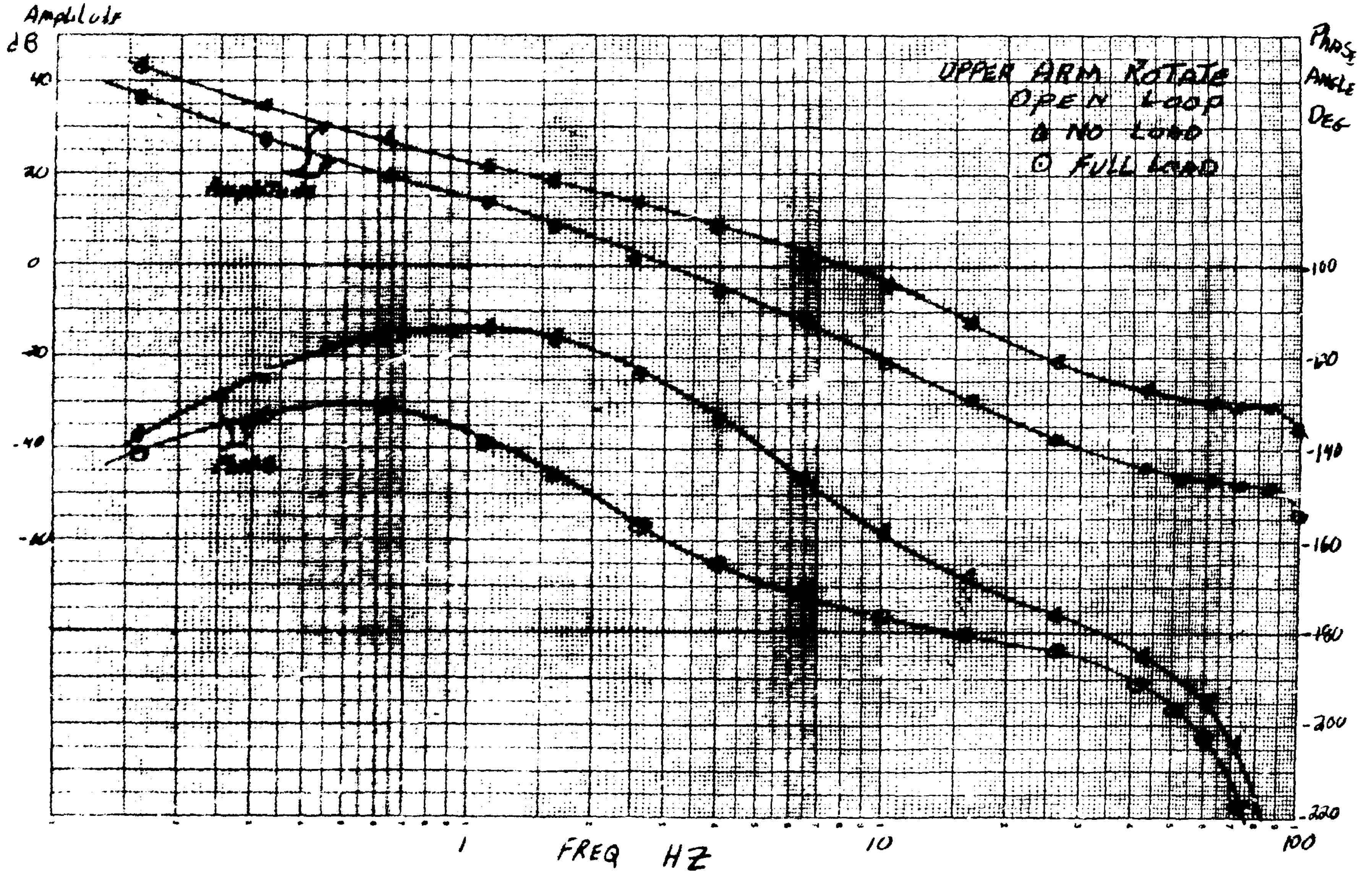

Amplitude
dB
40
20
0
-20
-40
-60
Phase
Angle
Deg
-100
-120
-140
-160
-180
-200
-220
UPPER ARM ROTATE
OPEN LOOP
△ NO LOAD
⊙ FULL LOAD
Amplitude
Phase
1
10
100
FREQ HZ

Figure 42

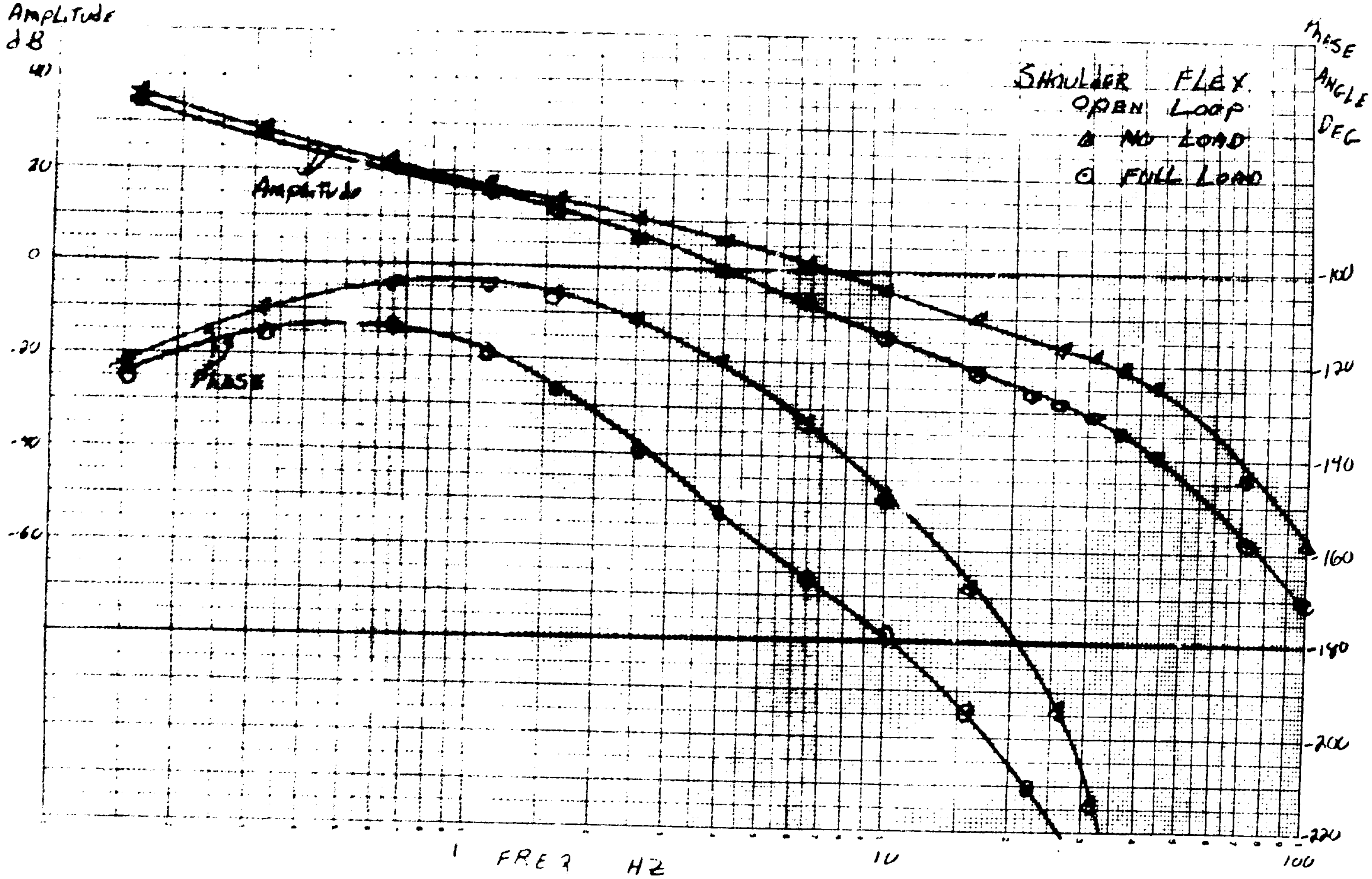

AMPLITUDE dB
40
20
0
-20
-40
-60
PHASE ANGLE DEG
-100
-120
-140
-160
-180
-200
-220
SHOULDER FLEX
OPEN LOOP
△ NO LOAD
⊙ FULL LOAD
AMPLITUDE
PHASE
1
10
100
FREQ HZ

Figure 43

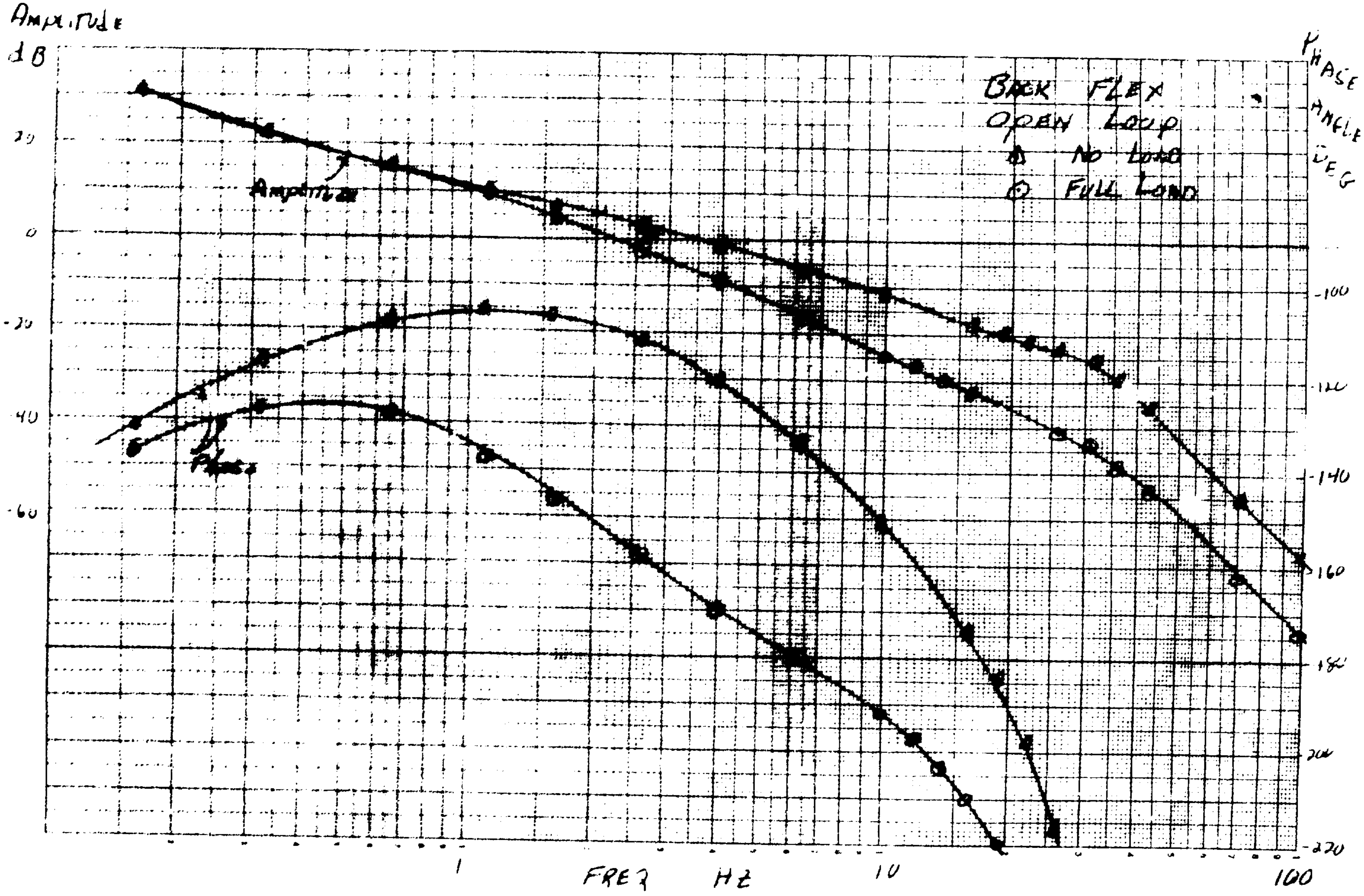

Amplitude
dB
20
0
-20
-40
-60
Phase
Angle
Deg
-100
-120
-140
-160
-180
-200
-220
Back Flex
Open Loop
No Load
Full Load
Amplitude
Phase
1
10
100
FREQ HZ

Figure 44

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13. ABSTRACT

This is a discussion of the test and evaluation of the HARDIMAN I left arm assembly.

The HARDIMAN I prototype is a powered exoskeletal harness which will amplify man's strength and endurance while retaining his versatility and dexterity.

The objective of the arm test was to investigate human factors and servo performance while lifting a load.

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