AD627671

01

AMRL-TR-65-174

EFFECTS OF DISPLAY QUICKENING ON HUMAN TRANSFER FUNCTIONS DURING A DUAL-AXIS COMPENSATORY TRACKING TASK

ANGELO P. VERDI, PhD
GEORGE N. ORNSTEIN, PhD
RICHARD P. HEYDORN

NORTH AMERICAN AVIATION, INCORPORATED

GEORGE FROST

AEROSPACE MEDICAL RESEARCH LABORATORIES

NOVEMBER 1965

AEROSPACE MEDICAL RESEARCH LABORATORIES
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Requests for copies of this report should be directed to either of the addressees listed below, as applicable:

Federal Government agencies and their contractors registered with Defense Documentation Center (DDC):

DDC
Cameron Station
Alexandria, Virginia 22314

Non-DDC users (stock quantities are available for sale from):

Chief, Input Section
Clearinghouse for Federal Scientific & Technical Information (CFSTI)
Sills Building
5285 Port Royal Road
Springfield, Virginia 22151

Change of Address

Organizations and individuals receiving reports via the Aerospace Medical Research Laboratories' automatic mailing lists should submit the addressograph plate stamp on the report envelope or refer to the code number when corresponding about change of address or cancellation.

Do not return this copy. Retain or destroy.

600 - January 1966 - 25-512-773

EFFECTS OF DISPLAY QUICKENING ON HUMAN TRANSFER FUNCTIONS DURING A DUAL-AXIS COMPENSATORY TRACKING TASK

ANGELO P. VERDI, PhD
GEORGE N. ORNSTEIN, PhD
RICHARD P. HEYDORN
GEORGE FROST

FOREWORD

This report describes an investigation of the effects of quickening upon both the operator's transfer function and system accuracy during a compensatory tracking task. The described investigation was performed under a contract with the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. Mr. George Frost of the Maintenance Design Branch, Human Engineering Division, Behavioral Sciences Laboratory, was the Air Force initiator and technical monitor for this study. The research was accomplished at North American Aviation, Inc., 4300 East Fifth Avenue, Columbus, Ohio, under Air Force Contract No. 33(657)-11102. The work was performed under Project 7184, "Human Performance in Advanced Systems," and Task 718402, "Criteria for Design and Arrangement of Controls and Control Systems." The research was conducted during the period May 1963 through June 1964. Dr. George N. Ornstein, Chief Scientist, Information Sciences, directed the research at North American Aviation and Dr. Angelo P. Verdi served as the Project Engineer.

The authors are indebted to several individuals who have aided this study directly. In particular, special gratitude is extended to Mr. T. F. Potts for very expertly programming the analog computer and for the very capable technical assistance he provided throughout the course of the study. Mr. Howard Zlotnick very capably served as a research assistant throughout the course of the project and was particularly helpful with respect to expediting many of the chores associated with data collection and reduction. Finally, special mention is given to Miss Judy Penn for her careful and dependable work in data analysis, data reduction, and other assistance in preparation of this report.

This technical report has been reviewed and is approved.

Walter F. Grether, **PhD**
Technical Director
Behavioral Sciences Laboratory
Aerospace Medical Research Laboratories

ABSTRACT

This research was concerned with the human's behavior in adapting his response mode to variations of certain conditions of a compensatory tracking task. The task conditions evaluated were quickening level, system gain, task load, and task complexity. The results of the studies show good agreement with the transfer function "adjustment rules" developed by other investigators. When quickening is introduced, the human adjusts his transfer function in a systematic and predictable manner in response to variations of the quickening level. As the amount of quickening increases the operator increases gain and lag but decreases lead -- going from a lead-lag form of transfer function for no quickening to a lag form for full quickening. The human adjusts his equalizing parameters to achieve stable loop performance for all quickening levels. Man's ability to reduce the system error is significantly affected by the distribution of gains in the overall man-machine system. The human's transfer function for single and dual task load conditions probably differs. Tracking error was found to be least when the quickening level used in the second axis is identical to that in the axis of primary interest; error increased as the quickening levels for the two axes became more dissimilar. Display error scoring yielded an order of merit for quickening levels that was directly contradictory to that obtained with system error scoring. System error was greater for a quickened system than for an unquickened system. This finding provides strong support of the need for an antibias network in many applications of display quickening to vehicle control problems.

TABLE OF CONTENTS

TABLE OF CONTENTS (Contd)

LIST OF TABLES

Table		Page
XVI	Single Versus Dual Axis Comparison of TF Lead Coefficient, T_L ~ Seconds	48
XVII	Single Versus Dual Axis Comparison of TF Coefficients ($T_N + T_I$) ~ Seconds	49
XVIII	Single Versus Dual Axis Comparison of TF Coefficients ($T_N \cdot T_I$) ~ Sec.^{2} X 100	50
XIX	Single Versus Dual Axis Comparison of System Error Scores, E_S	52
XX	Single Versus Dual Axis Comparison of Display Error Scores, E_D	53
XXI	Single Versus Dual Axis Comparison of System Error Scores, E_S	54
XXII	Single Versus Dual Axis Comparison of Display Error Scores, E_D	55
XXIII	Comparison of E_S for the Different Dual Axis Conditions	56
XXIV	Comparison of E_D for the Different Dual Axis Conditions	57
XXV	Rank Order of Mean Error Scores for the Different Dual Axis Conditions	58
XXVI	Error Score Comparisons of FQ_1 and FQ_2 for Trials 95 Through 100	83
XXVII	Error Scores for PQ and NQ for Trials 95 Through 100	84
XXVIII	Error Scores Comparisons of FQ_1, PQ, and NQ for Trials 105 Through 110	85
XXIX	Forcing Function Frequencies	197

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

One task frequently assigned to the human in a complex man-machine system is that of executing closed-loop system-control, i.e., tracking. In this task the human is required to minimize continually the discrepancy between an indicant of desired system performance and an indicant of actual system performance. The human is thus an element in a closed-loop, feedback system. Figure 1 presents a block diagram of this feedback (servo) system.

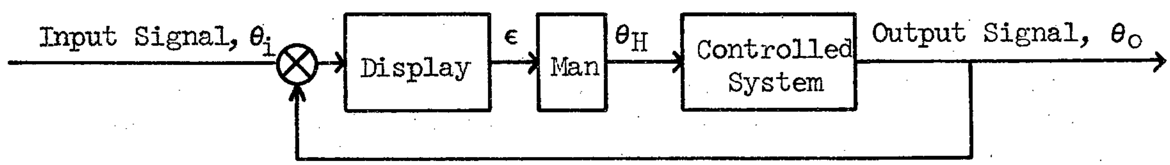


Figure 1. Block Diagram of Man-Machine Feedback System

Considering the human as a servo-system element has led to the application of various servo-system concepts in the study of the human's functional control properties. One such concept, the transfer function, has been applied since the early work of Tustin (ref 24) and Ragazzini (ref 19). To avoid any confusion, the term "transfer function" will be used herein specifically to refer to the linear component of an output-input relation in the complex variable domain. In this sense the human transfer function (HTF) is defined as:

$$HTF = L(\theta_H)/L(\epsilon)$$

where L indicates the Laplace transformation, θ_H represents human output and ϵ represents the (error) input to the human (see fig. 1). Interpretively, the transfer function maps the input signal into the output signal. (An excellent review of studies of human transfer function is presented in reference 16.)

One of the major efforts to consider the human as a functional servo system was undertaken at the Naval Research Laboratory (refs 2, 3, 4, 20). In a now-classic paper (ref 2), a "basic principle of control design" is developed stating, in essence, that when designing man-machine control systems, man should be required to act at no more complex a level than does a simple amplifier.

The primary technique offered in reference 2 as consonant with the above principle is that of display quickening. Specifically, in an unquickened system [see fig. 2(a)] the human views an error signal as $\epsilon = \theta_i - \theta_o$. In a quickened system [see fig. 2(b)], the human views an error signal $\epsilon = \theta_i - \left[k_1\theta_o + k_2\dot{\theta}_o + k_3\ddot{\theta}_o\right]$, where $\dot{\theta}_o$ and $\ddot{\theta}_o$ are the first and second time derivatives, respectively, of θ_o. A quickened display should result in better performance because the human using such a display would be required to do less differentiating (rate estimation), since derivative information would be inherent in the displayed signal. That is, the human would be performing functionally in a manner more analogous to a simple amplifier.

Therefore, a human transfer function derived under conditions involving the use of a quickened display should show characteristic and predictable difference from a human transfer function derived under unquickened conditions. This prediction was explicitly investigated in a single axis tracking task (ref 18) with results supportive of the prediction. Also, quickening of the display resulted in significantly lower display error.

Four questions of more general interest now arise. The first question concerns the manner in which various display quickenings influence <u>system</u> error. This question is important since virtually all of the previous research on quickening has treated displayed error as the criterion metric, e.g., references 3, 10, and 20. Contrastingly, very few studies have used system error, e.g., reference 23. The distinction between the system error score, ϵ_S, and display error score, ϵ_D, for quickened conditions is evident from the following equations [also see fig. 2(b)]:

$$\epsilon_s = \theta_i - k_1\theta_o \tag{1}$$

$$\epsilon_D = \theta_i - (k_1\theta_o + k_2\dot{\theta}_o + k_3\ddot{\theta}_o). \tag{2}$$

A second area of interest relates to the possibility of determining a set of rules governing the human's adaptive behavior in varying his transfer function in response to variations in display quickening. A third question concerns the degree of similarity of the operator's transfer function for single and dual axis tasks for different quickening conditions. A fourth area of interest is related to the effect of nonsymmetry in the quickening levels for the two coordinates during dual axis tracking tasks. These questions are approached in three separate experiments.

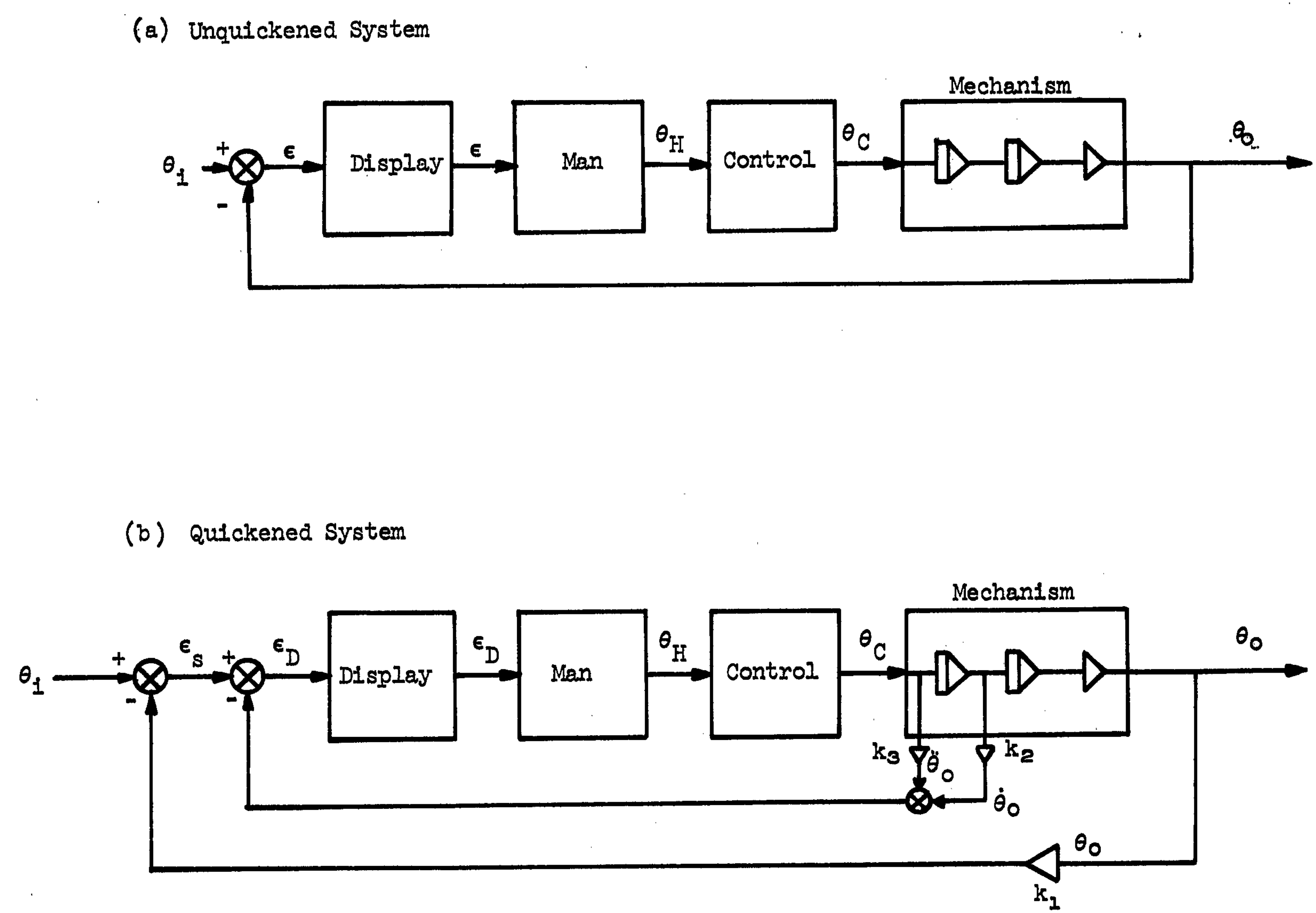


Figure 2. **Example of an unquickened and a quickened system**

SECTION II

EXPERIMENT I

PURPOSE

This experiment was designed to investigate the influence of various display quickenings on system accuracy and to provide transfer function data to be used for deriving rules which describe how the operator adjusts to differing quickening conditions. The "adjustment rules" offered by previous investigators in the area of aircraft handling qualities (refs 1, 13, 15, 16) were developed for nonquickened control systems. It is of interest, therefore, to determine the extent to which these same rules apply to quickened control systems. The existing "adjustment rules" are based on the large amount of data accumulated on human response characteristics during the past two decades concerning manual tracking situations in which the human maintains continuous closed-loop control in response to random appearing forcing functions. The human's adaptive behavior as a dynamic element in such situations has been found to be most succinctly expressed in servo-engineering terms. The most auspicious endeavor to develop a servo-theory model of the man based on all of the data available at the time was undertaken in reference 16. All of the quasi-linear describing function data examined by these authors were curve-fitted to provide mathematical expressions of the functional relations between the operator's response characteristics and various forcing functions and machine dynamics. On the basis of these mathematical expressions a hypothetical transfer function model of the man was developed. The basic element of the linear adaptable model of the human operator was given in reference 16 in the equation form:

$$\mathrm{HTF} = \frac{K_p\,(1 + aT_I s)}{(1 + T_I s)(1 + T_N s)}\, e^{-\tau s} = \frac{K_p\,(1 + T_L s)}{(1 + T_I s)(1 + T_N s)}\, e^{-\tau s} \tag{3}$$

where:

Reaction time delay, τ, is $0.12 < \tau < 0.20$ seconds,

Neuromuscular lag, T_N, is partially adjustable for task,

$$\text{Equalization term, } E = \frac{(1 + aT_I s)}{(1 + T_I s)} = \frac{(1 + T_L s)}{(1 + T_I s)} \tag{4}$$

Adjustable with forcing function and controlled element

Gain, K_p, is adjustable for overall system stability and low frequency performance (ref 16, p. 220, eq. IV-4).

The manner in which the human operator adapted his transfer function to most effectively contend with the tracking task was described in reference 16 as follows:

"Within the limitations of the above form the operator adapts his describing function (lag-lead, lead-lag, pure lead, pure lag, or pure gain) to obtain what he considers to be an optimum controller, controlled-element system response in the presence of the forcing function. The describing function form adopted is one consistent with stability and good low frequency control of the overall system. The constants are adjusted to some criteria akin to that of rms minimization criterion of servo theory. In most cases with forcing functions having a fairly low frequency content, the overall system probably exhibits marginally stable high frequency control. In other words, the operator transfer function for a given task is very similar to the one that a servo engineer would select if he were given an element to control together with a 'black box' having within it elements making up the describing function given ... and knobs on the outside for adjustment of a, T_I, and K_p." (ref 16, p. 220).

The above quoted passage is the first statement of "adjustment rules." It can be seen that the rules are essentially statements of an inferential nature based on a large number of empirical observations for a variety of tracking situations.

The pioneer work of McRuer and Krendal (ref 16) has been extended by more recent investigators to include additional adjustment rules (refs 1, 13, 15). A summary version of the servo model of human operation and adaption as currently envisioned by these investigators consists of two elements:

1. A general transfer function form, and

2. A series of "adjustment rules" which specify the values that the parameters in the general transfer function should assume in order to comprise an appropriate model of human behavior. The parameter values are recognized as being functions of the particular conditions (e.g., forcing function and controlled element) being considered.

The "adjustment rules" apply to the coefficients of the so-called "pilot equalizer" term,

$$E = \frac{T_L s + 1}{T_I s + 1} \tag{5}$$

and to the gain factor, K_p. (The other coefficients, T_N and τ, of the equation given earlier are considered in this first approximation as "not adjustable by pilot" (ref 15, p. 11).) The adjustments referred to above "can be divided artificially into two categories -- adaptation and optimalization. Broadly speaking, adaptation is the selection by the pilot of a specific form (lag-lead, lead-lag, pure lag, or unity) for the equalization characteristics, and optimalization is the adjustment of both the gain and the selected equalization parameters to satisfy some internally generated criteria," (ref 15, p. 11). A more detailed set of "rules" has been presented by Ashkenas and McRuer (ref 1) and restated with minor modifications by Jex and Cromwell (ref 13) in the context of aircraft handling qualities.

Thus, one of the objectives of the present study is to provide a similar set of rules describing changes in human transfer functions as quickening conditions are changed. The development of a set of such rules will comprise a major step forward in terms of a practical tool for use in system design. Further, an attempt will be made to relate the display quickening "rules" and the handling qualities "rules" within the framework of feedback theory.

SUBJECTS

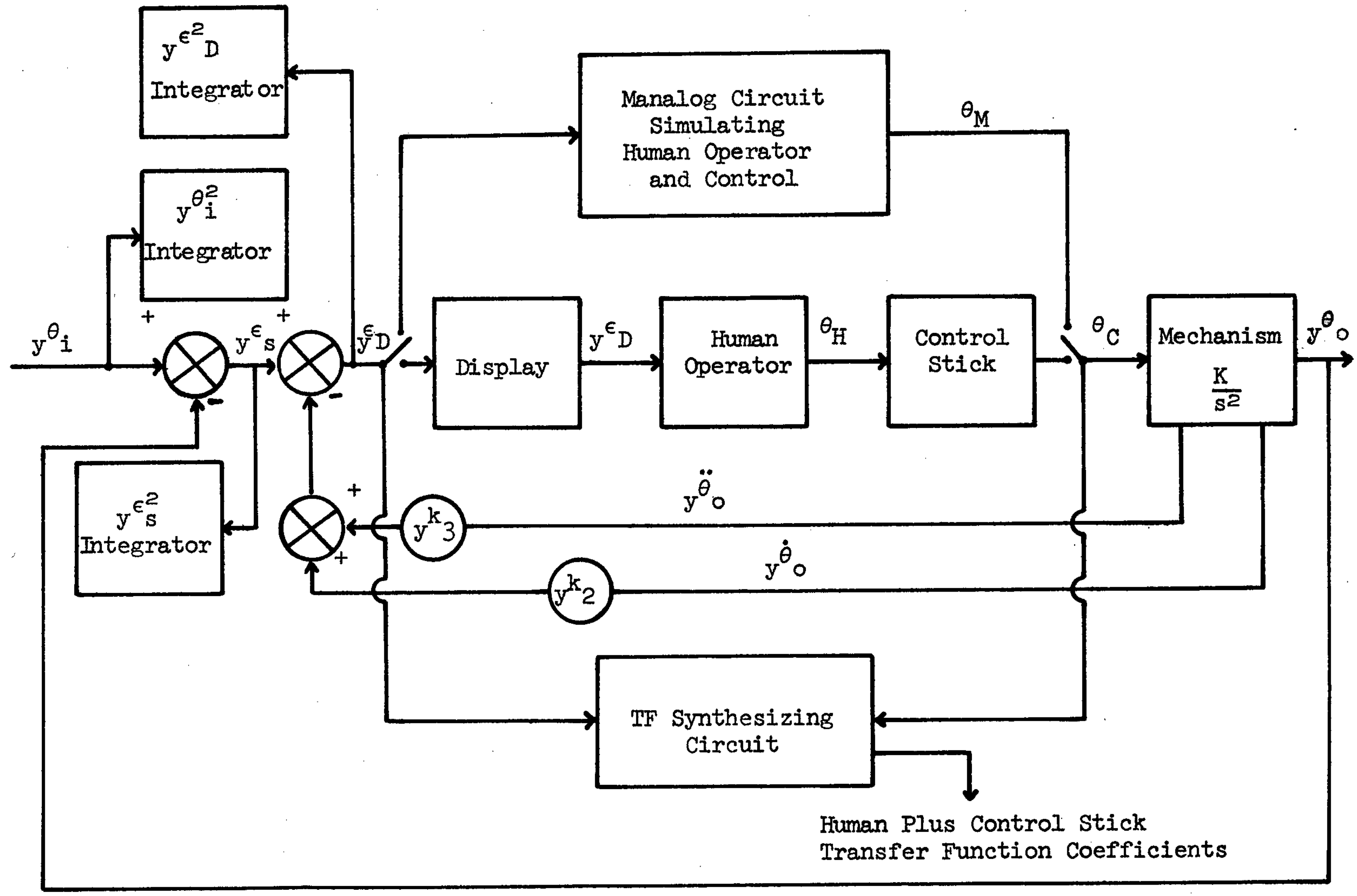
Ten male employees of North American Aviation, Inc., voluntarily served as subjects in the experiments. Subjects were engineering and technical personnel with ages ranging from 23 to 34. None of the subjects had had any prior tracking or flying experience.

APPARATUS

A block diagram of the complete apparatus for the longitudinal axis is presented in figure 3 (the lateral axis has the identical instrumentation). Six major elements may be identified. The first major element, the tracking device, consists of the operator's display and control stick. The second major element consists of the forcing function generator. Third, there is the transfer function synthesis circuit which computes the coefficients of the transfer function for the operator-control stick combination. Fourth, the Manalog Circuit simulates the latter transfer function and is used to test the synthesizing circuit. Fifth, there are auxiliary scoring circuits which provide various measures of system performance. Finally, there is the performance recording apparatus.

Tracking Device

The operator's work space is illustrated in figure 4. A TEKTRONIX Type 536 oscilloscope was used for the display, with a 1/16 inch diameter error dot. Hair-line crosshairs served as reference markers. The operator performed a compensatory tracking task, i.e., he operated the control stick as required to maintain minimum displacement of the error dot from the



Human Plus Control Stick
Transfer Function Coefficients

Figure 3. Overall block diagram of apparatus for the Y axis

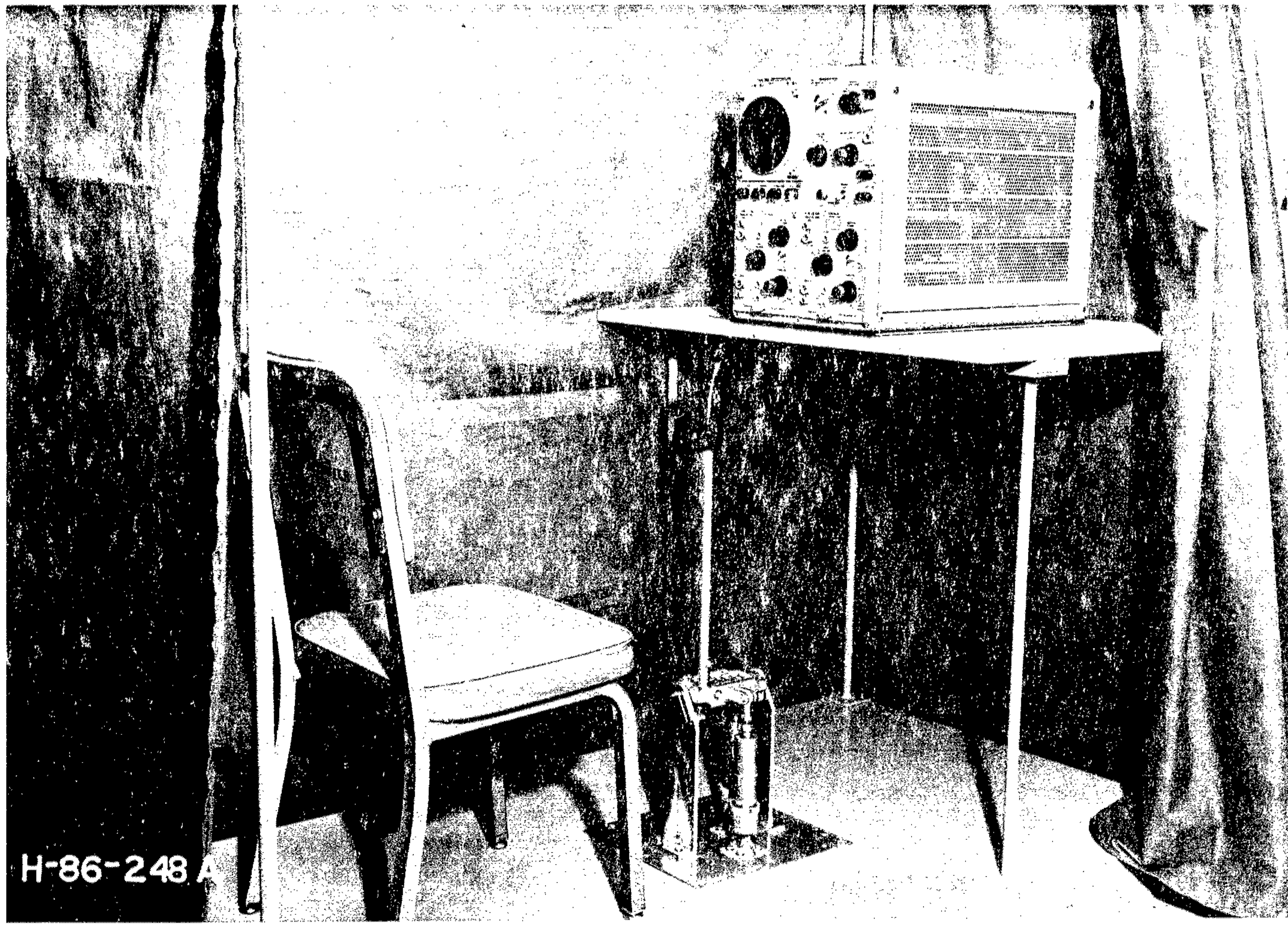


Figure 4. The Operator's Workspace

intersection of the crosshairs at the center of the 5-inch scope. The scope gain was one centimeter per volt.

The control was an aircraft type control stick pivoted at a hinge point located 48.9 centimeters from the second finger contact point (see Appendix I, fig. 15). Maximum control displacement was 12.7 centimeters forward, and 17.8 centimeters aft or to either side. Individual mechanical locks prohibited movement in the noncontrolled axis during single axis tracking tasks. For dual axis tracking tasks both locks were disengaged thereby permitting simultaneous longitudinal and lateral movements to be made.

The control stick had the same spring loading of approximately .60 lb/deg. in each axis. The force versus displacement function for the control stick is shown in figure 16 (Appendix I) for both the lateral and longitudinal axes. The breakout force was approximately .3 lbs. in all four directions. There was no stick damping and the mass of the stick was approximately five slugs. The stick was instrumented with position sensing potentiometers which transmitted 5 volts per degree of stick movement. The two potentiometer nulls were kept adjusted to the stick neutral position with negligible electrical deadband. The output from the control stick potentiometer, θ_c, was fed into a simulated mechanism consisting of gain, K_m, and two cascaded integrators. The system output, θ_o, its first derivative, $\dot{\theta}_o$, and the second derivative, $\ddot{\theta}_o$, were fed back to summers as illustrated in figure 3. Various quickening coefficient values were established by varying the gains, k_2 and k_3 in the quickening feedback loops for $\dot{\theta}_o$ and $\ddot{\theta}_o$, respectively.

Forcing Function Generator

The output of a random noise generator was passed through a second order lead fourth order lag filter to produce a forcing function having a nominal cut-off frequency of one radian per second. Figure 5 depicts the power spectral density of the forcing function. Two separate noise generators were used in order to provide independent forcing functions for the lateral (X) and longitudinal (Y) axes.

Transfer Function Synthesis Circuit

The transfer function (TF) for the man-control stick combination was measured by a modified version of the analog implicit synthesis technique used by Ornstein (ref 18).[1] A TF of the form:

$$\frac{K_p\,(1 + T_L s)}{(1 + T_I s)(1 + T_N s)}\, e^{-\tau s} \qquad (6)$$

was assumed (ref 16). For computational expediency the coefficients of the equivalent form:

[1] The modification of the technique is described in Appendix III.

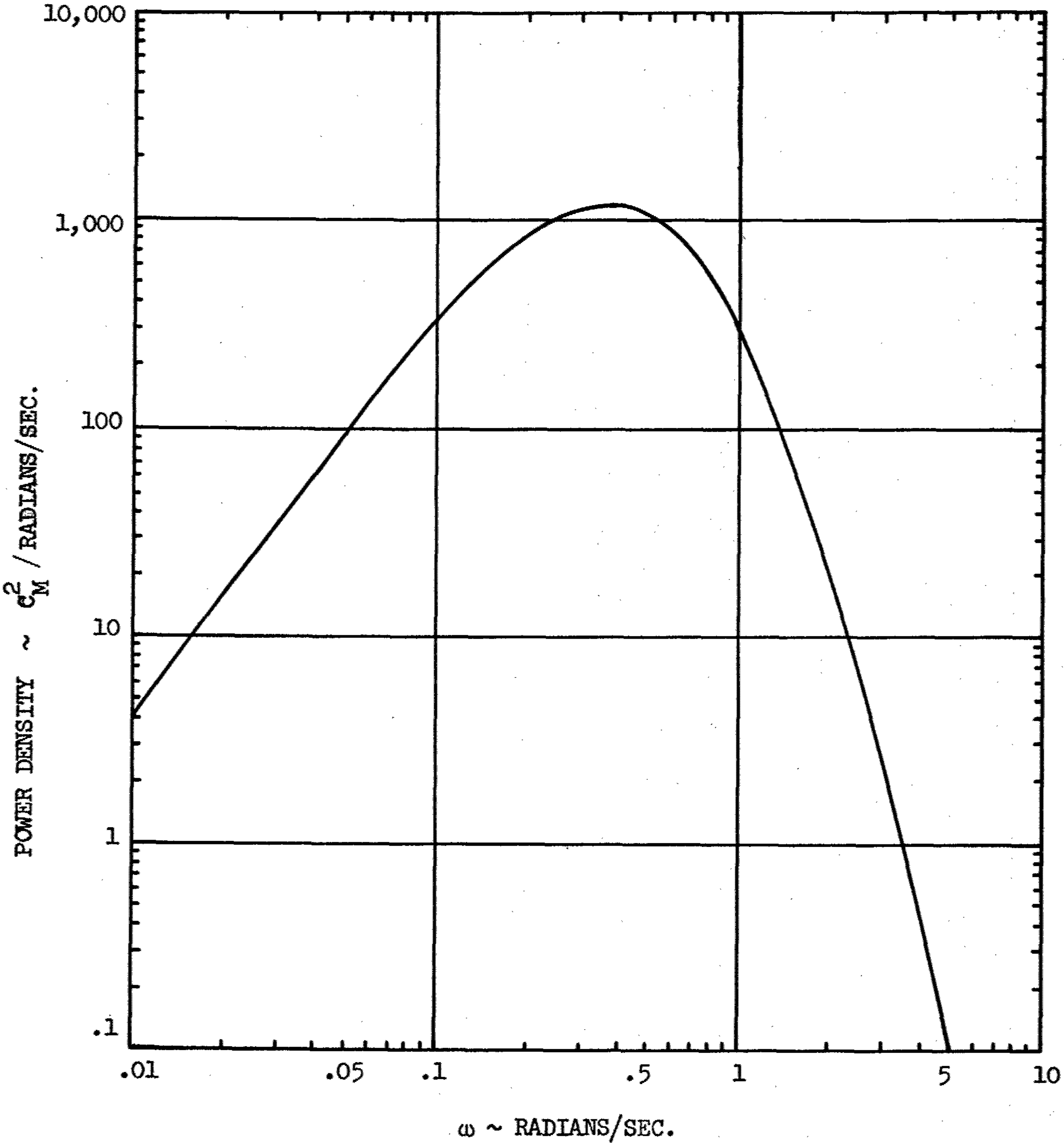


Figure 5. Power Spectral Density of Forcing Function

$$\frac{(A + Bs)}{(1 + Cs + Ds^2)} e^{-\tau s} \tag{7}$$

were synthesized where $A = K_p$, $B = K_p \cdot T_L$, $C = T_I + T_N$, and $D = T_I \cdot T_N$. The coefficient synthesis equations are contained in Appendix II. The reaction time exponent, τ, was assumed to have a fixed value of .2 seconds. A separate TF synthesis circuit was provided for each axis and the transfer functions coefficients were estimated "on line" for both the X (lateral) and Y (longitudinal) axes simultaneously.

A study was conducted to determine the variations of the transfer function coefficients due to error in the assumed τ value. The results are presented in table I and show that the computed transfer function has an accuracy of five degrees and one decibel over a bandwidth approaching ten radians per second at least for $.14 \leq \tau \leq .26$.

The control stick had a constant gain of 5 volts per degree; the synthesized man-control stick TF coefficients were adjusted by this factor to provide a measure of the man's TF per se.

The convergence rate of the transfer synthesizing circuit is improved if the TF coefficient values determined at the end of one trial are inserted as initial conditions for the next trial (ref 18). This procedure was automated in that the computer would automatically "hold" the terminal TF coefficient values from the end of one trial to the beginning of the next.

The Manalog Circuit

An analog circuit was instrumented to have the same TF form as was assumed for the man (ref 18). Separate circuits were placed in the overall network so that they could be substituted for the human operator in both axes simultaneously (see fig. 3). These circuits were assigned TF coefficient values similar to those of a human and were routinely used to check accuracy of the TF synthesis circuit.

Scoring Circuits

Scoring circuits were instrumented on two EAI consoles (Models 131R and 231R) for the following measures:

a. Mean Square System Error

$$\overline{\epsilon_s^2} = 1/T \int_0^T \epsilon_s^2 \, dt \tag{8}$$

Table I

GAIN AND PHASE ERROR BETWEEN ACTUAL TRANSFER

FUNCTION $\frac{(.12 + .18s)\ e^{-\tau s}}{1 + .075s}$ AND COMPUTED TRANSFER FUNCTION $\frac{(A + Bs)\ e^{-.2s}}{1 + Cs + Ds^2}$

ω (r/sec) \ τ (sec)	.14	.16	.18	.20	.22	.24	.26	
.1	0	0	.1	0	0	.1	0	Phase Error (Degrees)
.5	.1	.2	.2	.1	.2	.3	.1	
1	.3	.3	.5	.1	.3	.5	.2	
2	.6	.6	1.1	.3	.5	1.0	.6	
5	2.4	2.2	2.9	.6	.3	1.0	1.2	
10	8.7	7.8	7.2	.9	3.3	3.6	.5	
.1	0	0	0	0	0	0	0	Magnitude Error (Decibels)
.5	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	
2	.1	.1	0	0	.1	.3	0	
5	.5	.4	.2	0	.4	.6	.4	
10	1.8	1.3	.5	.1	1.1	1.6	1.4	

b. Mean Square Display Error

$$\overline{\epsilon_D^2} = 1/T \int_0^T \epsilon_D^2 \, dt \tag{9}$$

c. Mean Square Input

$$\overline{\theta_i^2} = 1/T \int_0^T \theta_i^2 \, dt \tag{10}$$

d. System Error Ratio Score

$$E_s = \overline{\epsilon_s^2}/\overline{\theta_i^2} \tag{11}$$

e. Display Error Ratio Score

$$E_D = \overline{\epsilon_D^2}/\overline{\theta_i^2} \tag{12}$$

f. Mean Transfer Function Coefficients

$$A = 1/T \int_0^T A \, dt \text{ (Similarly for B, C, and D).} \tag{13}$$

All scoring integrations automatically began 10 seconds after the initiation of a trial and terminated at the completion of the trial. All trials were one minute in length.

Performance Recording Equipment

The values for the integrated performance measures were printed out at the completion of each trial. During each trial 20 performance measures were continuously recorded on three oscilloscopes (an Offner Electronics, Inc., Model RMC and two Brush Mk. 200 recorders.) The ten measures recorded for each axis were A, B, C, D, ϵ_s^2, ϵ_D^2, θ_i, θ_o, θ_c, and ϵ_D.

EXPERIMENTAL PROCEDURE

The general procedure was standardized for all experiments. The detailed instructions read to each subject at the beginning of his first experimental session applied to all succeeding experiments. (See Appendix IV.)

Following the initial briefing for the session, the subject was seated directly in front of the oscilloscope. He was permitted to adjust his viewing distance within a range of 10 to 24 inches at eye level. He positioned his arm and hand as he desired with the restriction that he was to keep the control stick centered with reference to his body.

The experimenter initiated the trial upon obtaining confirmation that the subject was "ready." Completion of the trial was signalled by the error dot abruptly stopping at a fixed position. The subject then noted his system error ratio score which was directly displayed on a meter adjacent to the oscilloscope.[2] It required approximately 30 seconds for the experimenter to record data and reset the apparatus, whereupon he announced to the subject that the equipment was reset. The experimenter initiated the next trial when the subject replied that he was "ready." Trials were administered in blocks of five during all experiments. The subject was given a rest of 5 minutes or more after each block of trials. Experimental sessions usually lasted 1-1/2 hours but occasionally extended to two hours due to equipment malfunction.

DESCRIPTION OF THE EXPERIMENTAL VARIABLES

It can be seen in figure 2(b) that display error can be represented by the general equation:

$$\epsilon_D = \theta_i - (k_1 \theta_o + k_2 \dot{\theta}_o + k_3 \ddot{\theta}_o) \tag{14}$$

The four quickening conditions investigated in this experiment were as follows:

No Quickening (NQ): $k_1 = 1, k_2 = 0, k_3 = 0$ (15)

Partial Quickening (PQ): $k_1 = 1, k_2 = .5, k_3 = 0$ (16)

Full Quickening No. 1 (FQ_1): $k_1 = 1, k_2 = .5, k_3 = .125$ (17)

Full Quickening No. 2 (FQ_2): $k_1 = 1, k_2 = .7075, k_3 = .125$ (18)

---

[2] The correlation between system and display error scores was found to average .562 for the FQ_1, FQ_2, and PQ conditions, this value being significant beyond the .01 level. System error, rather than display error, was displayed to the operator because system error is the criterion of primary importance for vehicle control tasks.

Considerations based on the intermittency hypothesis regarding human tracking behavior have led researchers to specify optimal gain values of $k_1/k_2 = 1/0.5$ for the PQ condition and $k_1/k_2/k_3 = 1/0.5/0.125$ for the FQ condition (refs 6, 21). These values have, in general, been found to result in high performance in most applications. The FQ_1 and FQ_2 conditions have very similar Bode plots for the frequency range of interest (0-1 radians per second). It is of interest, therefore, to evaluate the effects on performance of the different gain factors for the first derivative feedback term of the two FQ conditions.

Each of the ten subjects was given 100 one minute trials for each of the four quickening conditions. Approximately 30 trials were administered in experimental sessions of 90 minutes duration each. A subject completed all 100 trials for a given condition before proceeding to the next condition. Two sequences were followed: (1) FQ_1, FQ_2, PQ, and NQ (5 subjects) and (2) FQ_2, FQ_1, PQ, and NQ (5 subjects). Thus, the order of presentation of the two FQ conditions was counterbalanced over two groups; five subjects having been randomly assigned to each group. The PQ and NQ conditions were administered last in order to secure maximum transfer of training from the higher quickening levels to the NQ conditions.[3]

At the conclusion of 400 trials the ten subjects were given an additional 10 trials each for FQ_1, PQ, and NQ. The order of presentation of these conditions was counterbalanced over subjects. These additional ten trials were required in order to permit a comparison of performance under these three quickening conditions. Such a comparison could not appropriately be made for the first 100 trials of each condition due to the effect of the order of presentation of these conditions.

RESULTS AND DETAILED DISCUSSION

This section presents the complete data for the experiment. First to be considered are the data pertaining to the effects on system accuracy of the various experimental treatments. The results with respect to the transfer function parameter values associated with the different experimental treatments are then presented in order to provide a basis for evaluation of the functional relationship portraying the operator adjustment rules.[4] Where appropriate, statistical analyses of the data are also presented.

---

[3] It has been known for some time that there is positive transfer of training from quickened to unquickened systems (ref 10). Hudson has found that use of an adaptive tracking simulator wherein the amount of quickening is steadily decreased with training results in faster learning than when the adaptive feature is not used (ref 11).

[4] The results unless otherwise explicitly stated are based on performance in both axes. It is interesting to note that performance trends with respect to quickening effects were found to be identical for the two axes in a separate study (ref 25).

Quickening Effects on System Accuracy

The system and display error ratio scores, E_S and E_D, respectively, summed for the two axes for trials 95 through 100 for the FQ_1 and FQ_2 conditions are presented in table II. The error scores for each axis are presented in Appendix V. A Wilcoxon Matched Replicates Test of the difference between the E_S means is highly significant ($p < .01$) whereas the difference between the E_D means is not significantly different.[5] It is to be noted that for subjects K, N, and R the order of merit for the two quickenings given by E_D contradicts that given by E_S.

Table III shows the error scores summed for the two axes for trials 105 through 110 for the FQ_1, PQ, and NQ conditions. The error scores for each axis are given in Appendix V.

Note that in table III the order of merit of the three quickenings is directly contradictory for the two types of error scores. All differences between means are significant with the exception of NQ < PQ for E_S and FQ_1 < PQ for E_D. As noted earlier, the FQ_2 condition was found to have a significantly higher system error score than did FQ_1. The characteristic distinguishing the two conditions is the higher gain for the first derivative feedback term of the FQ_2 condition. FQ_2, therefore, represents more quickening than FQ_1, i.e., the error signal is more anticipatory for FQ_2. The relationship of FQ_1 and FQ_2 is thus in line with that shown by the FQ_1, PQ, and NQ comparisons, viz., the more quickening, the greater the system error.

The discrepant results for the two types of error scores may, in part, be understood if one considers the functional relationship between the two errors by subtracting equation (2) from equation (1)

$$\epsilon_s = \epsilon_D + k_2\dot{\theta}_o + k_3\ddot{\theta}_o \tag{19}$$

We assume that the subject attempts to minimize the display error. If he should do a good job of minimizing ϵ_D so that it is very close to zero in value, we see that a system error would still exist that is proportional to the sum of the first and second derivatives of the system output. It can be seen that minimizing the system error requires that the subject make his display error equal the sum of the two derivative terms; thus, given that

$$\epsilon_D = \epsilon_s - (k_2\dot{\theta}_o + k_3\ddot{\theta}_o) \tag{20}$$

---

[5] As will be true throughout this report, a probability of .05 or less will be the significance level adopted for rejection of the null hypothesis.

Table II

ERROR SCORE COMPARISONS OF FQ_1 AND FQ_2
FOR TRIALS 95 THROUGH 100

	E_S (x+y)			E_D (x+y)		
Subject	FQ_1	FQ_2	T	FQ_1	FQ_2	T
B	.2994	.4844		.0507	.1016	
G	.2597	.5471		.0371	.0857	
H	.3156	.5496		.0519	.1450	
J	.3063	.4409		.0043	.0057	
K	.3065	.3848		.0470	.0257	
L	.2956	.4140		.0323	.0446	
M	.3462	.5029		.0602	.0728	
N	.2970	.4130		.1356	.0501	
R	.2847	.3838		.0534	.0306	
W	.3287	.4560		.0686	.0729	
Means	.3040	.4576	0*	.0541	.0635	20**

Significance levels (Wilcoxon Matched Replicates Test):

* $p < .01$ ** N.S.

Table III

ERROR SCORE COMPARISONS

OF FQ_1, PQ, AND NQ FOR TRIALS 105 THROUGH 110*

Subjects	E_s (x+y) FQ_1	E_s (x+y) PQ	E_s (x+y) NQ	E_D (x+y) FQ_1	E_D (x+y) PQ	E_D (x+y) NQ
B	.3719	.1958	.1995	.0672	.0562	.1995
G	.2993	.2341	.0992	.0406	.0374	.0992
H	.3235	.2588	.2575	.0622	.0943	.2575
J	.4289	.3099	.2317	.0911	.0796	.2317
K	.2855	.1982	.1558	.0619	.0392	.1558
L	.3367	.1897	.0587	.0387	.0280	.0587
M	.3972	.2277	.2533	.0590	.0524	.2533
N	.3567	.1987	.0944	.0624	.0374	.0944
R	.2969	.2378	.0882	.0360	.0371	.0882
W	.3982	.3446	.4618	.1020	.2107	.4618
Means	.3495	.2395	.1900	.0621	.0672	.1900

* Any two treatment means not underscored by the same line are significantly different. Any two treatment means underscored by the same line are not significantly different. The Wilcoxon Matched Replicates Test was used for the comparisons.

we see that when ϵ_S equals zero that

$$\epsilon_D = -(k_2\dot{\theta}_o + k_3\ddot{\theta}_o) \tag{21}$$

That is, the subject must deliberately keep the error signal displaced away from the center of the scope by an amount proportional to the sum of the two derivative terms. It may readily be appreciated that this would be a very difficult task.

This is directly related to the requirement for an antibias network as discussed by Birmingham and Taylor (ref 2). Specifically, Birmingham and Taylor stipulated that an antibias network should be included whenever display quickening is used for inputs other than step function changes. (ref 2, p. 20). The demonstrated discrepancy between the E_D and E_S results offers strong evidence of the importance of including an antibias network in the application of display quickening to a vehicle control problem.

Analysis of Obtained Transfer Function Coefficients

Table IV presents the values of the transfer function parameters K_p, T_L, $T_N + T_I$, and $T_N \cdot T_I$ for the 10 subjects for the FQ_1, FQ_2, PQ, and NQ conditions. Each entry in table IV is the mean value of the TF parameter for trials 95 through 100. Also presented are the corresponding coefficient values of the optimum linear transfer function which a servo engineer would select in order to achieve minimum display error ratio score. According to reference 16, the human TF is very similar to this theoretically optimum transfer function. The optimum transfer functions were obtained by simulating the complete closed loop system on an analog computer with the assumed form of the man's transfer function substituted for the man and then adjusting the TF coefficients until a minimal E_D was realized. No predetermined convergence scheme was used. Initial estimates of these coefficients were obtained from Bode plots constructed with the aid of an IBM 7094 digital computer.

The values of the subjects' gains show considerable variability for all quickening conditions. The subjects' gains generally tend to be lower than optimum when the optimum value is relatively high (FQ_1) and higher than optimum when the optimum is relative low (NQ). For the PQ condition, the lead terms for all of the subjects were substantially higher than the optimum. For the NQ condition, the values of the subjects' leads show considerable variability, some being larger and others smaller than the optimum. All of the subjects showed negligible leads for the FQ_1 and FQ_2 conditions. The sum of the two lags, $T_N + T_I$ for the subjects was generally lower than optimum for NQ, FQ_1, and FQ_2 and higher than optimum for PQ. For the partial quickening case, there exists a high correlation between T_L and $T_N + T_I$. This suggests that the subject on the average introduces a lead to compensate for his lag thus producing a nearly flat

Table IV

COMPARISON OF OBTAINED AND OPTIMUM TF PARAMETER VALUES FOR FQ_1, FQ_2, PQ, AND NQ FOR TRIALS 95 THROUGH 100*

Subjects	FQ_1 - X Axis K_p Deg/cm	T_L Sec.	T_N+T_I Sec.	$T_N \cdot T_I$ Sec.^{2}	FQ_1 - Y Axis K_p Deg/cm	T_L Sec.	T_N+T_I Sec.	$T_N \cdot T_I$ Sec.^{2}
B	53.37	0.61	27.62	0.25	39.69	0.00	23.34	0.76
G	49.75	0.00	23.90	0.43	40.24	0.00	23.40	0.53
H	42.10	1.03	22.00	0.54	32.63	0.32	17.12	0.60
J	36.90	0.00	17.28	0.52	31.06	0.00	15.18	0.50
K	56.11	1.37	27.80	0.31	39.27	0.00	21.32	0.40
L	54.66	0.24	16.36	0.13	39.73	0.00	11.94	0.22
M	36.50	0.00	21.58	0.56	29.24	0.00	18.56	0.90
N	22.35	0.00	12.04	0.89	20.27	0.00	12.66	1.07
R	39.81	0.28	13.42	0.23	29.96	0.00	9.64	0.35
W	28.81	0.00	13.44	0.63	21.06	0.00	13.00	1.14
Means	42.04	0.35	19.54	0.45	32.32	0.03	16.62	0.65
Optimum Values	50.00	0.00	30.00	0.00	50.00	0.00	30.00	0.00

	FQ_2 - X Axis K_p Deg/cm	T_L Sec.	T_N+T_I Sec.	$T_N \cdot T_I$ Sec.^{2}	FQ_2 - Y Axis K_p Deg/cm	T_L Sec.	T_N+T_I Sec.	$T_N \cdot T_I$ Sec.^{2}
B	25.95	0.00	21.28	0.34	17.54	0.00	17.80	0.85
G	35.57	0.97	26.00	0.10	21.82	0.00	15.72	0.47
H	23.53	0.00	14.88	0.54	20.44	0.00	14.74	0.73
J	32.88	0.00	9.00	0.18	24.70	0.00	7.96	0.32
K	38.14	0.30	17.18	0.12	28.92	0.00	14.50	0.27
L	38.20	0.00	10.70	0.11	25.58	0.00	6.06	0.23
M	29.84	0.58	21.90	0.42	20.72	0.00	12.44	0.76
N	30.66	0.00	19.78	0.32	24.50	0.58	18.46	0.42
R	37.22	0.00	14.76	0.12	25.90	0.00	9.34	0.30
W	30.50	0.00	19.80	0.45	15.30	0.00	13.70	1.18
Means	32.25	0.18	17.53	0.27	22.54	0.06	13.07	0.55
Optimum Values	26.00	0.00	21.00	0.00	26.00	0.00	21.00	0.00

* All values in the table have been multiplied by 100. Each table entry is the mean value for trials 95 through 100.

Table IV (cont'd)

COMPARISON OF OBTAINED AND OPTIMUM TF PARAMETER VALUES FOR FQ_1, FQ_2, PQ, AND NQ FOR TRIALS 95 THROUGH 100*

	PQ - X Axis				PQ - Y Axis			
	K_p	T_L	T_N+T_I	$T_N \cdot T_I$	K_p	T_L	T_N+T_I	$T_N \cdot T_I$
Subjects	Deg/cm	Sec.	Sec.	Sec.^{2}	Deg/cm	Sec.	Sec.	Sec.^{2}
B	31.58	23.05	21.22	0.51	30.46	24.36	20.28	0.75
G	26.94	7.37	3.56	0.69	22.54	12.01	7.04	0.79
H	31.36	6.82	8.10	0.64	30.01	8.55	8.72	0.77
J	37.20	2.43	0.00	0.50	14.35	14.35	6.70	0.78
K	38.31	12.97	12.42	0.46	23.94	31.46	16.12	0.58
L	54.13	2.76	0.00	0.29	40.77	3.88	0.00	0.34
M	30.64	11.06	13.00	0.52	22.23	22.16	14.56	0.64
N	30.78	10.28	9.98	0.89	29.04	8.89	7.08	0.67
R	40.85	1.53	0.00	0.48	31.86	2.96	0.00	0.57
W	31.33	19.44	17.54	0.57	21.37	22.84	13.46	0.83
Means	35.31	9.77	8.58	0.56	27.34	15.15	9.40	0.67
Optimum Values	24.00	0.62	1.50	1.00	24.00	0.62	1.50	1.00

	NQ - X Axis				NQ - Y Axis			
	K_p	T_L	T_N+T_I	$T_N \cdot T_I$	K_p	T_L	T_N+T_I	$T_N \cdot T_I$
	Deg/cm	Sec.	Sec.	Sec.^{2}	Deg/cm	Sec.	Sec.	Sec.^{2}
B	25.43	50.24	0.00	0.65	14.07	90.86	0.00	0.73
G	43.11	40.97	0.00	0.20	22.60	77.42	0.00	0.17
H	22.80	54.09	1.88	0.81	12.96	100.57	5.28	0.82
J	20.95	63.66	0.00	0.43	14.77	89.90	0.00	0.40
K	26.64	48.97	1.50	0.75	14.90	92.90	2.66	0.93
L	51.59	30.47	0.00	0.63	31.02	57.40	0.00	0.52
M	12.27	102.13	8.98	1.05	9.11	123.86	9.72	1.15
N	31.30	40.69	0.00	0.56	21.59	61.70	0.00	0.54
R	21.77	58.44	0.00	0.44	12.58	101.92	0.00	0.49
W	12.21	96.72	1.56	0.52	8.66	118.44	3.06	0.63
Means	26.81	58.64	1.39	0.60	15.23	91.50	2.07	0.64
Optimum Values	11.00	81.82	5.00	1.00	11.00	81.82	5.00	1.00

* All values in the table have been multiplied by 100. Each table entry is the mean value for trials 95 through 100.

response. Bode plots for each simulated man-machine system are presented in Appendix VI for the transfer functions given in table IV. These plots show that the subjects adjusted their equalizing parameters to achieve stable loop performance (as similarly noted in the adjustment rules formulated by McRuer, et al., refs 1, 13, 15, and 16).

From table IV, a set of adjustment rules describing the behavior of the average subject for different quickening levels can be stated as follows:

1) The human increases his gain as the amount of quickening increases.

2) The human decreases his lead as the amount of quickening increases.

3) The human increases his lag as the amount of quickening increases.

The data of table IV are summarized in figure 6.

It may be seen that these adjustment rules are consistent with those developed earlier in references 1, 13, 15, and 16. In both cases, the human adjusts his equalizing characteristics to achieve stable control. Furthermore, a lag is generated as required to achieve good low-frequency characteristics accompanied by whatever is needed to retain high frequency stability. In the NQ case a predominately lead form of TF is assumed whereas a predominantly lag form is observed for the two FQ conditions which is as would be predicted by the earlier adjustment rules (refs 1, 13, 15, and 16).

The above rules do not infer how the subject adjusts his transfer function during the learning period. This phenomenon is illustrated in figures 7 through 10.[6] Based on these curves a set of rules governing the transitional effects of learning on the TF coefficients can be inferred as follows:

1) Given full quickening or partial quickening the subjects increase both their lag and gain terms as learning progresses. This has the overall effect of placing more emphasis on low frequency information as learning progresses.

---

[6] No curves are presented for the values of the lead coefficients for the two full quickening conditions, since the lead values are either zero or are so small as to be negligible. In each graph, two curves are illustrated for the best and poorest subject of the group as determined by error scores at the completion of training.

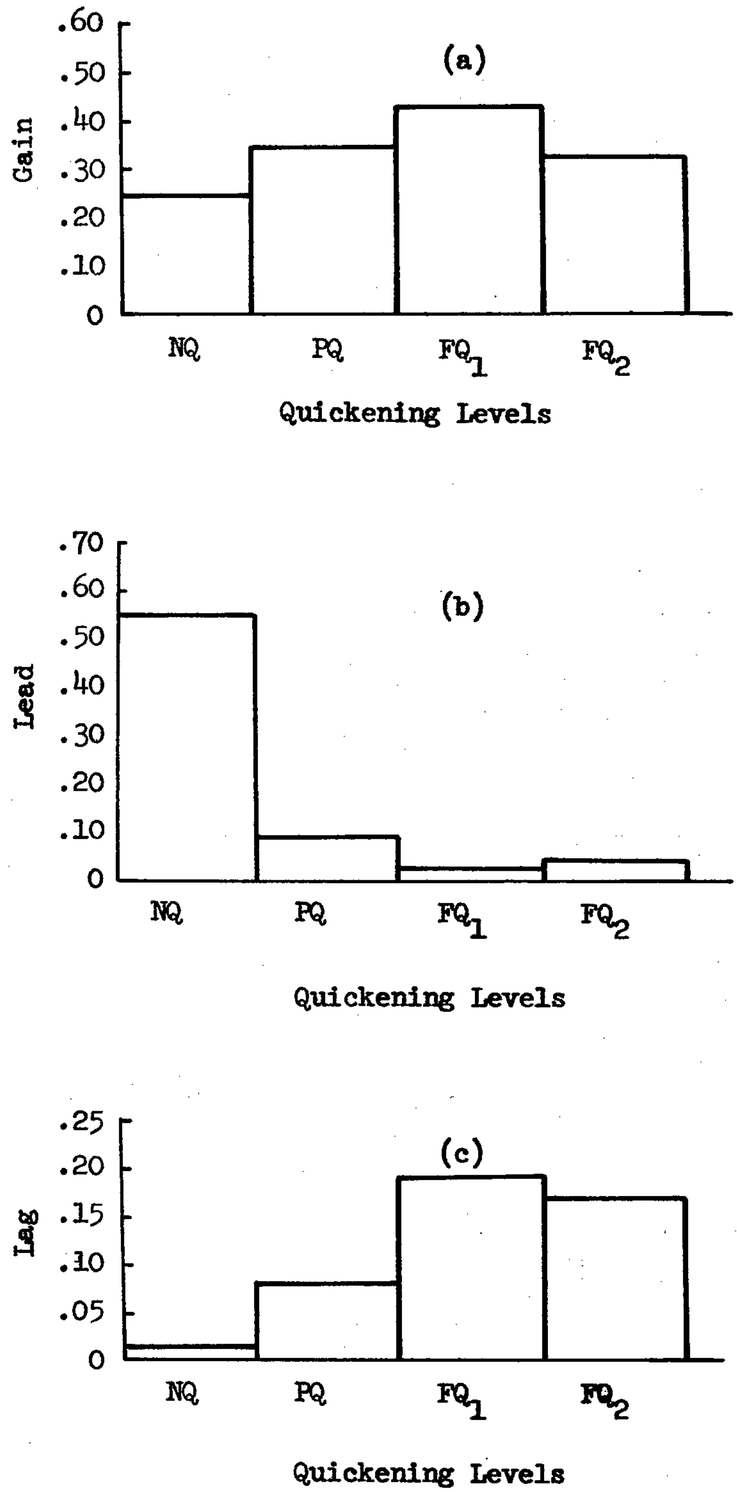
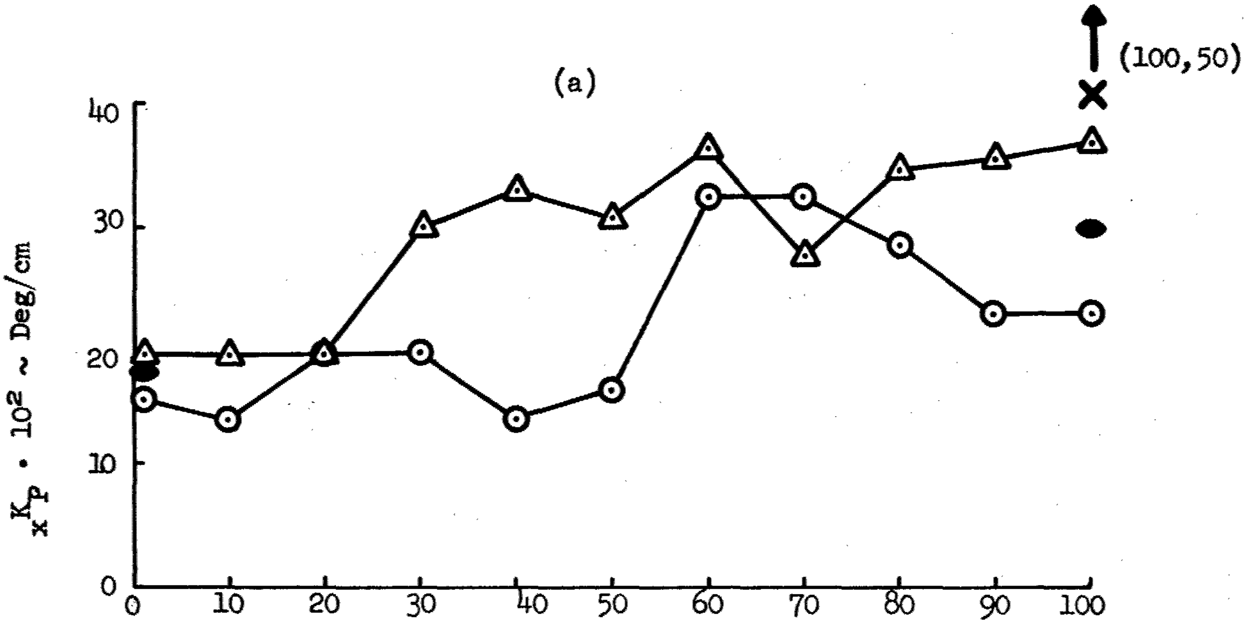


Figure 6. Comparison of TF parameter values for the different quickening levels, for the X Axis.



(b)

The TF lead coefficient was essentially zero throughout training for all subjects for this full quickening condition.

(c)

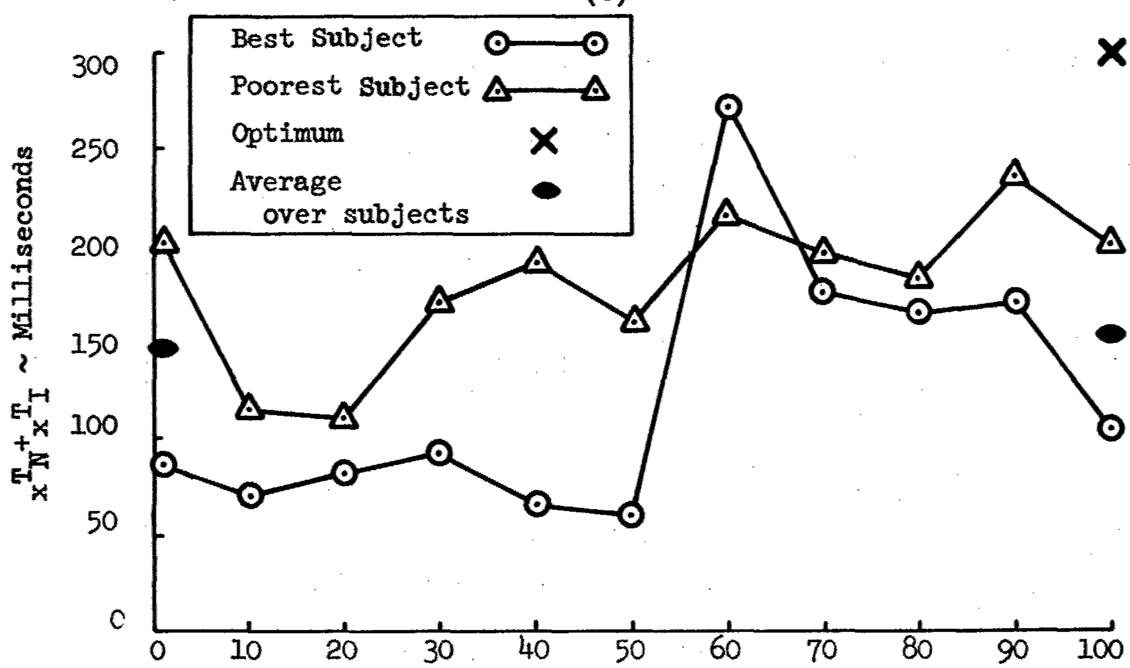
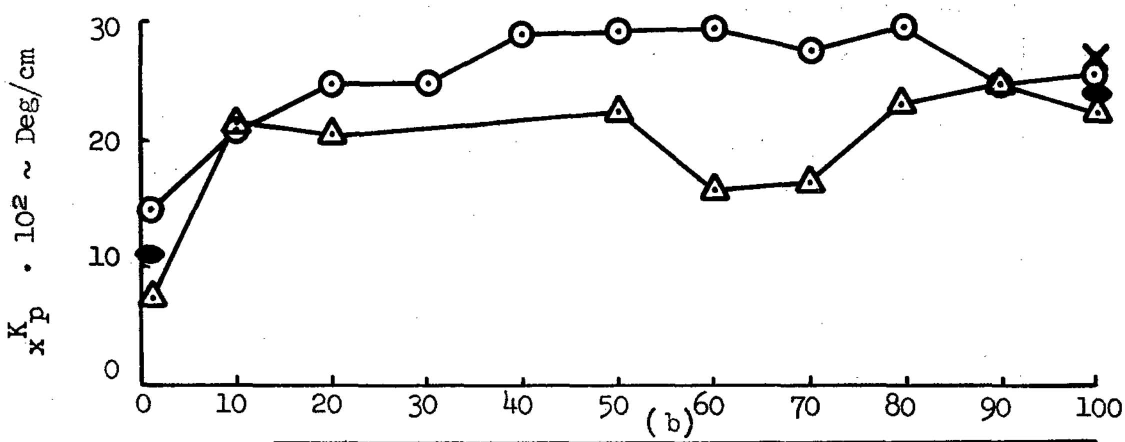


Figure 7. TF Changes During Learning - Full Quickening[1]. Data points are for one trial only. (a) Gain changes, (b) Lead changes, (c) Lag changes

(a)



(b)

The TF lead coefficient was essentially zero throughout training for all subjects for this full quickening condition.

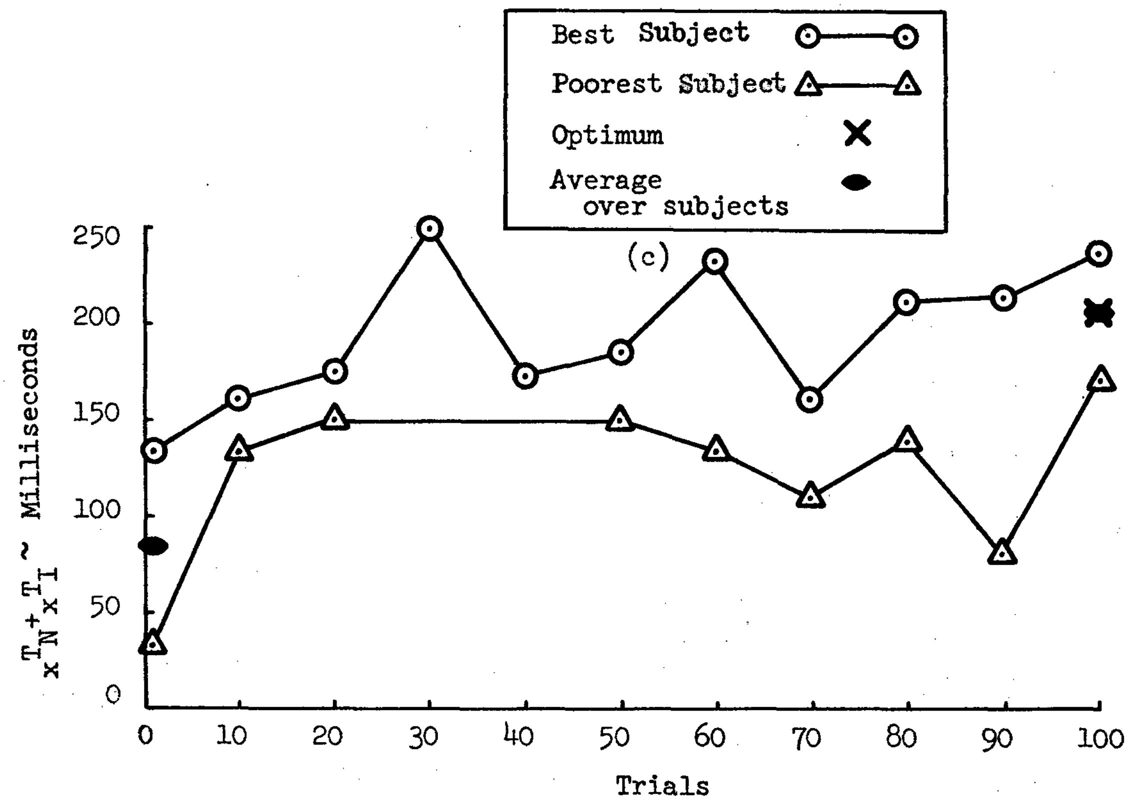


Figure 8. TF Changes During Learning - Full Quickening$_2$. Data points are for one trial only. (a) Gain changes, (b) Lead changes, (c) Lag changes

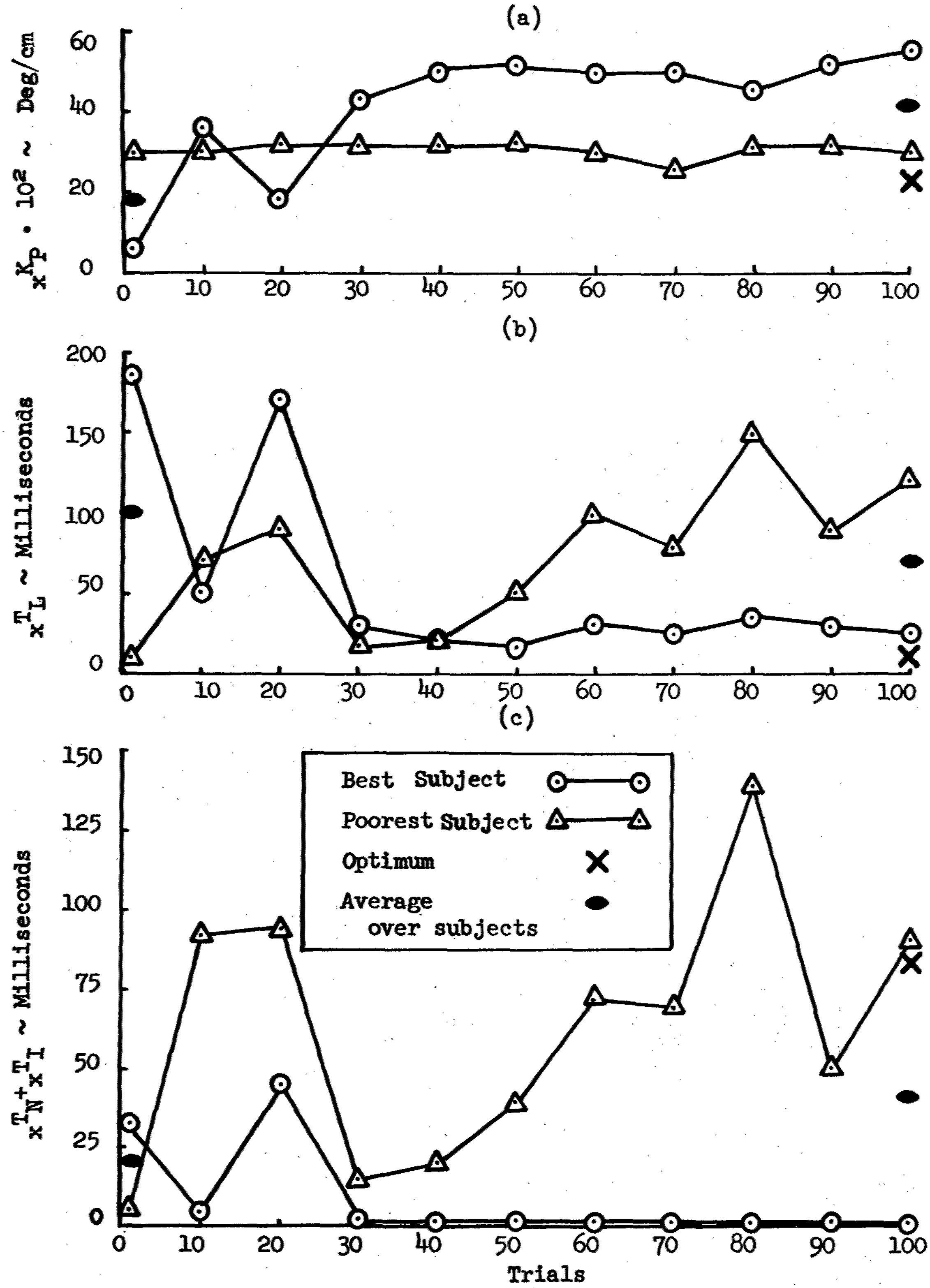


Figure 9. TF Changes During Learning - Partial Quickening. Data points are for one trial only. (a) Gain changes, (b) Lead changes, (c) Lag changes

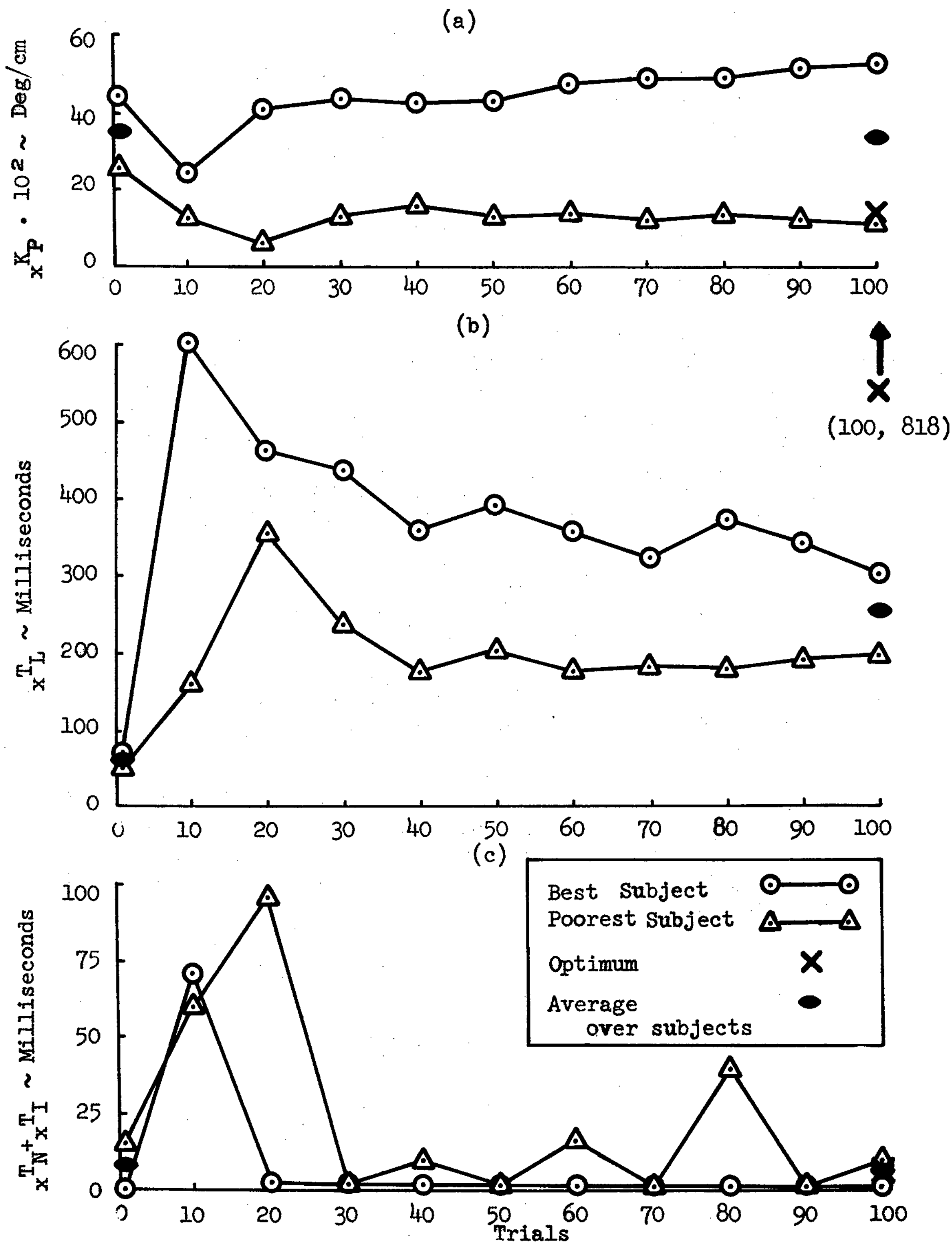


Figure 10. TF Changes During Learning - No Quickening. Data points are for one trial only. (a) Gain Changes, (b) Lead changes, (c) Lag changes

2) For partial and no quickening the human modifies his lead, during the learning phase, towards the optimum. For full quickening, the lead is initially zero (the optimum) and remains at zero.

3) During the learning phase, the human adjusts his lag towards the optimum value for all quickening levels.

Variation of TF Coefficients as a Function of Forcing Function Bandwidth

Data from experiment I do not permit an investigation of adjustment rules relating the behavior of TF parameters to the bandwidth of the forcing function. Such an investigation, however, was accomplished based upon an experiment (ref 25) in which the forcing function was an aggregate of sine and cosine terms arranged to represent a random appearing display to the subject (Appendix VII). The results, as shown in Appendix VII, indicated that for the three quickening conditions the gain could be described very nicely by the second order differential equation.

$$\frac{d^2K}{d\omega^2} + \beta_1 \frac{dK}{d\omega} + \beta_2 K = c \qquad (22)$$

where the terms, β_1, β_2, and c are a function of the quickening condition but are constant for a given quickening and where ω is the frequency in radians/sec.

The values found for β_1 and β_2 which best fit the data yields a solution for K that is either exponentially decreasing or damped sinusoidally. As the amount of quickening increases the gain becomes less oscillatory but there is a consistent tendency for the gain to decrease as the bandwidth increases.

GENERAL DISCUSSION AND CONCLUSIONS

The results of this study are generally well correlated with those of other investigators. In particular, the transfer function adjustment rules that describe the operator's adaptation to different quickening levels show good agreement with the rules developed by other investigators in the context of aircraft handling qualities research (refs 1, 13, 15, and 16). One therefore can conclude that the human employs the same criteria to optimize his performance for different quickenings as he does for different aircraft control systems. Specifically, he initially adapts the form of his equalizing characteristics to achieve stable control, good low frequency response, and high frequency system stability. After initial adaptation of equalizing characteristic form, the particular value of each transfer function parameter is generally adjusted in the appropriate direction for realization of a transfer function that is optimum for minimizing error. The present research thus provides additional support for the conclusion that man's adaptive behavior during a compensatory tracking task is very similar to that which would be prescribed on the basis of linear servotheory.

System error and display error yield discrepant orders of merit when one compares a display quickened system to an unquickened system. This is due to the bias between system input and system output that is inherent in the display quickening network. (Such a bias is not necessarily present in other forms of quickening.) System error is a monotonic increasing function of quickening level due to the presence of this bias. As a consequence, an antibias network will be required in most of the practical applications of display quickening.

SECTION III

EXPERIMENT II

PURPOSE

This experiment was designed to investigate the effects upon tracking performance of varying the values of various machine gains in the control loop. It may be noted in figure 11 that there are three "machine" gains in the forward loop, viz., scope gain, K_s, the control stick gain, K_c, and the mechanism gain, K_m. From the "adjustment rules," it can be hypothesized that if any machine gain is changed, the operator will make a compensating change in his own gain, K_p, to keep the overall loop gain the same. It can also be seen that increasing K_s and decreasing K_m by equal factors will increase ϵ_D, θ_H, and θ_c without affecting

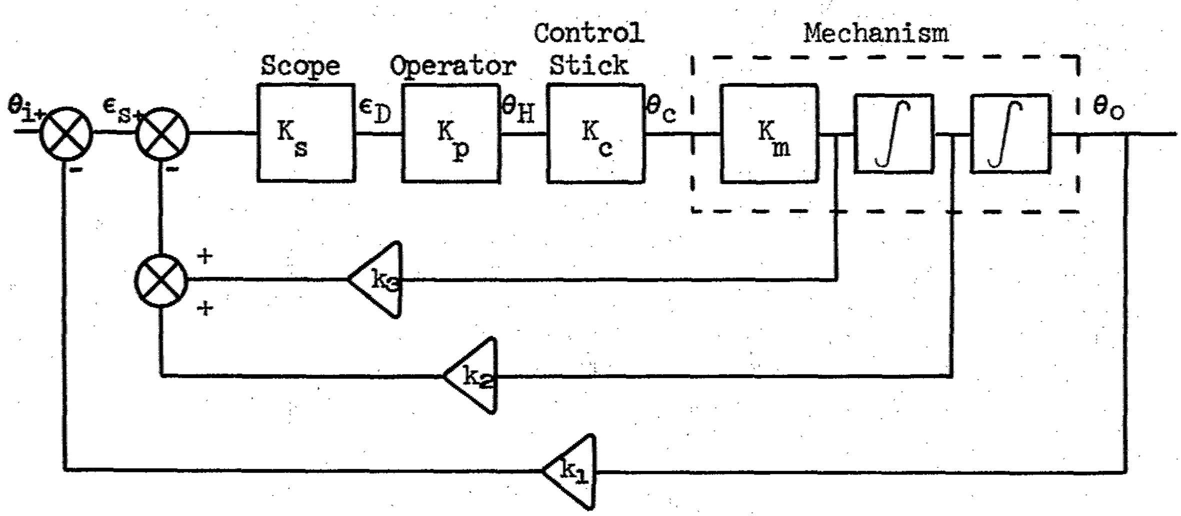


Figure 11. Block Diagram Illustrating Location of the Various Loop Gains

the overall system gain, i.e., the gains are simply redistributed. Both of these types of changes can be used to force an increase in the amplitude of stick movement.

It was of particular interest to determine the effects on performance accuracy of an increase in θ_c since the range of control stick movement was observed to be very small in experiment I. For example, the maximum control stick excursion value in table V varied from a minimum of .37° to a maximum of 1.54° whereas the maximum available stick movement range is 20°. Further, the mean range of control stick excursion from center was a function of the quickening level and varied in experiment I from approproximately .4° for FQ to 1.4° for NQ. The observed differences in stick movement range between quickening levels are to be expected since less stick movement is required for the quickened conditions due to the additional gain(s) in the feedback loop(s).

There are several reasons for predicting that longer stick movements would facilitate performance. It has been known for some time that positioning errors are greater for short movements than for long movements (ref 14). It is also known that man's ability to discriminate force differences varies with the magnitude of the force output required and that such discrimination seriously deteriorates below 5 lbs. (ref 14).

Table V

EXPERIMENT I

MEAN CONTROL STICK EXCURSION RANGE FROM CENTER
(Peak-to-Peak/2, in Degrees)

Subjects	FQ_x	PQ_x	NQ_x
K	.37°	.54°	.98°
L	.44°	.58°	1.49°
N	.42°	.47°	1.54°
R	.44°	.70°	1.51°
Means	.42°	.57°	1.38°

This is of particular importance since, with a stick force/displacement of .60 lbs. per degree (fig 12) and a stick breakout force of approximately .3 lbs., the average FQ stick movement of .4 degrees required a total of about .55 lbs. of force whereas the average NQ stick movement required a total of around 1.1 lbs. of force.

Another factor influencing the prediction of better performance with longer stick movement is the fact the breakout force itself may adversely affect performance when the range of stick movement is small. A nonlinearity of the stick displacement force curve is introduced by the stick bungee breakout force as is shown in figure 12. This nonlinearity consists of the force feel deadband at the origin in which forces less than .3 lbs. are ineffective. Now, a certain amount of breakout force is desirable in many tracking situations. For example, in the case of military aircraft, a minimum of .5 lbs. breakout force is required with the maximum specified as not to exceed 3 lbs. (ref 7). A small breakout force results in reduced control sensitivity to small, inadvertent operator movements. In an aircraft control situation, the nonlinearity introduced by the breakout force is of little significance due to the relatively large excursion range of stick movements. In experiment I,

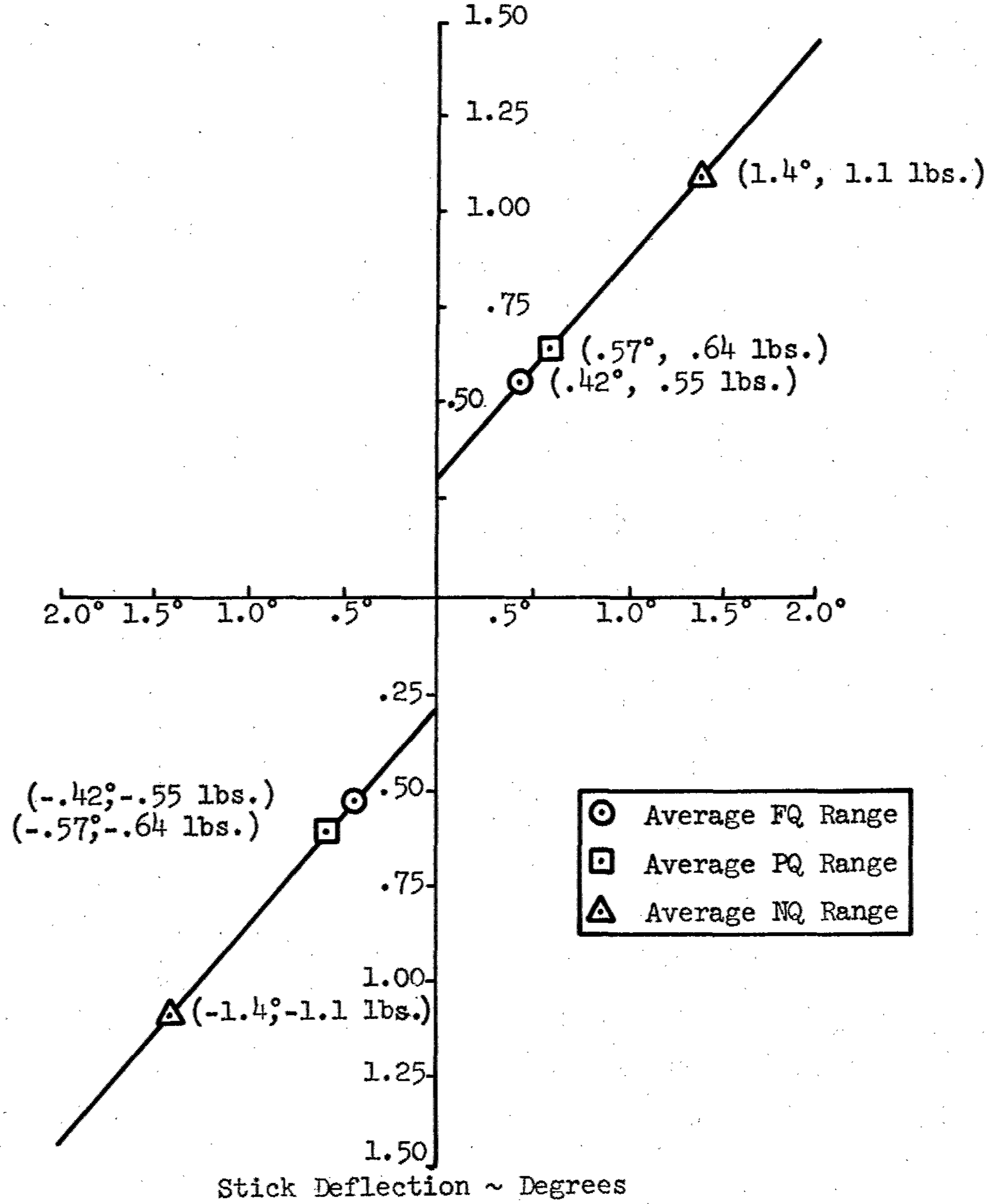


Figure 12. Control Stick Force/Displacement Function Showing Average Stick Movement Range

however, the effect of this nonlinearity was probably greater since the breakout force varied from roughly 33% to 50% of the total average force exerted. The appearance of dithering behavior on the part of some (but not all) subjects provides further indirect support of the view that the breakout force played a significant role in shaping the man's performance. (It seems reasonable to assume that dithering was found by some subjects to be beneficial because it provided a technique for avoiding the inertia effect of the deadzone.)

Increase in stick movement amplitude should decrease the relative effect of the nonlinearity in the stick force-displacement curve. This, in turn, could result in changes in compensation (lead-lag) adopted by the operator. Such changes, if any, would be in a direction such as to make the adaptation closer to the optimum transfer function and the magnitude of change would depend on the extent of stick movement change.

The above consideration provides the basis for the following four hypotheses explicitly tested in this experiment:

1. Forcing an increase in stick movement amplitude will result in a lower error score.

2. Redistribution of machine gains with no overall change will not change the operator's gain.

3. Any change in the gain(s) of machine component(s), will result in exactly compensatory operator gain change.

4. Increase in stick movement range should result in operator TF's which are closer to the optimum transfer function.

EXPERIMENTAL PROCEDURE

The method chosen for forcing the subjects to execute longer stick movements was to decrease the mechanism gain, K_m, and/or increase the scope gain, K_s. The ten subjects were divided into groups (A and B) that were matched on the basis of the mean system error ratio scores (E_s) for the last ten NQ trials of experiment I as shown in table VI. Noted in table VII are the mechanism, control stick, and scope gain values used in this experiment and those used in experiment I. Note that the product of the machine gains, viz., $K_s \cdot K_c \cdot K_m$, is lower by a factor of five for experiment II than for experiment I for both groups. Furthermore, the machine gain product is identical for both groups of experiment II.

The subjects in each group of experiment II were given 100 NQ trials for each of the mechanism and scope gain combinations of this experiment (see table VII). The same general experimental procedure used in experiment I was followed.

Table VI

MEAN SYSTEM ERROR SCORES FOR NQ TRIALS
90 THROUGH 100 of EXPERIMENT I

Group A		Group B	
Subject	E_s (x+y)	Subject	E_s (x+y)
G	.1052	L	.0441
N	.1096	R	.1273
K	.2066	J	.2009
M	.2893	B	.2172
H	.2377	W	.3609
Means	.1897	Means	.1901

Table VII

SCOPE, STICK, AND MECHANISM GAINS

Experiment	Group(s)	K_s cm/v	K_c/deg	K_m v/v	Product cm/deg
I	A and B	1	5	5	25
II	A	1	5	1	5
II	B	2	5	.5	5

RESULTS AND DETAILED DISCUSSION

Table VIII presents a comparison of the mean control stick excursion ranges for experiments I and II. Both groups of experiment II show a marked increase in stick movement amplitude over that of experiment I, indicating that lowering of the total machine gain effectively forced larger stick movements. The movement range for group A may be seen to be approximately half that for group B. This result would be predicted from the increase of the scope gain by a factor of two, given that the operator's gain remains the same.

The mean E_s for the two groups for the last five trials is presented in table IX along with the corresponding error scores for experiment I. For each group the mean E_s is significantly lower than that for experiment I. This produces support for hypothesis number 1 above (that forcing an increase on stick movement amplitude will result in less error). The difference between the means for the two groups for the present experiment is not significant.

Table VIII

MEAN CONTROL STICK
EXCURSION RANGE FROM CENTER
(Peak-to-Peak/2 in Degrees)

NQ_x	Experiment I	Experiment II
Group A	1.26°	4.45°
Group B	1.50°	8.98°

Table IX

COMPARISON OF E_s (x+y) FOR THE
THREE EXPERIMENTAL CONDITIONS

	Group A			Group B	
Subject	Exp. I	Exp. II	Subject	Exp. I	Exp. II
G	.1052	.0763	L	.0441	.0315
N	.1096	.0771	R	.1273	.0713
K	.2066	.0769	J	.2009	.0853
M	.2893	.1621	B	.2172	.1300
H	.2377	.1214	W	.3609	.1773
Means	.1897	.1028	Means	.1901	.0991
Comparison	I > II		AII > BII	I > II	
T Value*	0		7	0	
	$P < .031$		$P = 1.0$	$P < .031$	

* Wilcoxon Matched Replicates Test

Table X presents the mean values of E_S, K_p, T_L, $T_N + T_I$, and $T_N \cdot T_I$ for the last five trials for each subject in the two groups. Comparisons of the mean values of the TF parameters for each group indicate that there is no significant difference between groups for any parameter. The lack of difference in operator gains for the two groups of this experiment supports hypothesis number 2 above (that redistribution of machine gains with no overall changes will not change the operator's gain).

Comparisons of the mean values of the operator's gains for experiments I and II (see tables IV and X) shows that the gains for groups A and B of this experiment are significantly higher than those of experiment I by factors of approximately 4 and 5, respectively. This finding supports hypothesis number 3 above (that any change in the gain(s) of machine component(s), will result in compensatory operator gain change).

In order to evaluate hypothesis number 4, consideration of the integrated effect of these various TF parameters is required. Such consideration was accomplished by comparison of the experiment I and experiment II Bode plots. Further, Bode plots for groups A and B were compared to the Bode plot for the optimum transfer function in order to ascertain whether or not any changes were in correspondence with the prediction of more optimal performance for the experiment II conditions. A summary of such comparisons is as follows:

1) There is no significant difference in the phase and gain margins for group A between experiments I and II. A comparison of group A with the optimum shows that the phase and gain margins are below optimum.

2) For group B, the phase and gain margins are significantly higher for experiment II than they were for experiment I. The gain margins increase by about a factor of 4 and the phase margins increase by a factor of 1.5. Group B exhibits phase margins near optimal but gain margins of about three times the optimal value for experiment II.

These comparisons do not provide support for hypothesis 4. It is noted, however, that a comparison based upon gain and phase margins is not strictly sufficient to encompass all of the important aspects of system behavior.

Table X

MEAN VALUES OF E_s AND TF PARAMETERS FOR TRIALS 95 THROUGH 100[a]

Subject	X Axis					Y Axis				
	E_s	K_p Deg/cm	T_L Sec.	T_N+T_I Sec.	$T_N \cdot T_I$ Sec.^{2}	E_s	K_p Deg/cm	T_L Sec.	T_N+T_I Sec.	$T_N \cdot T_I$ Sec.^{2}
Group A ($K_m = 1$; $K_s = 1$ cm/v)										
G	.0254	132.58	63.98	0.00	0.35	.0509	86.91	93.71	0.08	0.42
N	.0277	123.87	64.30	0.42	0.54	.0494	88.13	76.32	0.38	0.54
K	.0300	108.00	74.17	2.70	0.78	.0469	94.75	80.75	2.12	0.84
M	.0664	75.87	85.66	7.86	0.92	.0957	54.62	115.23	9.22	1.14
H	.0457	91.36	70.91	3.20	0.85	.0757	71.39	98.94	6.44	0.84
Means	.0390	106.34	71.80	2.84	0.69	.0637	79.16	92.97	3.65	0.76
Group B ($K_m = .5$; $K_s = 2$ cm/v)										
L	.0141	215.58	45.30	0.00	0.53	.0175	155.28	65.19	0.00	0.49
R	.0251	89.54	94.05	1.16	0.40	.0462	87.87	92.53	0.84	0.49
J	.0351	131.60	66.76	0.00	0.57	.0502	98.93	90.30	0.00	0.49
B	.0354	76.64	101.14	9.02	0.63	.0946	52.19	134.92	9.42	0.88
W	.0749	66.75	101.85	4.78	0.74	.1024	43.25	133.86	5.58	0.84
Means	.0369	116.02	81.82	2.99	0.55	.0622	87.50	103.36	3.17	0.64
Comparison	E_s	K_p	T_L	T_N+T_I	$T_N \cdot T_I$	E_s	K_p	T_L	T_N+T_I	$T_N \cdot T_I$
	A > B	B > A	B > A	B > A	B < A	A > B	B > A	B > A	B < A	B < A
T Values[b]	6	6.5	4	4	3	7	8	4	5	2

[a] All TF values in table have been multiplied by 100. Each table entry is the mean value for trials 95 through 100.

[b] None of these obtained T values for the Wilcoxon Matched Replicates Test is significant.

GENERAL DISCUSSION AND CONCLUSIONS

Lowering the gain(s) of machine component(s) of the tracking network, results in a compensatory change in the operator's gain, a larger range of stick movements, and a lower system error score; it does not, however, effect the man's ability to adopt a more optimum transfer function. Redistribution of gains from one machine component to another, with no overall change, has no effect on any of the following: the operator's gain, his error performance, or his ability to optimize his transfer function; the redistribution does, however, result in an appropriate change in the control stick movement range.

It is concluded that man can quite accurately adjust his gain to compensate for changes in machine gain. It is also concluded that increase in stick movement range from a very small value to a moderately larger value improves system error performance but any additional increase in movement range has no further effect on system accuracy.

SECTION IV

EXPERIMENT III

PURPOSE

This section presents a study designed to investigate, in a preliminary way, the degree of similarity between the operator's transfer functions for single and dual axis tasks for different quickening conditions. The transfer function, by definition, treats a system in which input and output are each defined along one dimension. The values on this dimension are amplitude variations with time. A question thus arises in regard to the operator's transfer function determined in a <u>two-dimensional</u> task, viz., "Is a one-dimensional transfer function derived within a two-dimensional display-control task the same as the function that would have been derived within a pure one-dimensional task?" The answer to this question must be known in order to permit a general interpretation of the results of studies involving two-dimensional tracking tasks -- especially as they relate to the one-dimensional transfer function research with which the literature now abounds.

In order to investigate properly the question raised above, one must be able to isolate those factors (if any) which induce a negative answer to the question. The prime control test, of course, is to obtain and directly compare human transfer functions for both single and dual axis performance. Let us suppose, however, that the results of such a comparison should indicate that the single and dual axis transfer functions differ from one another. There are two possible factors which could account for a difference in performance. First, just the movement of the error signal in one axis may constitute a form of visual "noise" that influences performance in controlling the other axis. A control condition, in this instance, would consist of a one-dimensional control, two-dimensional display task. In such a task, the operator would control the displayed error signal in one axis while error signal movement would be displayed but not controlled by him in the second axis. This will be referred to as the "noise" control condition. The transfer function for such a task can then be compared to those for the conventional single and dual axis tasks, thus, permitting one to isolate the possibly different effects of the number of axes being controlled (task load) and visual noise.

A second factor relevant to a single vs. dual axis comparison is the degree of symmetry of the quickening levels for the two axes during dual coordinate tracking. Conceivably, the transfer functions for the single and dual axis cases may be similar when the dual task entails symmetric quickening in the two axes and dissimilar when the dual task presents a symmetric quickening in the two axes. One can consider the degree of symmetry of the quickenings for the two axes during a dual tracking task as constituting a task complexity dimension. The requirement to adopt different transfer functions for the two axes has been shown to adversely effect performance (ref 3). Thus, the investigation of various combinations of display axis quickening is required for a true understanding of quickening influences in a two-axis or two-dimensional tracking system.

EXPERIMENTAL PROCEDURE

Subjects were given tasks falling into three basic categories: (1) single coordinate control with second coordinate completely absent; (2) single coordinate control with second coordinate displayed but not controlled by the subject; and (3) dual coordinate control. Three quickening conditions were investigated: FQ_1, PQ, and NQ. For task category (1) there were six different single axis conditions: FX:-,[7] PX:-, NX:-, -:FY, -:PY, and -:NY. For task categories (2) and (3) there were nine possible combinations of quickening for the two coordinates X and Y: FX:FY,[8] PX:PY, NX:NY, FX:NY, FX:PY, PX:NY, NX:FY, PX:FY, and NX:PY. The particular combinations of conditions studied in this experiment are presented in figure 13.

The experiment was conducted in three phases, each phase being devoted to a particular task category. Four subjects (K, L, N, and R) participated in all three phases of the experiment. The same general experimental procedure used in experiment I was followed.

Phase I: Single Coordinate Control - Second Coordinate Absent

During this phase each subject completed a total of six sessions of approximately 90 minutes duration each. Subjects were first given 20 training trials on each of the following six conditions: FX:-, PX:-, NX:-, -:FY, -:PY, and -:NY. They were subsequently given an additional ten trials for each of the six conditions. The mean scores for the last block of five trials were used as the test data. The order of presentation of the quickening levels and axes was counterbalanced over the four subjects.

Phase II: Single Coordinate Control with Second Coordinate Displayed But Not Controlled

During this phase each subject completed a total of ten sessions of approximately 90 minutes duration each. Subjects were given 30 trials for each of the following combinations of quickening levels and axes:

---

[7] FX:- signifies full quickening in the lateral (X) axis and no longitudinal (Y) axis displayed or control task.

[8] FX:FY signifies full quickening in both lateral (X) axis and longitudinal (Y) axis.

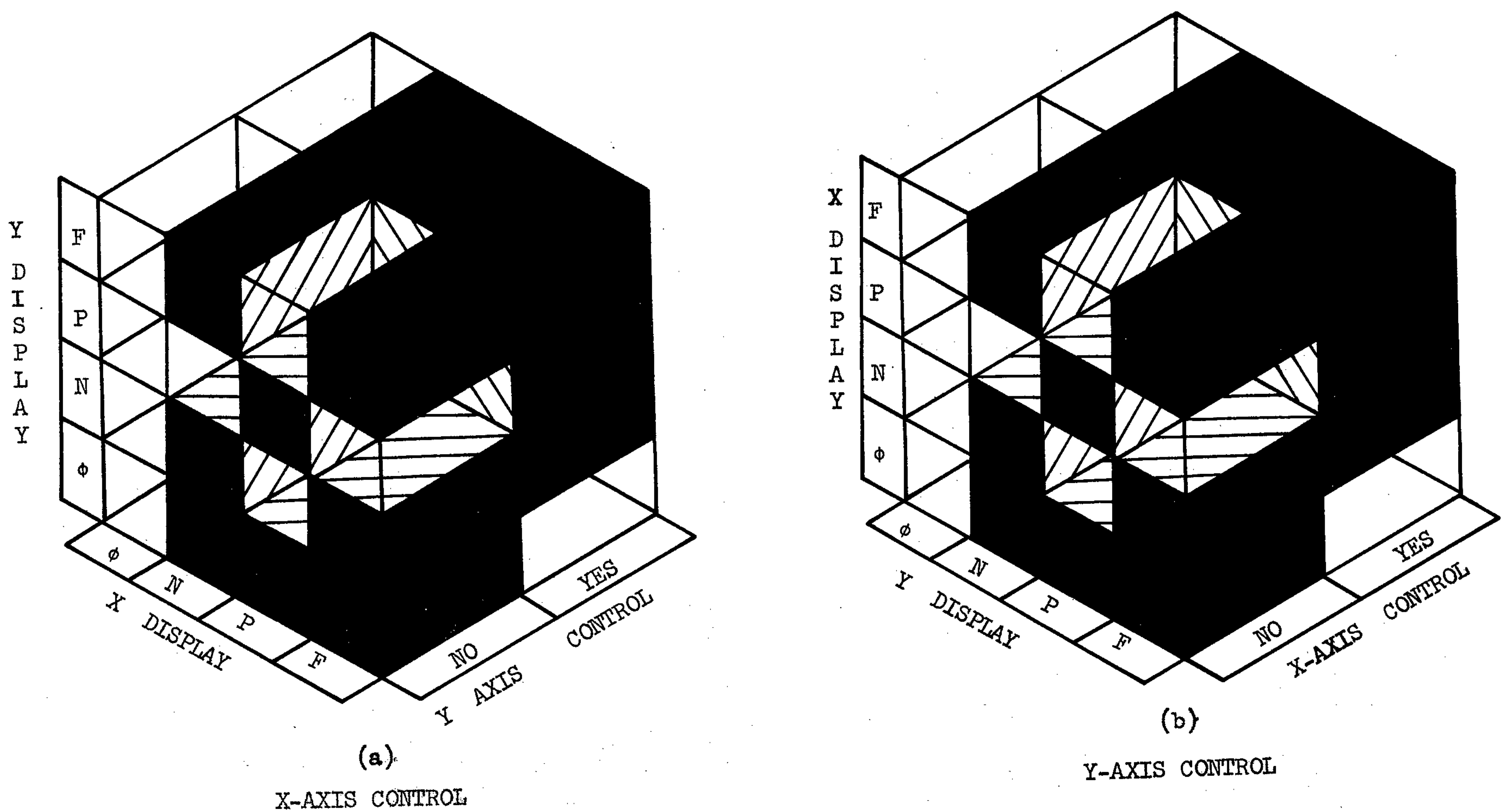


Figure 13. Matrices illustrating the experimental conditions for the comparisons of single and dual axis performance. Only the filled cells in the two matrices were run. There are four levels of display possible for each axis, viz., Φ: No display; N: No quickening; P: Partial quickening; and F: Full Quickening. For each axis there are conditions when the axis is displayed but not controlled. (a) In this matrix, the X axis was always controlled. (b) In this matrix the Y axis was always controlled

FXD:FY, NXD:FY, PXD:PY, FXD:NY, NXD:NY, FX:FYD, FX:NYD, PX:PYD, NX:FYD, and NX:NYD. (The designation D signifies that error in the dimension is displayed but is not controllable by the operator.) The axis not controlled by the operator was stabilized by the Manalog circuit which was instrumented to have the specific transfer function adopted by the particular operator in experiment I for the particular quickening level being studied. The mean scores for the last block of five trials were used as the test data. The order of presentation of the ten experimental treatments was counterbalanced over the four subjects.

Phase III: Dual Coordinate Control

During this phase, each subject completed a total of eight sessions of approximately 90 minutes duration each. Ten training trials were given for each of the three symmetric quickening conditions: FX:FY, PX:PY, and NX:NY; and twenty training trials were given for each of the nonsymmetric quickening conditions: FX:PY, FX:NY, PX:NY, PX:FY, NX:FY, and NX:PY. The subjects were subsequently given an additional ten trials for each of the nine conditions. The mean scores for the last block of five trials were used as the test data. The order of presentation of the nine experimental treatments was counterbalanced over subjects.

RESULTS AND DETAILED DISCUSSION

The results of the single versus dual axis comparisons of this experiment are summarized in tables XI through XVIII. Tables XI through XIV treat single versus dual axis comparisons for symmetric quickening and tables XV through XVII treat single versus dual axis comparison for nonsymmetric quickening. It is noted that in each of these tables, coefficients for the X axis are presented on the left and coefficients for the Y axis on the right. In all cases, single versus dual axis comparisons were evaluated statistically for each of these sets of coefficients.

It was originally planned that coefficients would be collapsed over "axes" in order to offset the sensitivity loss expected on the basis of an N = 4. However, inspection of tables XI through XVIII contraindicated such a procedure due to the frequency of reversal of relationship over "axes." In consequence, the following procedure was used. An overall evaluation of the differences between the mean values of the TF coefficients for the three different conditions for each quickening level (within an "axis") was made by use of the Friedman χ_r^2 test. It was decided that only those relationships adjudged significant for both of the axes would be treated as sufficiently stable to merit confidence. This decision was based upon the fact that there seemed to be no reason to predict differential relationships over "axes" and upon consideration of the low power associated with N = 4.

Table XI

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF GAIN COEFFICIENT, K_p ~ DEG/CM X 100

Symmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:FY	FX:FYD	χ_r^2	P	Subject	- :FY	FX:FY	FXD:FY	χ_r^2	P
K	70.15	55.48	25.86			K	50.47	43.74	28.14		
L	53.22	24.06	39.08			L	40.12	27.68	31.86		
N	31.26	44.77	37.83			N	22.38	39.04	30.16		
R	44.78	48.20	41.06			R	42.74	40.24	40.72		
Means	49.86	43.12	35.96	1.5 =	.653	Means	38.93	37.68	32.72	1.5 =	.653
Subject	PX: -	PX:PY	PX:PYD	χ_r^2	P	Subject	- :PY	PX:PY	PXD:PY	χ_r^2	P
K	41.02	36.91	32.77			K	32.63	31.27	27.74		
L	41.15	40.50	41.04			L	39.64	30.98	40.74		
N	34.56	38.31	31.86			N	30.86	31.18	24.40		
R	40.46	39.90	18.98			R	44.64	31.61	38.53		
Means	39.30	38.90	31.16	4.5 =	.125	Means	36.94	31.26	32.85	1.5 =	.653
Subject	NX: -	NX:NY	NX:NYD	χ_r^2	P	Subject	- :NY	NX:NY	NXD:NY	χ_r^2	P
K	37.86	26.38	14.18			K	20.85	19.45	18.78		
L	54.33	50.57	32.06			L	28.98	31.10	31.28		
N	31.46	34.97	27.79			N	23.25	21.76	14.78		
R	31.34	16.10	14.72			R	21.77	14.19	25.90		
Means	38.50	32.00	22.19	6.5 =	.042	Means	23.71	21.62	22.68	0.5 =	.931

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
D: Displayed But Not Controlled
X: Lateral Axis
Y: Longitudinal Axis

Table XII

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF LEAD COEFFICIENT, T_L ~ SECONDS

Symmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:FY	FX:FYD	χ_r^2	P	Subject	- :FY	FX:FY	FXD:FY	χ_r^2	P
K	.0134	.0126	.0310			K	.0135	.0068	.0388		
L	.0133	.1974	.0000			L	.0000	.0058	.0000		
N	.0000	.0054	.0000			N	.0000	.0074	.0054		
R	.0146	.0062	.0094			R	.0057	.0087	.0090		
Means	.0103	.0552	.0101	.125	>.931	Means	.0048	.0072	.0133	2.375	>.27
Subject	PX: -	PX:PY	PX:PYD	χ_r^2	P	Subject	- :PY	PX:PY	PXD:PY	χ_r^2	P
K	.0503	.1319	.0930			K	.1281	.1663	.2840		
L	.0272	.0200	.0660			L	.0315	.0655	.0765		
N	.0194	.0303	.1025			N	.0832	.1302	.1290		
R	.0438	.0248	.2142			R	.0400	.0421	.0656		
Means	.0352	.0518	.1189	3.5	= .273	Means	.0707	.1010	.1388	6.5	= .042
Subject	NX: -	NX:NY	NX:NYD	χ_r^2	P	Subject	- :NY	NX:NY	NXD:NY	χ_r^2	P
K	.3460	.5277	1.1786			K	.6612	.6530	.8218		
L	.3212	.3081	.6907			L	.7432	.5640	1.0334		
N	.4076	.4564	.6381			N	.6477	.7188	.9142		
R	.4825	.8888	.9264			R	.7931	.9246	.6596		
Means	.3893	.5452	.8584	6.5	= .042	Means	.7113	.7151	.8572	1.1	>.653

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
D: Displayed But Not Controlled
X: Lateral Axis
Y: Longitudinal Axis

Table XIII

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF LAG COEFFICIENTS ($T_N + T_I$) ~ SECONDS

Symmetric Quickening

Coefficients for the X Axis

Subject	FX: -	FX:FY	FX:FYD	χ_r^2	P
K	.3236	.2514	.0956		
L	.2026	.1020	.0820		
N	.1258	.2282	.1136		
R	.1910	.1654	.1308		
Means	.2108	.1868	.1055	6.5	= .042

Subject	PX: -	PX:PY	PX:PYD	χ_r^2	P
K	.0306	.1256	.0178		
L	.0152	.0000	.0000		
N	.0236	.0272	.0322		
R	.0000	.0084	.0838		
Means	.0174	.0403	.0334	7.9	>.042

Subject	NX: -	NX:NY	NX:NYD	χ_r^2	P
K	.0000	.0490	.0272		
L	.0000	.0000	.0000		
N	.0000	.0000	.0000		
R	.0000	.0000	.0142		
Means	.0000	.0122	.0104	7.6	>.042

Coefficients for the Y Axis

Subject	- :FY	FX:FY	FXD:FY	χ_r^2	P
K	.2226	.2192	.1444		
L	.1344	.1124	.0514		
N	.0740	.2118	.0798		
R	.1310	.1186	.1148		
Means	.1405	.1655	.0976	3.5	= .273

Subject	- :PY	PX:PY	PXD:PY	χ_r^2	P
K	.0774	.1428	.1824		
L	.0000	.0324	.0000		
N	.0584	.1066	.0304		
R	.0000	.0098	.0000		
Means	.0340	.0729	.0532	3.5	= .273

Subject	- :NY	NX:NY	NXD:NY	χ_r^2	P
K	.0000	.0200	.0110		
L	.0000	.0000	.0000		
N	.0000	.0000	.0000		
R	.0000	.0000	.0000		
Means	.0000	.0050	.0028	0.5	= .931

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
D: Displayed But Not Controlled
X: Lateral Axis
Y: Longitudinal Axis

Table XIV

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF LAG COEFFICIENTS $(T_N \cdot T_I) \sim SEC^2 \times 100$

Symmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:FY	FX:FYD	χ_r^2	P	Subject	- :FY	FX:FY	FXD:FY	χ_r^2	P
K	0.05	0.03	1.15			K	0.15	0.33	1.19		
L	0.17	0.07	0.26			L	0.32	0.74	0.27		
N	0.50	0.02	0.48			N	0.42	3.06	0.63		
R	0.19	0.03	0.35			R	0.15	0.23	0.30		
Means	0.22	0.04	0.56	6.5 =	.042	Means	0.26	1.09	0.60	3.5 =	.273
Subject	PX: -	PX:PY	PX:PYD	χ_r^2	P	Subject	- :PY	PX:PY	PXD:PY	χ_r^2	P
K	0.33	0.33	0.35			K	0.38	0.43	0.34		
L	0.44	0.55	0.27			L	0.37	0.73	0.19		
N	0.46	0.49	0.37			N	0.59	0.67	0.49		
R	0.18	0.40	0.72			R	0.36	0.46	0.30		
Means	0.35	0.44	0.43	.5 =	.931	Means	0.42	0.57	0.33	8.0 >	.042
Subject	NX: -	NX:NY	NX:NYD	χ_r^2	P	Subject	- :NY	NX:NY	NXD:NY	χ_r^2	P
K	0.84	0.56	0.45			K	0.97	0.72	0.44		
L	0.52	0.43	0.33			L	0.45	0.35	0.24		
N	0.40	0.41	0.45			N	0.50	0.46	0.52		
R	0.28	0.39	0.54			R	0.41	0.46	0.36		
Means	0.51	0.45	0.44	0.0 =	1.0	Means	0.58	0.50	0.39	2.0 =	.431

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
D: Displayed But Not Controlled
X: Lateral Axis
Y: Longitudinal Axis

Table XV

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF GAIN COEFFICIENT, K_p ~ DEG/CM X 100

Nonsymmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:NY	NX:NYD	χ_r^2	P	Subject	- :FY	NX:FY	NXD:FY	χ_r^2	P
K	70.15	30.34	41.44			K	50.47	29.60	28.01		
L	53.22	38.48	43.56			L	40.12	27.38	40.25		
N	31.26	23.46	42.28			N	22.38	14.13	19.13		
R	44.78	30.16	42.04			R	42.74	20.44	33.92		
Means	49.86	30.61	42.33	6.5	=.042	Means	38.93	22.89	30.33	4.5	= .125

Subject	NX: -	NX:FY	NX:FYD	χ_r^2	P	Subject	- :NY	FX:NY	FXD:NY	χ_r^2	P
K	37.83	20.93	16.96			K	20.85	7.99	9.97		
L	54.33	55.36	39.14			L	28.98	30.85	31.44		
N	31.46	30.26	29.70			N	23.25	13.74	14.84		
R	31.34	21.33	13.02			R	21.77	13.08	15.12		
Means	38.50	31.97	24.71	6.5	=.042	Means	23.71	16.42	18.09	3.5	=.273

F: Full Quickening (FQ)
N: No Quickening (NQ)

D: Displayed But Not Controlled

X: Lateral Axis
Y: Longitudinal Axis

Table XVI

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF LEAD COEFFICIENT, T_L ~ SECONDS

Nonsymmetric Quickening

Coefficients for the X Axis

Subject	FX: -	FX:NY	FX:NYD	χ_r^2	P
K	.0134	.0028	.0030		
L	.0133	.0000	.0166		
N	.0000	.0106	.0286		
R	.0146	.0009	.0092		
Means	.0103	.0036	.0144	3.5=.273	

Subject	NX: -	NX:FY	NX:FYD	χ_r^2	P
K	.3460	.4974	.9860		
L	.3212	.2704	.5459		
N	.4076	.4108	.6048		
R	.4825	.6470	1.0499		
Means	.3893	.4564	.7966	6.5=.042	

Coefficients for the Y Axis

Subject	- :FY	NX:FY	NXD:FY	χ_r^2	P
K	.0135	.0090	.0000		
L	.0000	.0143	.0138		
N	.0000	.0229	.0000		
R	.0057	.0002	.0000		
Means	.0048	.0116	.0034	2.62 > .273	

Subject	- :NY	FX:NY	FXD:NY	χ_r^2	P
K	.6612	1.3904	1.6366		
L	.7432	.5620	.7188		
N	.6477	.9053	1.0209		
R	.7931	.9784	1.0172		
Means	.7113	.9590	1.0984	3.5 = .273	

F: Full Quickening (FQ)
N: No Quickening (NQ)

D: Displayed But Not Controlled

X: Lateral Axis
Y: Longitudinal Axis

Table XVII

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF COEFFICIENTS ($T_N + T_I$) ~ SECONDS

Nonsymmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:NY	FX:NYD	χ_r^2	P	Subject	- :FY	NX:FY	NXD:FY	χ_r^2	P
K	.3236	.1430	.1416			K	.2226	.1326	.1014		
L	.2026	.1516	.1310			L	.1344	.0802	.0904		
N	.1258	.0864	.2196			N	.0740	.0660	.0502		
R	.1910	.0652	.1624			R	.1310	.0638	.1110		
Means	.2108	.1116	.1636	3.5 =	.273	Means	.1405	.0856	.0882	6.0 =	.069
Subject	NX: -	NX:FY	NX:FYD	χ_r^2	P	Subject	- :NY	FX:NY	FXD:NY	χ_r^2	P
K	.0000	.0588	.0080			K	.0000	.2606	.0180		
L	.0000	.0000	.0000			L	.0000	.0000	.0000		
N	.0000	.0074	.0104			N	.0000	.0256	.0000		
R	.0000	.0246	.0046			R	.0000	.0146	.0000		
Means	.0000	.0227	.0046	3.9	>.125	Means	.0000	.0752	.0045	3.5 =	.273

F: Full Quickening (FQ)
N: No Quickening (NQ)

D: Displayed But Not Controlled

X: Lateral Axis
Y: Longitudinal Axis

Table XVIII

SINGLE VERSUS DUAL AXIS COMPARISON
OF TF LAG COEFFICIENTS $(T_N \cdot T_I) \sim SEC^2 \times 100$

Nonsymmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:NY	FX:NYD	χ_r^2	P	Subject	- :FY	NX:FY	NXD:FY	χ_r^2	P
K	0.05	0.77	0.47			K	0.15	0.95	0.62		
L	0.17	0.33	0.21			L	0.32	0.67	0.21		
N	0.50	0.54	0.68			N	0.42	0.89	0.67		
R	0.19	0.37	0.34			R	0.15	0.60	0.34		
Means	0.22	0.50	0.42	6.5	=.042	Means	0.26	0.78	0.46	6.5	= .273

Subject	NX: -	NX:FY	NX:FYD	χ_r^2	P	Subject	- :NY	FX:NY	FXD:NY	χ_r^2	P
K	0.84	0.70	0.49			K	0.97	1.35	0.53		
L	0.52	0.47	0.31			L	0.45	0.38	0.29		
N	0.40	0.55	0.39			N	0.50	0.64	0.45		
R	0.28	0.42	0.43			R	0.41	0.58	0.39		
Means	0.51	0.54	0.40	1.5	= .653	Means	0.58	0.74	0.42	6.5	= .042

F: Full Quickening (FQ)
N: No Quickening (NQ)
D: Displayed But Not Controlled
X: Lateral Axis
Y: Longitudinal Axis

Based upon the above rationale, no specific difference among the three experimental conditions was considered sufficiently stable to merit confidence. It is explicitly recognized that this interpretation is conservative. Nevertheless, in spite of certain suggestive aspects of the data, it is held that a more discriminating statement must await further data. The expectation is good that such data may reveal stable differences since 11 out of 40 of the χ_r^2 statistics reported in tables XI through XVIII were significant at the .05 level; the chance probability of this occurring is less than .001.[9]

Tables XIX through XXII present a comparison of error scores for the single versus dual axis comparisons. Only one of the eighteen χ_r^2's in those tables was significant at the .05 level. Again, however, the results are suggestive, see, e.g., table XXII, wherein the value of χ_r^2 has an associated probability of .069 for each "axis" under the NQ nonsymmetric conditions. This finding suggests the possibility of a quickening level-asymmetry interaction.

Tables XXIII and XXIV present a comparison of error scores for the various dual axis conditions. Table XXV presents the rank order of the mean error scores for the different dual axis conditions (the lower the rank, the lower the error score). For both axes and for both error scores the same rank order relationships emerge. The best scores are located on the diagonal of the matrix which represents the symmetric quickening combinations. Conversely, the results generally show that the more dissimilar the quickening conditions, the greater the error in performance. (There is only one exception to this finding in all four matrices of table XXV, viz., the X axis system error for FX:PY was greater than that for FX:NY.)

This experiment was designed to answer the questions: "Is a one-dimensional transfer function derived within a two-dimensional display-control task the same as the function that would have been derived within a pure one-dimensional task?" The results reported herein indicate that the answer to this question is "No." Unfortunately, the specific nature of the dual axis tasks were not revealed due to the low sensitivity of this study. It is fully expected that further research will result in a clarification of the specific nature of such differences.

The effects of nonsymmetric quickening were clearly shown. These results are consistent with those of reference 3, whose authors postulated that the more dissimilar the transfer functions required in the two axes,

---

[9] Based upon the procedure provided by Sakoda, Cohen, and Beall (ref 22).

Table XIX

SINGLE VERSUS DUAL AXIS COMPARISON OF SYSTEM ERROR SCORES, E_S

Symmetric Quickening

Coefficients for the X Axis						Coefficients for the Y Axis					
Subject	FX: -	FX:FY	FX:FYD	χ_r^2	P	Subject	- :FY	FX:FY	FXD:FY	χ_r^2	P
K	.1455	.1468	.1494			K	.1320	.1772	.1821		
L	.1423	.1080	.1421			L	.1455	.1645	.1904		
N	.1715	.1861	.1653			N	.1513	.1597	.1718		
R	.1790	.2008	.1543			R	.1749	.1688	.1789		
Means	.1596	.1604	.1528	0.5	.931	Means	.1509	.1676	.1808	6.5	.042
Subject	PX: -	PX:PY	PX:PYD	χ_r^2	P	Subject	- :PY	PX:PY	PXD:PY	χ_r^2	P
K	.1049	.1115	.1350			K	.0869	.1169	.1202		
L	.0943	.0790	.0766			L	.1073	.1160	.0931		
N	.1189	.0958	.1215			N	.1014	.1208	.1813		
R	.0822	.1008	.1172			R	.0981	.1096	.1085		
Means	.1001	.0968	.1126	1.5	.653	Means	.0984	.1158	.1258	3.5	.273
Subject	NX: -	NX:NY	NX:NYD	χ_r^2	P	Subject	- :NY	NX:NY	NXD:NY	χ_r^2	P
K	.0313	.0873	.0526			K	.0383	.0726	.0422		
L	.0100	.0157	.0070			L	.0179	.0266	.0262		
N	.0306	.0238	.0300			N	.0373	.0559	.0695		
R	.0328	.0434	.0612			R	.0474	.0754	.0351		
Means	.0262	.0426	.0377	0.5	.931	Means	.0352	.0576	.0432	4.5	.125

F: Full Quickening (FQ) N: No Quickening (NQ) X: Lateral Axis
P: Partial Quickening (PQ) D: Displayed But Not Controlled Y: Longitudinal Axis

Table XX

SINGLE VERSUS DUAL AXIS COMPARISON OF DISPLAY ERROR SCORES, E_D

Symmetric Quickening

Coefficients for the X Axis

Subject	FX: -	FX:FY	FX:FYD	χ_r^2	P
K	.0072	.0080	.0129		
L	.0112	.0204	.0175		
N	.0252	.0221	.0181		
R	.0188	.0137	.0145		
Means	.0156	.0161	.0158	0	1.0
Subject	PX: -	PX:PY	PX:PYD	χ_r^2	P
K	.0098	.0167	.0168		
L	.0108	.0093	.0105		
N	.0207	.0152	.0171		
R	.0120	.0089	.0261		
Means	.0133	.0125	.0176	3.5	.273
Subject	NX: -	NX:NY	NX:NYD	χ_r^2	P
K	.0313	.0873	.0526		
L	.0100	.0157	.0070		
N	.0306	.0238	.0300		
R	.0328	.0434	.0612		
Means	.0262	.0426	.0377	0.5	.931

Coefficients for the Y Axis

Subject	- :FY	FX:FY	FXD:FY	χ_r^2	P
K	.0054	.0131	.0217		
L	.0120	.0230	.0135		
N	.0228	.0208	.0207		
R	.0148	.0131	.0166		
Means	.0137	.0175	.0181	0.5	.931
Subject	- :PY	PX:PY	PXD:PY	χ_r^2	P
K	.0090	.0191	.0152		
L	.0086	.0175	.0069		
N	.0177	.0263	.0327		
R	.0236	.0126	.0164		
Means	.0147	.0189	.0178	0.5	.931
Subject	- :NY	NX:NY	NXD:NY	χ_r^2	P
K	.0383	.0726	.0422		
L	.0179	.0266	.0262		
N	.0373	.0559	.0695		
R	.0474	.0754	.0351		
Means	.0352	.0576	.0432	4.5	.125

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
D: Displayed But Not Controlled
X: Lateral Axis
Y: Longitudinal Axis

Table XXI

SINGLE VERSUS DUAL AXIS COMPARISON
OF SYSTEM ERROR SCORES, E_S

Nonsymmetric Quickening

E_S for the X Axis

Subject	FX: -	FX:NY	FX:NYD	χ_r^2	P
K	.1455	.1679	.1481		
L	.1423	.1320	.0485		
N	.1715	.1725	.1333		
R	.1790	.1856	.1991		
Means	.1596	.1645	.1322	> 3.5	.273

Subject	NX: -	NX:FY	NX:FYD	χ_r^2	P
K	.0313	.1317	.0294		
L	.0100	.0250	.0078		
N	.0306	.0936	.0344		
R	.0328	.0974	.0865		
Means	.0262	.0869	.0395	6.0	.069

E_S for the Y Axis

Subject	- :FY	NX:FY	NXD:FY	χ_r^2	P
K	.1320	.1721	.1625		
L	.1455	.1778	.1810		
N	.1513	.2089	.2577		
R	.1749	.1845	.1581		
Means	.1509	.1858	.1898	3.5	.273

Subject	- :NY	FX:NY	FXD:NY	χ_r^2	P
K	.0383	.2626	.0440		
L	.0179	.0485	.0089		
N	.0373	.1090	.0653		
R	.0474	.0836	.0269		
Means	.0352	.1259	.0363	6.0	.069

F: Full Quickening (FQ)
N: No Quickening (NQ)

D: Displayed But Not Controlled

X: Lateral Axis
Y: Longitudinal Axis

Table XXII

SINGLE VERSUS DUAL AXIS CONDITIONS
OF DISPLAY ERROR SCORES, E_D

Nonsymmetric Quickening

E_D for the X Axis						E_D for the Y Axis					
Subject	FX: -	FX:NY	FX:NYD	χ_r^2	P	Subject	- :FY	NX:FY	NXD:FY	χ_r^2	P
K	.0072	.0209	.0114			K	.0054	.0220	.0146		
L	.0112	.0140	.0144			L	.0120	.0244	.0111		
N	.0252	.0314	.0165			N	.0228	.0360	.0584		
R	.0188	.0237	.0022			R	.0148	.0259	.0207		
Means	.0156	.0225	.0111	3.5	.273	Means	.0137	.0271	.0262	4.5	.125
Subject	NX: -	NX:FY	NX:FYD	χ_r^2	P	Subject	- :NY	FX:NY	FXD:NY	χ_r^2	P
K	.0313	.1317	.0294			K	.0383	.2626	.0440		
L	.0100	.0250	.0078			L	.0179	.0485	.0089		
N	.0306	.0936	.0344			N	.0373	.1090	.0653		
R	.0328	.0974	.0865			R	.0474	.0836	.0269		
Means	.0262	.0869	.0395	6.0	.069	Means	.0352	.1259	.0363	6.0	.069

F: Full Quickening (FQ)
N: No Quickening (NQ)

D: Displayed But Not Controlled

X: Lateral Axis
Y: Longitudinal Axis

Table XXIII

COMPARISON OF E_S FOR THE DIFFERENT DUAL AXIS CONDITIONS

E_S for the X Axis

Subject	FX:FY	FX:PY	FX:NY	χ_r^2	P
K	.1468	.1382	.1679		
L	.1080	.1611	.1320		
N	.1861	.1844	.1725		
R	.2008	.1832	.1856		
Means	.1604	.1667	.1645	0.5	.931

Subject	PX:FY	PX:PY	PX:NY	χ_r^2	P
K	.1141	.1115	.1081		
L	.1060	.0790	.1086		
N	.1034	.0958	.0998		
R	.1234	.1008	.1438		
Means	.1117	.0968	.1151	3.5	.273

Subject	NX:FY	NX:PY	NX:NY	χ_r^2	P
K	.1317	.1034	.0873		
L	.0250	.0149	.0157		
N	.0936	.0324	.0238		
R	.0974	.0378	.0434		
Means	.0869	.0471	.0426	6.0	.069

E_S for the Y Axis

Subject	FX:FY	PX:FY	NX:FY	χ_r^2	P
K	.1772	.1432	.1721		
L	.1645	.1879	.1778		
N	.1597	.2026	.2089		
R	.1688	.1477	.1845		
Means	.1676	.1704	.1858	1.5	.653

Subject	FX:PY	PX:PY	NX:PY	χ_r^2	P
K	.1199	.1169	.1610		
L	.1192	.1160	.1069		
N	.1703	.1208	.1345		
R	.1214	.1096	.1347		
Means	.1327	.1158	.1343	3.5	.273

Subject	FX:NY	PX:NY	NX:NY	χ_r^2	P
K	.2626	.1290	.0726		
L	.0485	.0211	.0266		
N	.1090	.0545	.0559		
R	.0836	.1081	.0754		
Means	.1259	.0782	.0576	3.5	.273

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
X: Lateral Axis
Y: Longitudinal Axis

Table XXIV

COMPARISON OF E_D FOR THE DIFFERENT DUAL AXIS CONDITIONS

E_D for the X Axis

Subject	FX:FY	FX:PY	FX:NY	χ_r^2	P
K	.0080	.0111	.0209		
L	.0204	.0246	.0140		
N	.0221	.0225	.0314		
R	.0137	.0157	.0237		
Means	.0160	.0185	.0225	3.5	.273

Subject	PX:FY	PX:PY	PX:NY	χ_r^2	P
K	.0195	.0165	.0262		
L	.0143	.0093	.0180		
N	.0273	.0152	.0175		
R	.0172	.0089	.0212		
Means	.0196	.0125	.0210	6.5	.042

Subject	NX:FY	NX:PY	NX:NY	χ_r^2	P
K	.1317	.1034	.0873		
L	.0250	.0149	.0157		
N	.0936	.0324	.0238		
R	.0974	.0378	.0434		
Means	.0869	.0471	.0426	6.0	.069

E_D for the Y Axis

Subject	FX:FY	PX:FY	NX:FY	χ_r^2	P
K	.0131	.0142	.0220		
L	.0230	.0207	.0244		
N	.0208	.0336	.0360		
R	.0131	.0166	.0259		
Means	.0175	.0213	.0271	6.5	.042

Subject	FX:PY	PX:PY	NX:PY	χ_r^2	P
K	.0259	.0191	.0477		
L	.0294	.0175	.0200		
N	.0513	.0263	.0265		
R	.0233	.0126	.0296		
Means	.0325	.0189	.0310	6.0	.069

Subject	FX:NY	PX:NY	NX:NY	χ_r^2	P
K	.2626	.1290	.0726		
L	.0485	.0211	.0266		
N	.1090	.0545	.0559		
R	.0836	.1081	.0754		
Means	.1259	.0782	.0576	3.5	.273

F: Full Quickening (FQ)
P: Partial Quickening (PQ)
N: No Quickening (NQ)
X: Lateral Axis
Y: Longitudinal Axis

Table XXV

RANK ORDER OF MEAN ERROR SCORES FOR THE DIFFERENT DUAL AXIS CONDITIONS*

	${}_{X}^{E}{}_{S}$				${}_{Y}^{E}{}_{S}$		
	FY	PY	NY		FX	PX	NX
FX	1	3	2	FY	1	2	3
PX	2	1	3	PY	2	1	3
NX	3	2	1	NY	3	2	1

	${}_{X}^{E}{}_{D}$				${}_{Y}^{E}{}_{D}$		
	FY	PY	NY		FX	PX	NX
FX	1	2	3	FY	1**	2**	3**
PX	2**	1**	3**	PY	2	1	3
NX	3	2	1	NY	3	2	1

* Each cell entry in a matrix represents the rank order of the error score for the specified axis for the particular quickening combination indicated by the matrix marginal entries. The lowest rank represents the lowest error score. The Friedman two-way analysis of variance was used to test for differences between scores in any one row.

** The ranks in this row differ from each other at $p < .042$ ($\chi_r^2 = 6.5$).

the greater the performance deterioration. According to Chernikoff, Duey, and Taylor (ref 3), the greater the difference between control in the two coordinates, the less the information handling capacity or human bandwidth which remains for the performance of either task. Bandwidth may be said to be consumed by the act of shifting from one transfer function to another. As more of the human's capacity is thus dissipated with increasing dissimilarity between tasks, the accuracy of performance drops in both axes.

GENERAL DISCUSSION AND CONCLUSIONS

The human's transfer function probably differs for single and dual axis tracking conditions and it appears quite likely that larger differences will be found as the transfer functions required for the two axes of the dual task become more dissimilar. The extent of asymmetry of the quickening levels of the two coordinates of a dual axis tracking task effects both system and display error in a similar manner. Error is least when the quickening level used in the second axis is identical to that of the axis of primary interest; error increases as the similarity of the quickening levels decreases for the two axes. It is concluded that the greater the dissimilarity of the transfer functions required for the two axes of a two-dimensional tracking task, the greater the error.

SECTION V

SUMMARY

This research was concerned with the human's behavior in adapting his response mode to variations of certain conditions of a compensatory tracking task. Each of the following task conditions were evaluated in a separate experiment: quickening level, system gain, and task load. Adaptive behavior in response to the experimental treatments was assessed by evaluation of changes in the human's transfer function (TF) and error scores. Values of various human transfer function parameters served as indicants of the subject's response mode.

In each of the three reported studies, the tracking task required centering of an error signal on an oscilloscope display by use of an aircraft-type control stick. The forcing function consisted of a randomly generated signal with a one radian per second cutoff. The human's transfer function was measured on an analog computer by an implicit synthesis technique and was of the following assumed form:

$$TF = \frac{K_p\,(1 + T_L s)}{(1 + T_I s)(1 + T_N s)}\, e^{-\tau s}$$

The analog computer was also used to compute system error and display error scores.

EXPERIMENT I

This experiment was designed to investigate the influence of various display quickenings on system accuracy and to provide transfer function adjustment rules similar to those offered by previous investigators in the area of aircraft handling qualities. Four levels of quickening were investigated.

Certain fundamental relationships were observed between quickening level, the various transfer function parameters, and the degree to which the parameters approached the optimum value for error minimization. For the two full quickenings the operator selected the optimal TF form, a gain plus a pure lag form (i.e., having zero lead). For the partial quickening and no quickening conditions, the operator assumed the optimal TF form having a gain, a lead, and two lag terms. With practice the operator usually modified his TF so as to approach the "optimum TF."

The following quickening adjustment rules are offered in summary. First, for all conditions studied the human, in general, selects the correct TF form and adjusts his parameters toward the optimum required for a minimal mean squared tracking error. Second, the adaptive pattern

for no quickening during the learning phase indicates that the human first adapts the form of his transfer function to achieve good tracking of low frequencies and then adapts to achieve good tracking of the high frequencies while still maintaining good low frequency tracking. (For full and partial quickening, the human continues to emphasize the low frequencies during the learning period.) Lastly, the relationship of the operator's gain to input signal bandwidth has the form best described by a second order linear differential equation.

The quickening adjustment rules stated above show good agreement with the rules developed by other investigators in the context of aircraft handling qualities research. It was concluded that the human employs the same criteria to optimize his performance for different quickenings as he does for different aircraft control systems. It was also concluded that man adapts his transfer function during a compensatory tracking task in a manner very similar to that which a servo engineer would employ if he were to design a hardware replacement for the man.

The two types of error scores, system error and display error, gave directly contradictory order of merit for the full, partial, and no quickening conditions. The results of this study show that the more quickening, the greater the system error. This was undoubtedly due to the absence of an antibias network for the quickened conditions; such a network will be required in most of the practical applications of display quickening.

EXPERIMENT II

This experiment was designed to investigate the effects upon tracking performance of varying the values of various machine gains in the control loop.

The operator was observed to respond in a generally predictable manner to either lowering of machine gain or redistribution of gain from one machine component to another. Lowering of machine gain resulted in an accurate compensatory change in the operator's gain, a concomitant increase in stick movement range of appropriate magnitude, and an improved error score. Redistribution of gain from one machine component to another with no overall change effected neither the operator's gain nor his error score; the redistribution did, however, result in an appropriate change in the stick movement range. Bode plot analysis indicated that neither lowering nor redistribution of machine gain resulted in a more optimal transfer function.

It was concluded that an increase in control stick movement range from a very small value to a moderately larger value improves system error performance, but that any additional increase in movement range has no further effect on system accuracy.

EXPERIMENT III

This experiment was designed to investigate, in a preliminary way, the degree of similarity between the operator's transfer functions for single and dual axis tracking tasks for different quickening conditions.

In 11 out of 40 comparisons of transfer function coefficients, significant differences were found between the single and dual tasks. It was concluded that a one-dimensional TF derived within a conventional two-dimensional display-control task is probably not the same as the TF derived under pure one-dimensional control. An appreciation of the specific nature of the differences between TF's for the two conditions could not be attained due to the small N (4 subjects) that was used. Both system and display error scores were influenced similarly by the extent of asymmetry of quickening in the two coordinates of a dual tracking task. Error was least when the quickening level used in the second axis was identical to that of the axis of primary interest; error increased as the quickening levels for the two axes became more dissimilar.

It was concluded that the greater the dissimilarity of the transfer functions required for the two axes of a two-dimensional tracking task the greater the error.

A need for future research comparing transfer functions for single and dual axis tasks based on a larger N than used in this study is indicated.

APPENDIX I

CONTROL STICK SPECIFICATIONS

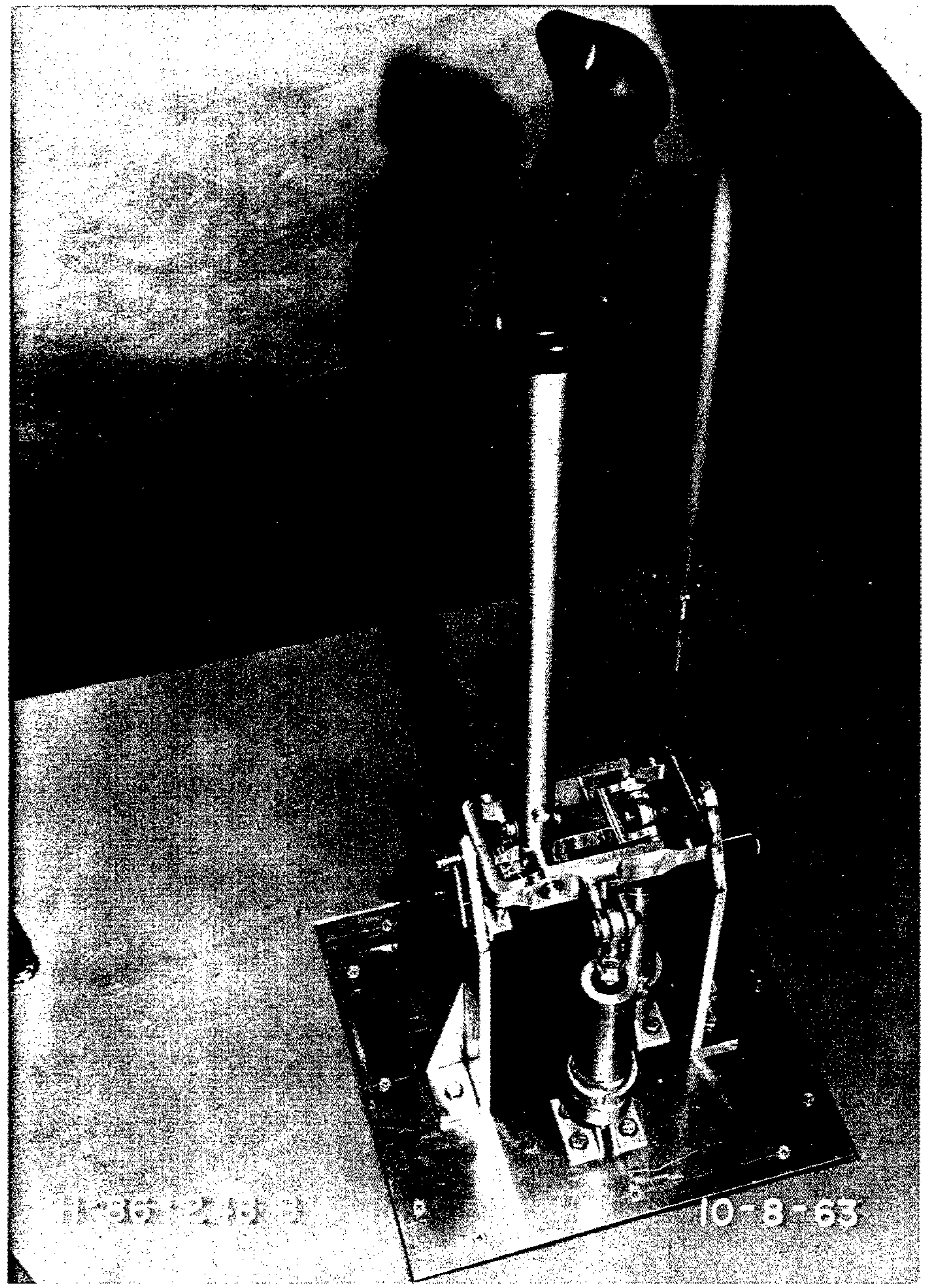


Figure 14. The Control Stick

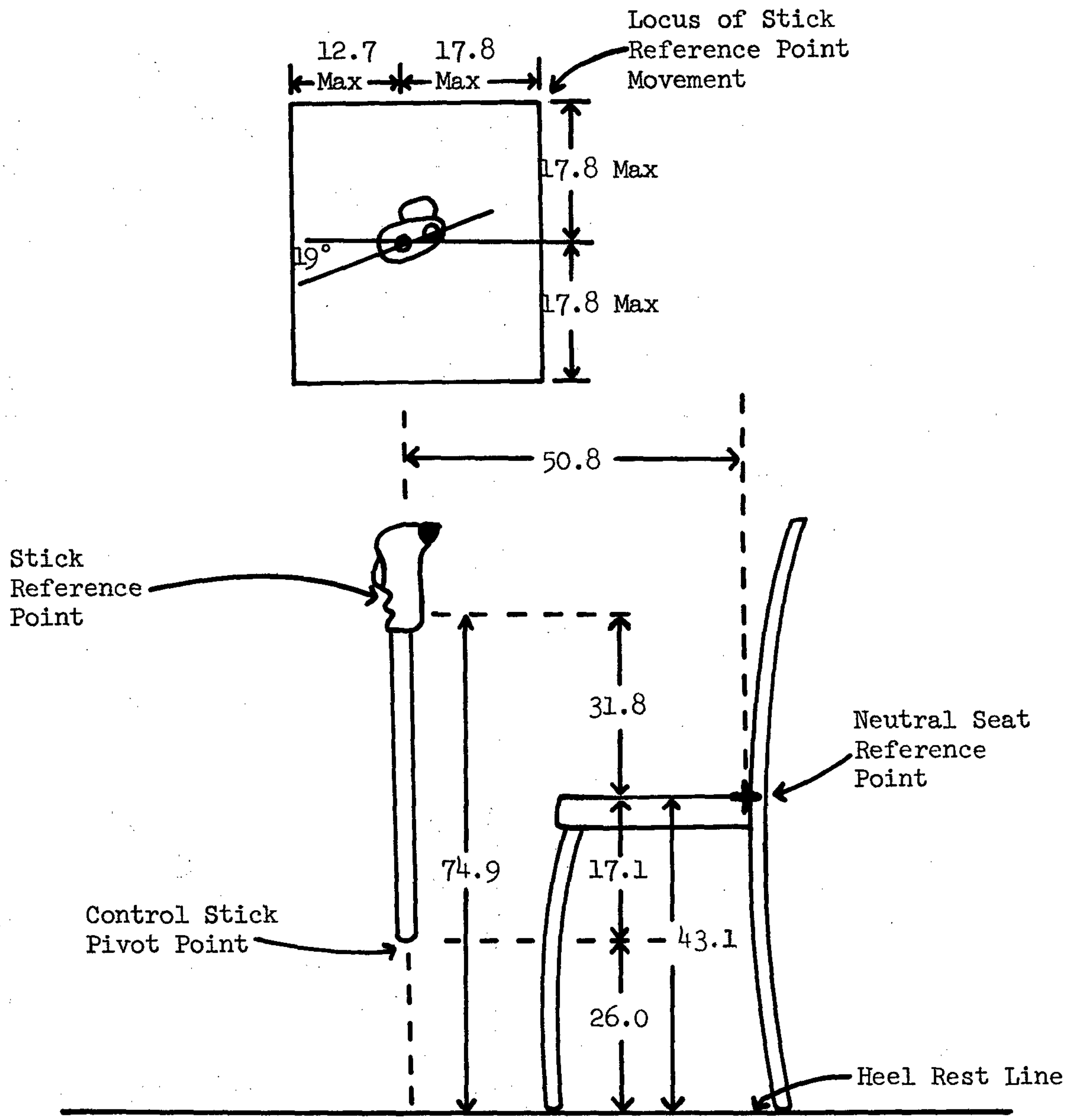


Figure 15. Control Stick Dimensions in Centimeters

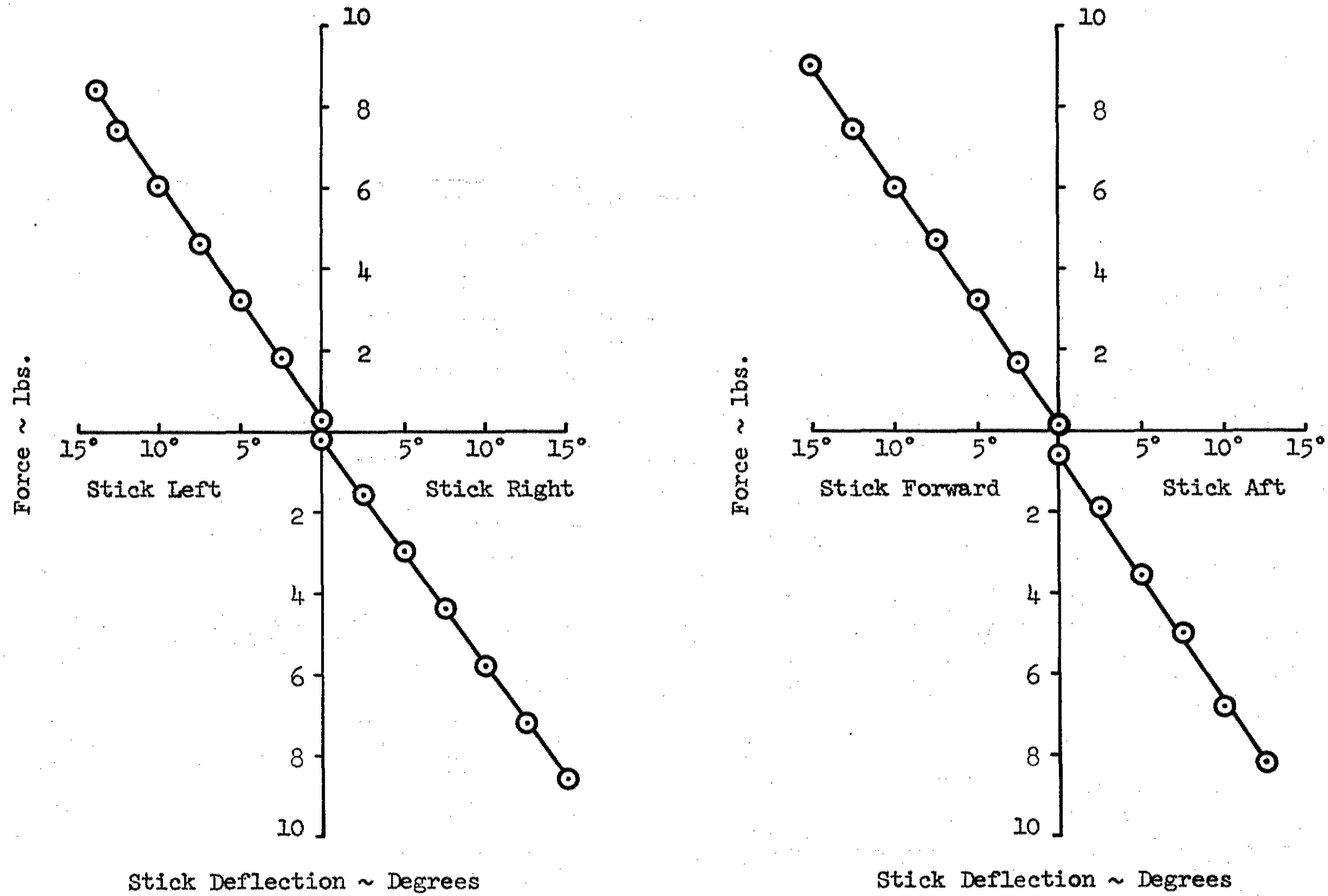
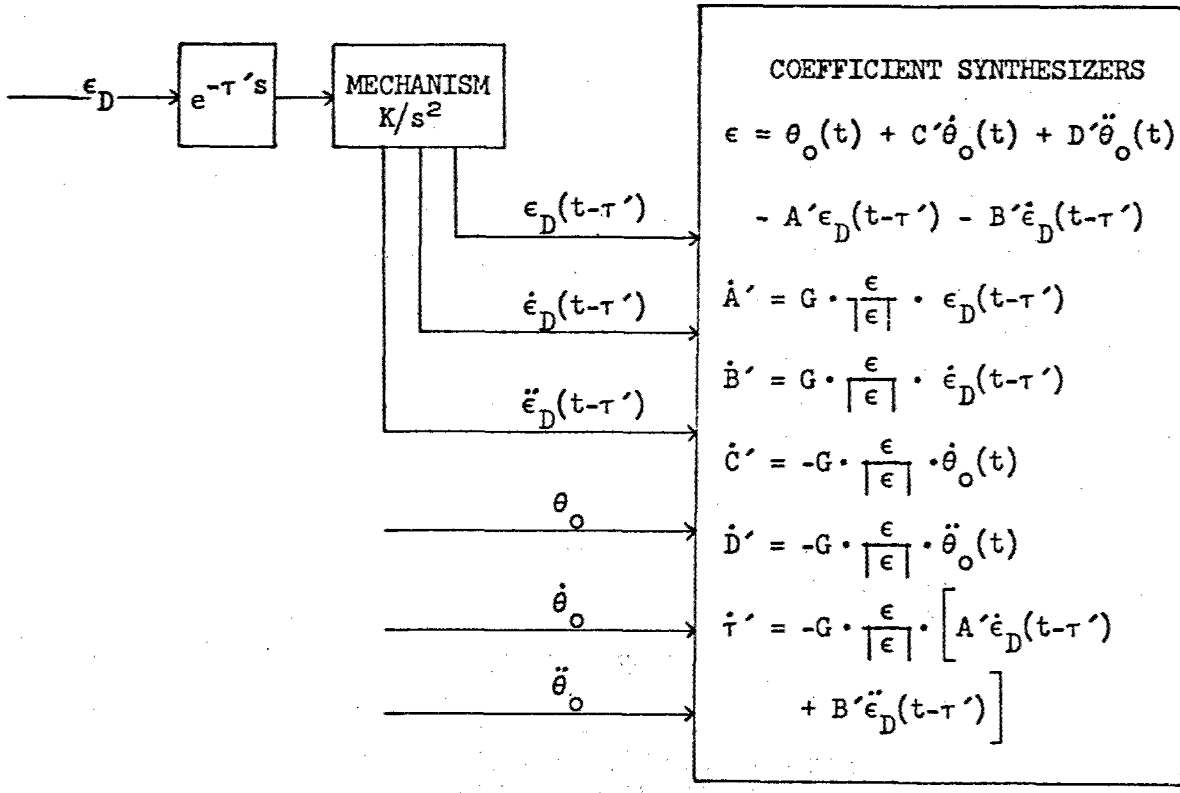


Figure 16. Control Stick Force/Displacement Curves

APPENDIX II

TRANSFER FUNCTION COEFFICIENT SYNTHESIS EQUATIONS AND COMPUTER DIAGRAMS



$e^{-\tau' s}$ By 2nd order PADÉ networks

$$\left[\frac{\tau^2 s^2 - 6\tau s + 12}{\tau^2 s^2 + 6\tau s + 12}\right]$$

Figure 17. Transfer function coefficient synthesis equations

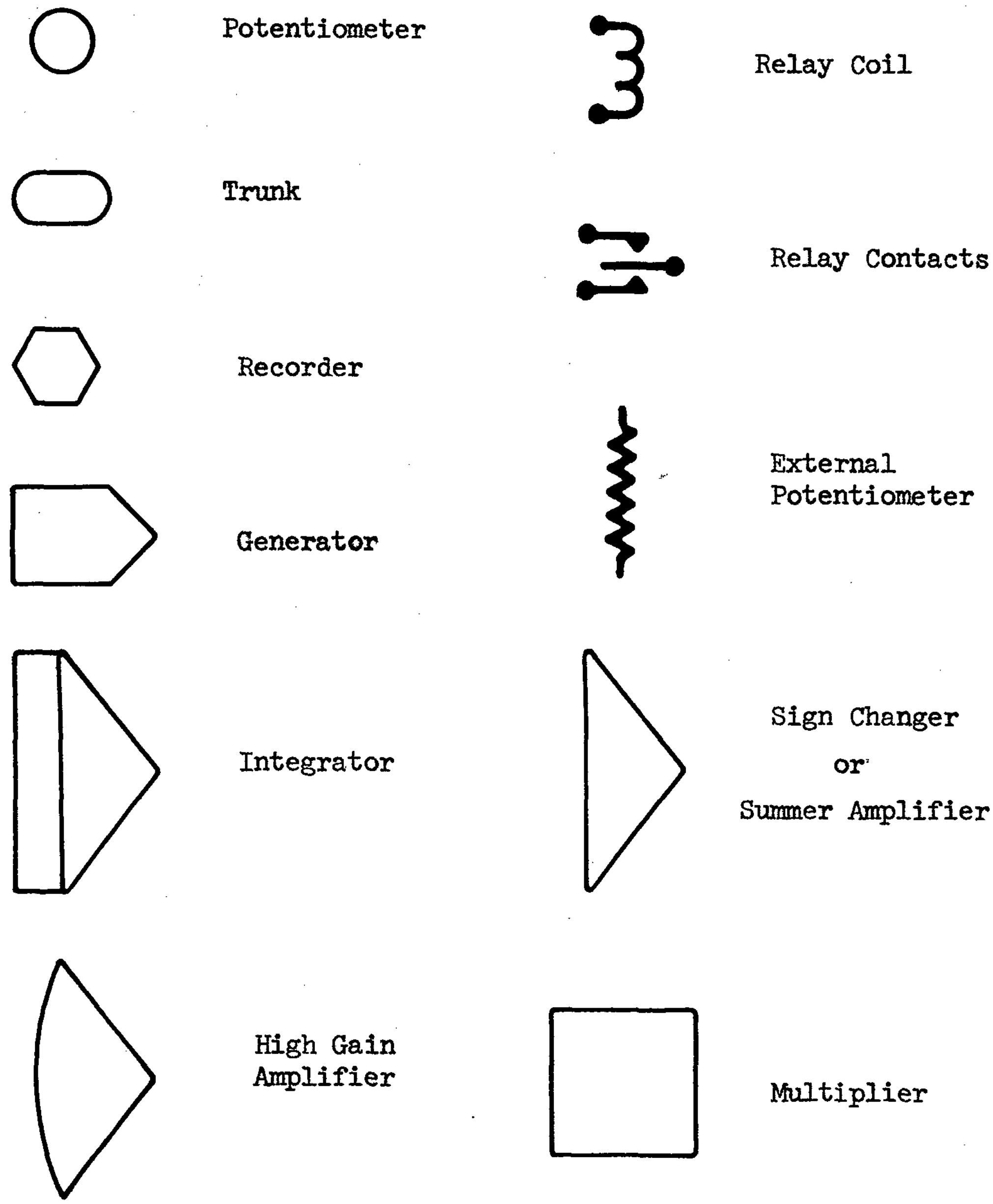
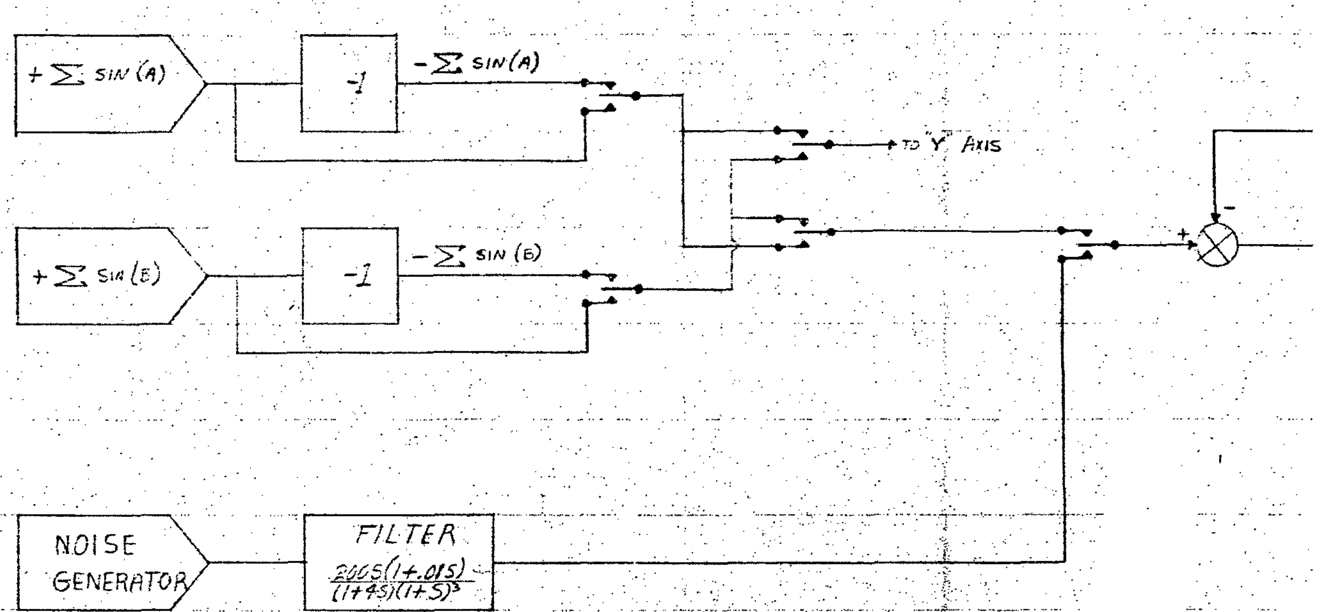
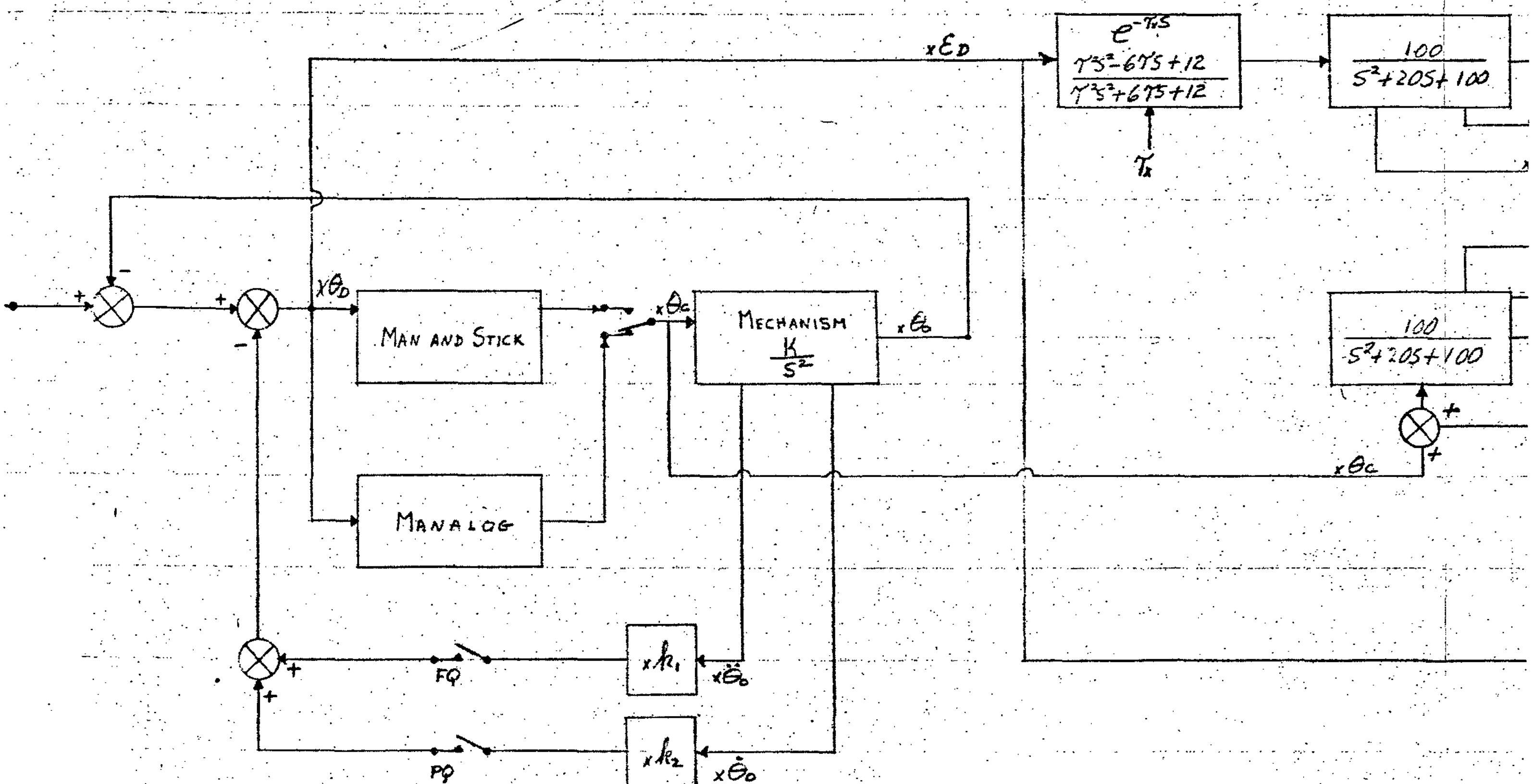


Figure 18. Wiring Diagram Symbols

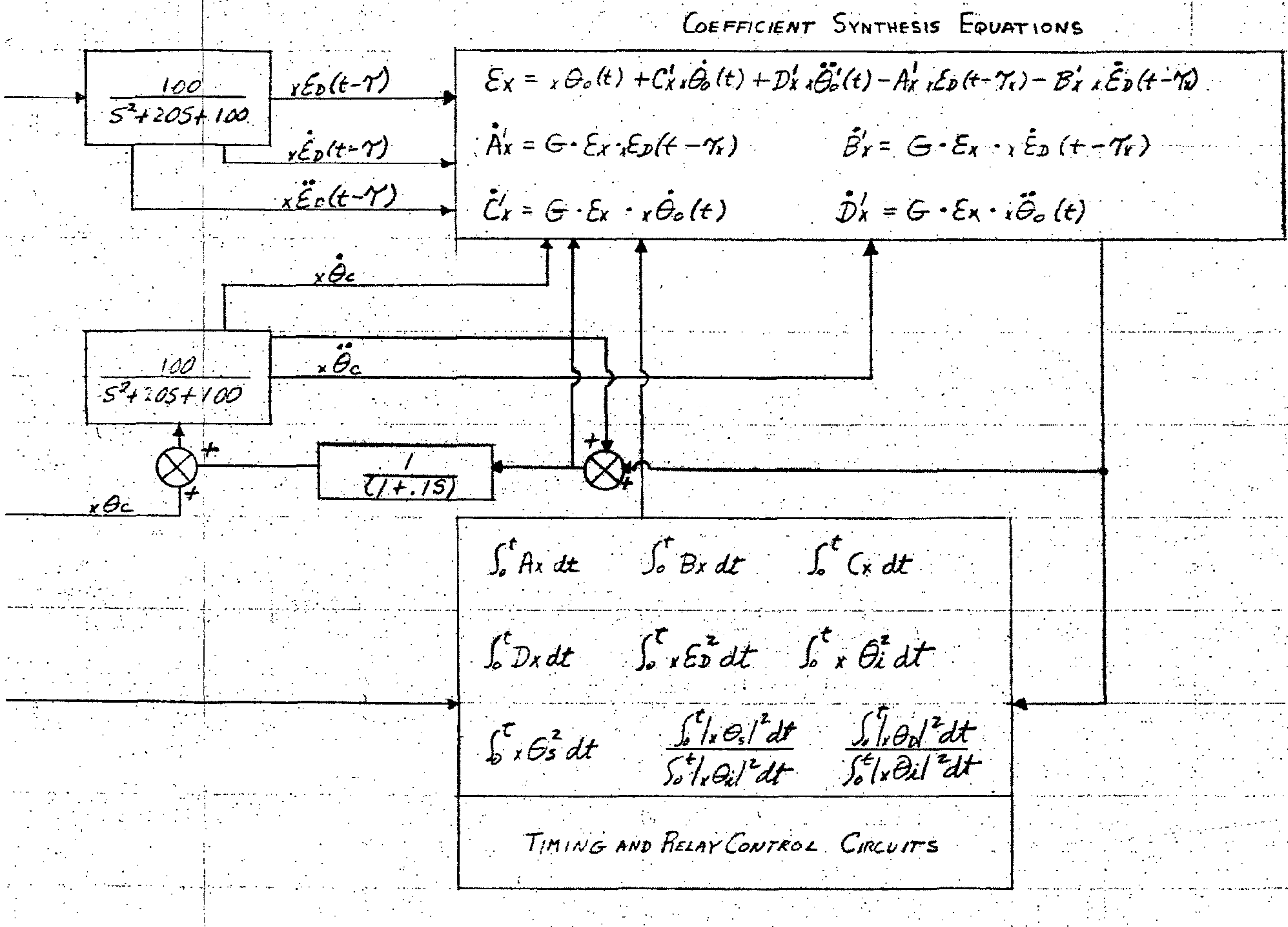
This Page Intentionally
Left Blank



$+\sum \sin(A)$
-1
$-\sum \sin(A)$
$+\sum \sin(B)$
-1
$-\sum \sin(B)$
TO 'Y' AXIS
NOISE GENERATOR
FILTER
$\frac{200S(1+.01S)}{(1+4S)(1+S)^3}$

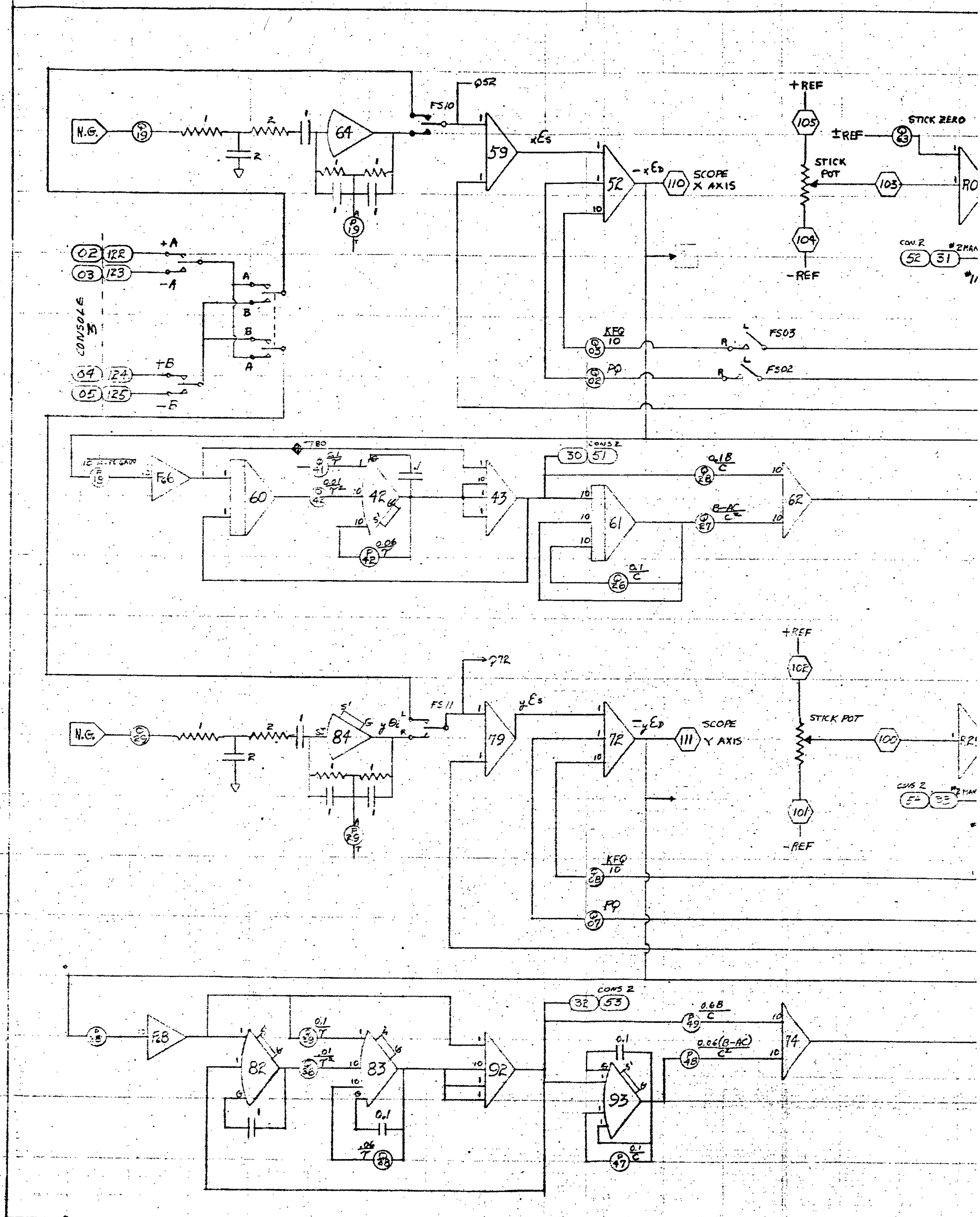


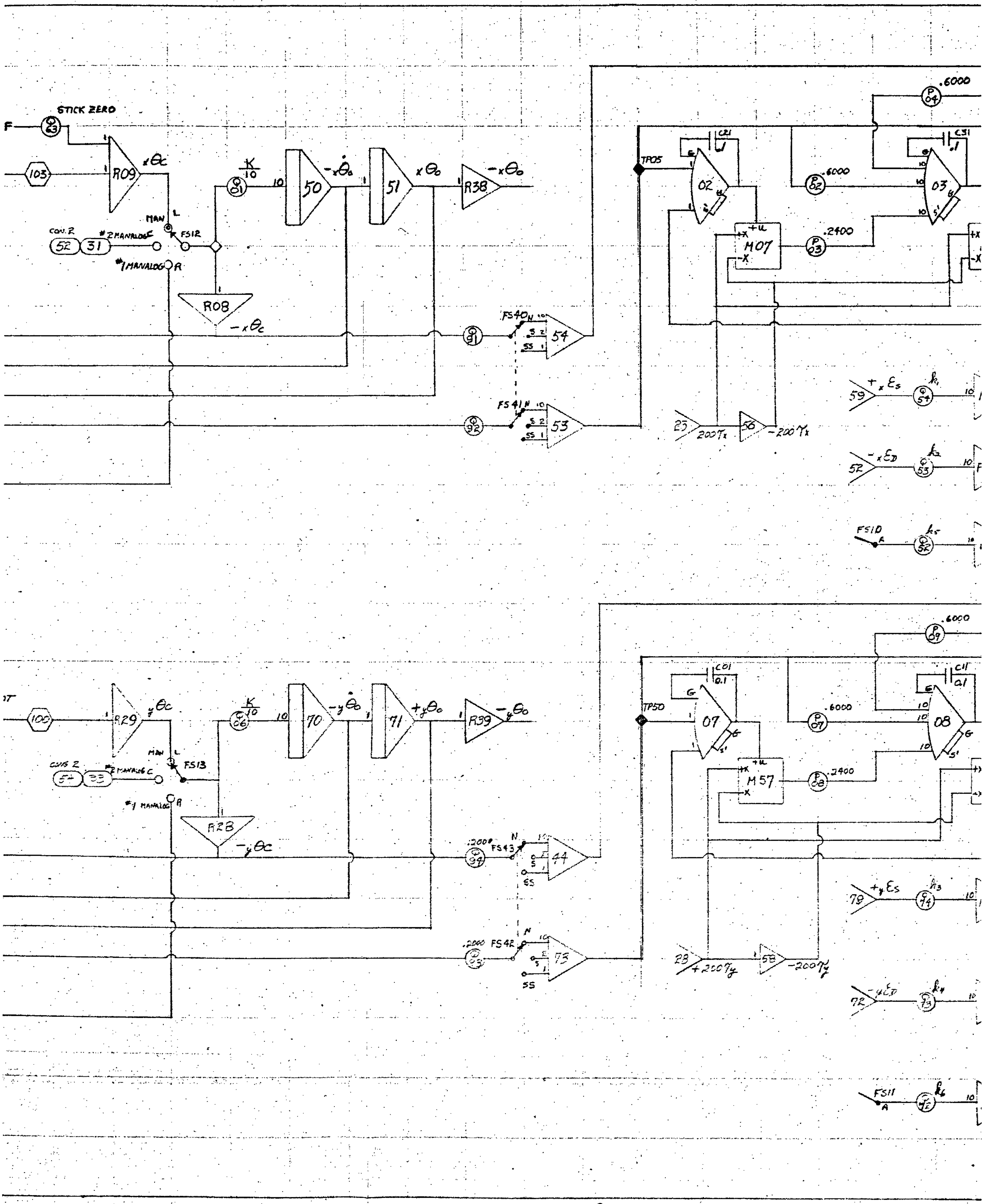
$x\mathcal{E}_D$
$e^{-\tau_x s}$
$\frac{\tau^2 s^2 - 6\tau s + 12}{\tau^2 s^2 + 6\tau s + 12}$
τ_x
$\frac{100}{s^2+20s+100}$
$x\theta_D$
Man and Stick
Manalog
$x\theta_c$
Mechanism
$\frac{K}{s^2}$
$x\theta_o$
$\frac{100}{s^2+20s+100}$
$x\theta_c$
FQ
PQ
xk_1
xk_2
$x\ddot{\theta}_o$
$x\dot{\theta}_o$

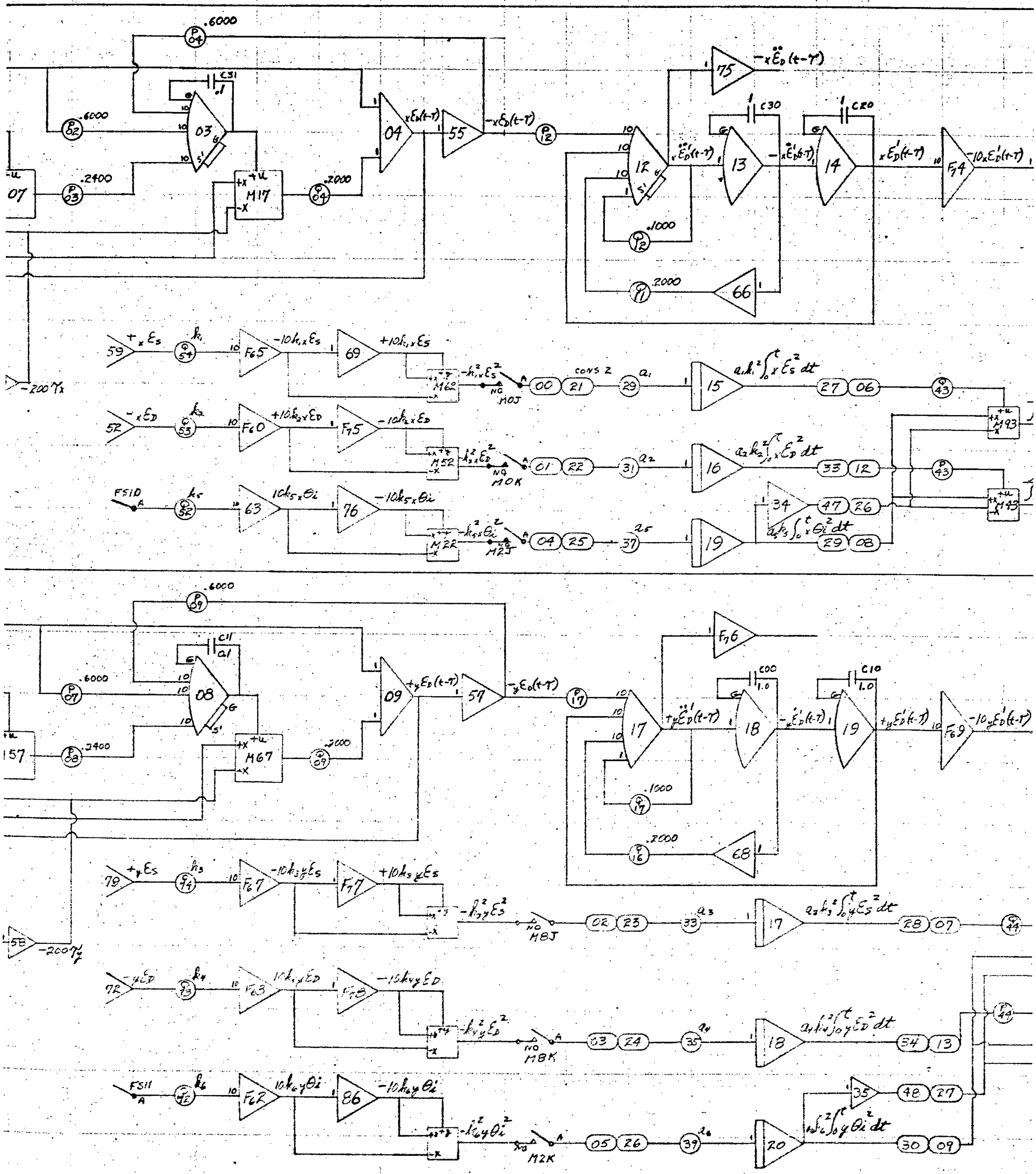


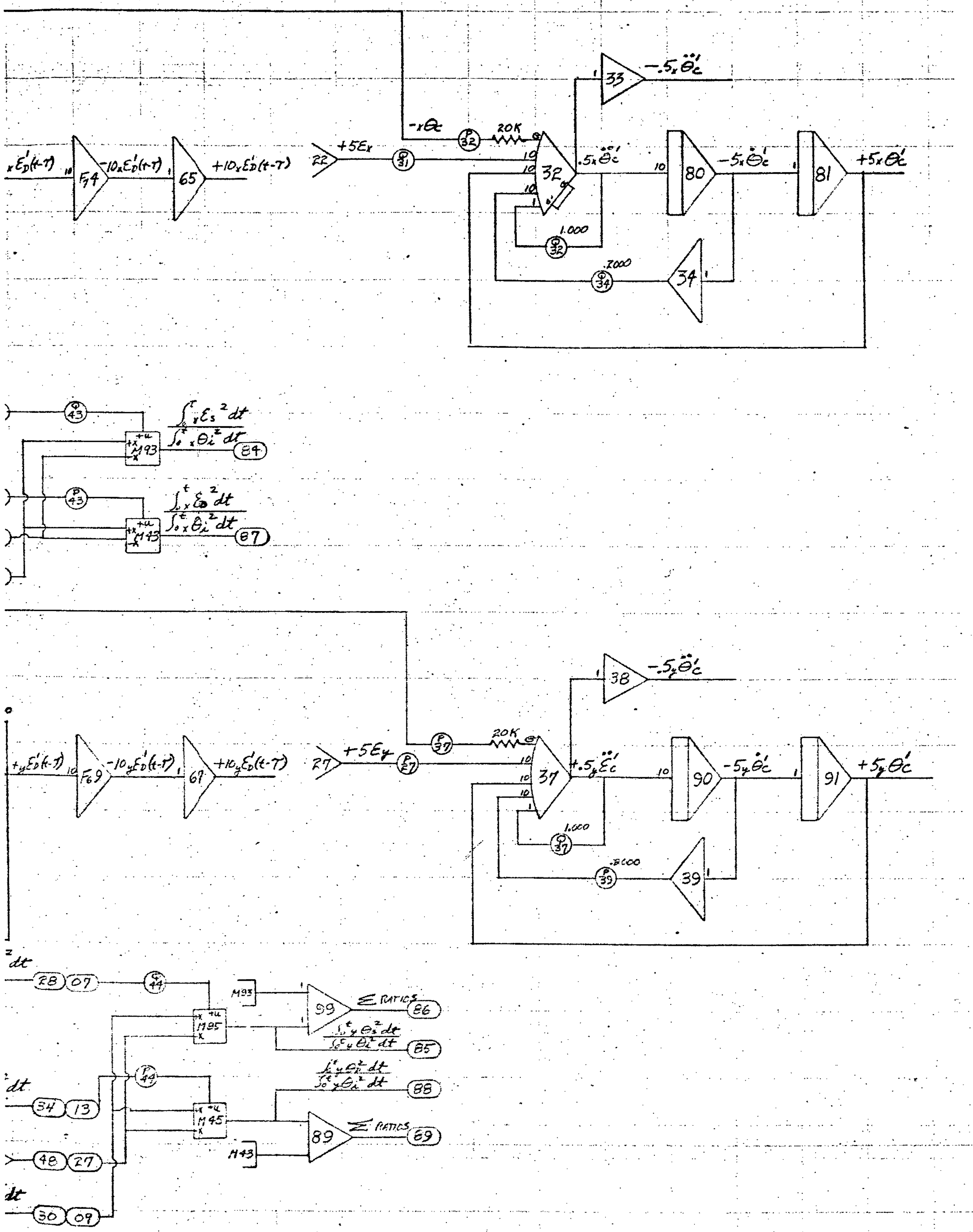
THE DIAGRAM AND EQUATIONS SHOWN ARE FOR "X" CHANNEL ONLY. "Y" CHANNEL IS IDENTICAL, THEREFORE NOT SHOWN.

Figure 19. Master Circuit Diagram and Equations

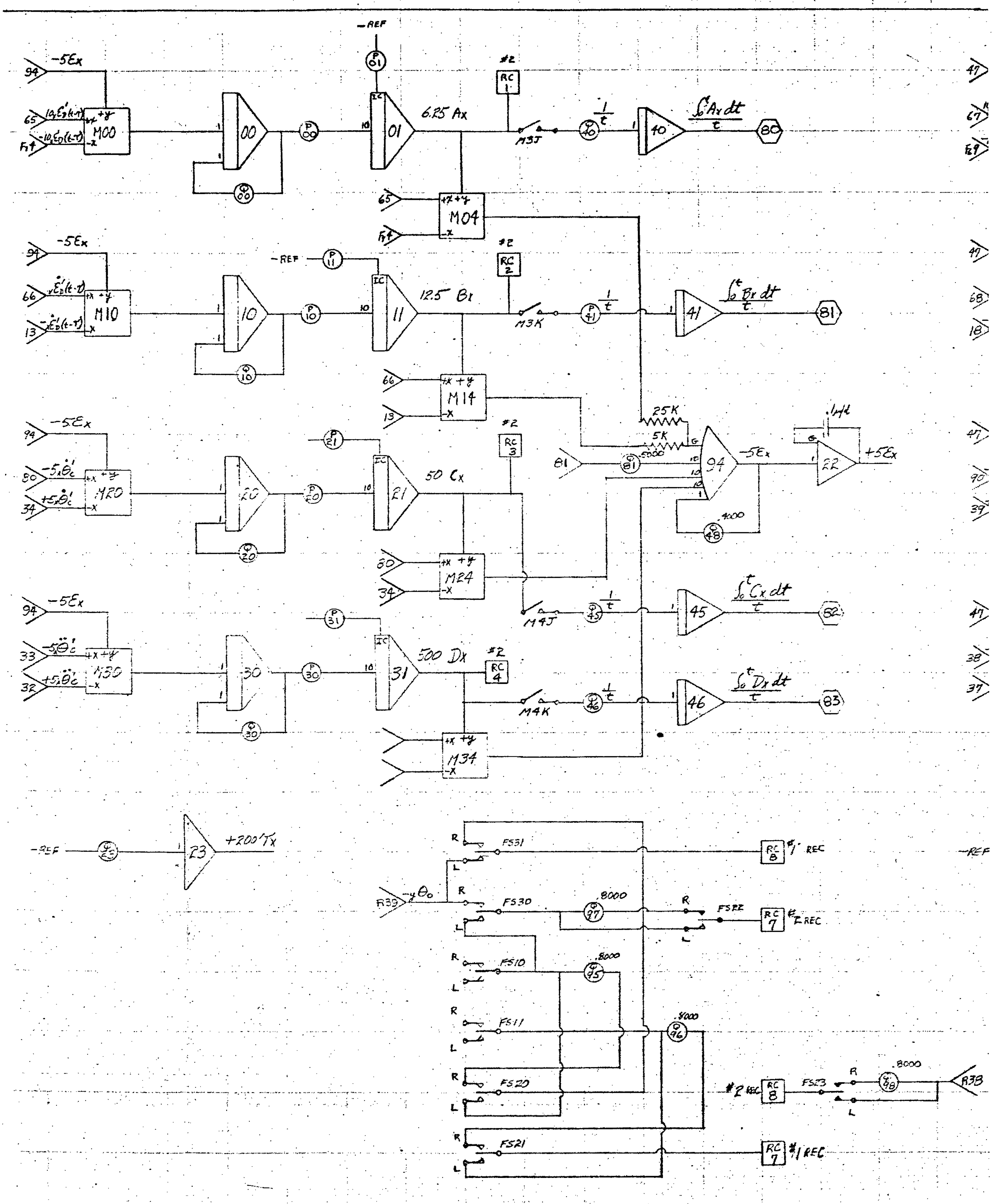

N.G.
64
FS10
Q52
59
$x\mathcal{E}_s$
52
$-x\mathcal{E}_D$
110
SCOPE
X AXIS
+REF
105
STICK ZERO
±REF
STICK POT
103
104
-REF
CONSOLE M
+A
-A
+B
-B
KFQ 10
FS03
FS02
F66
60
42
43
30
51
CONS 2
61
62
$\frac{0.18}{C}$
$\frac{B-AC}{C^2}$
$\frac{0.1}{C}$
$\frac{0.06}{T}$
N.G.
84
FS11
Q72
79
$y\mathcal{E}_s$
72
$-y\mathcal{E}_D$
111
SCOPE
Y AXIS
+REF
STICK POT
100
101
-REF
KFQ 10
F68
82
83
92
93
74
CONS 2
32
53
$\frac{0.1}{T}$
$\frac{0.1}{T^2}$
$\frac{.06}{T}$
$\frac{0.68}{C}$
$\frac{0.06(B-AC)}{C^2}$
$\frac{0.1}{C}$


STICK ZERO
R09
R08
50
51
R38
FS12
MAN
#2 MANALOG C
#1 MANALOG
FS40
54
FS41
53
TP05
02
03
M07
.6000
.2400
56
59
FS10
R29
R28
70
71
R39
FS13
FS43
44
FS42
73
.2000
TP50
07
08
M57
58
78
72
FS11





$-_x\theta_c$
20K
$+5E_x$
$.5_x\ddot{\theta}_c'$
$-.5_x\ddot{\theta}_c'$
$-5_x\dot{\theta}_c'$
$+5_x\theta_c'$
$_xE_D'(t-\tau)$
$-10_xE_D'(t-\tau)$
$+10_xE_D'(t-\tau)$
1.000
.2000
$\frac{\int_0^t {_x\varepsilon_s}^2 dt}{\int_0^t {_x\theta_i}^2 dt}$
$\frac{\int_0^t {_x\varepsilon_D}^2 dt}{\int_0^t {_x\theta_i}^2 dt}$
M93
M43
$-.5_y\ddot{\theta}_c'$
$+5E_y$
$+.5_y\ddot{\varepsilon}_c'$
$-5_y\dot{\theta}_c'$
$+5_y\theta_c'$
$+_yE_D'(t-\tau)$
$-10_yE_D'(t-\tau)$
$+10_yE_D'(t-\tau)$
M95
M45
Σ RATIOS
$\frac{\int_0^t {_y\theta_s}^2 dt}{\int_0^t {_y\theta_i}^2 dt}$
$\frac{\int_0^t {_y\varepsilon_D}^2 dt}{\int_0^t {_y\theta_i}^2 dt}$


-REF
-5Ex
M00
00
01
6.25 Ax
RC 1
M3J
40
80
M04
12.5 Bx
M10
10
11
RC 2
M3K
41
81
M14
25K
5K
94
-5Ex
22
+5Ex
50 Cx
M20
20
21
RC 3
M24
M4J
45
82
500 Dx
M30
30
31
RC 4
M4K
46
83
M34
23
+200 Tx
FS31
FS30
FS10
FS11
FS20
FS21
FS22
FS23
RC 8
RC 7
#1 REC
#2 REC
R39
R38

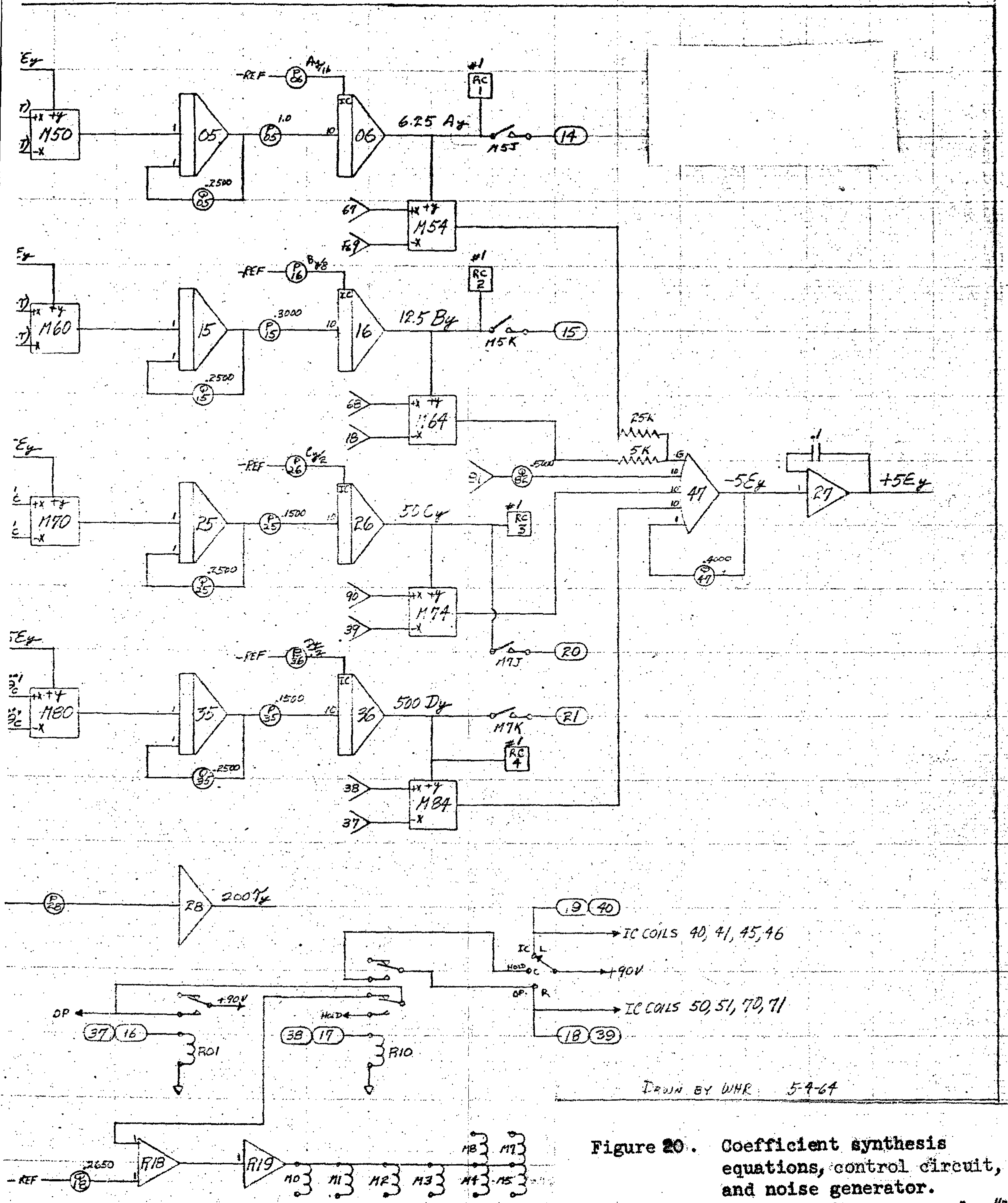
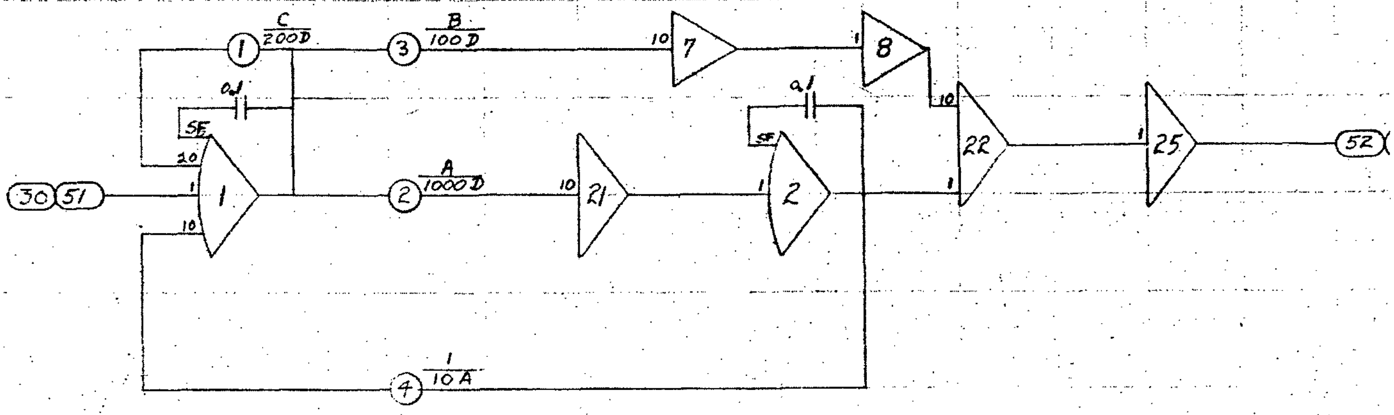
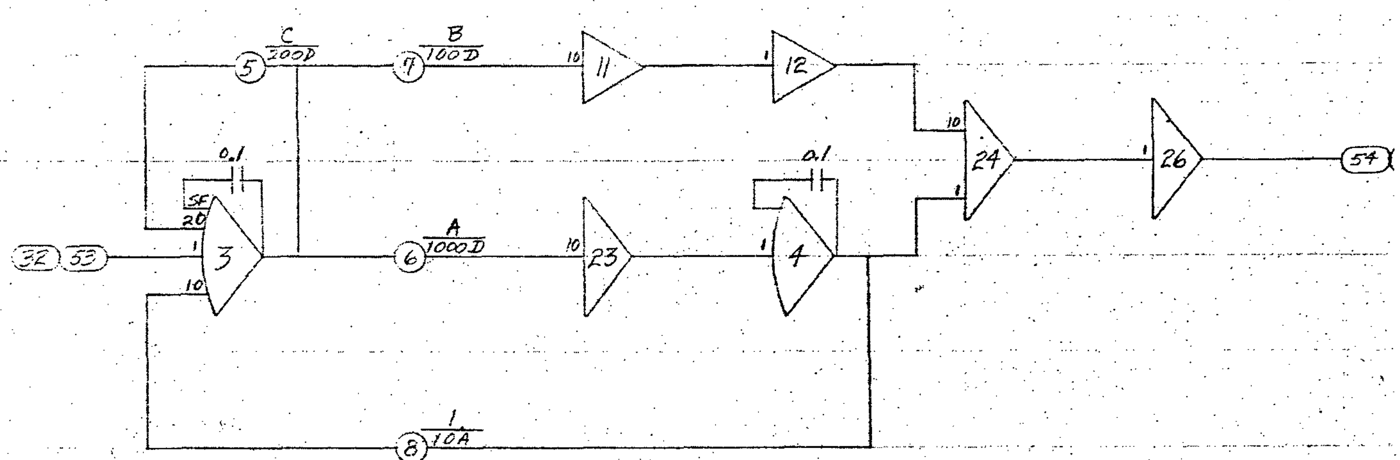


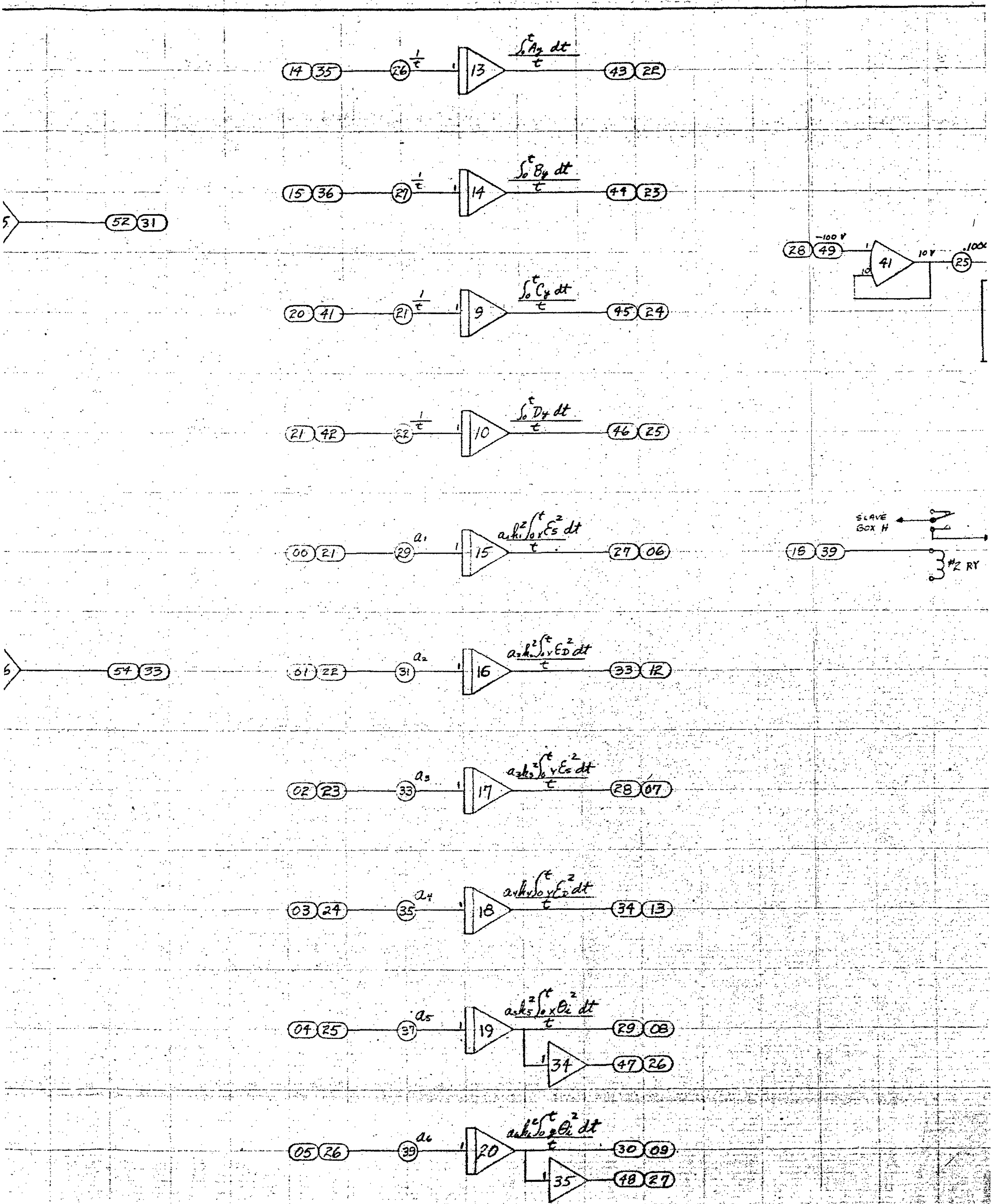
Figure 20. Coefficient synthesis equations, control circuit, and noise generator. Computer diagram, console #1

"X" Axis #2 Manalog



"Y" Axis #2 Manalog




14 35 26 1/t 13 ∫₀ᵗ Ay dt / t 43 22
15 36 27 1/t 14 ∫₀ᵗ By dt / t 44 23
52 31
28 49 -100 V 41 10 V 25
20 41 21 1/t 9 ∫₀ᵗ Cy dt / t 45 24
21 42 22 1/t 10 ∫₀ᵗ Dy dt / t 46 25
SLAVE BOX H
18 39 #2 RY
00 21 29 a1 15 27 06
54 33
01 22 31 a2 16 33 12
02 23 33 a3 17 28 07
03 24 35 a4 18 34 13
04 25 37 a5 19 29 08 34 47 26
05 26 39 a6 20 30 09 35 48 27

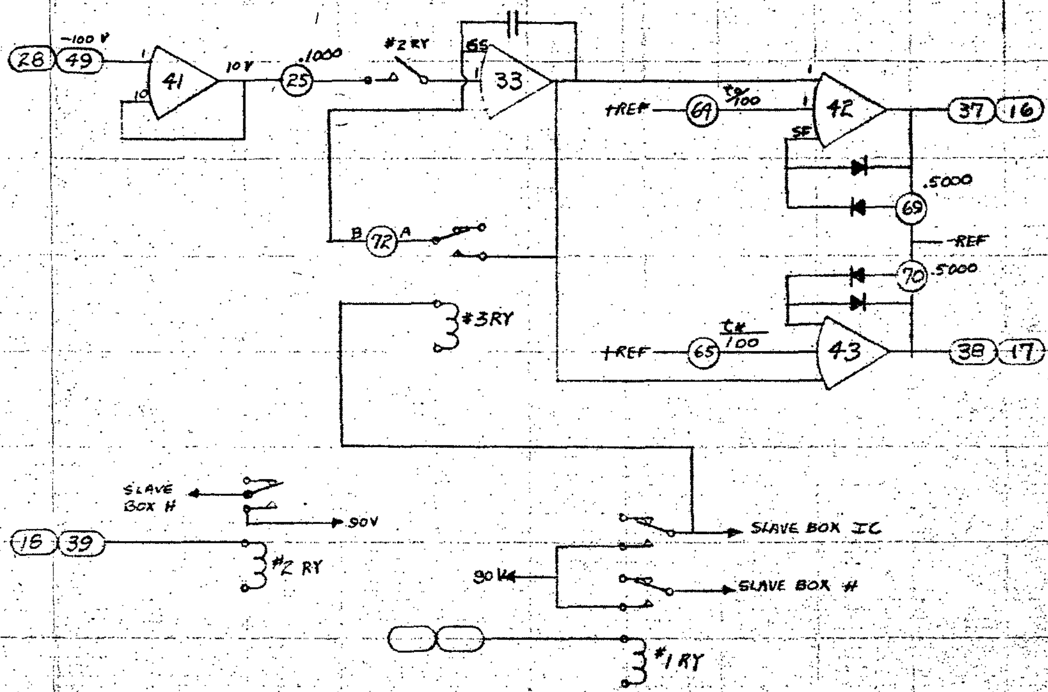
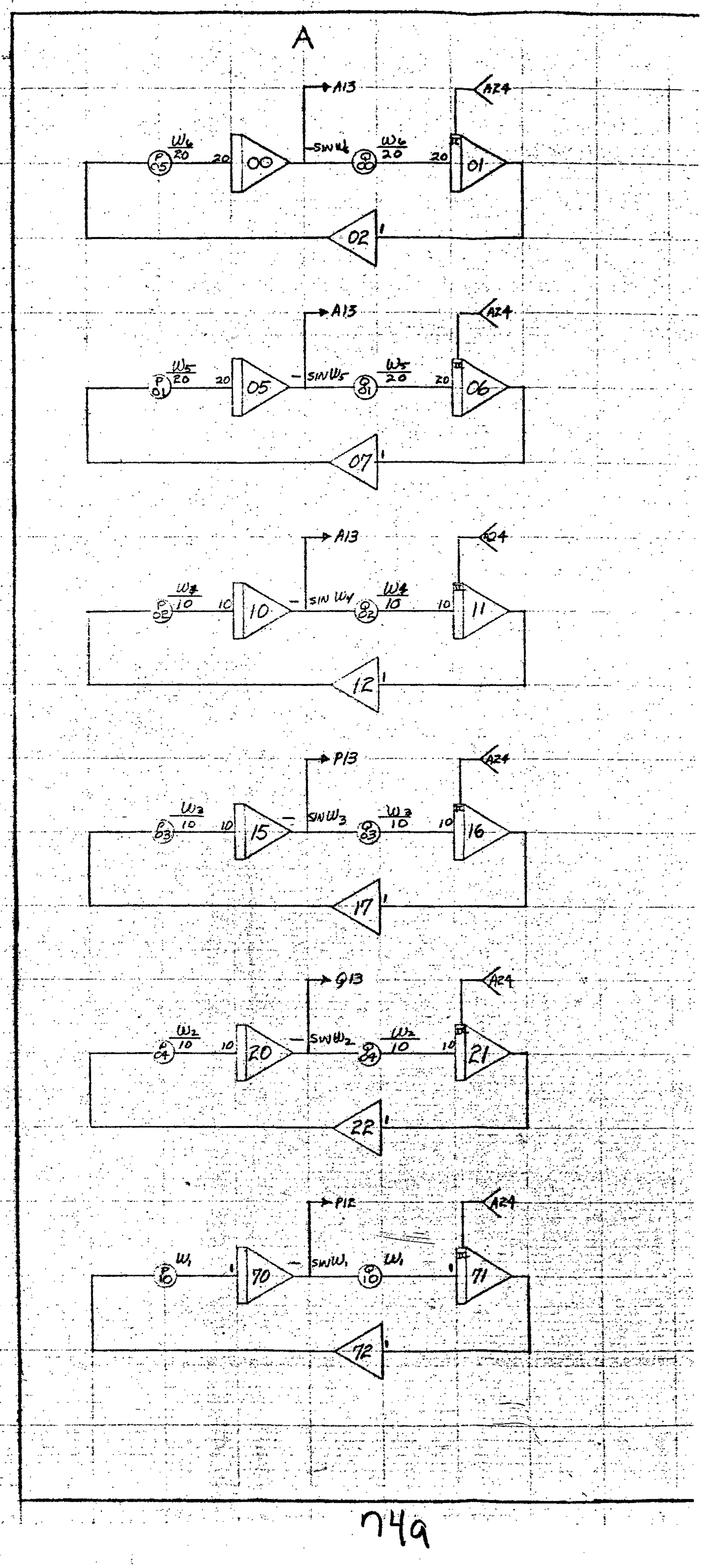
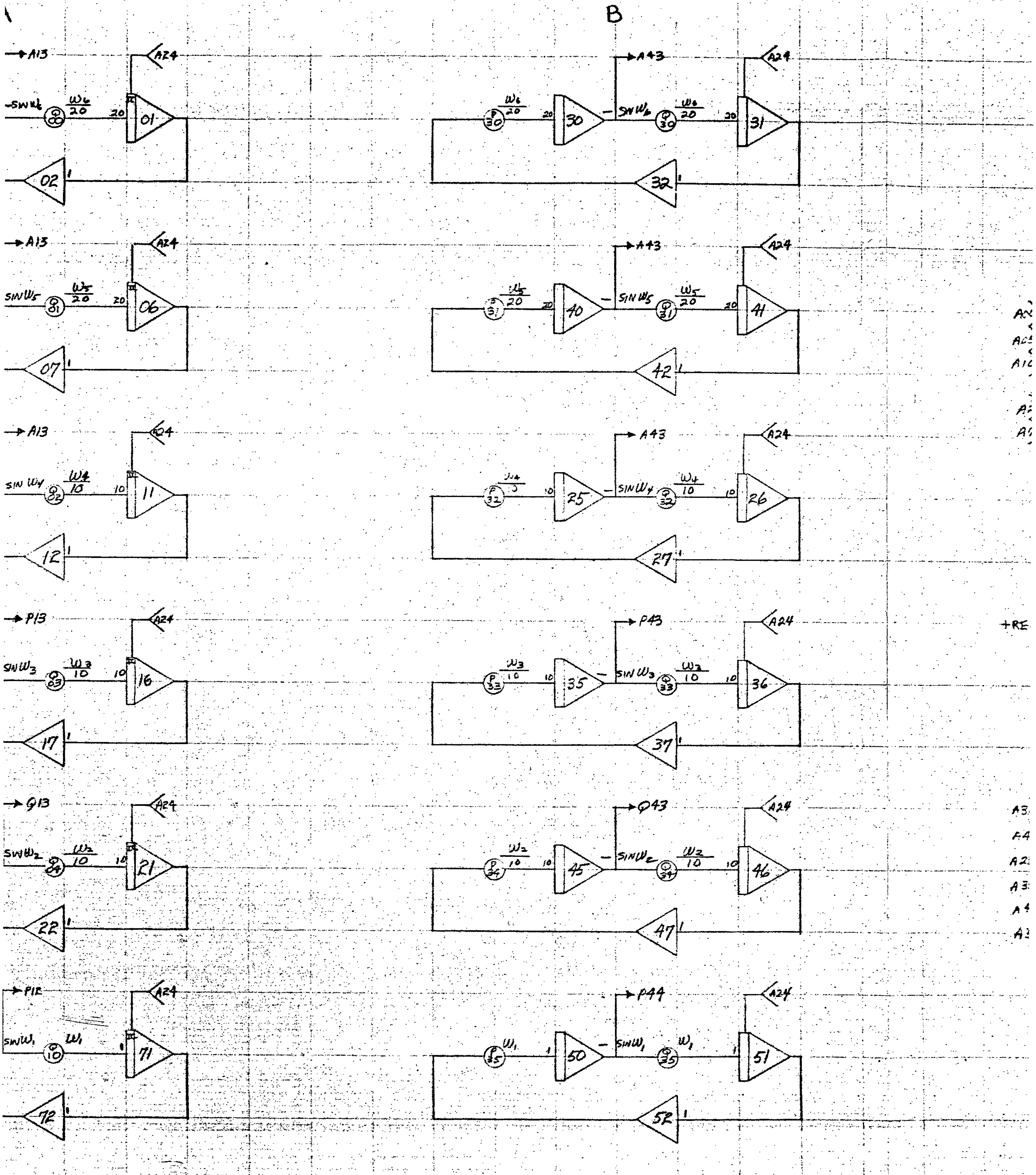


Figure 21. Display Quickening study scoring, timing, and relay control. Computer diagram, Console #2


A
A13
AZ4
00
01
02
05
06
07
10
11
12
P13
15
16
17
Q13
20
21
22
P12
70
71
72



B
A13
A24
$\frac{W_6}{20}$
01
02
A43
30
31
32
SIN W_6
06
07
SIN W_5
$\frac{W_5}{20}$
40
41
42
11
12
SIN W_4
$\frac{W_4}{10}$
25
26
27
P13
16
17
SIN W_3
$\frac{W_3}{10}$
P43
35
36
37
Q13
21
22
SIN W_2
$\frac{W_2}{10}$
Q43
45
46
47
P12
71
72
SIN W_1
W_1
P44
50
51
52

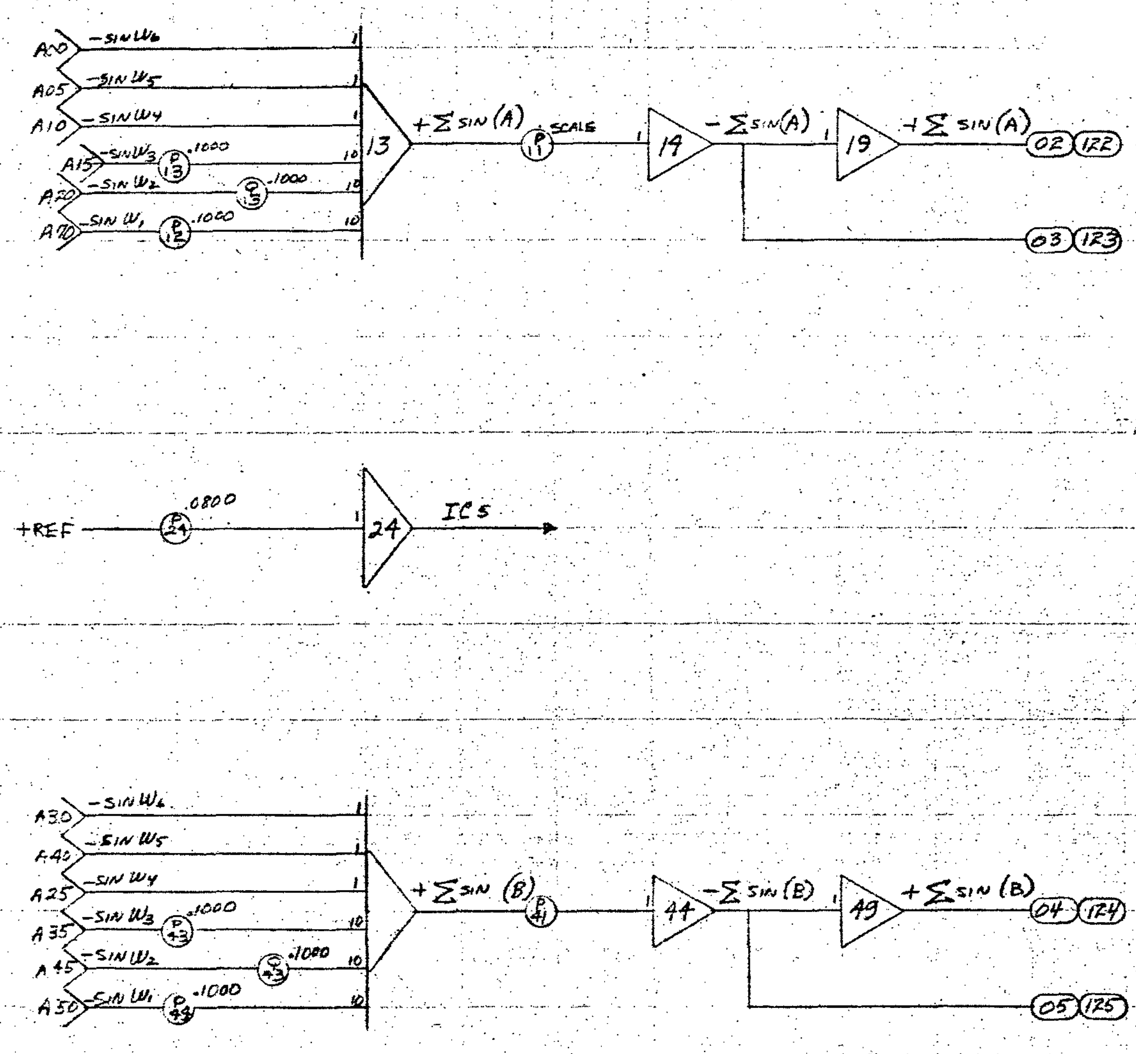


Figure 22. Signal generators. Computer diagram, console #3

APPENDIX III[10]

MODIFICATION OF TF SYNTHESIS PROCEDURE

The model chosen to represent the operator is shown in figure 23. The model was assumed to be valid for both controlled axes, with no coupling between the axes. N represents a noise source which accounts for the portion of the operators output, θ_o, which cannot be accounted

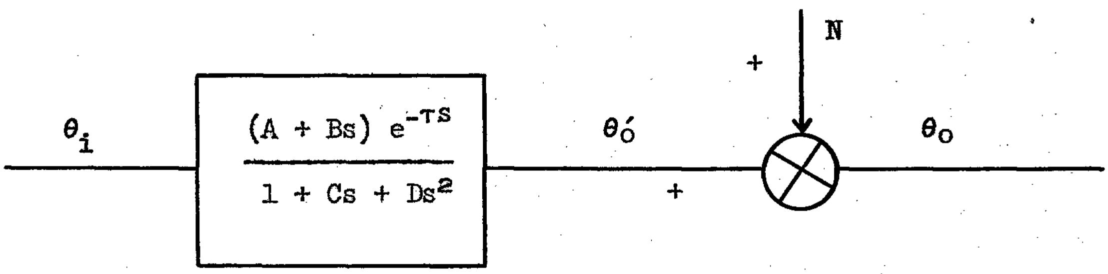


Figure 23. Model of One Operator Control Axis

for by the transfer function model. Although it had been intended to compute all five coefficients (A, B, C, D, τ), preliminary studies indicated that this effort necessitated computer set-up accuracies too stringent to be maintained with reasonable effort during the course of a long experimental program. Accordingly, a fixed value of two-tenths of a second was assumed for τ.

Figure 24 shows a block diagram of the continuous regression analysis program for one axis. The other axis is identical. Basically, the program makes use of the method of steepest descent to continuously drive the partial derivatives of an error function with respect to the coefficients to be determined to zero. Ideally, the error function would be

$$\epsilon(T) = \frac{1}{T} \int_0^t \left(\theta_o' + \hat{C}\dot{\theta}_o' + \hat{D}\ddot{\theta}_o' - \hat{A}\theta_i(t-.2) - \hat{B}\dot{\theta}_i(t-.2) \right)^2 e^{\frac{T-t}{T}} \, dt \qquad (23)$$

where the hats represent computer estimates of the coefficients and τ is chosen to be long enough to give a good sample for the regression analysis

---

[10] This appendix was written by T. F. Potts.

but short enough so the program can track slowly changing coefficients. It was found that a τ of four seconds worked quite well. The signal θ_o' is not available for use in the program. If θ_o were to be used directly in place of θ_o' the computed coefficients would contain a bias due to the uncorrelated noise N (ref 5). Accordingly, attempts were made to reduce the effects of the noise. It was not expected that the bandwidth of the θ_o' signal would much exceed five radians per second with an input signal bandwidth limited to one radian per second, so all signals were passed with a cut-off frequency of ten radians per second. It was noted that if the program produces a good estimate $\hat{\theta}_o'$ for θ_o', the difference $\theta_o-\hat{\theta}_o'$ provides a good estimate of the uncorrelated noise N. This estimate was then low-passed and subtracted from θ_o to improve the estimate of θ_o'. The program was tested on a computer mechanized transfer function with the filtered output of a second noise generator serving as the uncorrelated noise signal N. (The output of a standard EAI noise generator was filtered to yield a noise signal with a bandwidth of approximately 10 radians per second.) The simulated transfer function with known coefficients was substituted into the system loop, i.e., the loop was closed around the manalog. It was found that the program would compute the transfer function coefficients with no detectable bias if the uncorrelated noise power did not represent more than about twenty percent of the total power in the output signal.

The pertinent analog computer mechanization diagrams are shown in Appendix II.

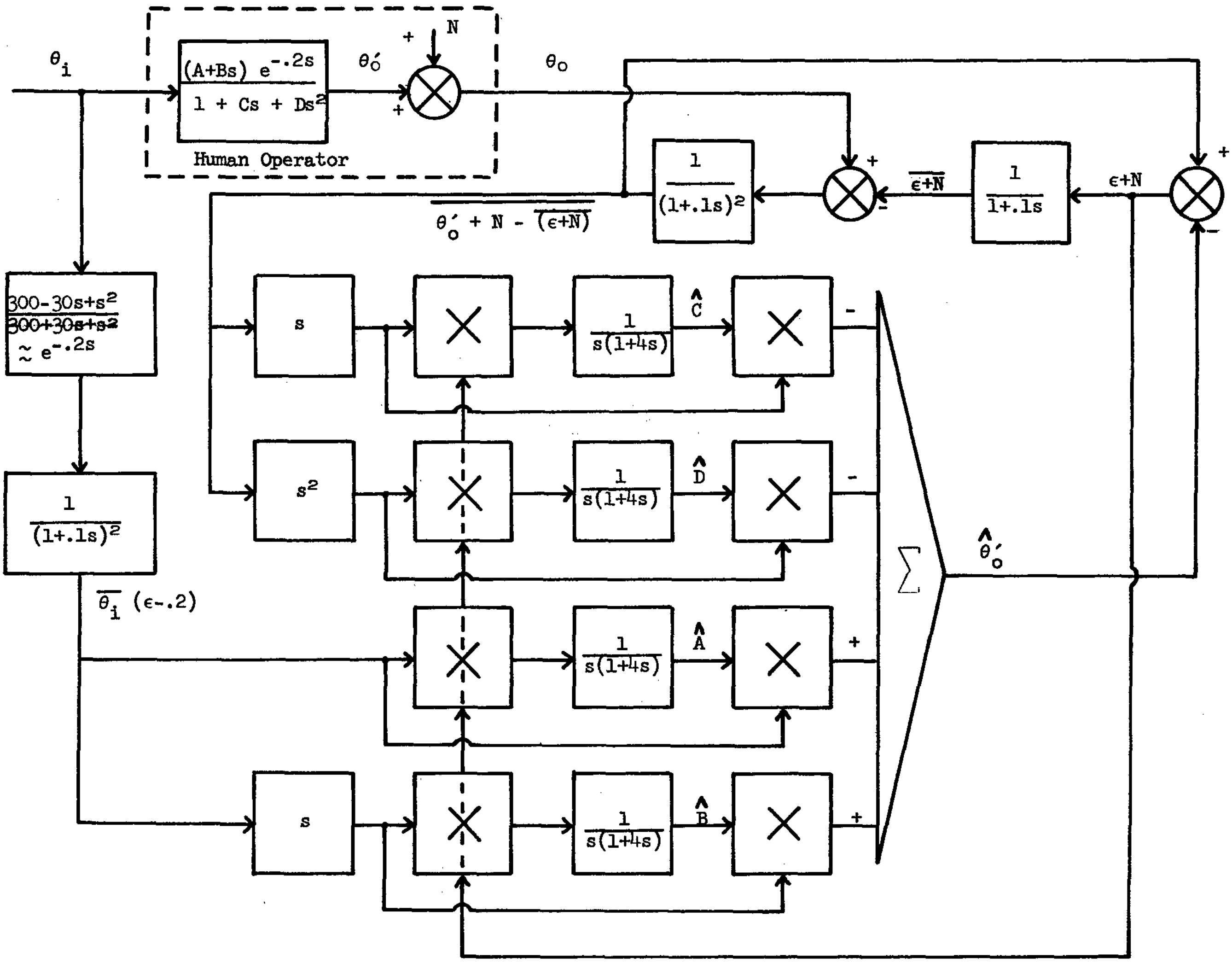


Figure 24. Block Diagram of Continuous Regression Analysis Program

APPENDIX IV

INSTRUCTIONS TO SUBJECTS

APPENDIX IV

INSTRUCTIONS TO SUBJECTS

INSTRUCTIONS FOR EXPERIMENT I

You will be participating in a tracking experiment that we have contracted to perform for the Air Force. The purpose of the experiment is to evaluate an aiding technique known as quickening. The effects upon your tracking performance of different levels of quickening will be measured in several ways. One performance measure will be your tracking error score. Your tracking task will require that you keep an error dot centered on an oscilloscope display. The longer you are able to keep the signal centered the better will be your error score. We will also use an analog computer to derive a human transfer function equation which describes your performance. This equation is derived by comparing the movements of the displayed error signal to the movements of the control stick that you make in response to the signal. The human transfer function equation includes lead, lag, and simple gain terms. A primary objective of this experiment is to determine how the relative weighting of these transfer function terms vary with the different quickening levels that are used.

The tracking task is a compensatory type. Essentially, this means that you make control movements to compensate or correct for errors. The control stick is used to keep the error dot centered at the zero position (pointing). Forward movement of the stick causes the dot to move downward (demonstrating) and rightward movement causes the dot to move to the right (demonstrating). You will sometimes be tracking the dot in both axes and at other times in one or the other single axis with the second axis locked out (demonstrating). You can adjust the intensity and null position of the error signal by these controls.

You will be scheduled for several 1-1/2 hour sessions on different days. Each session will consist of a series of 60-second runs with one minute breaks between each run and a five minute break after every group of five runs. You may also ask for additional breaks whenever you feel you need one.

One of the purposes of the experiment is to evaluate how your performance improves with practice. You should therefore do the very best you can throughout the experiment as we will be recording your performance beginning with the very first trial. For each experimental condition you will be given from one to several hours of practice depending on how long it takes you to reduce your error score below a certain criterion level.

At the end of each run your error score will be indicated on these two meters, one for each axis. The error score is actually computed as the ratio of your tracking error RMS to the input signal RMS. Tracking error RMS tends to be proportional to the input signal RMS and the ratio of these two values tends to be a more stable measure of your progress than does the error RMS alone.

Earlier I mentioned that your runs would be 60 seconds long. Before each run I will ask if you are ready. The run will start within two seconds after you say "ready." You should immediately start tracking the error dot as closely as you can. The end of the run will be easily detected since the error dot will then remain fixed at the center position. There will then be at least a one minute break before the next run starts. Feel free to ask for longer breaks whenever you feel you need one. We will now adjust your seat so that you are seated at the proper distance from the apparatus. Be sure that you adjust the seat to the same position for all runs. During your first trial there will be no input signal and the error dot will merely be following your stick movements. We'll have you fly this way for a couple minutes so that you can orient yourself to the display control directional relations.

INSTRUCTIONS FOR EXPERIMENT II

For the next three sessions you will be given a total of 100 trials under the no quickened condition. You will probably notice that the system response differs from what it was earlier. This is due to changes we have made in various gains in the tracking network. We will follow the same general procedure as we did previously. You will be given blocks of five one minute trials with the normal short break between trials and a five minute break between each block. As before, feel free to ask for a longer break whenever you need one.

INSTRUCTIONS FOR EXPERIMENT III - Phase I

During each of the next six sessions you will be exclusively tracking under one quickening condition in one axis only. You note that we have locked the control stick so that it will operate only in the one axis (demonstrating) and that we have disconnected the second lead to the oscilloscope. Here is your copy of the schedule showing the order of the tracking conditions you will have.

INSTRUCTIONS FOR EXPERIMENT III - Phase II

During each of the next ten sessions you will be controlling one axis, with the Manalog controlling the second axis. In other words, even though the dot will be moving in both coordinates you need control it only in the one axis. Note that the control stick has been locked so that it will operate only in the one axis (demonstrating). Here is a copy of your schedule showing the order in which you will get the different tracking conditions.

INSTRUCTIONS FOR EXPERIMENT III - Phase III

During the next eight sessions you will have a dual axis tracking task. During these sessions you will be tracking under a variety of quickening combinations for the two axes as noted here on your copy of the schedule. Note that we will be changing conditions every ten or twenty trials. We will keep you posted on the changes as we make them so that you'll know where you are on the schedule.

APPENDIX V

ERROR SCORES - EXPERIMENT I

Table XXVI

ERROR SCORE COMPARISONS OF
FQ_1 AND FQ_2 FOR TRIALS 95 THROUGH 100

	$_xE_S$		$_xE_D$		$_yE_S$		$_yE_D$	
Subjects	FQ_1	FQ_2	FQ_1	FQ_2	FQ_1	FQ_2	FQ_1	FQ_2
B	.1461	.2049	.0164	.0302	.1534	.2785	.0343	.0716
G	.1316	.2340	.0133	.0252	.1290	.3128	.0238	.0605
H	.1603	.2543	.0227	.0649	.1554	.2954	.0292	.0806
J	.1691	.1701	.0021	.0020	.1371	.2700	.0022	.0038
K	.1371	.2094	.0109	.0120	.1696	.1754	.0360	.0136
L	.1354	.2427	.0096	.0163	.1595	.1715	.0229	.0283
M	.1946	.2382	.0294	.0344	.1516	.2614	.0306	.0392
N	.1427	.2183	.0463	.0250	.1522	.1947	.0890	.0251
R	.1629	.1969	.0263	.0159	.1219	.1876	.0272	.0147
W	.1744	.2033	.0332	.0234	.1544	.2544	.0356	.0470
Means	.1554	.2172	.0210	.0249	.1484	.2402	.0331	.0384
T Values	$F_1<F_2$:	0*	$F_1 < F_2$:	21**	$F_1<F_2$:	0*	$F_1<F_2$:	21**

Significance levels (Wilcoxon Matched Replicates Test):
* $p < .01$ ** N.S.

Table XXVII

ERROR SCORES FOR PQ AND NQ
FOR TRIALS 95 THROUGH 100

Subjects	${}_{x}E_{S}$ PQ	${}_{x}E_{S}$ NQ	${}_{x}E_{D}$ PQ	${}_{x}E_{D}$ NQ	${}_{y}E_{S}$ PQ	${}_{y}E_{S}$ NQ	${}_{y}E_{D}$ PQ	${}_{y}E_{D}$ NQ
B	.0996	.0894	.0279	.0894	.1276	.1259	.0937	.1259
G	.1006	.0265	.0203	.0265	.1344	.0788	.0429	.0788
H	.1044	.0959	.0340	.0959	.1242	.1417	.0431	.1417
J	.1106	.0558	.0233	.0558	.1381	.1452	.0491	.1452
K	.0989	.0830	.0356	.0830	.1071	.1237	.0514	.1237
L	.0872	.0181	.0611	.0181	.1024	.0252	.0124	.0252
M	.1151	.1217	.0248	.1217	.1233	.1678	.0314	.1678
N	.1201	.0429	.0276	.0429	.0868	.0668	.0233	.0668
R	.0911	.0626	.0186	.0626	.0822	.0648	.0285	.0648
W	.1173	.1267	.0278	.1267	.1013	.2342	.0294	.2342
Means	.1045	.0723	.0301	.0723	.1127	.1174	.0405	.1174

Table XXVIII

ERROR SCORE COMPARISONS* OF FQ_1, PQ, AND NQ
FOR TRIALS 105 THROUGH 110

Subjects	x^E_S FQ_1	x^E_S PQ	x^E_S NQ	x^E_D FQ_1	x^E_D PQ	x^E_D NQ
B	.1604	.0923	.0758	.0260	.0198	.0758
G	.1452	.1126	.0227	.0172	.0154	.0227
H	.1769	.1277	.1447	.0344	.0405	.1447
J	.1979	.1529	.0577	.0374	.0359	.0577
K	.1282	.0896	.0758	.0184	.0155	.0758
L	.1516	.0920	.0206	.0141	.0148	.0206
M	.1996	.1225	.0968	.0328	.0244	.0968
N	.1625	.1022	.0317	.0262	.0159	.0317
R	.1323	.1105	.0393	.0146	.0134	.0393
W	.1625	.1659	.1809	.0305	.0943	.1809
Means	.1617	.1168	.0746	.0252	.0290	.0746

Subjects	y^E_S FQ_1	y^E_S PQ	y^E_S NQ	y^E_D FQ_1	y^E_D PQ	y^E_D NQ
B	.2114	.1036	.1237	.0412	.0363	.1237
G	.1540	.1217	.0765	.0234	.0220	.0765
H	.1468	.1313	.1129	.0278	.0538	.1129
J	.2312	.1571	.1741	.0527	.0438	.1741
K	.1575	.1089	.0801	.0435	.0237	.0801
L	.1851	.0977	.0384	.0245	.0132	.0384
M	.1978	.1053	.1566	.0262	.0280	.1566
N	.1942	.0965	.0628	.0381	.0215	.0628
R	.1647	.1274	.0490	.0215	.0238	.0490
W	.2358	.1787	.2810	.0715	.1164	.2810
Means	.1878	.1228	.1155	.0370	.0383	.1155

* Any two treatment means not underscored by the same line are significantly different. Any two treatment means underscored by the same line are not significantly different. The Wilcoxon Matched Replicates Test was used for the comparisons.

APPENDIX VI

TRANSFER FUNCTION BODE PLOTS

APPENDIX VI

TRANSFER FUNCTION BODE PLOTS

The following Bode Plots are for the combined man-machine system. Plots are presented for the individual subject and also for the optimum man-machine transfer function for the various quickening levels. The Bode Plots were generated from a consideration of

$$\frac{\theta_o}{E_s} = \frac{G_1 \, G_2}{1 + G_1 \, G_2 \, G_3}$$

where

$$G_1 = \frac{K_s \, K_C \, K_P \, \epsilon^{-\tau S} \, (T_L S + 1)}{1 + (T_N + T_I) \, S + T_N \cdot T_I S^2}$$

$$G_2 = \frac{K_m}{S^2}$$

$$G_3 = \alpha_1 S + \alpha_2 S^2$$

The general configuration is shown in figure 25.

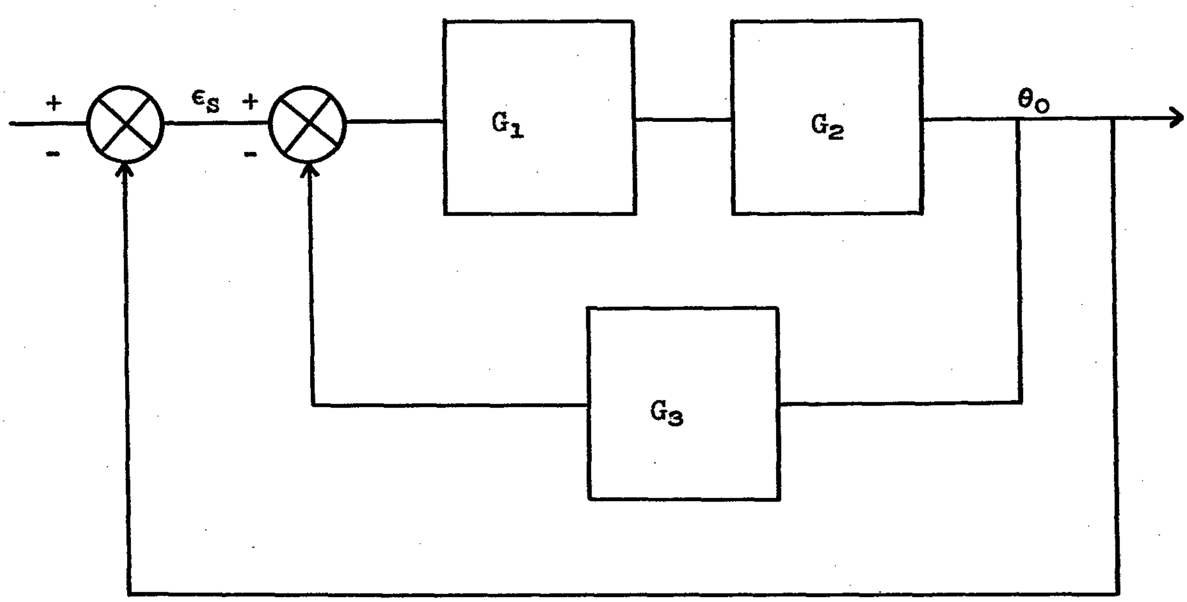


Figure 25. Block Diagram Used for the Construction of Bode Plots

The terms T_L, $T_N + T_I$, $T_N \cdot T_I$, and K_p are given in table IV for trials 95 through 100 of experiment I and in table X for trials 95 through 100 of experiment II. For experiment I

Scope Gain, $K_S = 1$

Control Stick Gain, $K_C = 5$

Mechanism Gain, $K_M = 5$

For experiment II, group A

$K_S = 1$

$K_C = 5$

$K_M = 1$

and for experiment II, group B

$K_S = 2$

$K_C = 5$

$K_M = .5$

for FQ_1

$\alpha_1 = .5$

$\alpha_2 = .125$

and for FQ_2

$\alpha_1 = .707$

$\alpha_2 = .125$

In the PQ case

$\alpha_1 = .5$

$\alpha_2 = 0$

and in the NQ case

$\alpha_1 = 0$

$\alpha_2 = 0$

All Bode plots were constructed by using a transport delay of .2 seconds.

In the figures that follow note that the subject, the quickening level, and the axis are designated at the top of the figure according to the following conventions:

FQ: Full Quickening

PQ: Partial Quickening

NQ: No Quickening

X: Lateral Axis

Y: Longitudinal Axis

For experiment I, Bode plots are presented in the order FQ_1, FQ_2, PQ, and NQ. Twenty-one Bode plots are presented for each of these quickening levels with the first plot being that for the optimum transfer function followed by two plots (for the X and Y axes) for each of the 10 subjects. The Bode plots for experiment II follow those for experiment I. There are 10 plots (5 subjects x 2 axes) for each of the two groups of experiment II. The Bode plot for the optimum transfer function for both groups of experiment II is identical to that presented in figure 89 for the NQ condition of experiment I.

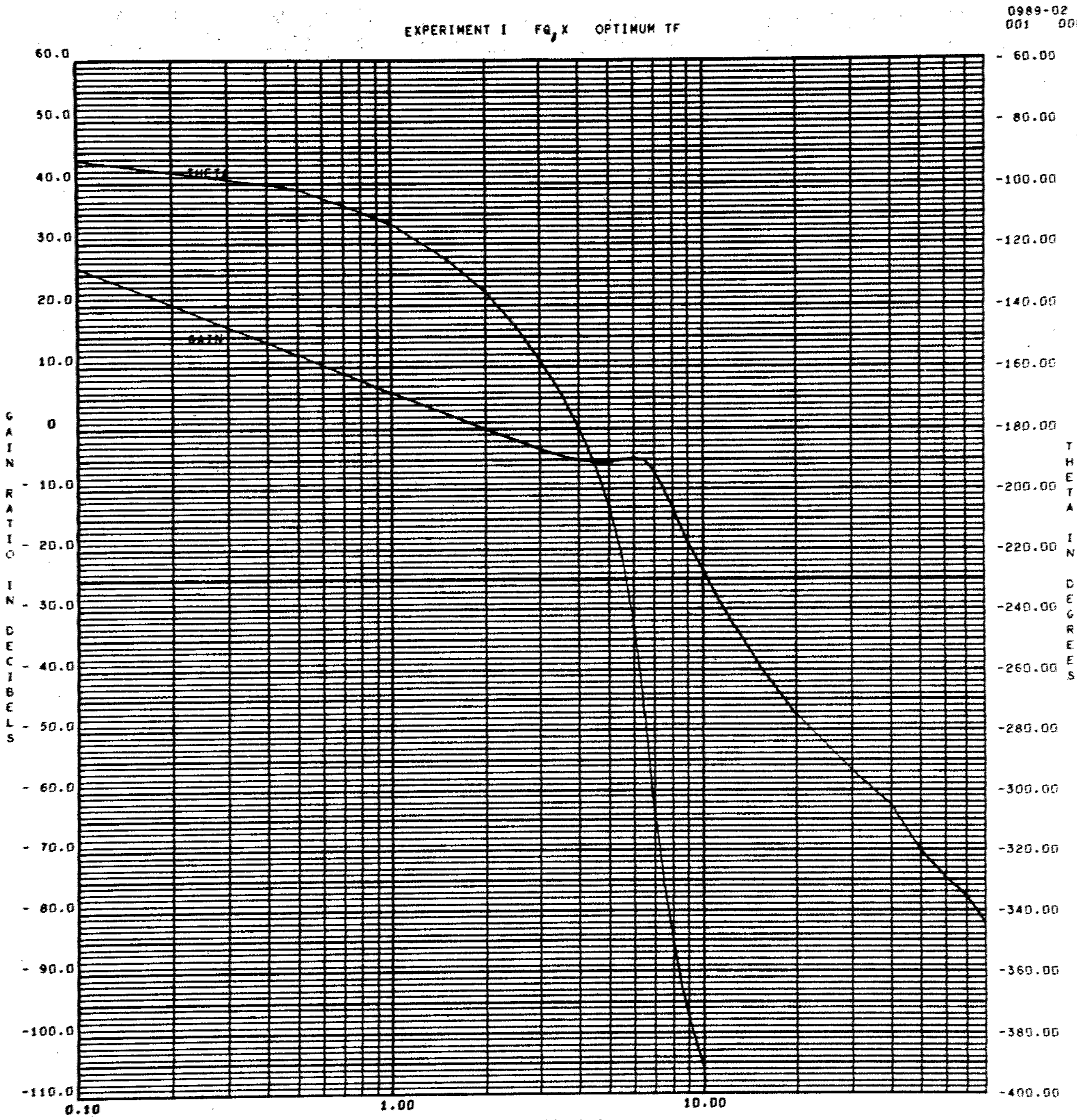

0989-02
001 000
EXPERIMENT I FQ,X OPTIMUM TF
THETA
GAIN
GAIN RATIO IN DECIBELS
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
THETA IN DEGREES
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00
FREQUENCY

Figure 26.

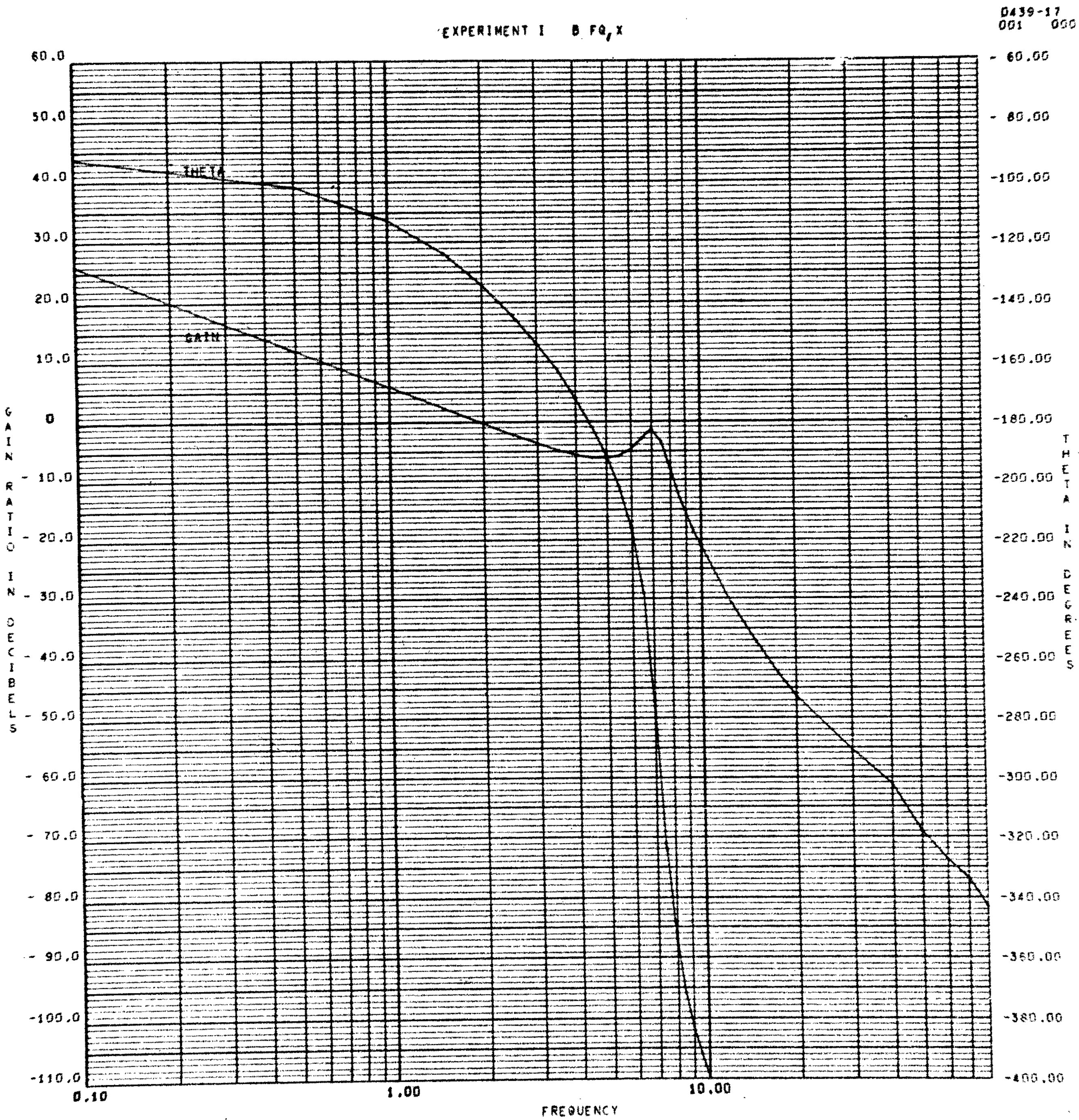

0439-17
001 000
EXPERIMENT I B FQ,X
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 27.

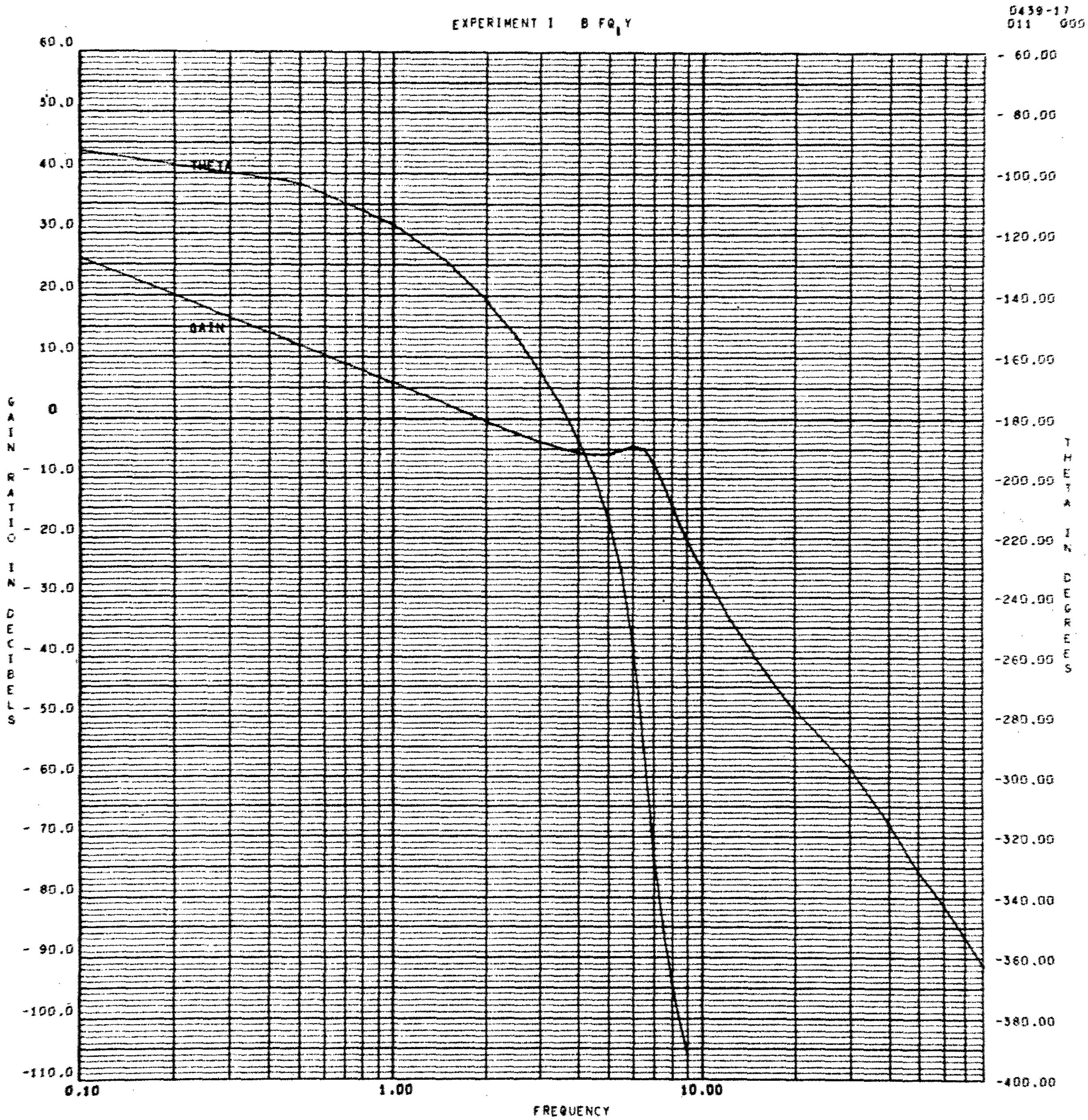

EXPERIMENT I B FQ1Y
0439-17
011 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 28.

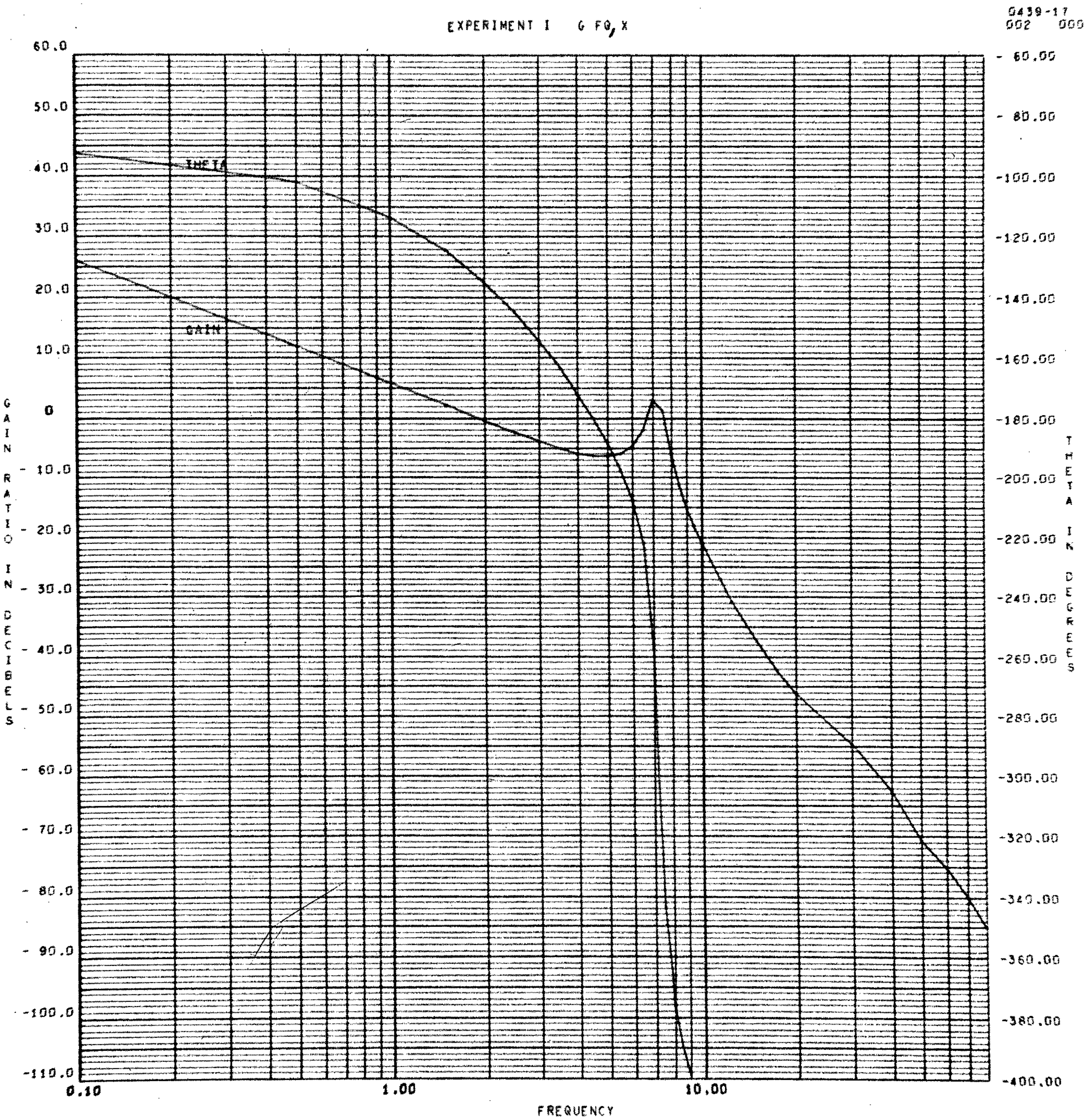

EXPERIMENT I G FQ, X
0439-17
002 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 29.

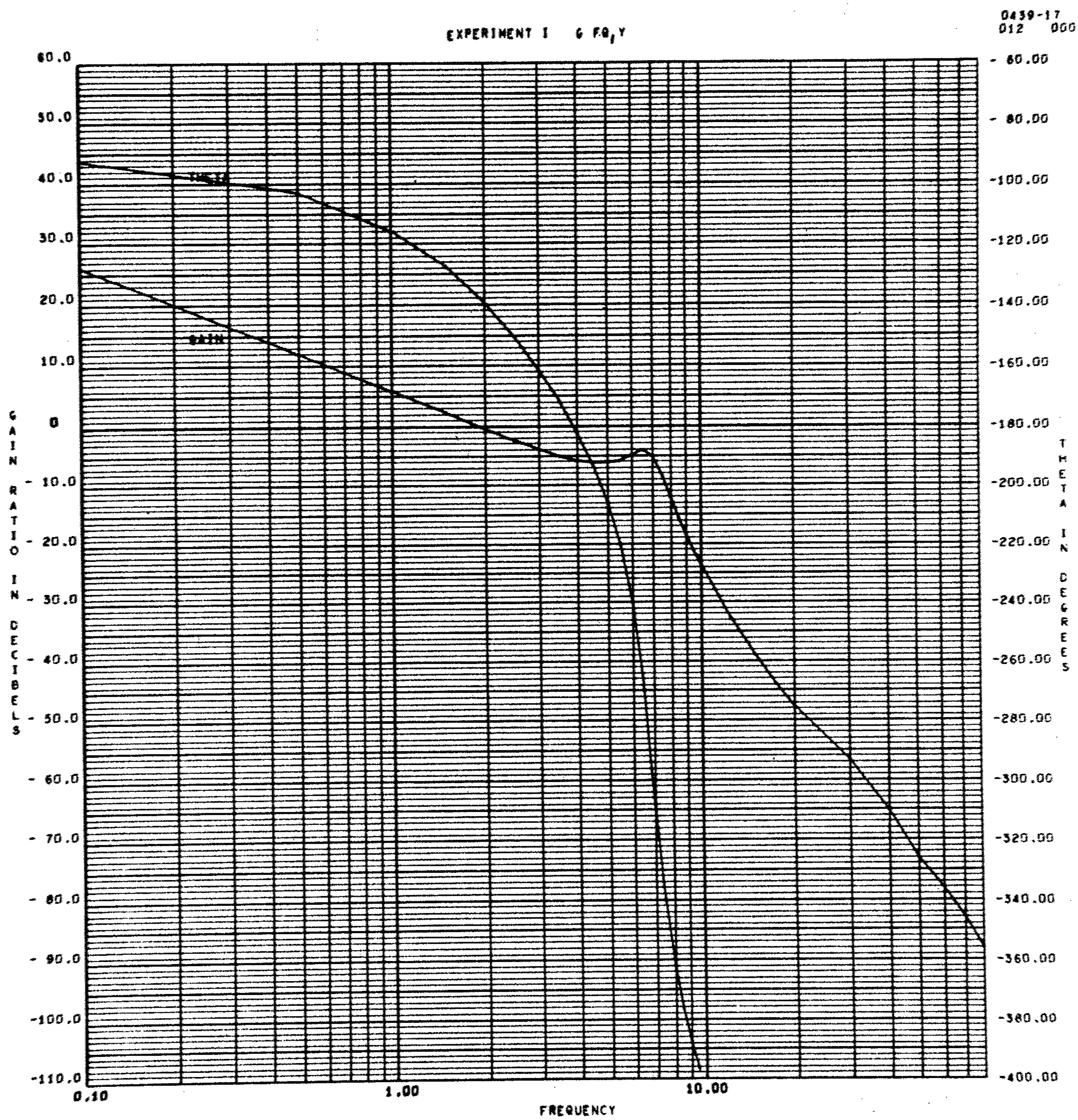

0439-17
012 000
EXPERIMENT I
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 30.

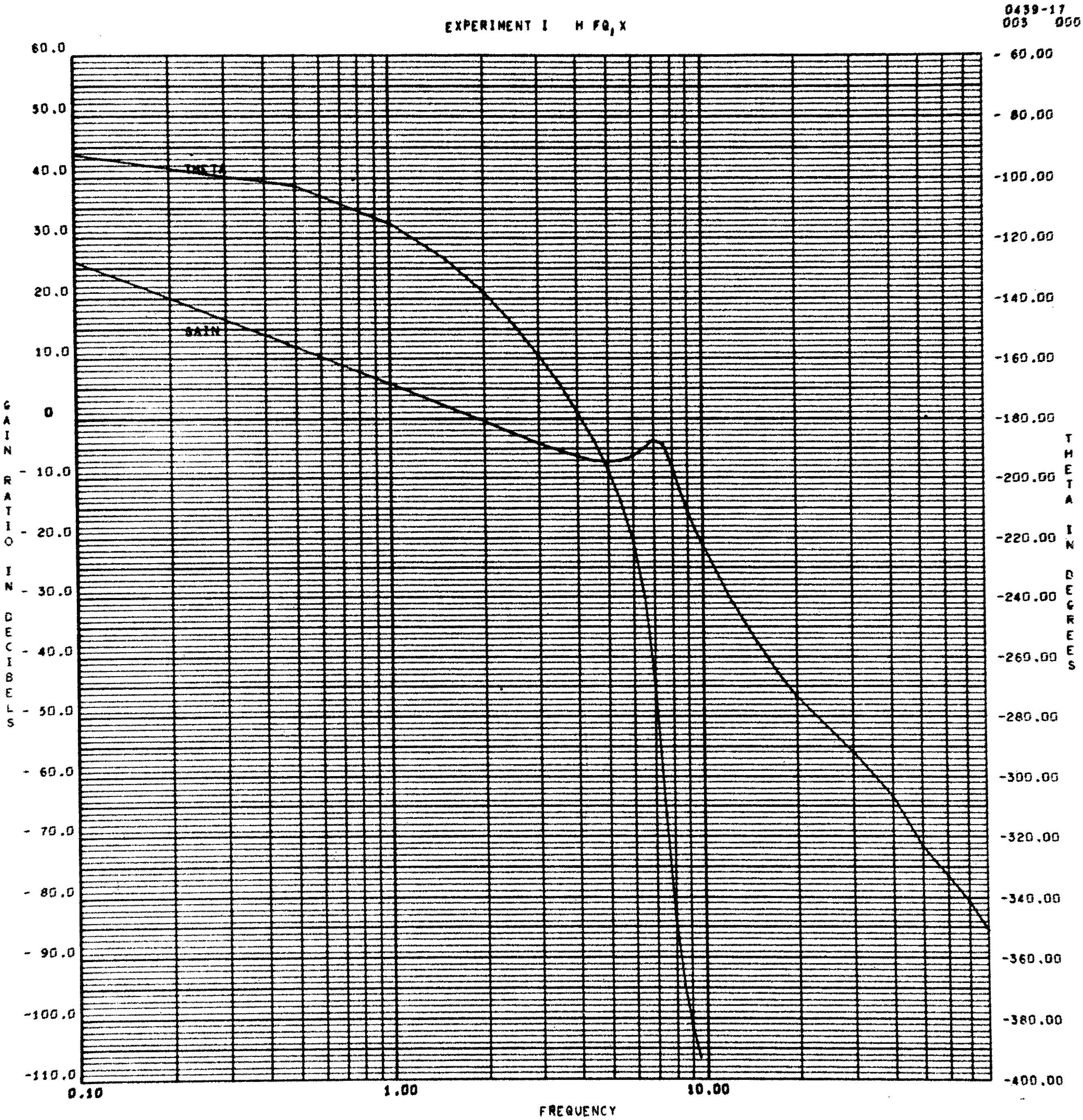

EXPERIMENT I H FQ, X
0439-17
003 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 31.

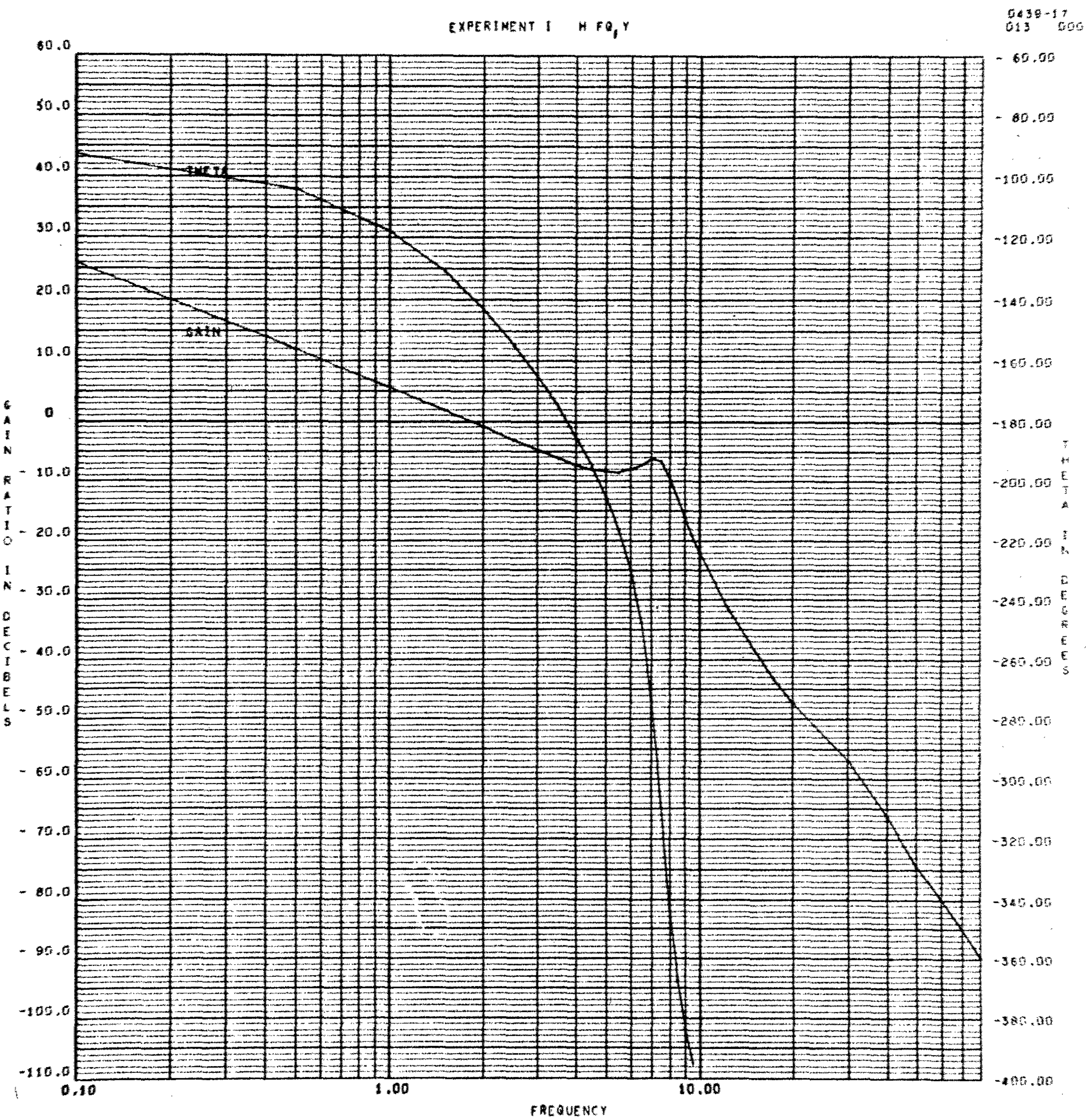
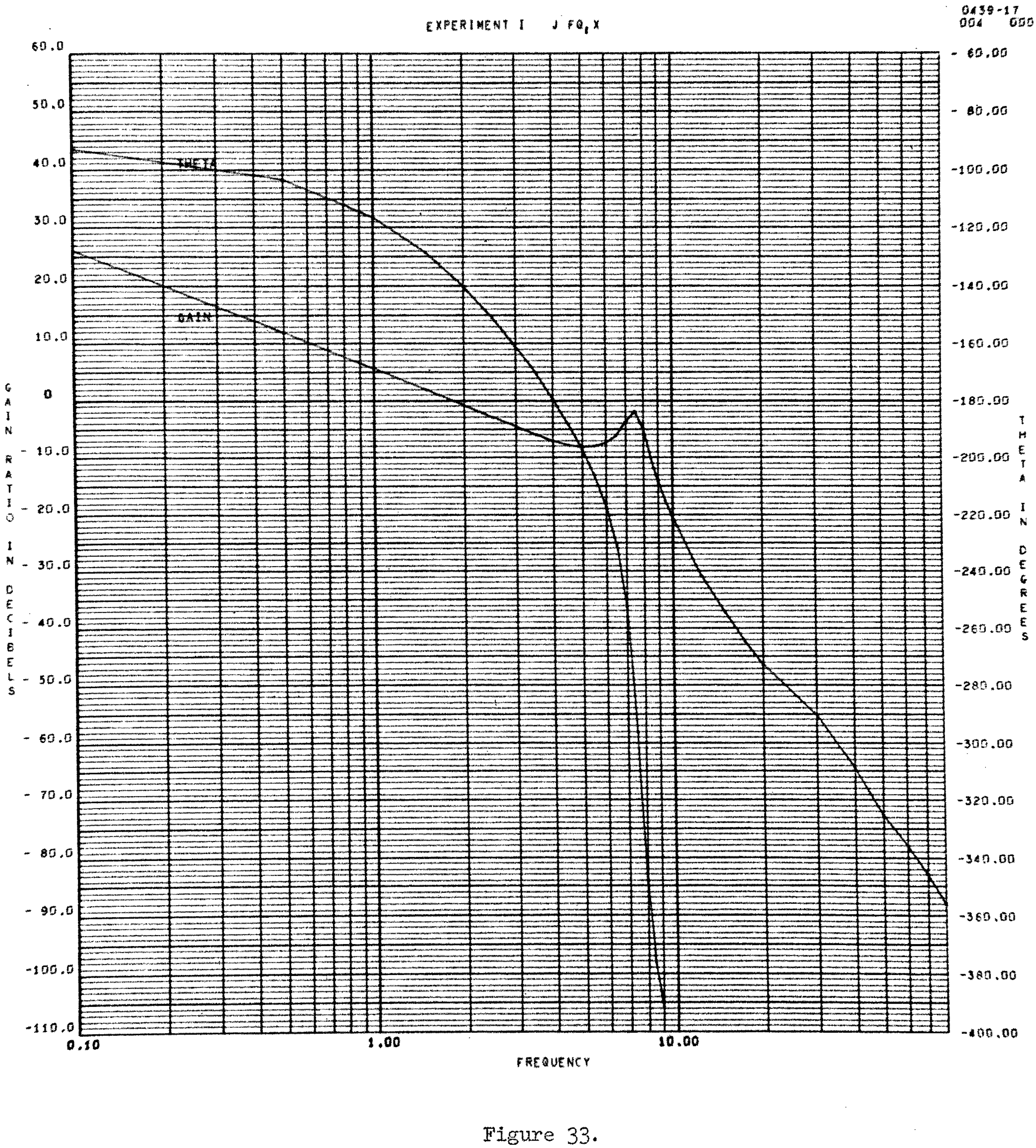

EXPERIMENT I H FQ, Y
0439-17
013 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
THETA
GAIN
0.10
1.00
10.00
FREQUENCY

Figure 32.



0439-17
004 000
EXPERIMENT I J FQ,X
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 33.

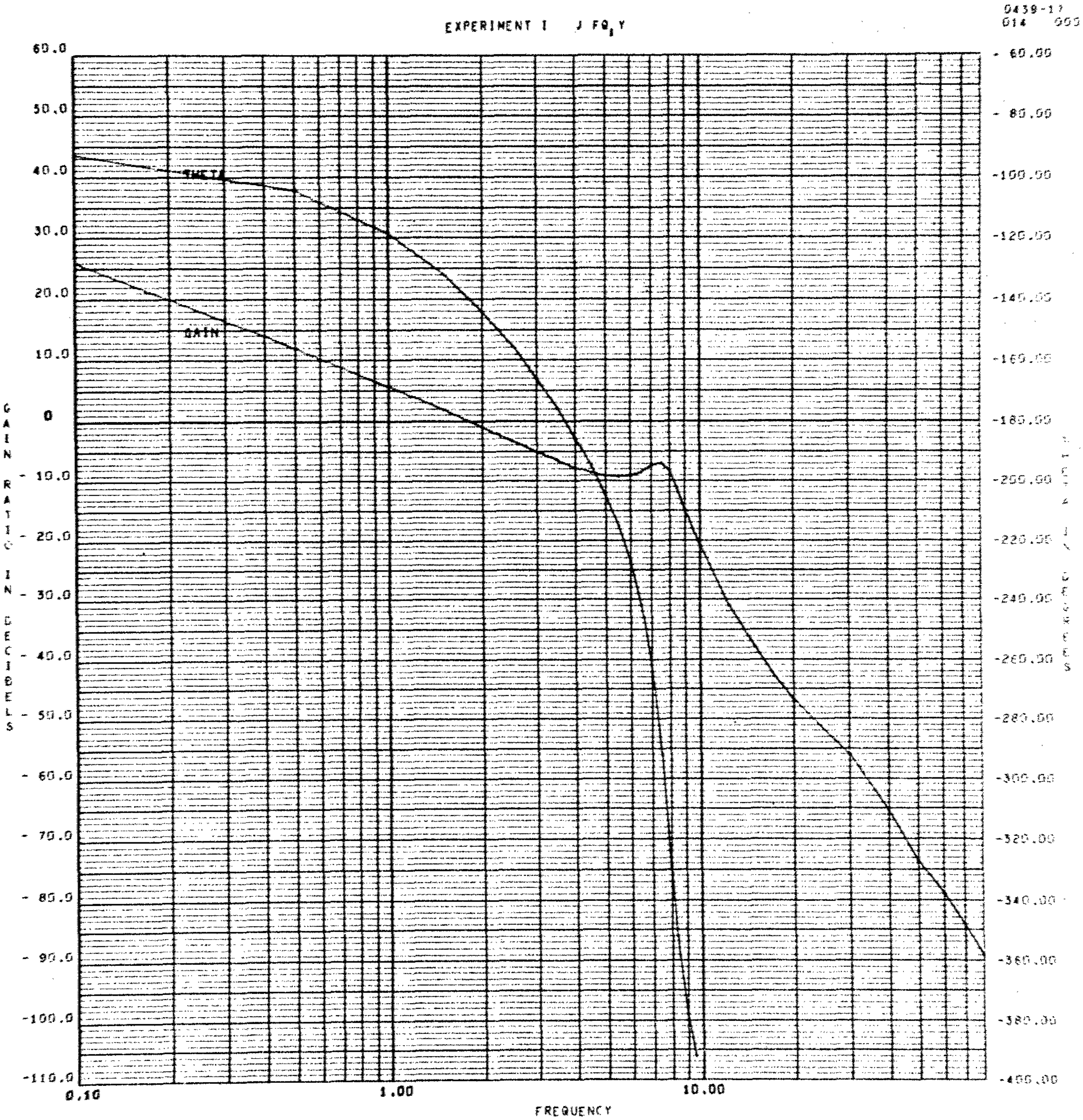

EXPERIMENT I
GAIN RATIO IN DECIBELS
THETA
GAIN
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 34.

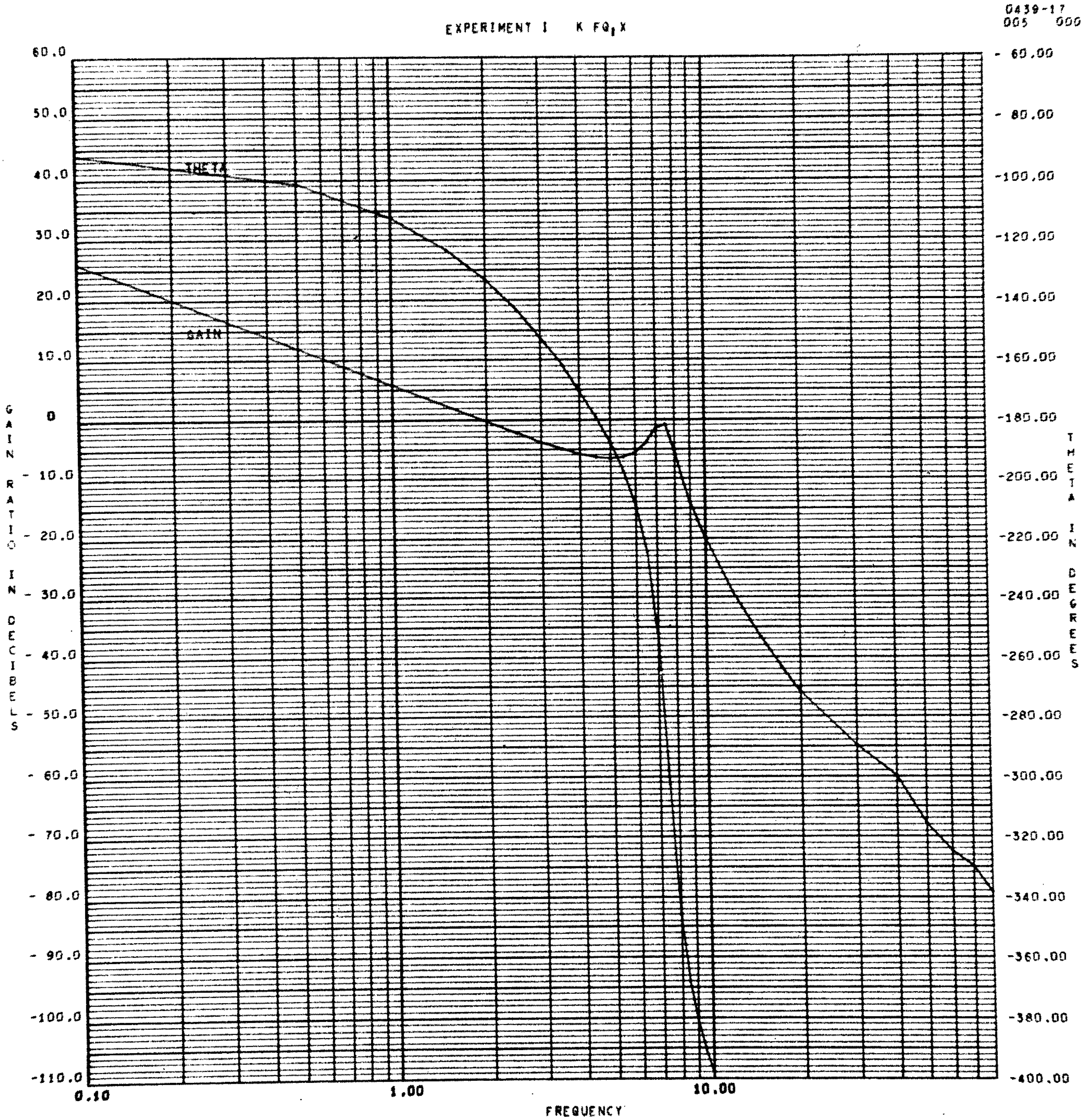
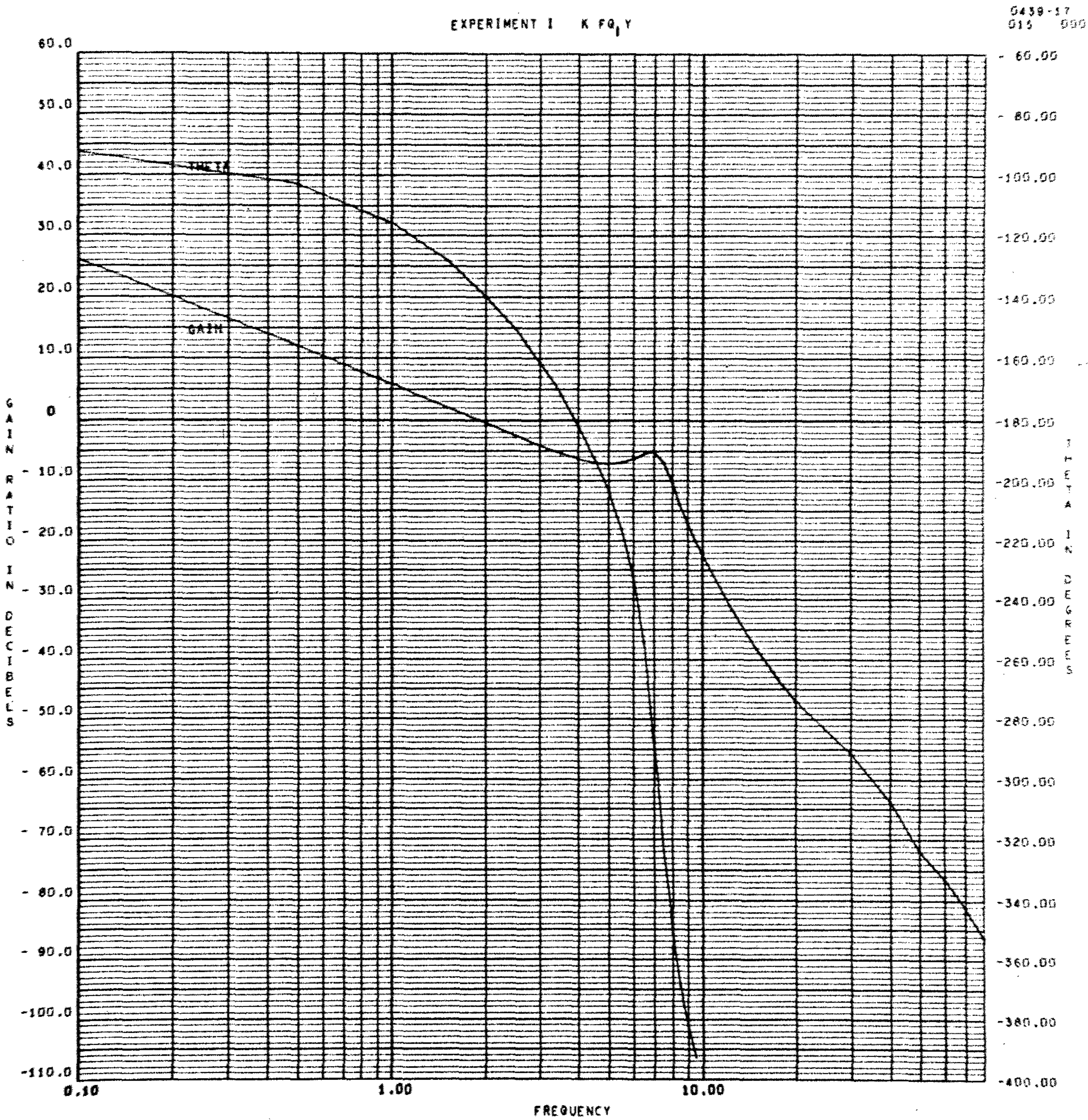

0439-17
005 000
EXPERIMENT I K FQ,X
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 35.



EXPERIMENT I K FQ Y
G439-17
015 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
THETA
GAIN
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 36.

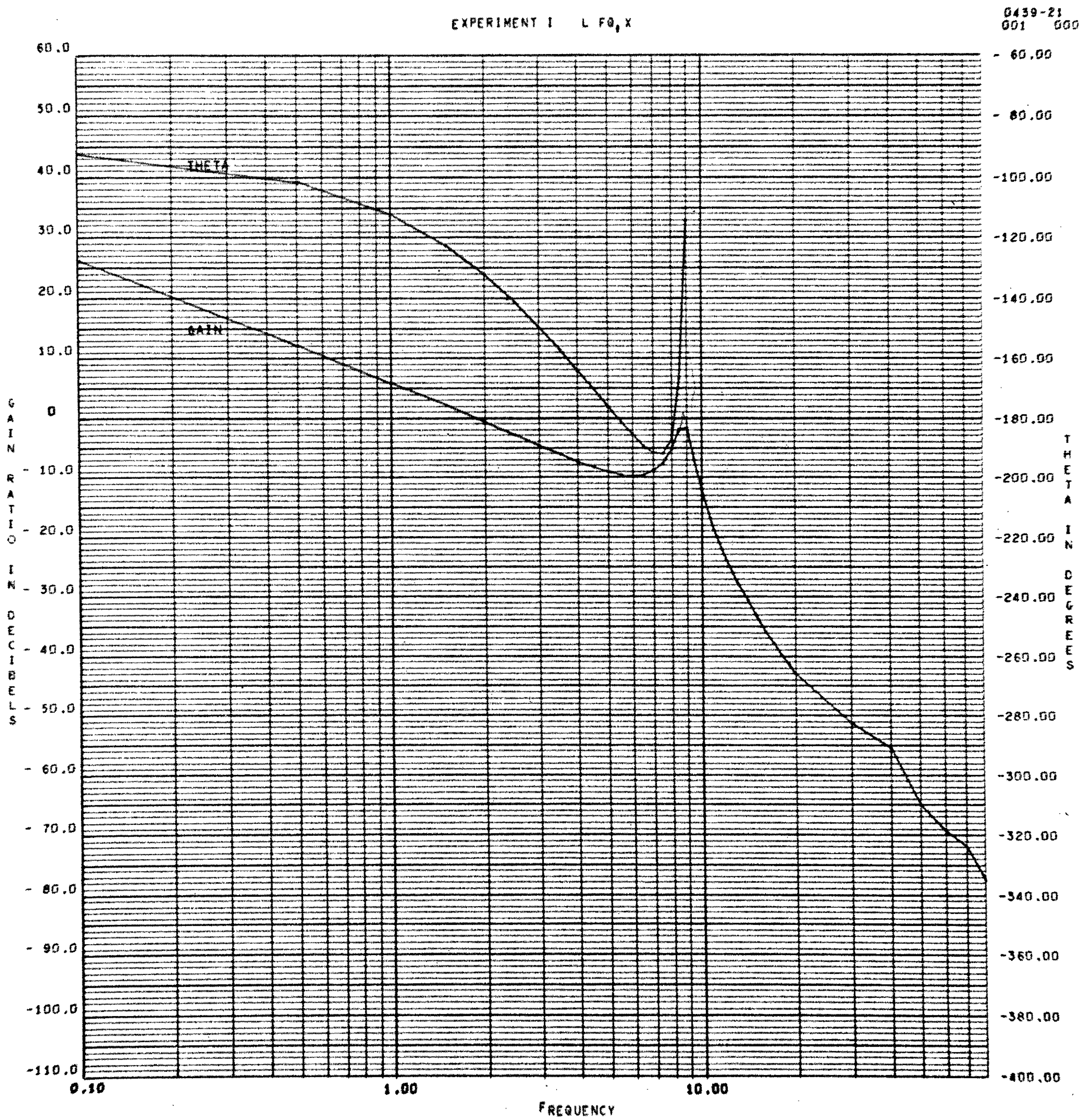

EXPERIMENT I L FQ, X
0439-21
001 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 37.

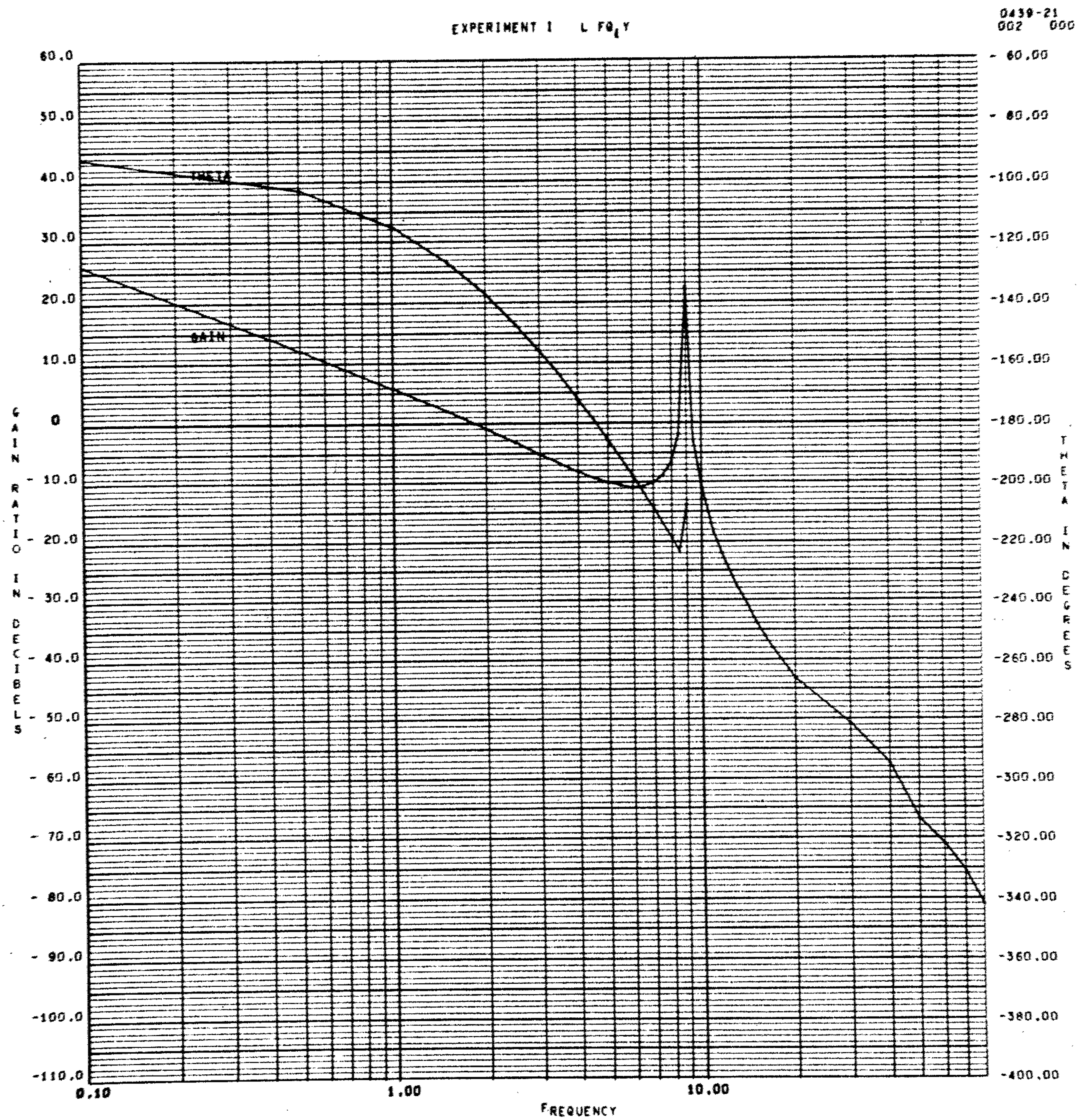
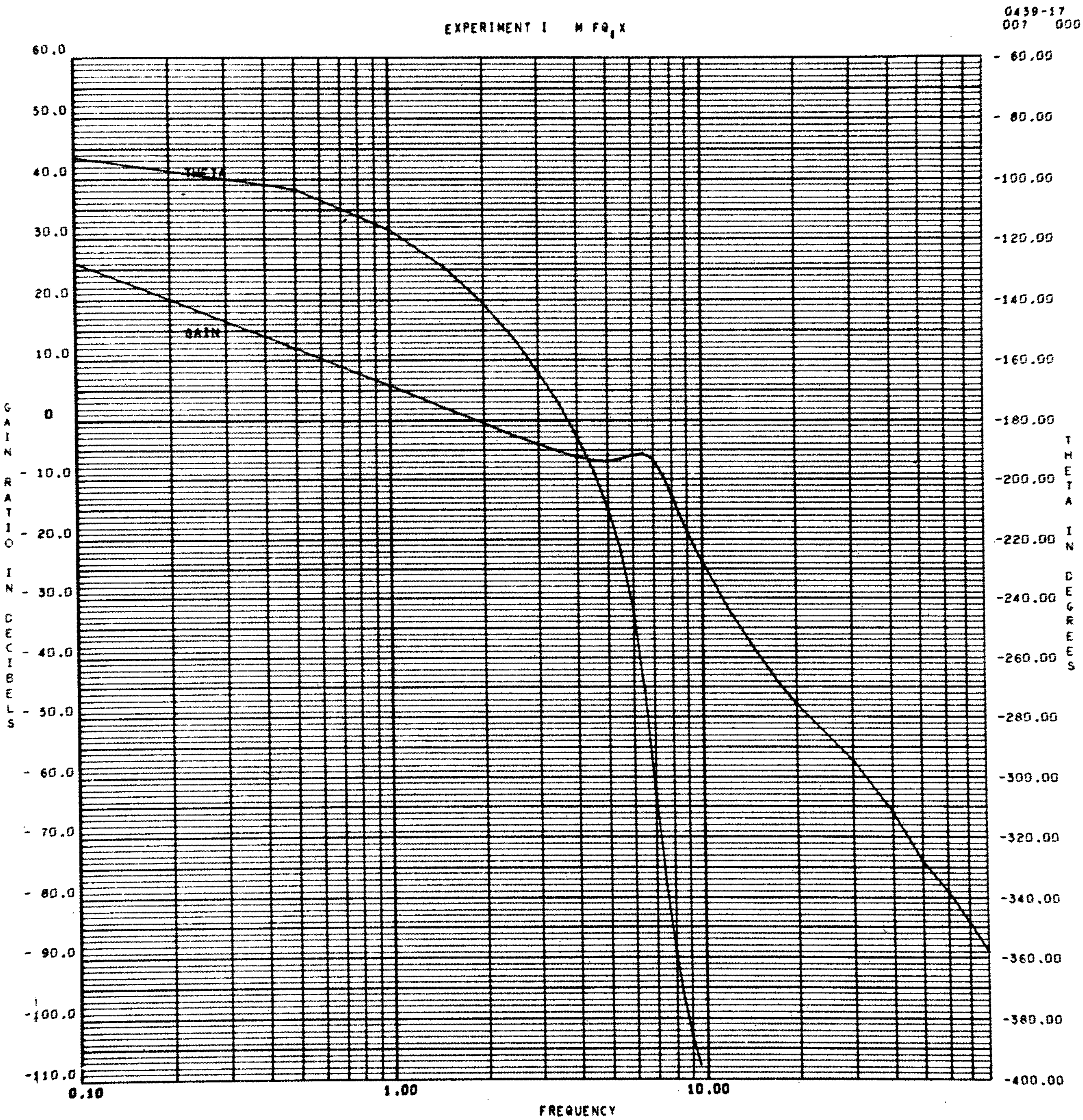
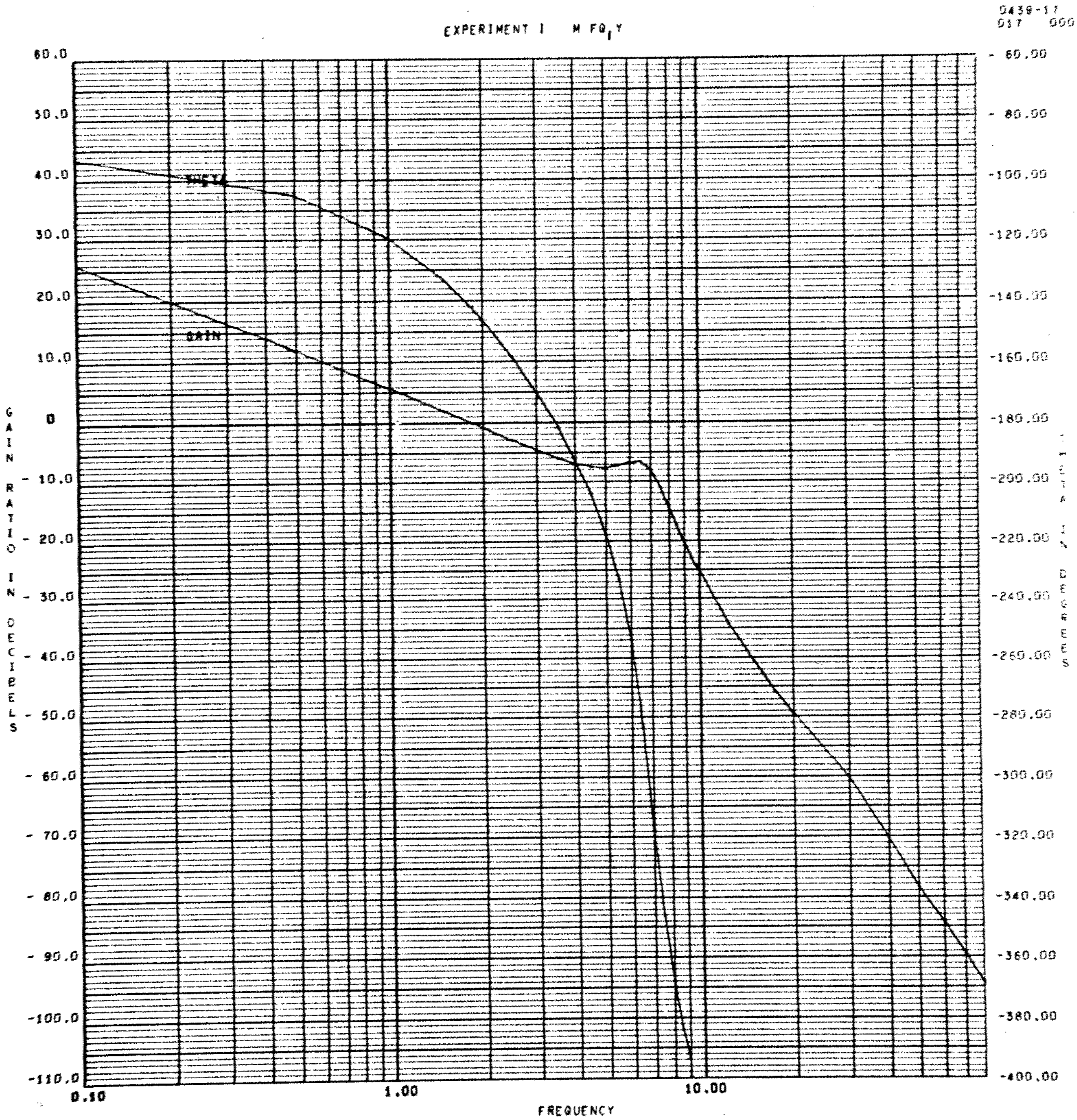

EXPERIMENT I L FQ_1 Y
0439-21
002 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
THETA
GAIN
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 38.



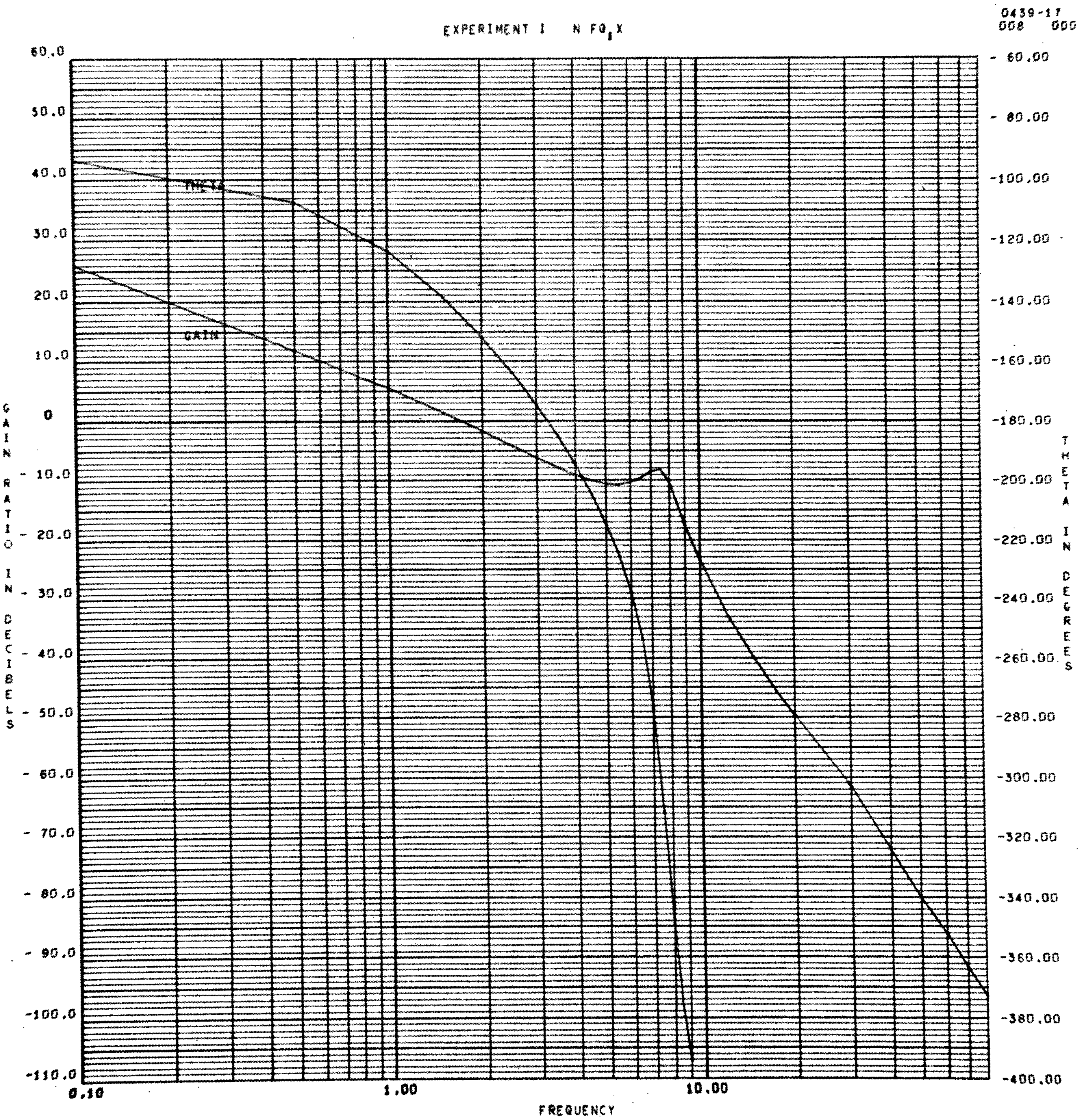
0439-17
007 000
EXPERIMENT I M FQ X
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 39.



0439-17
017 000
EXPERIMENT I M FQ Y
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
0.10
1.00
10.00
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 40.



EXPERIMENT I N FQ1X
0439-17
008 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
THETA
GAIN
0.10
1.00
10.00
FREQUENCY

Figure 41.

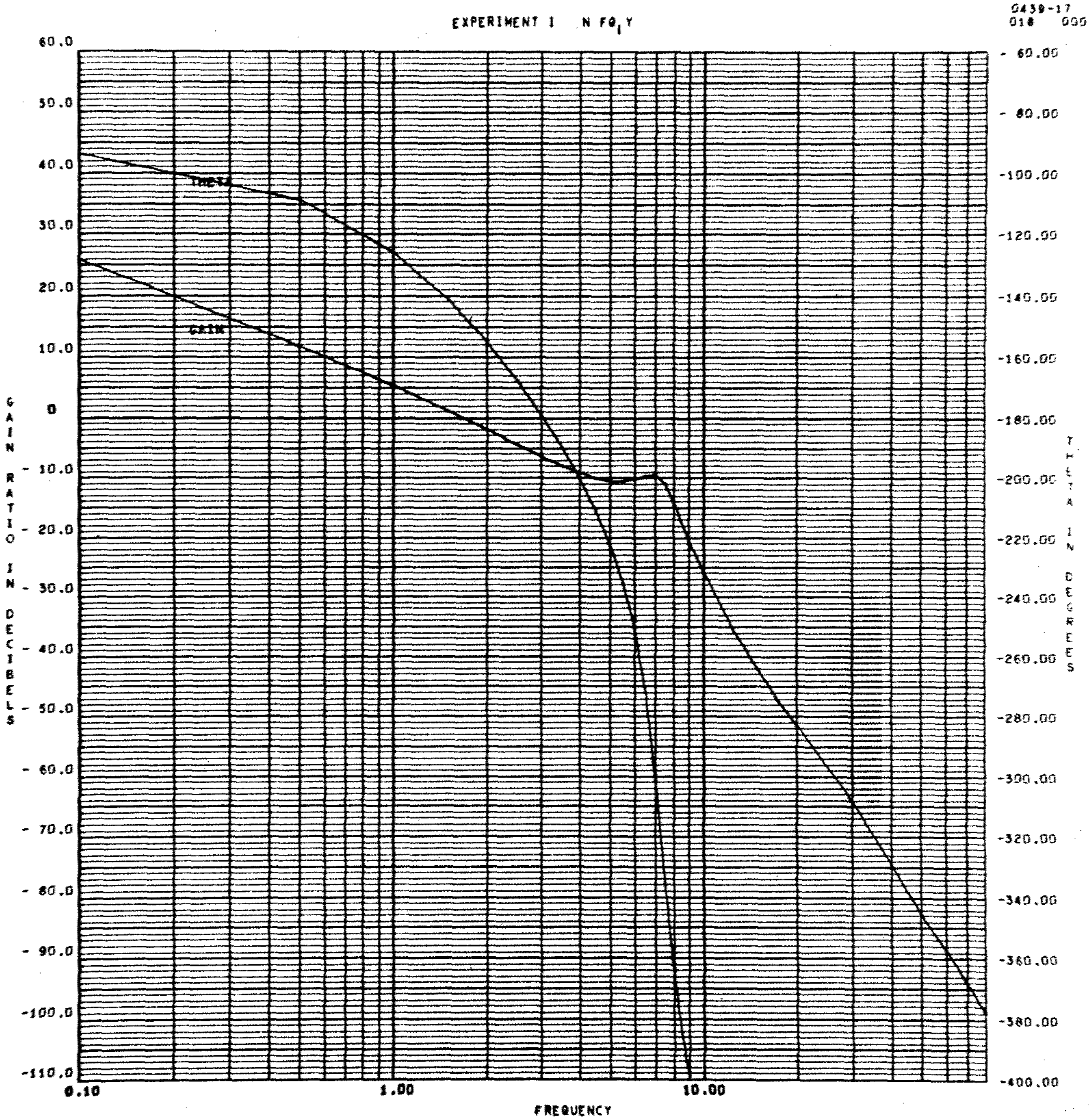

EXPERIMENT I N FQ Y
0439-17
018 005
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
THETA
GAIN
0.10
1.00
10.00
FREQUENCY
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES

Figure 42.

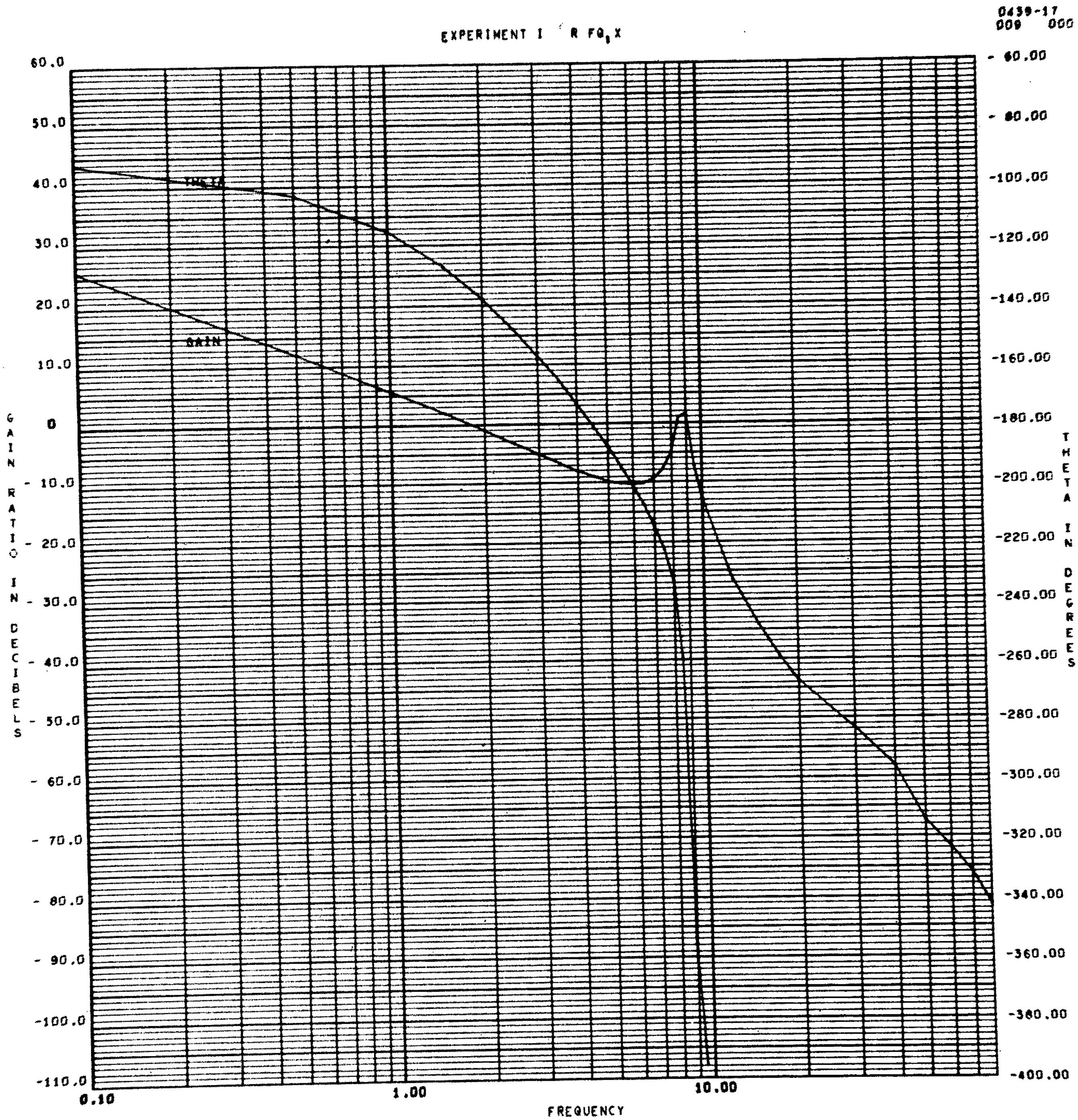
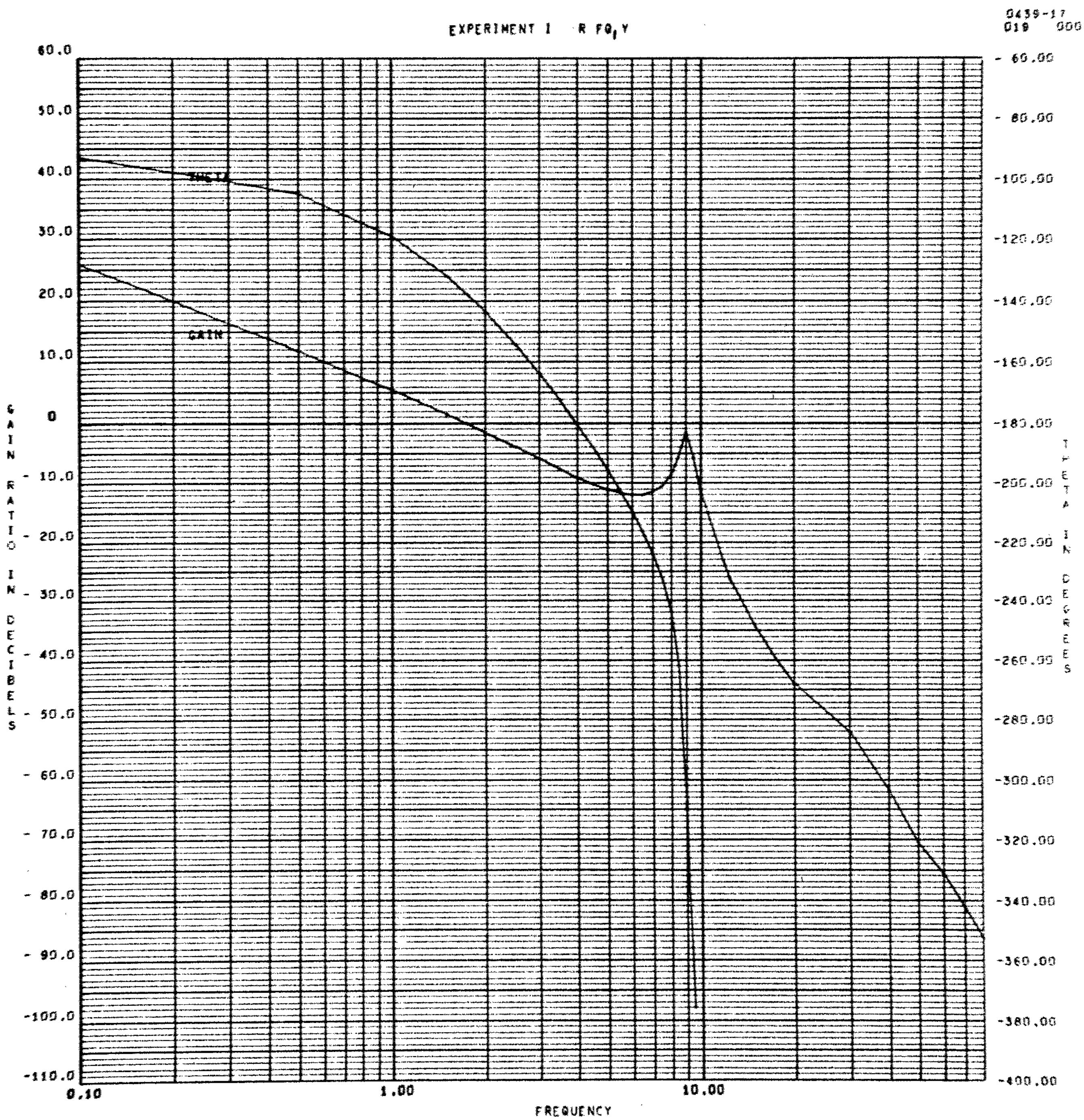
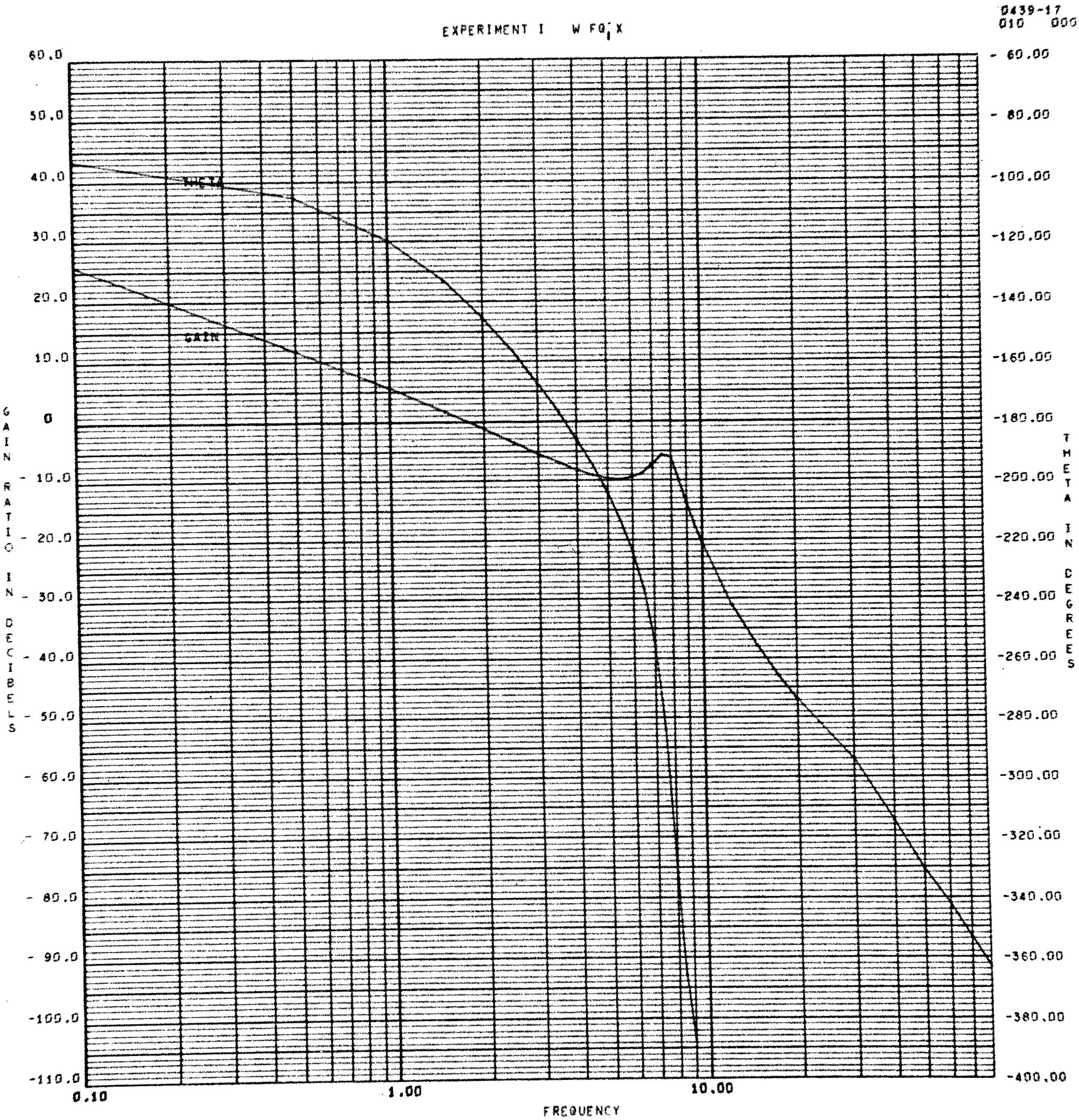

EXPERIMENT I R FQ,X
0439-17
009 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 43.



EXPERIMENT I R FQ, Y
0439-17
019 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
THETA
GAIN
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 44.



0439-17
010 000
EXPERIMENT I W FQ X
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 45.

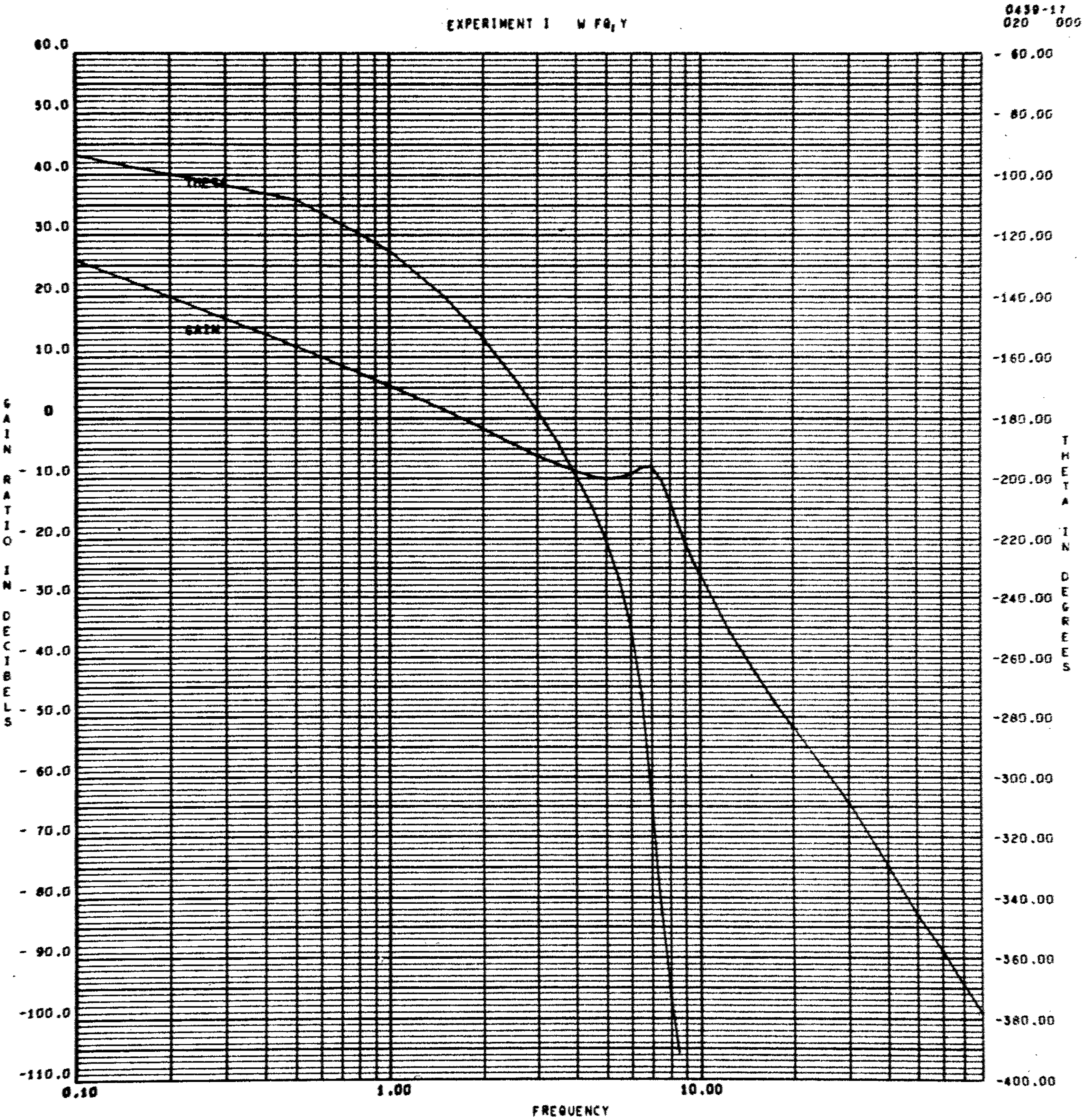
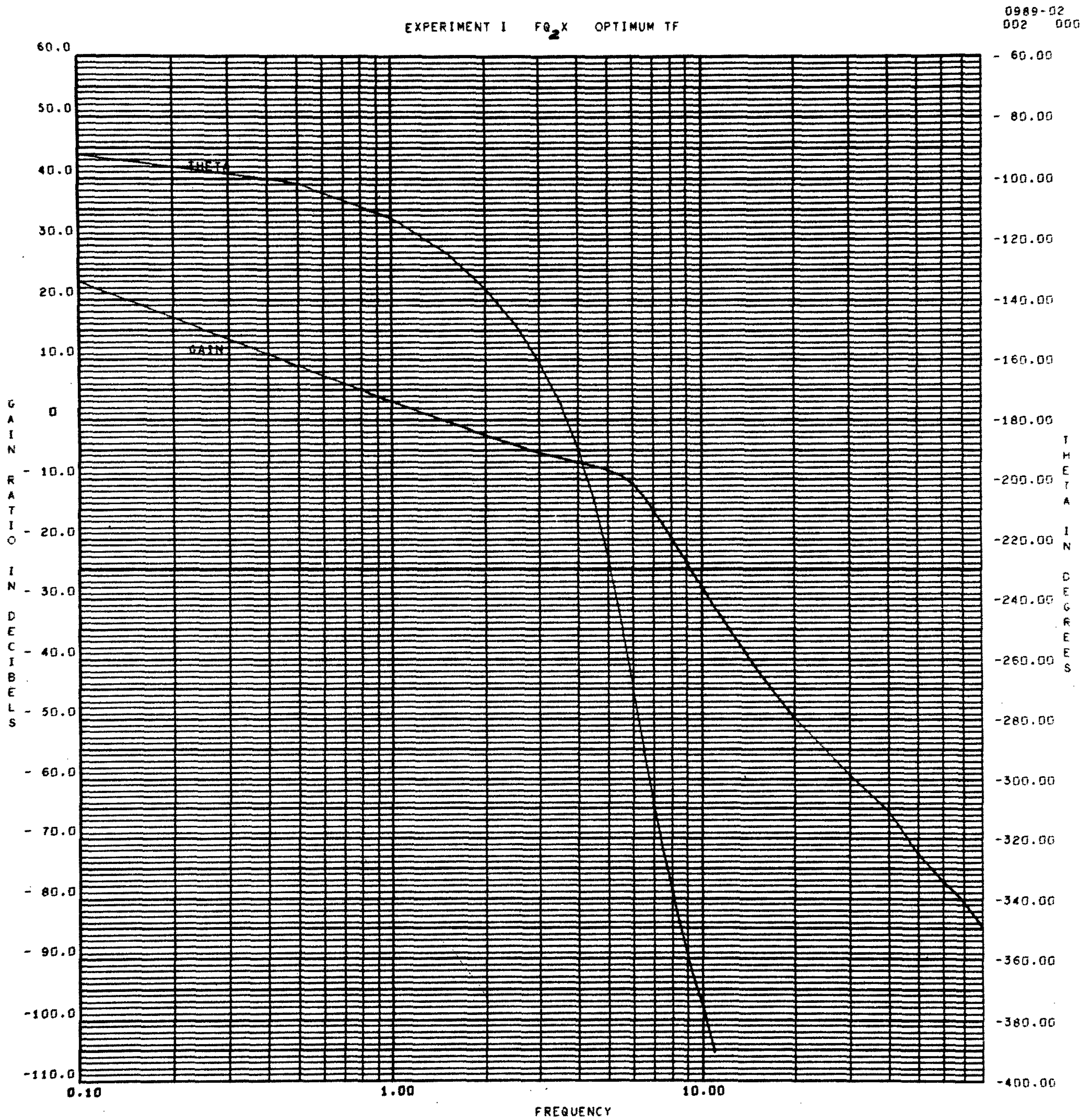

EXPERIMENT I W Fθ, Y
0459-17
020 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 46.



0989-02
002 000
EXPERIMENT I FQ2X OPTIMUM TF
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 47.

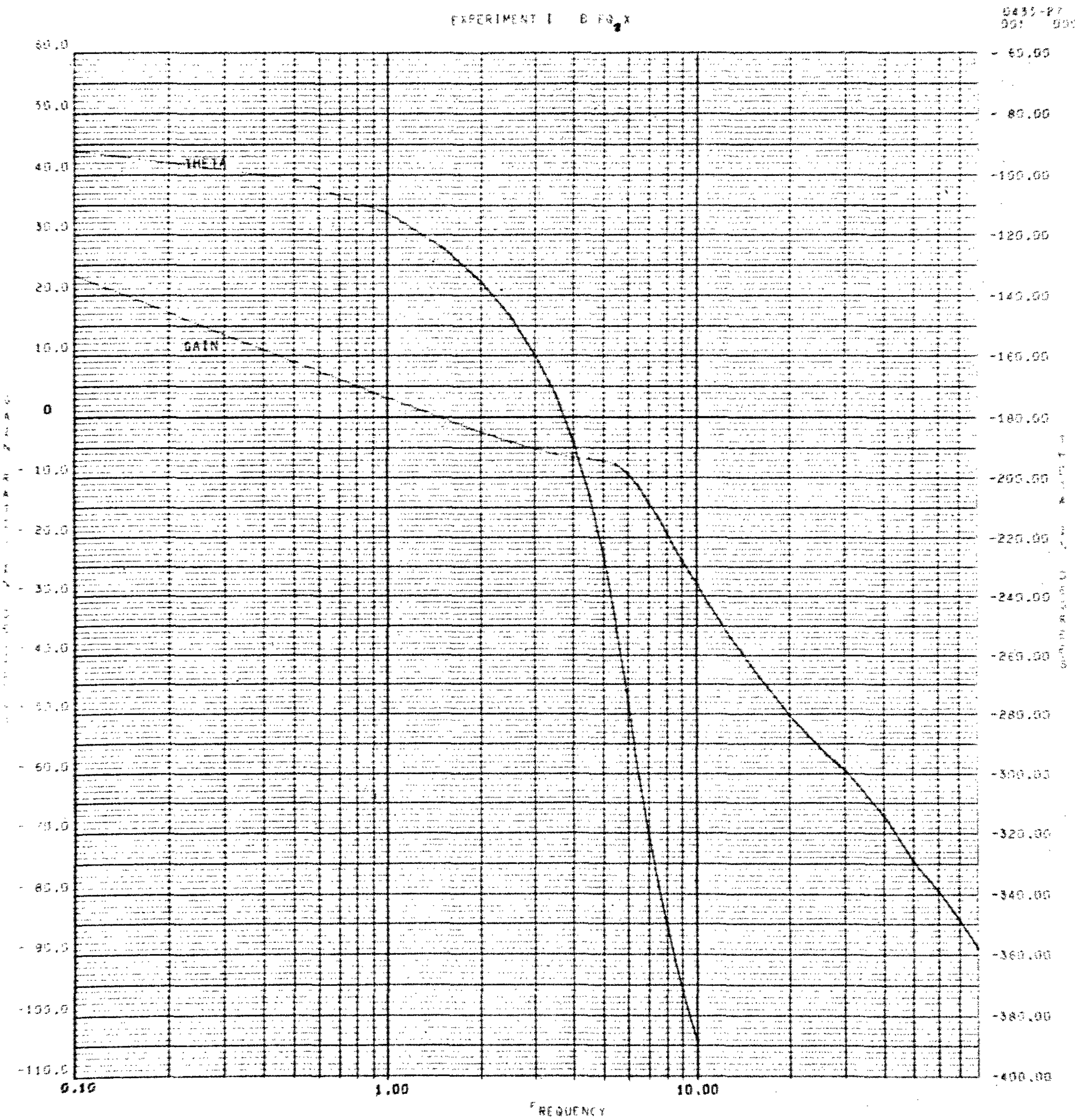


Figure 48.

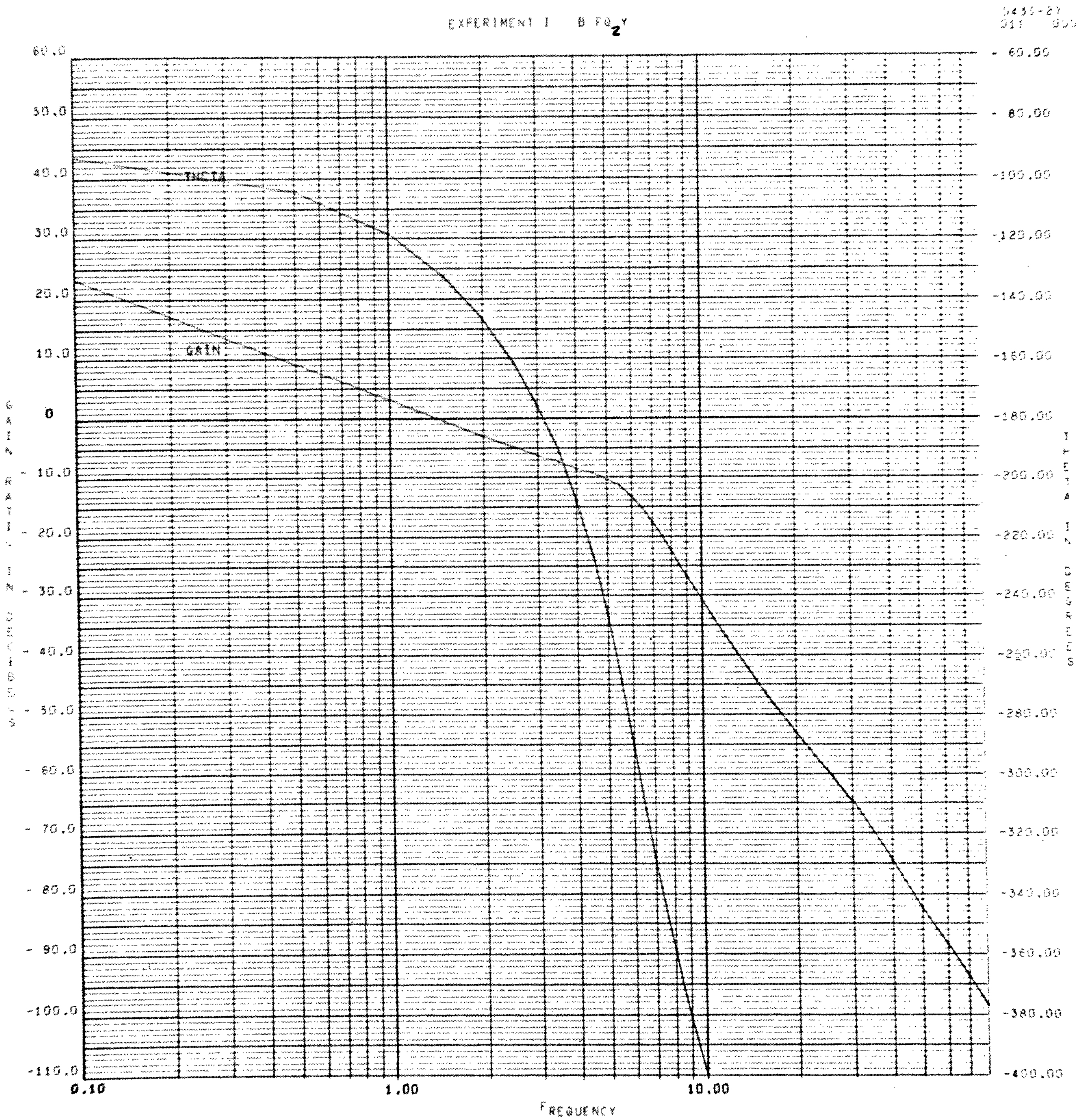
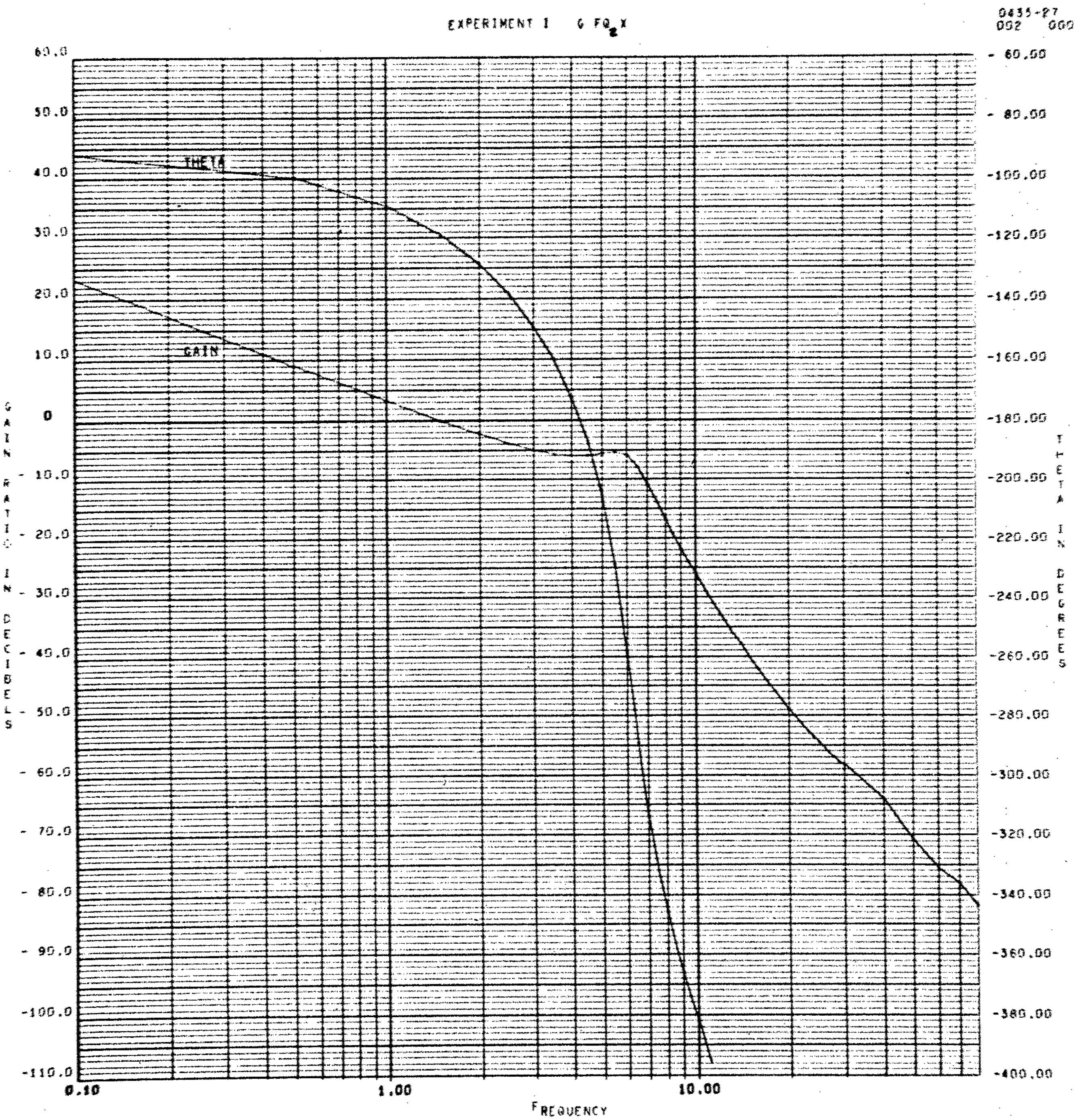
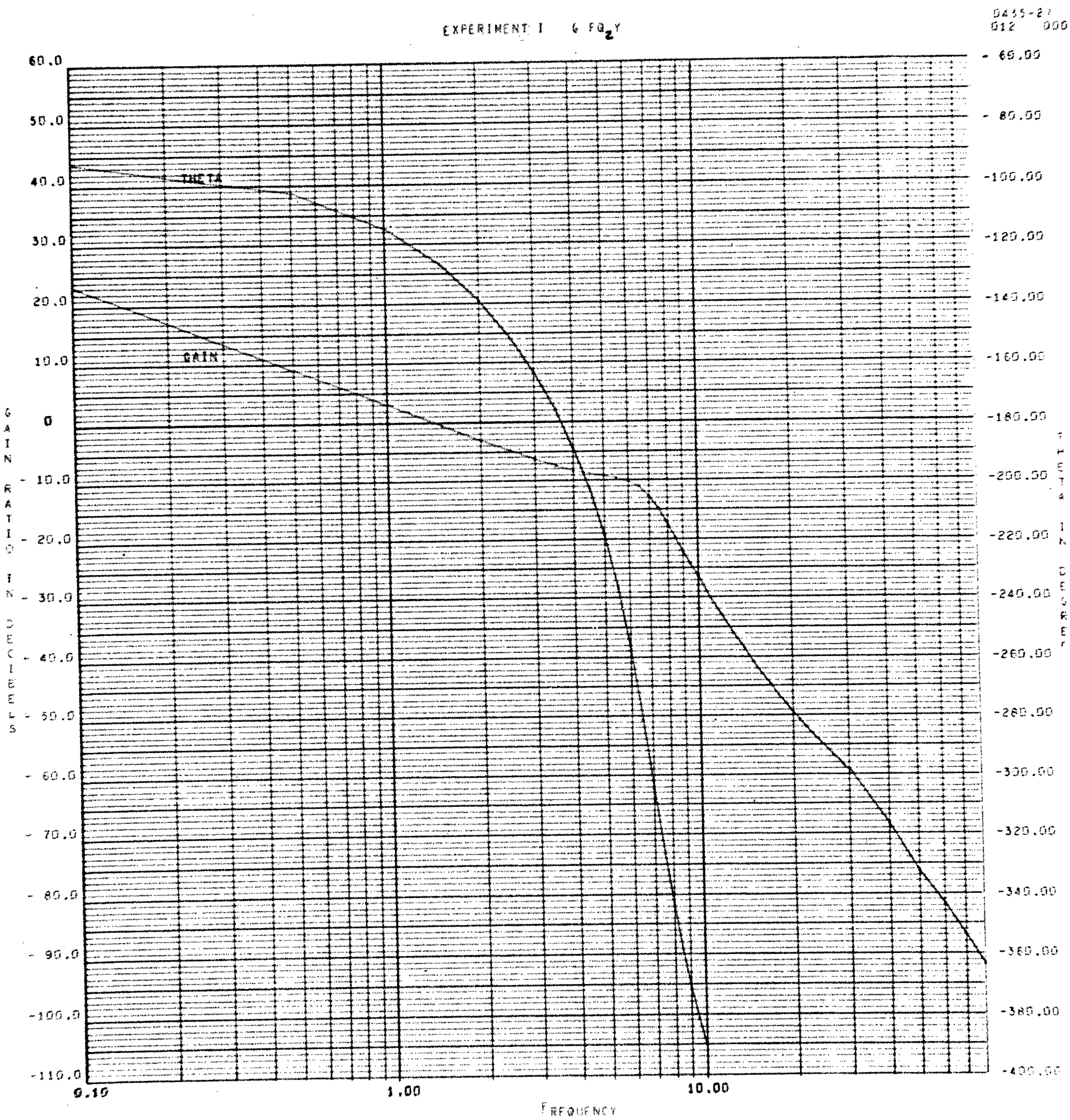

EXPERIMENT I B FQ2Y
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00

Figure 49.



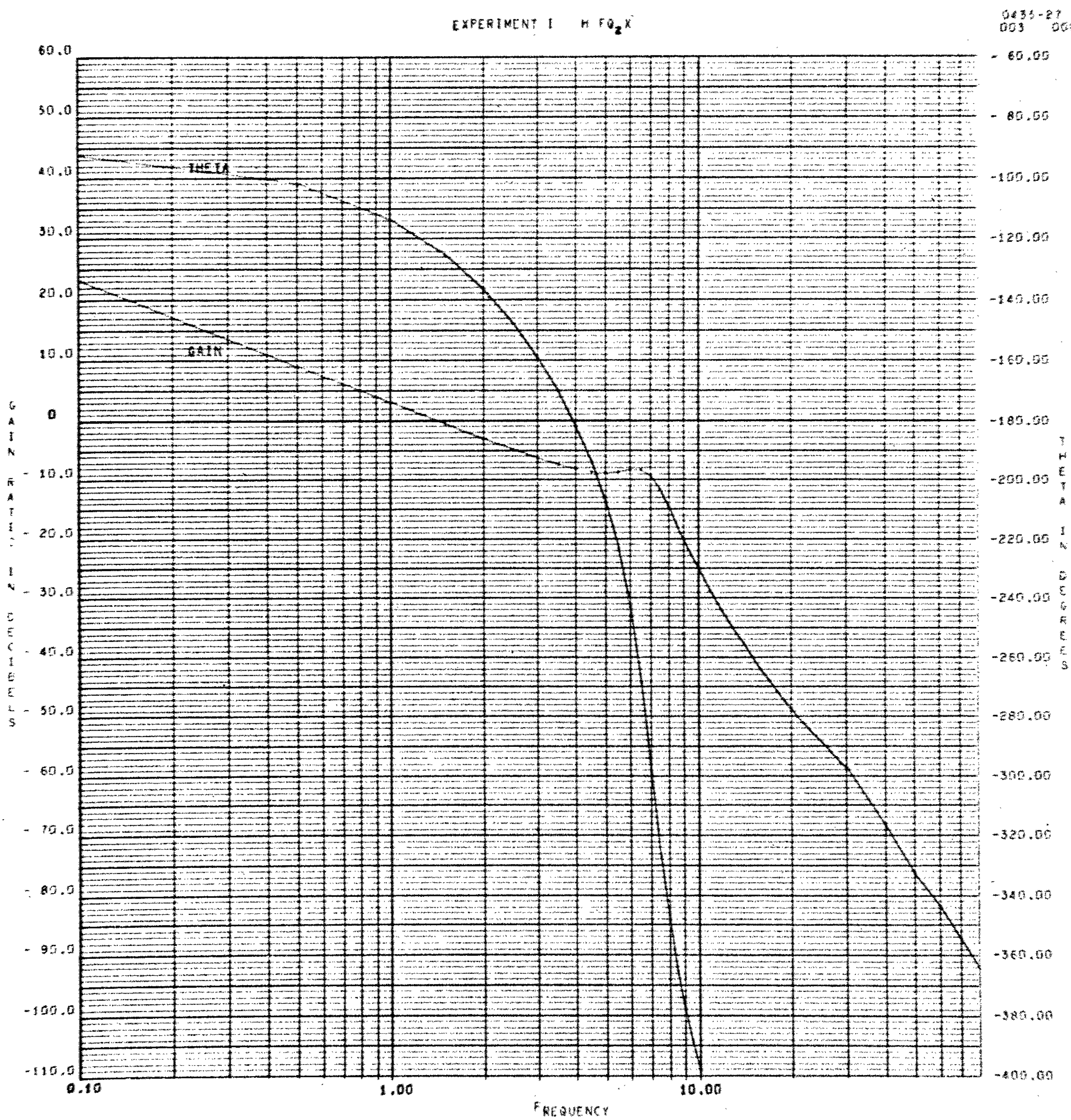
EXPERIMENT I G FQ X
0435-27
002 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 50.



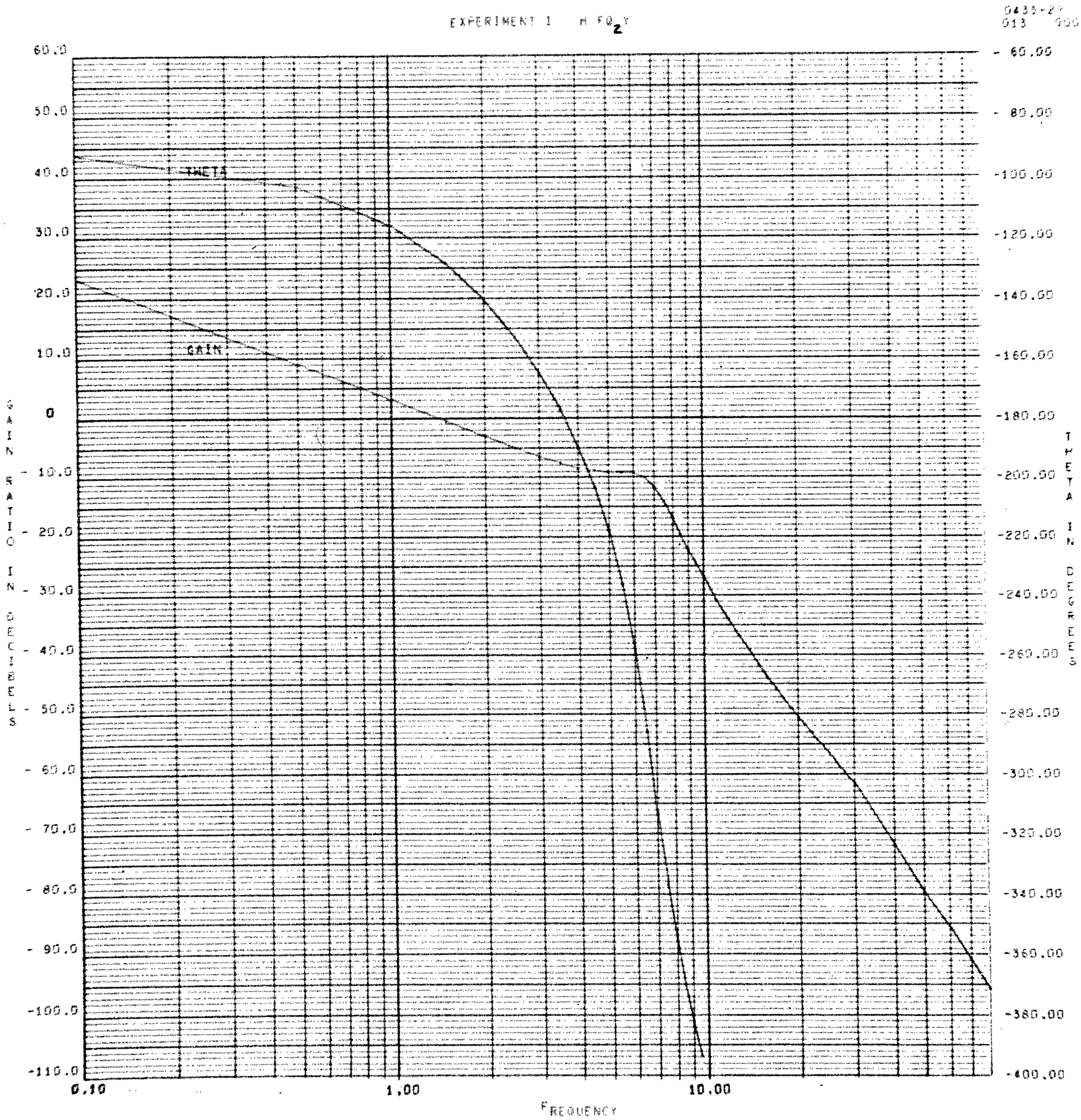
EXPERIMENT I G FQ$_2$Y
0435-27
012 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 51.



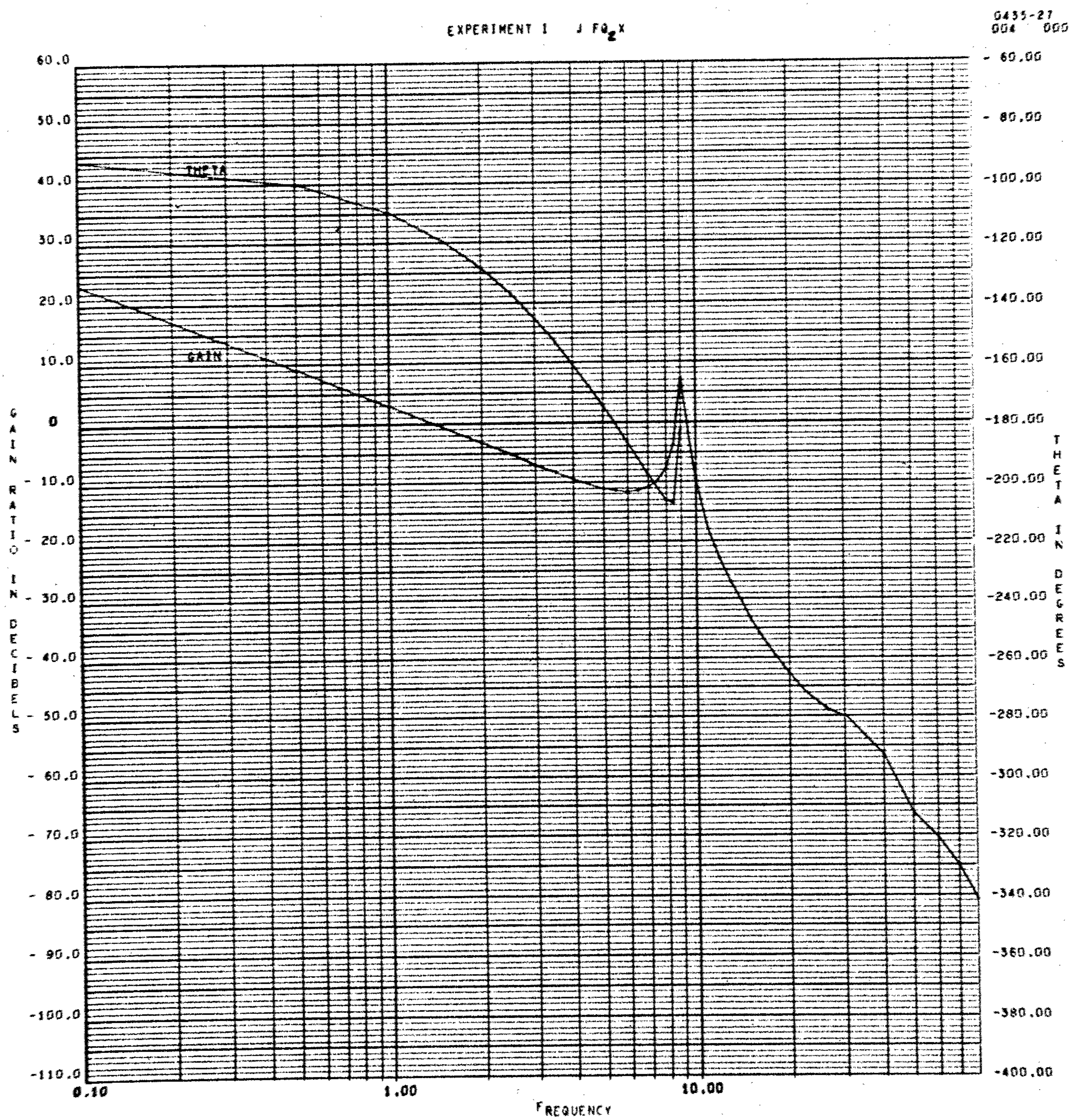
EXPERIMENT I H FQzX
0435-27
003 000
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
GAIN RATIO IN DECIBELS
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 52.



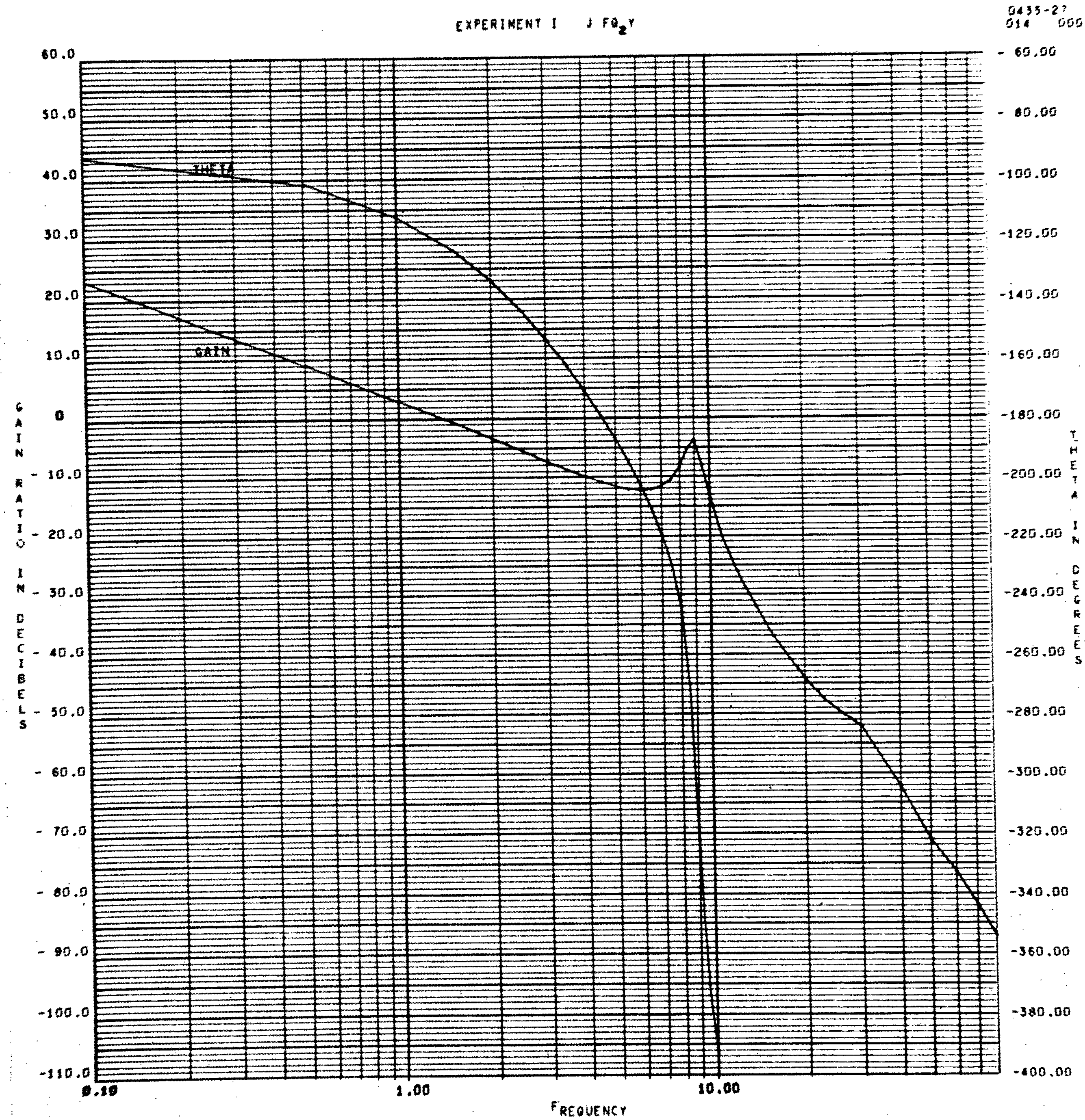
EXPERIMENT I H FQ$_z$Y
0435-2Y
013
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 53.



0435-27
004 005
EXPERIMENT I J FQ$_z$X
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 54.



EXPERIMENT I J FQ2Y
0435-27
014 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 55.

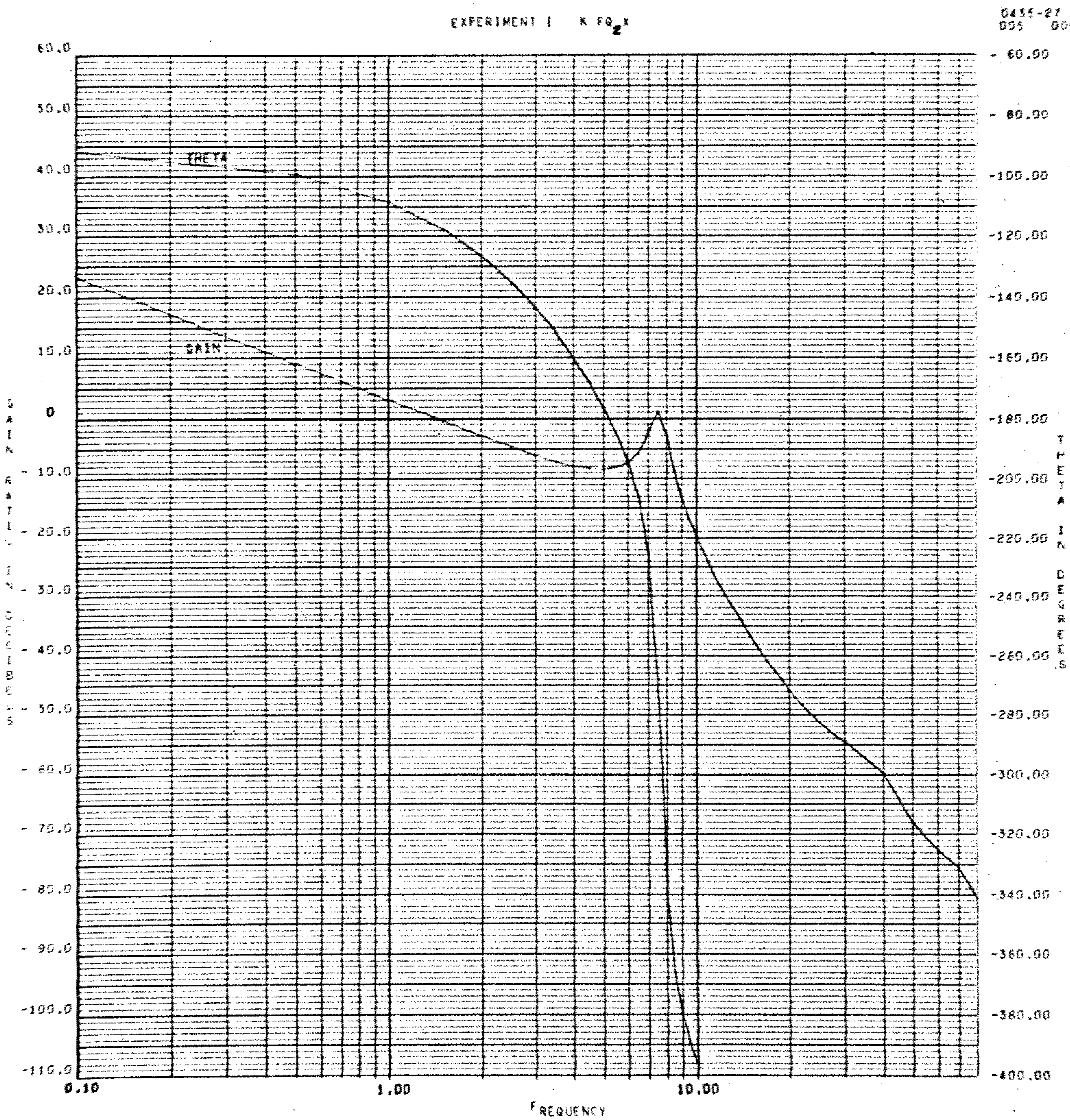

EXPERIMENT I K FQ$_z$X
0435-27
005 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 56.

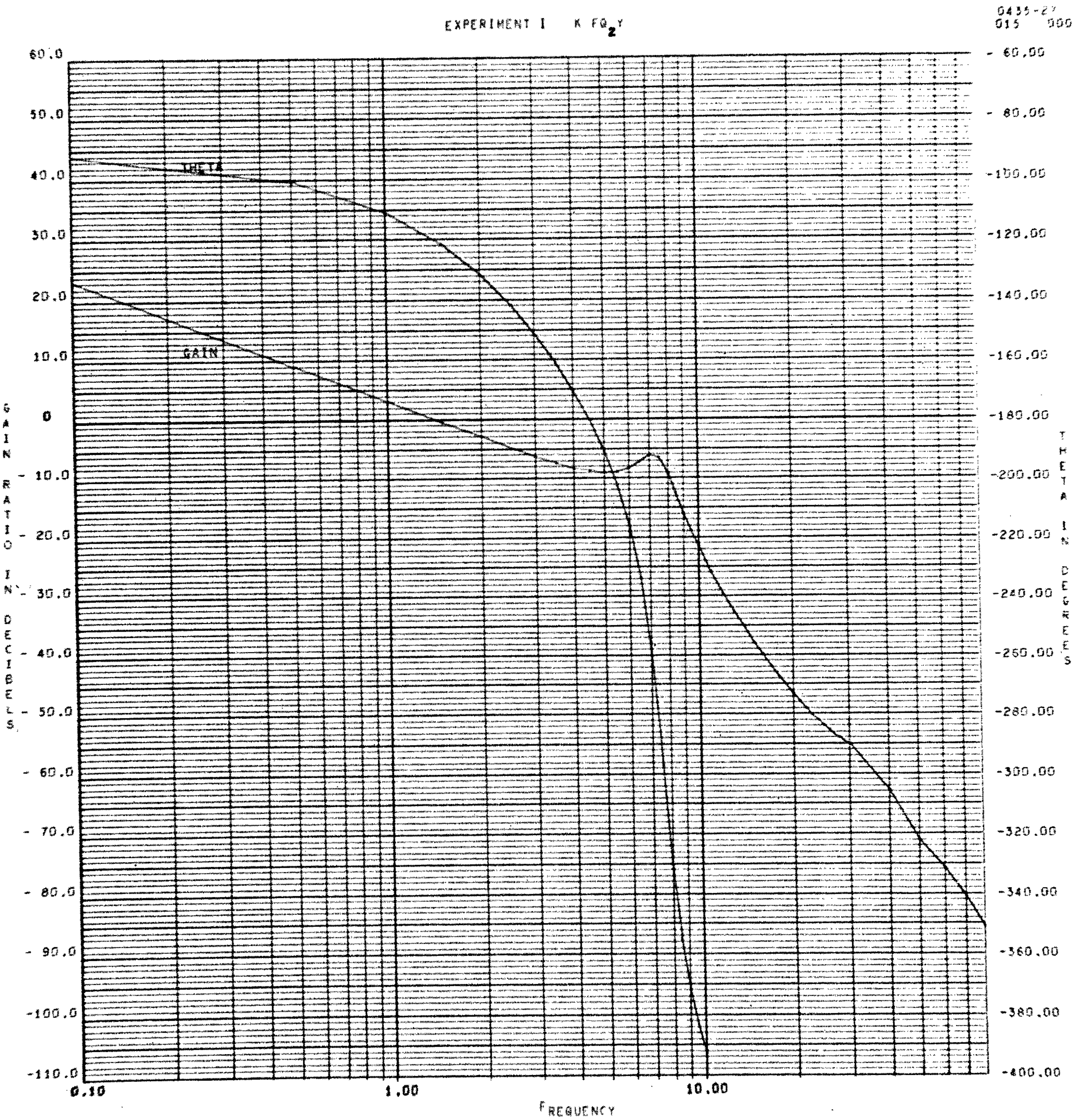

EXPERIMENT I K FQ2Y
0435-27
015 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 57.

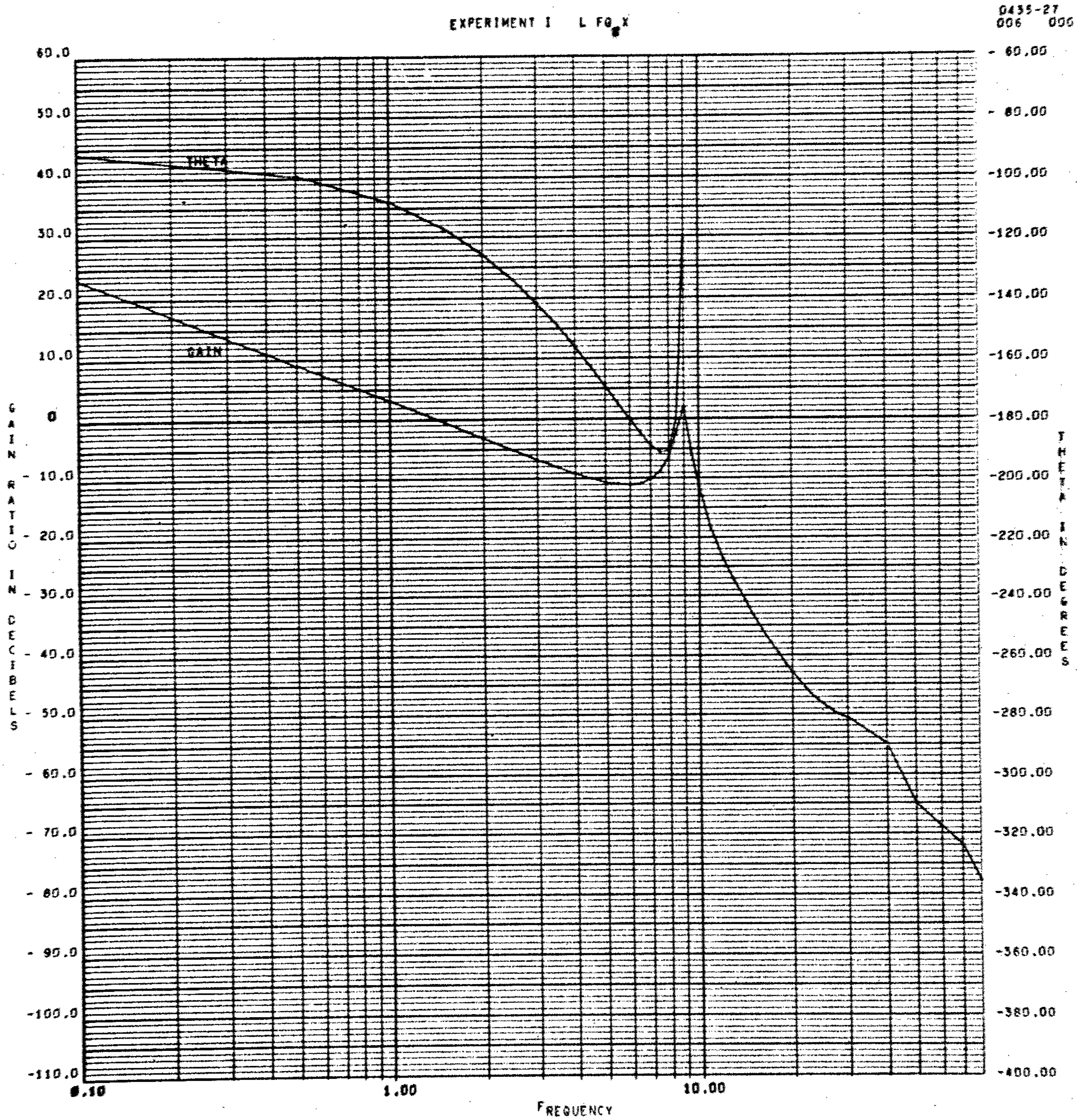

EXPERIMENT I L FQ X
0435-27
006 000
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
THETA
GAIN
0.10
1.00
10.00
FREQUENCY

Figure 58.

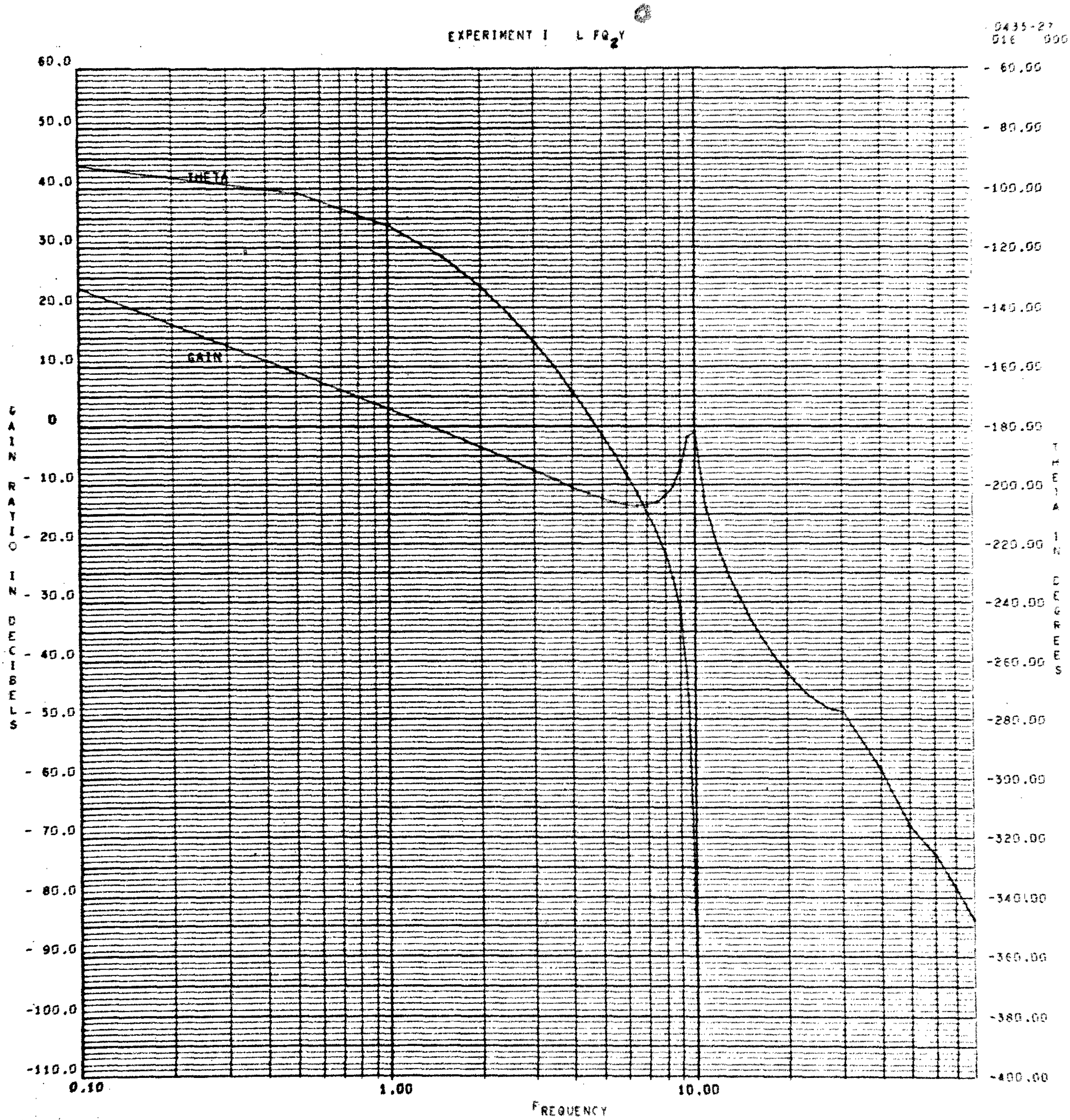
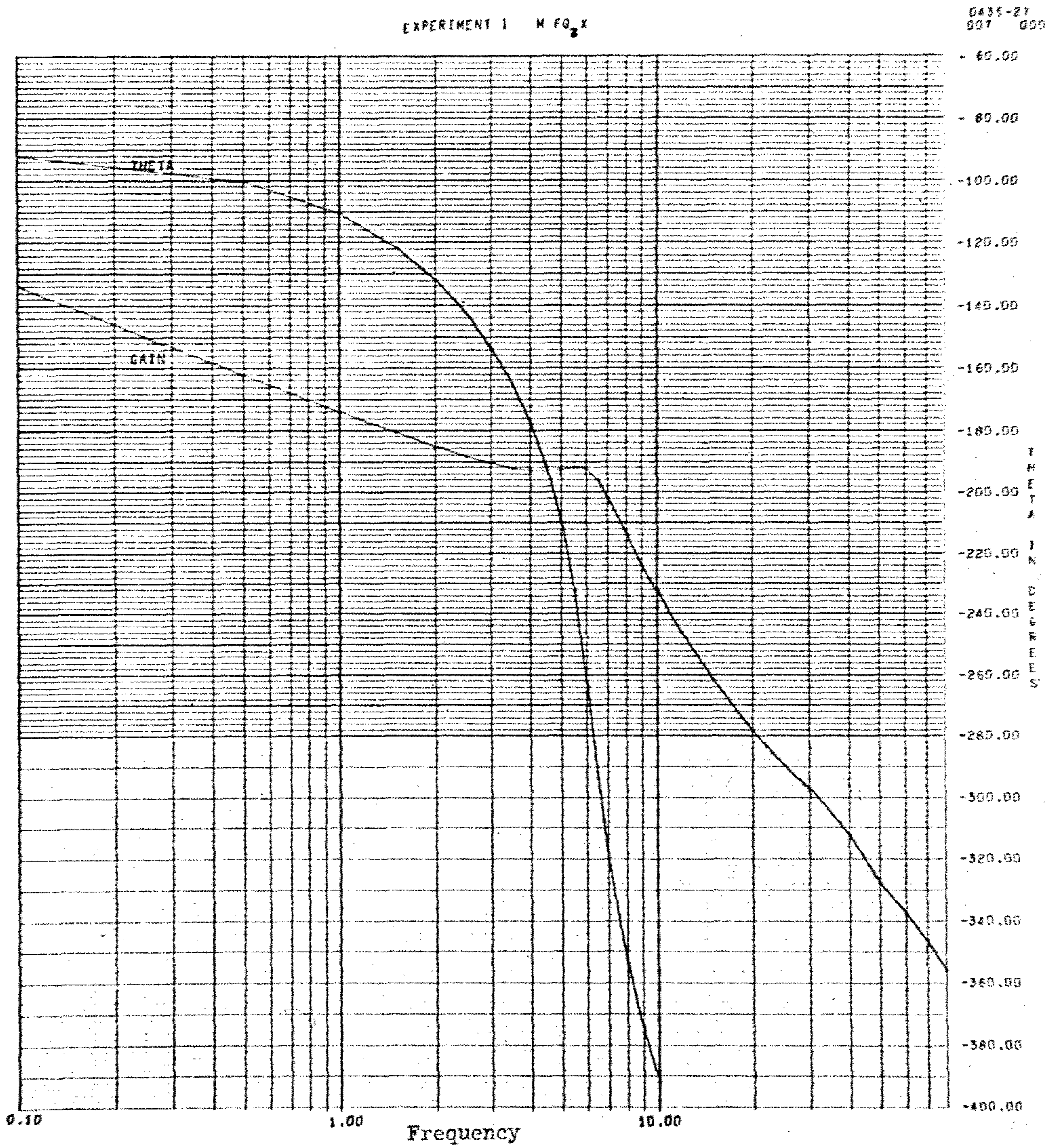

EXPERIMENT I L FQ2Y
THETA
GAIN
GAIN RATIO IN DECIBELS
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
THETA IN DEGREES
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00
FREQUENCY

Figure 59.



EXPERIMENT I M FQ$_2$X
OA35-27
007 009
THETA
GAIN
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
Frequency

Figure 60.

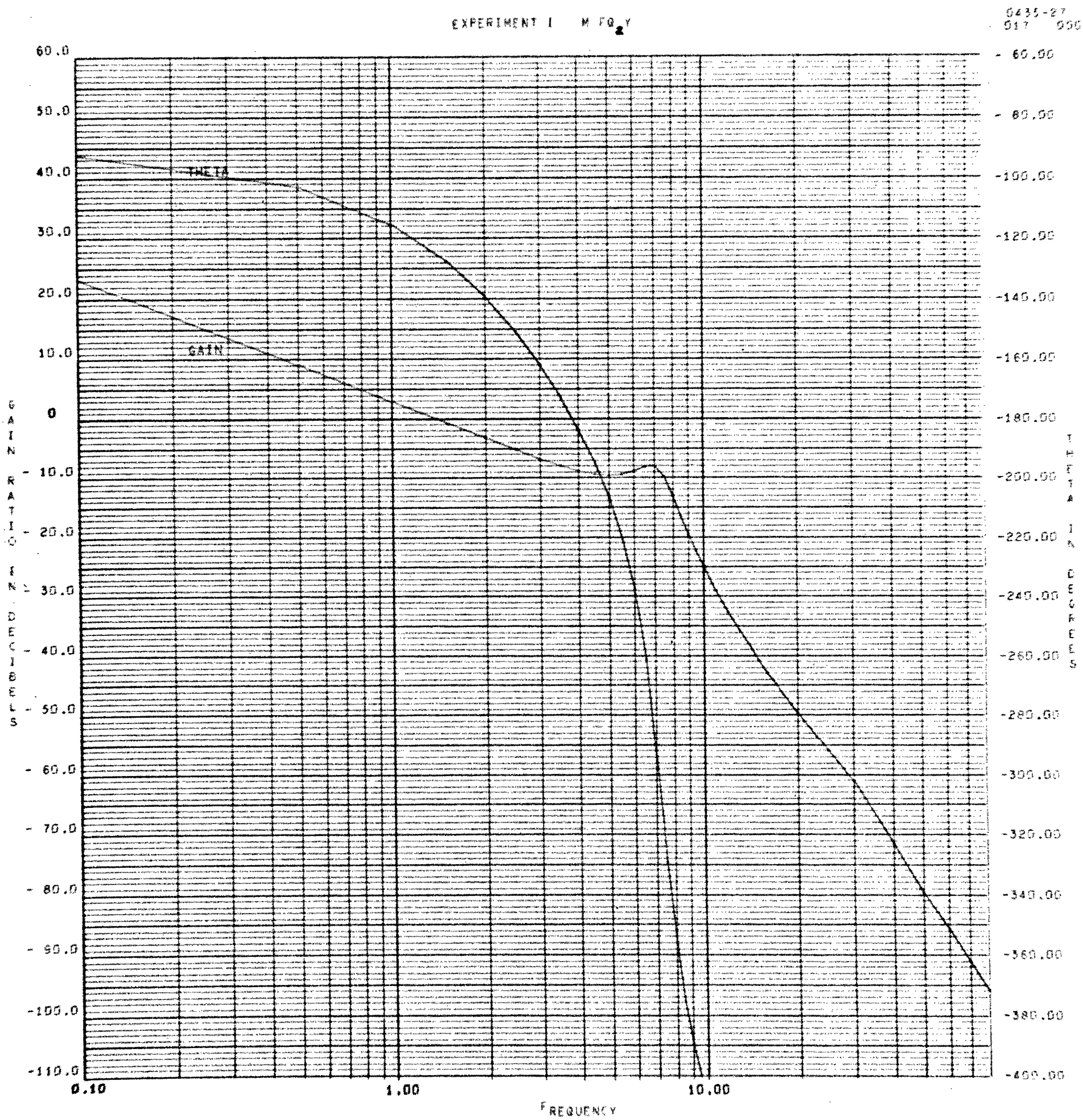

EXPERIMENT I M FQ2Y
0435-27
GAIN RATIO IN DECIBELS
THETA IN DEGREES
THETA
GAIN
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
0.10
1.00
10.00
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 61.

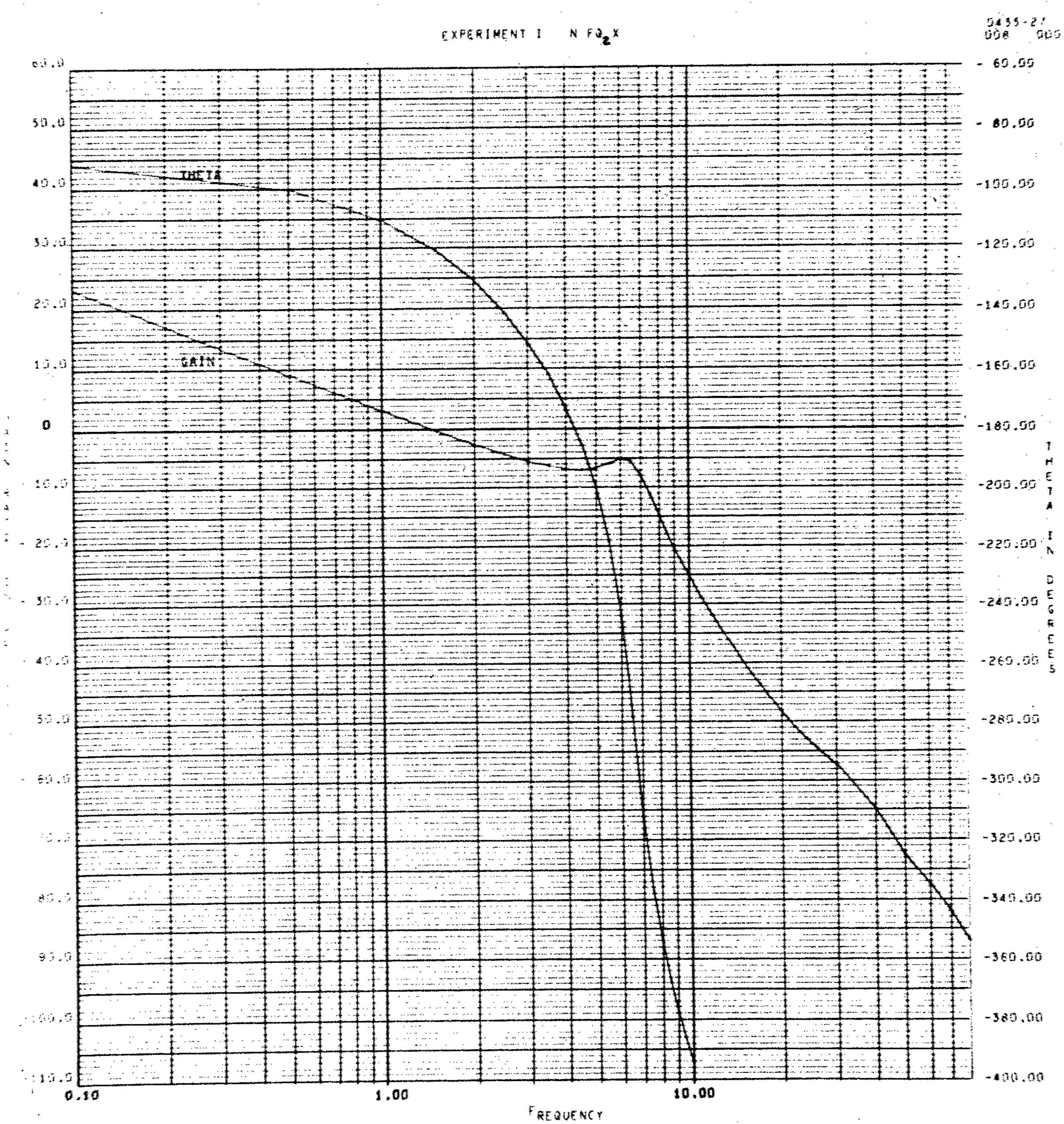
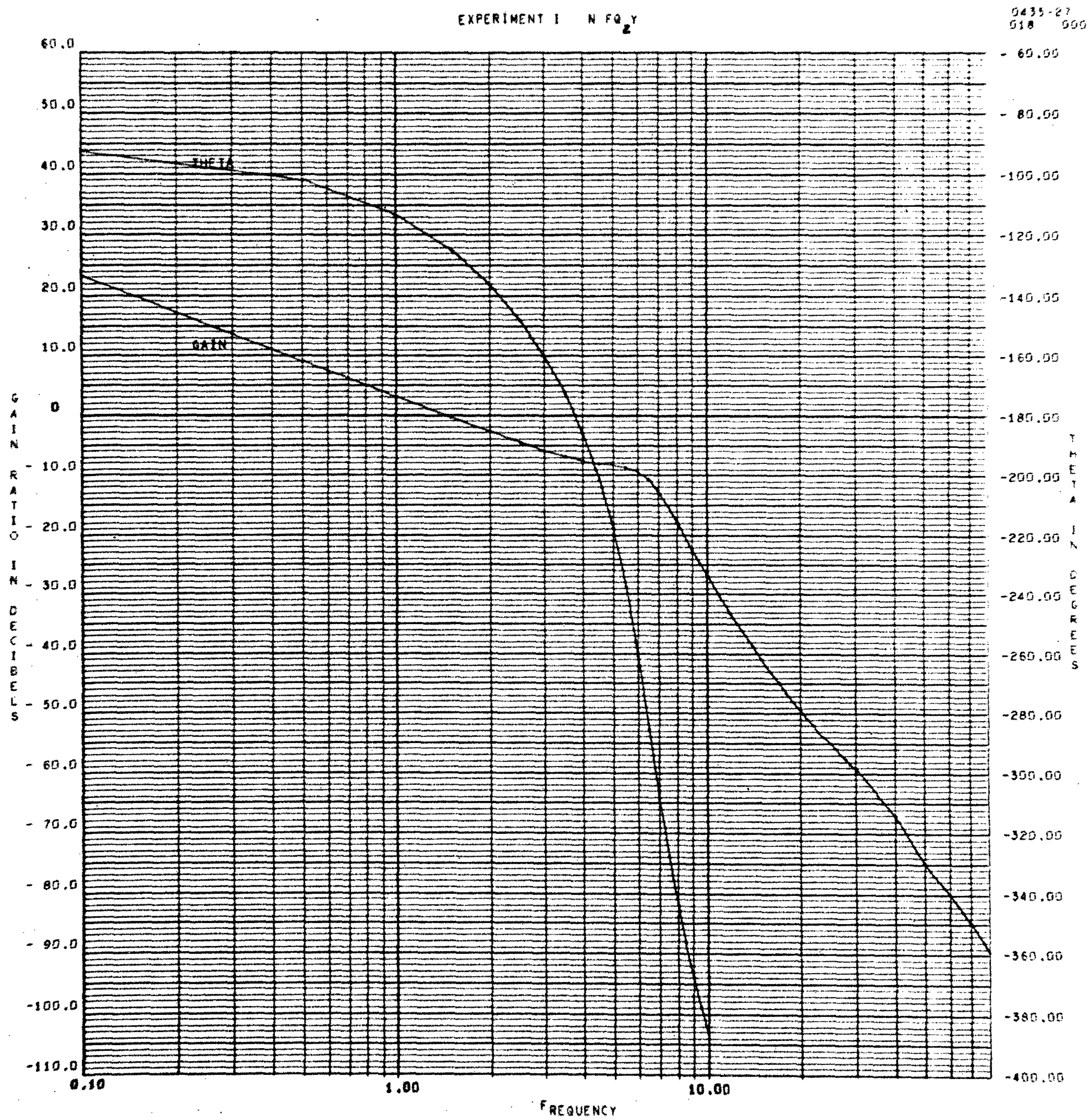

EXPERIMENT I N FQ2X
9435-27
008 005
THETA
GAIN
0
0.10
1.00
10.00
FREQUENCY
60.00
80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES

Figure 62.



EXPERIMENT I N FQ Y
0435-27
018 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
THETA
GAIN
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 63.

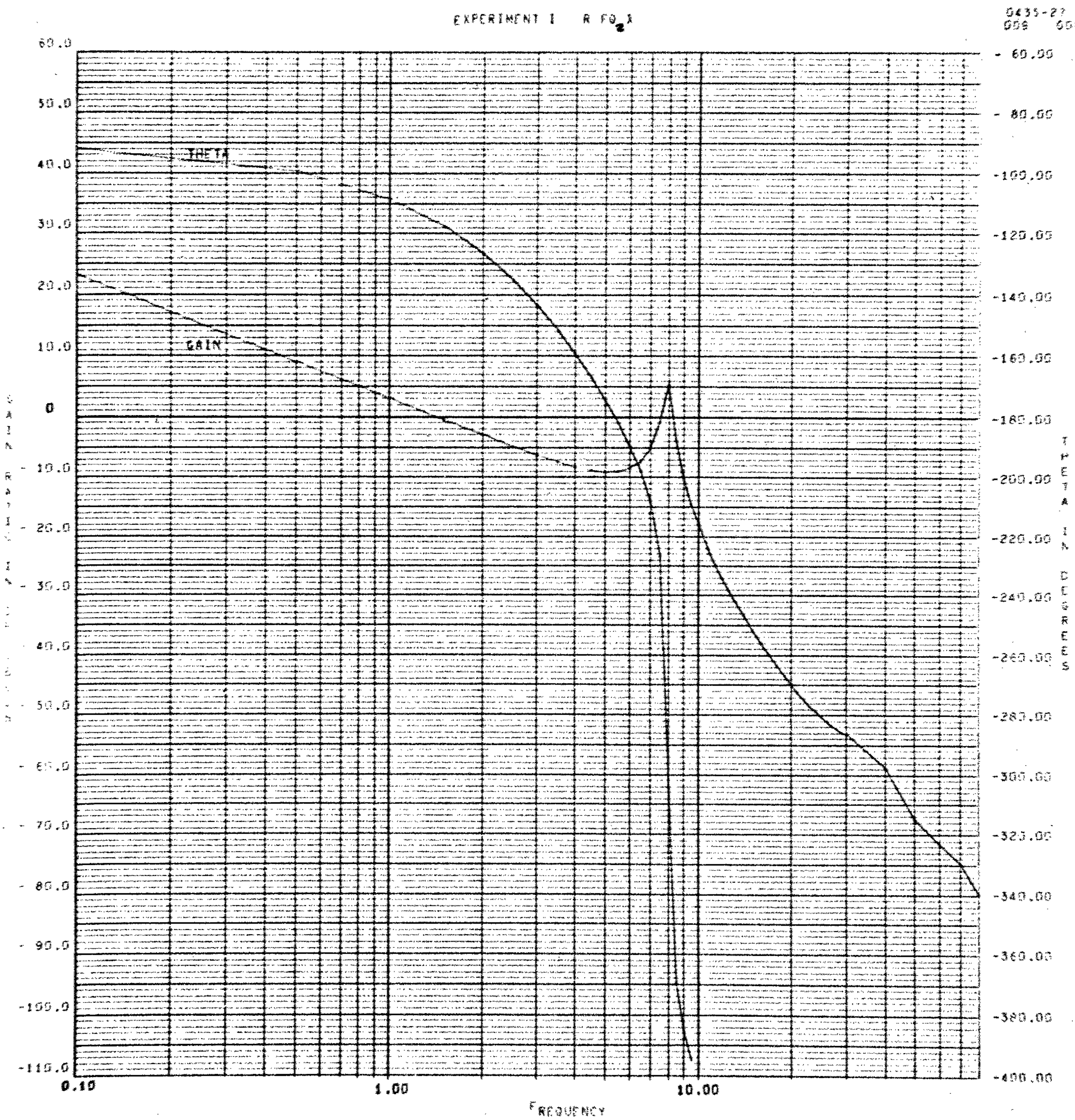
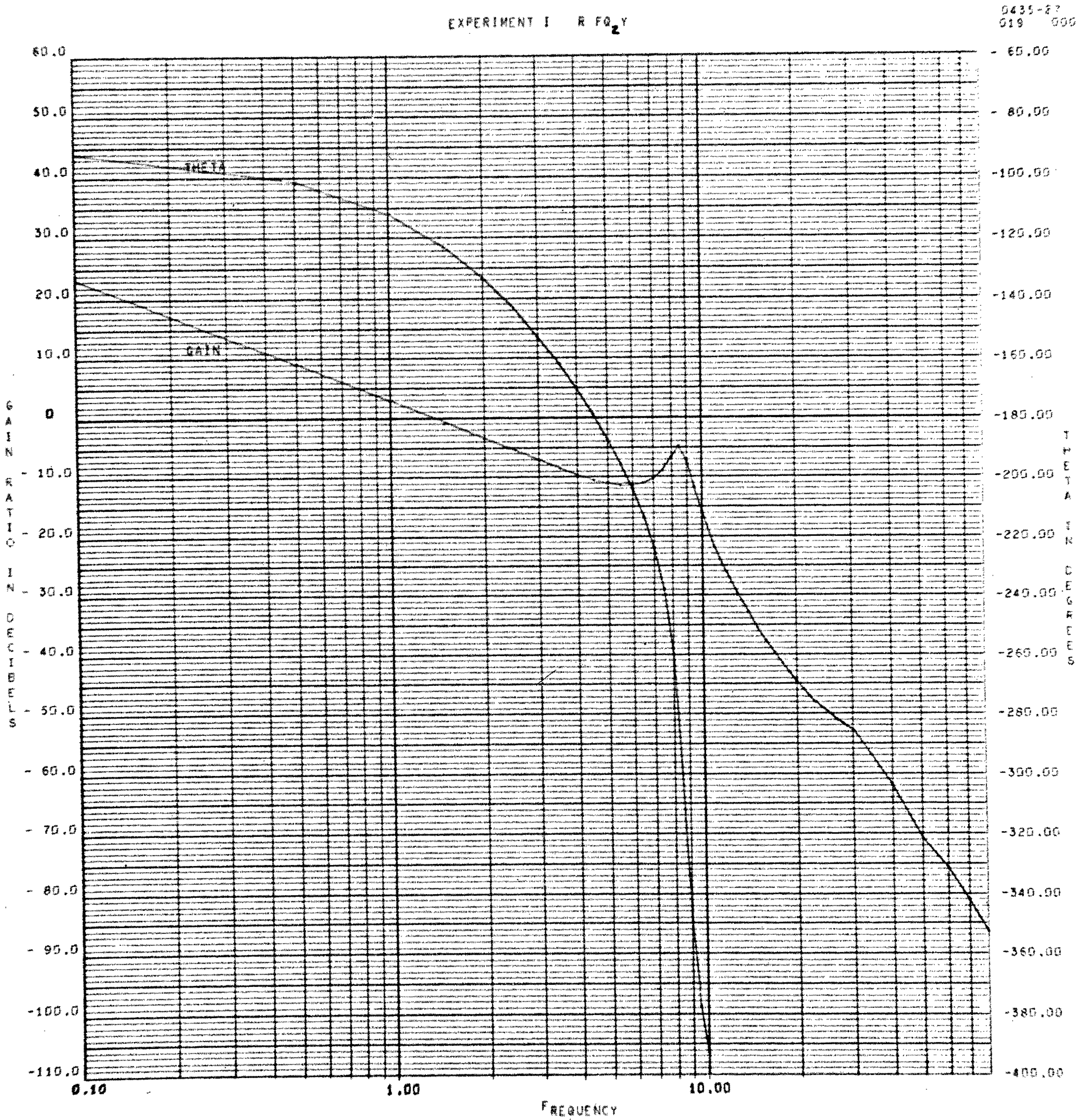

EXPERIMENT I R FQ X
0435-27
THETA
GAIN
FREQUENCY
GAIN RATIO IN DB
THETA IN DEGREES
0.10
1.00
10.00

Figure 64.



EXPERIMENT I R FQZY
0435-27
019 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY

Figure 65.

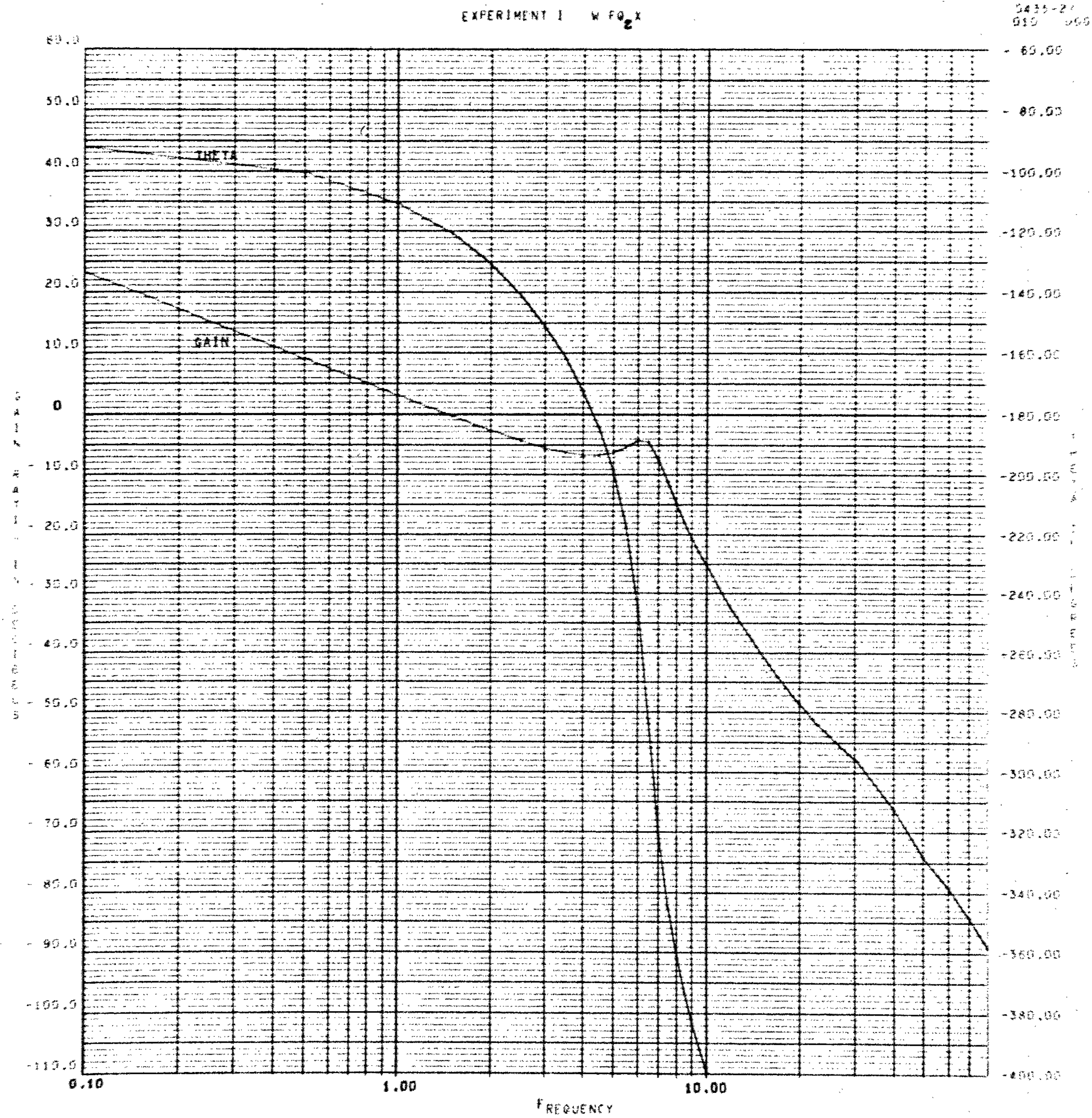


Figure 66.

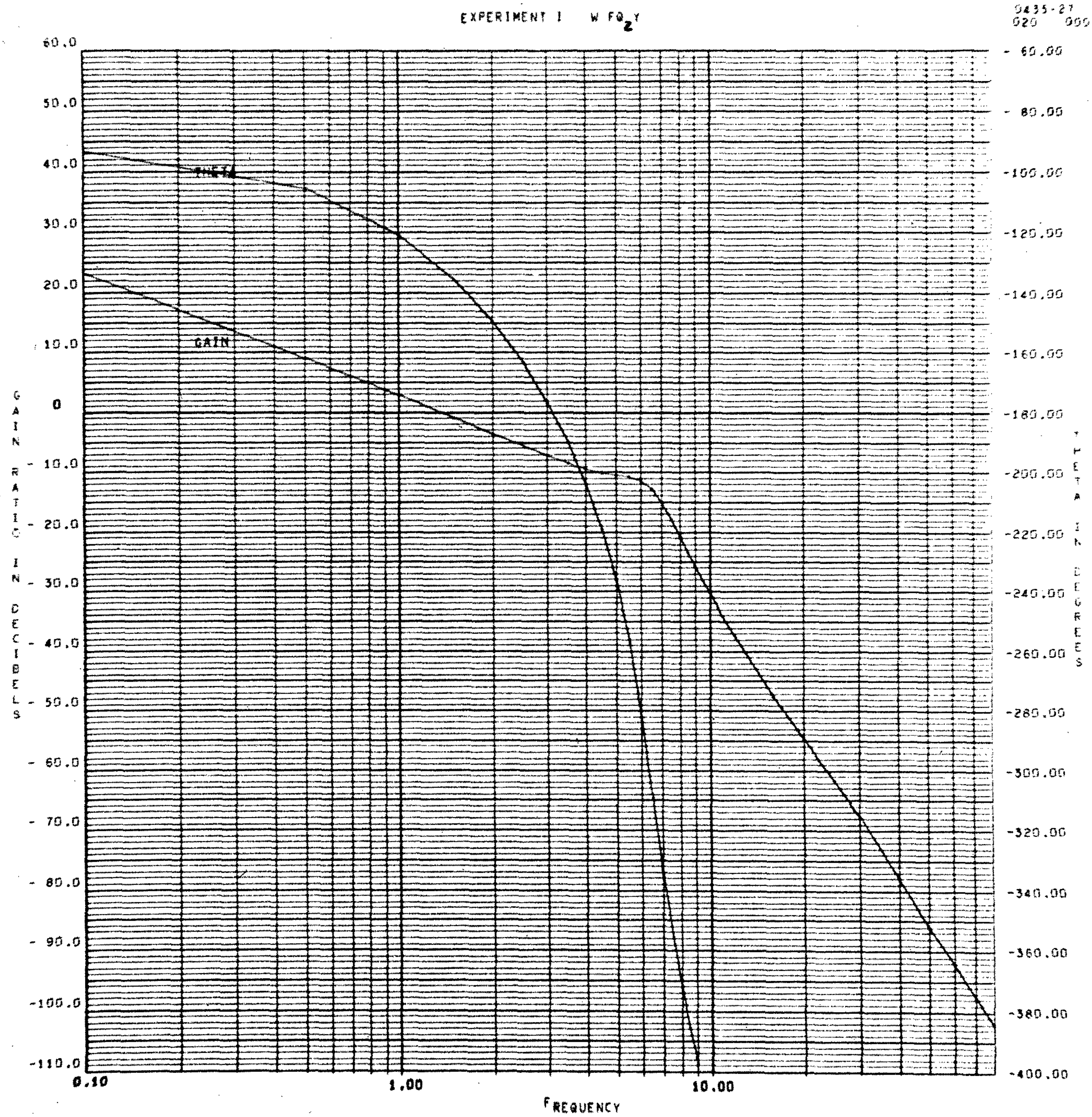

EXPERIMENT I W FQ Z Y
9435-27
020 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 67.

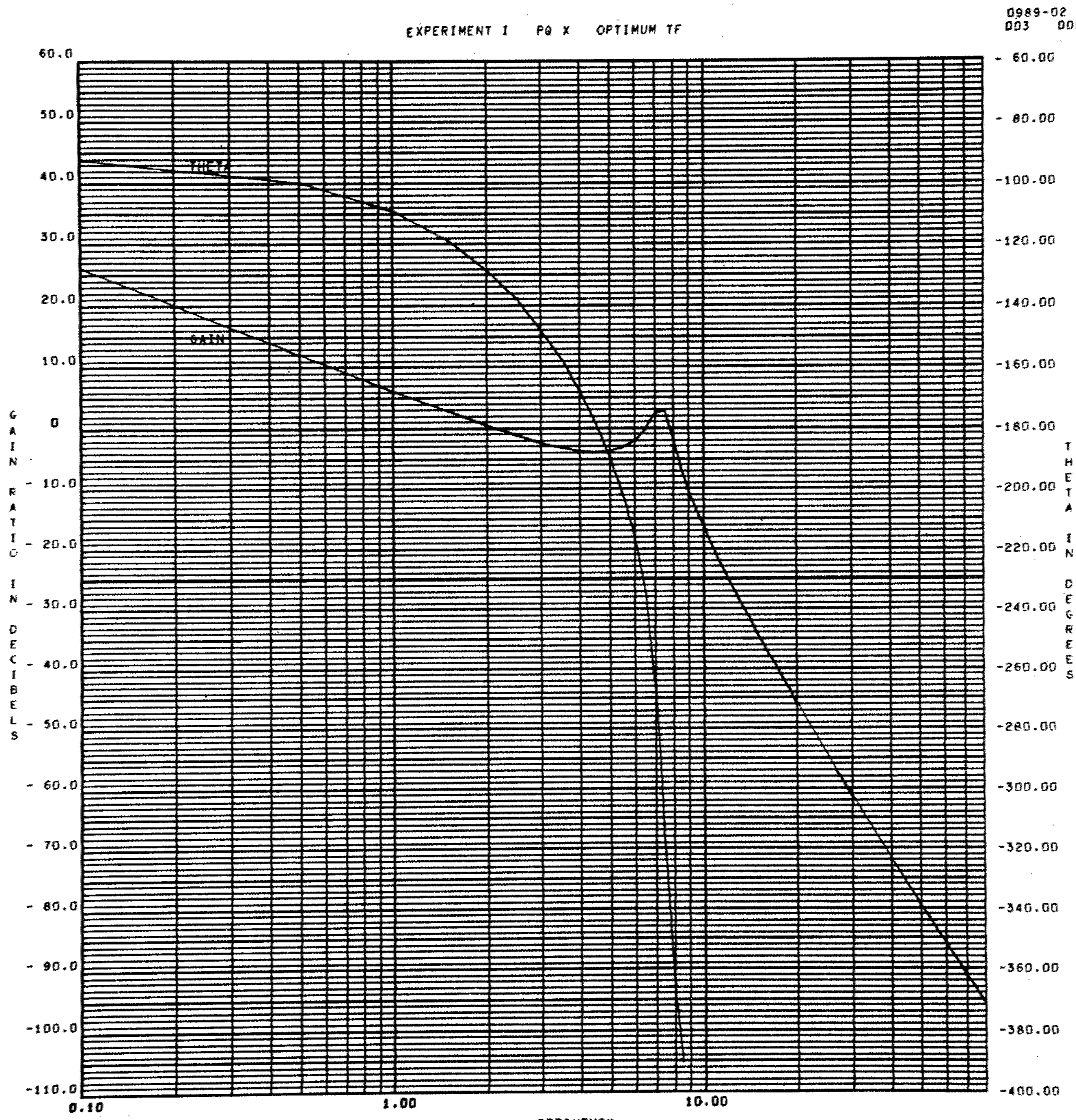

0989-02
003 000
EXPERIMENT I PQ X OPTIMUM TF
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 68.

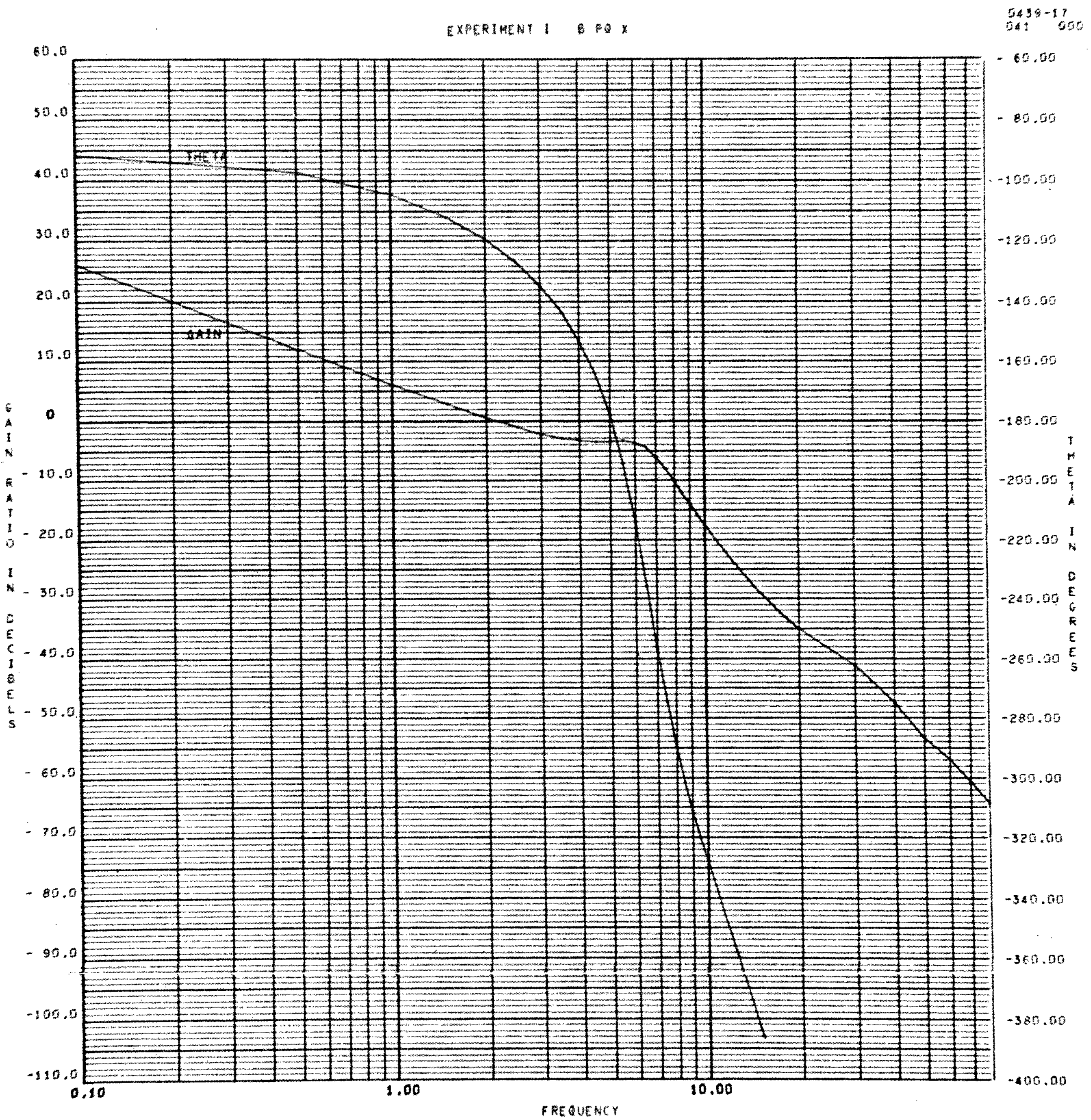

EXPERIMENT I B PQ X
5439-17
041 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 69.

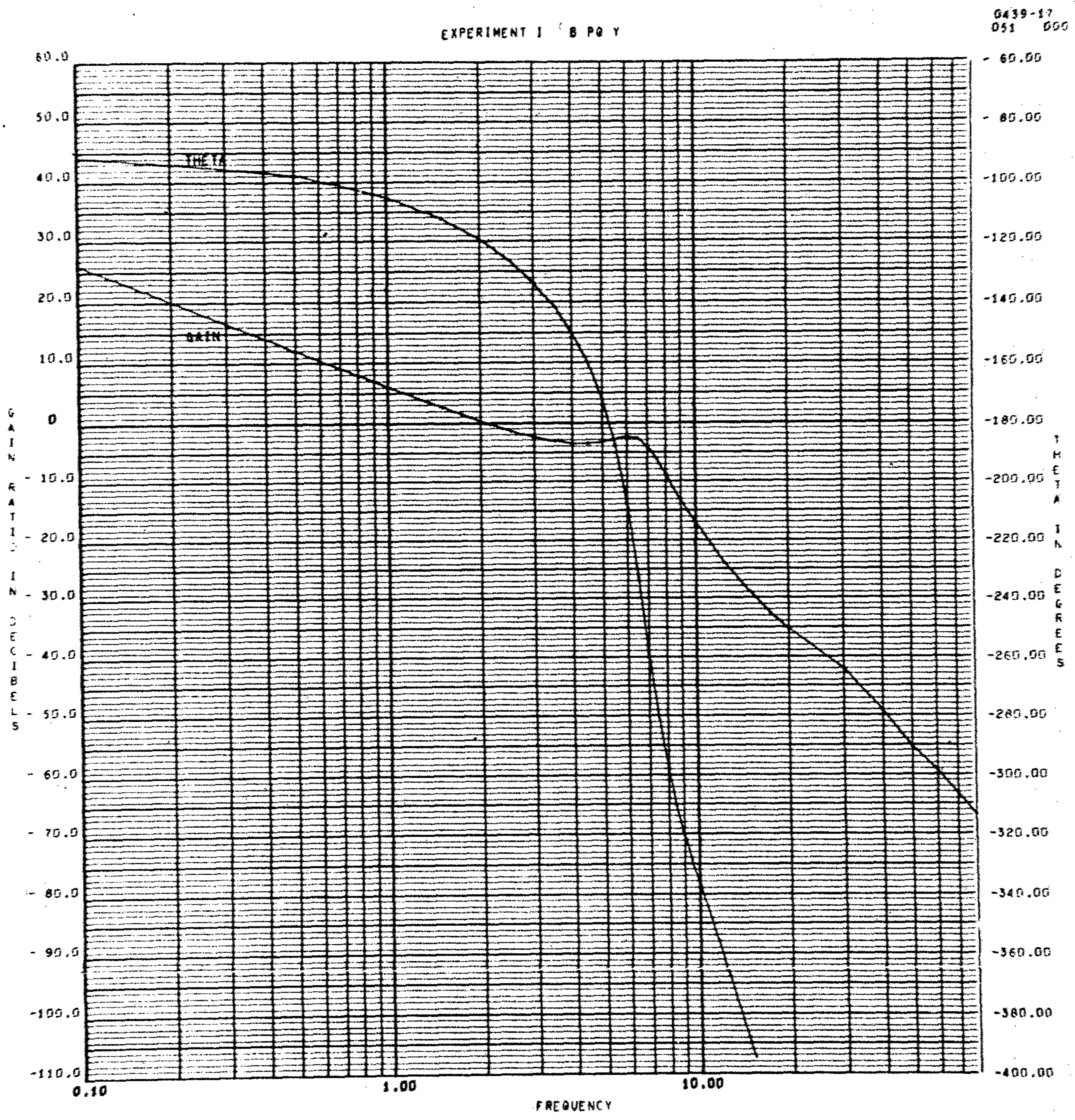
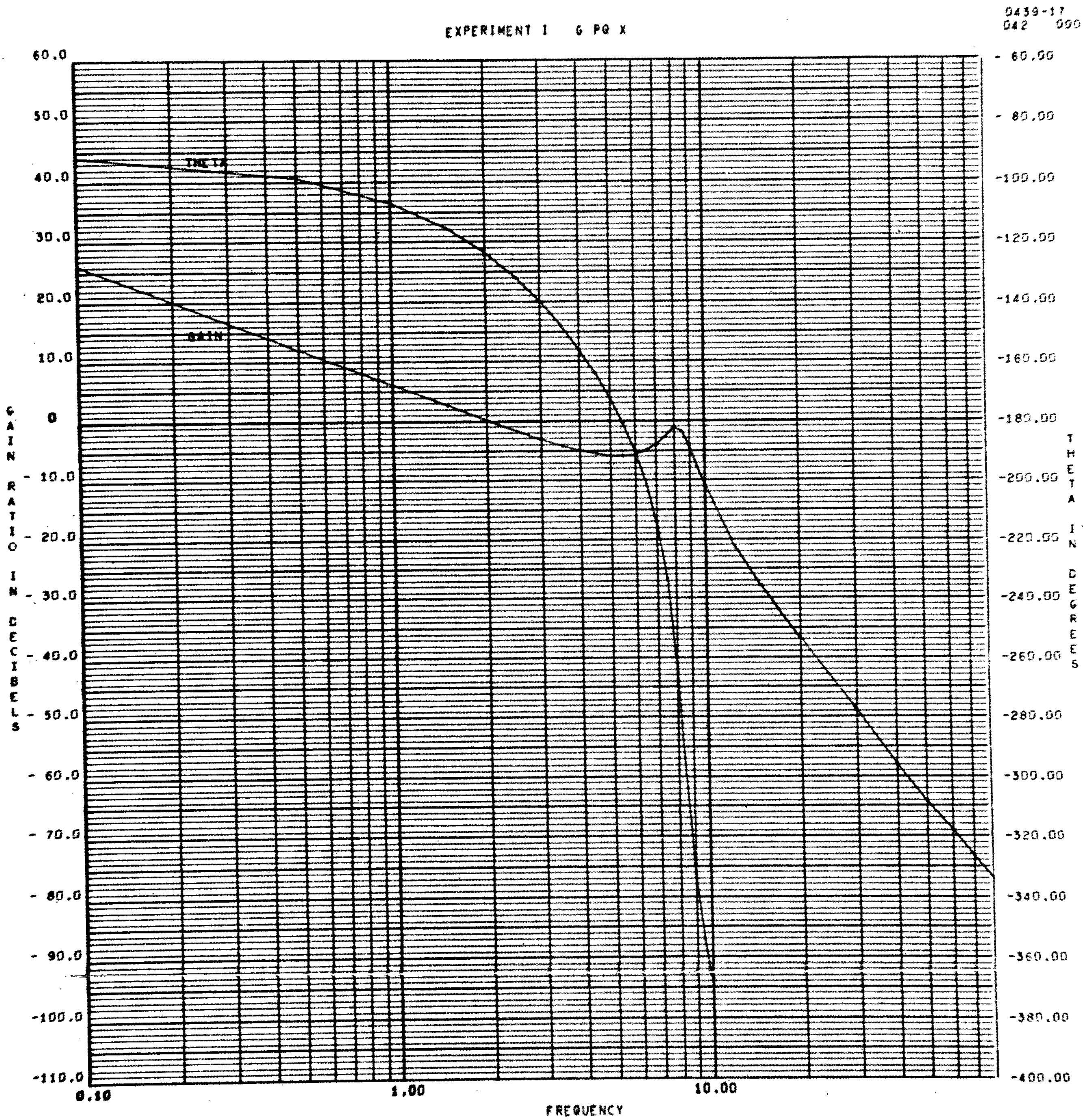

EXPERIMENT I B PQ Y
0439-17
051 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
THETA
GAIN
0.10
1.00
10.00
FREQUENCY

Figure 70.



0439-17
042 000
EXPERIMENT I G PQ X
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 71.

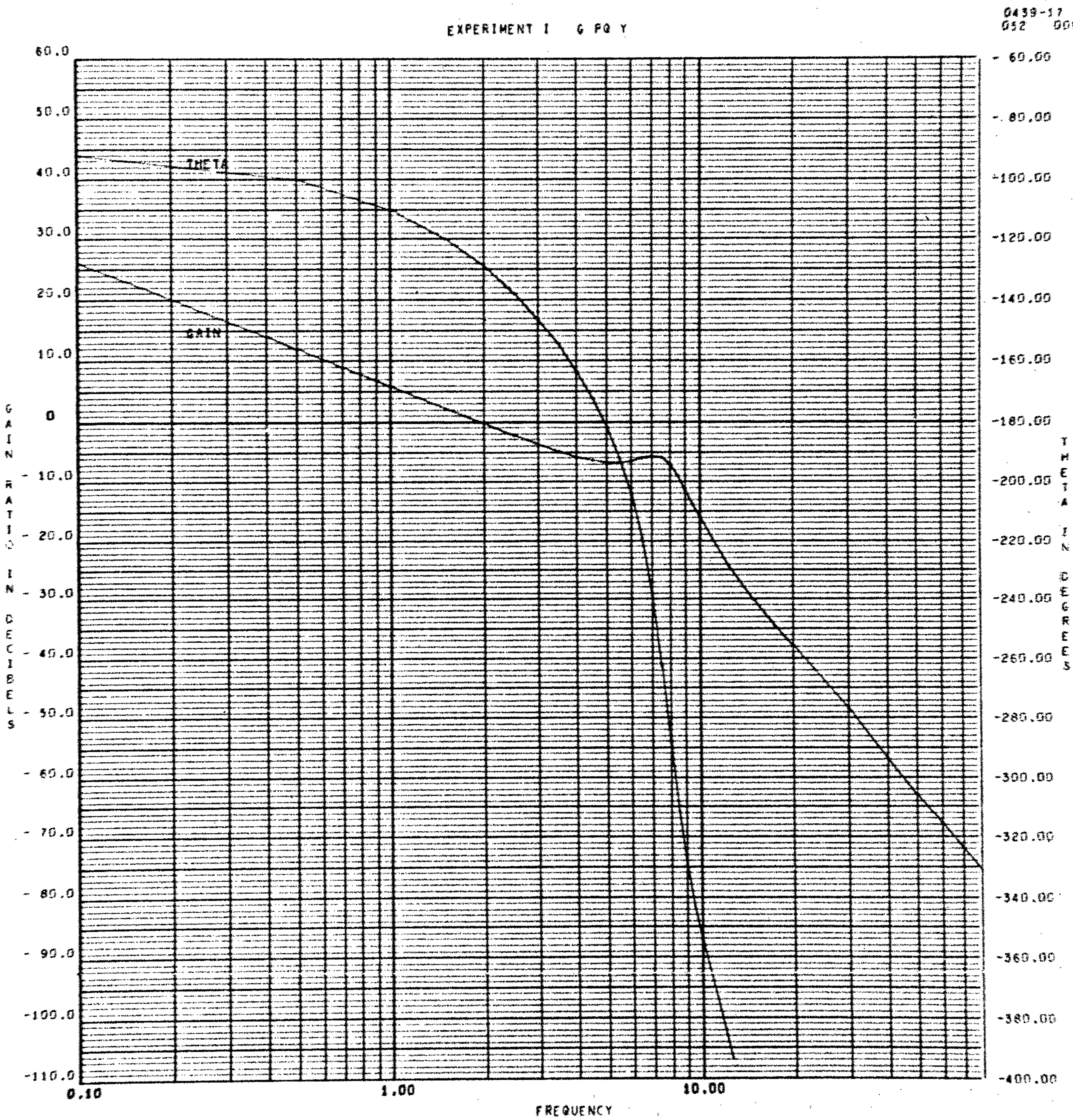

0439-17
052 000
EXPERIMENT I G PQ Y
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00
FREQUENCY

Figure 72.

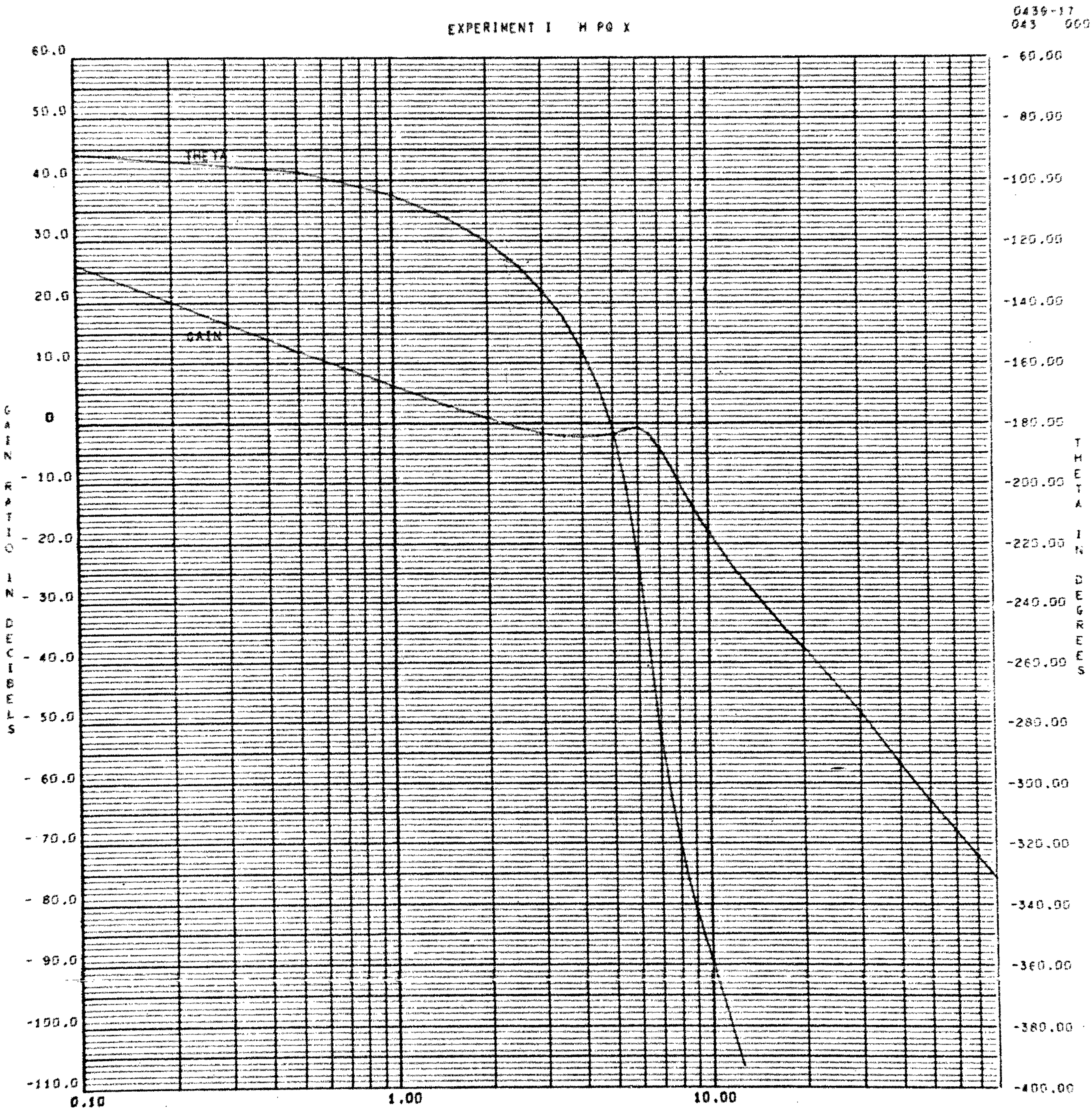
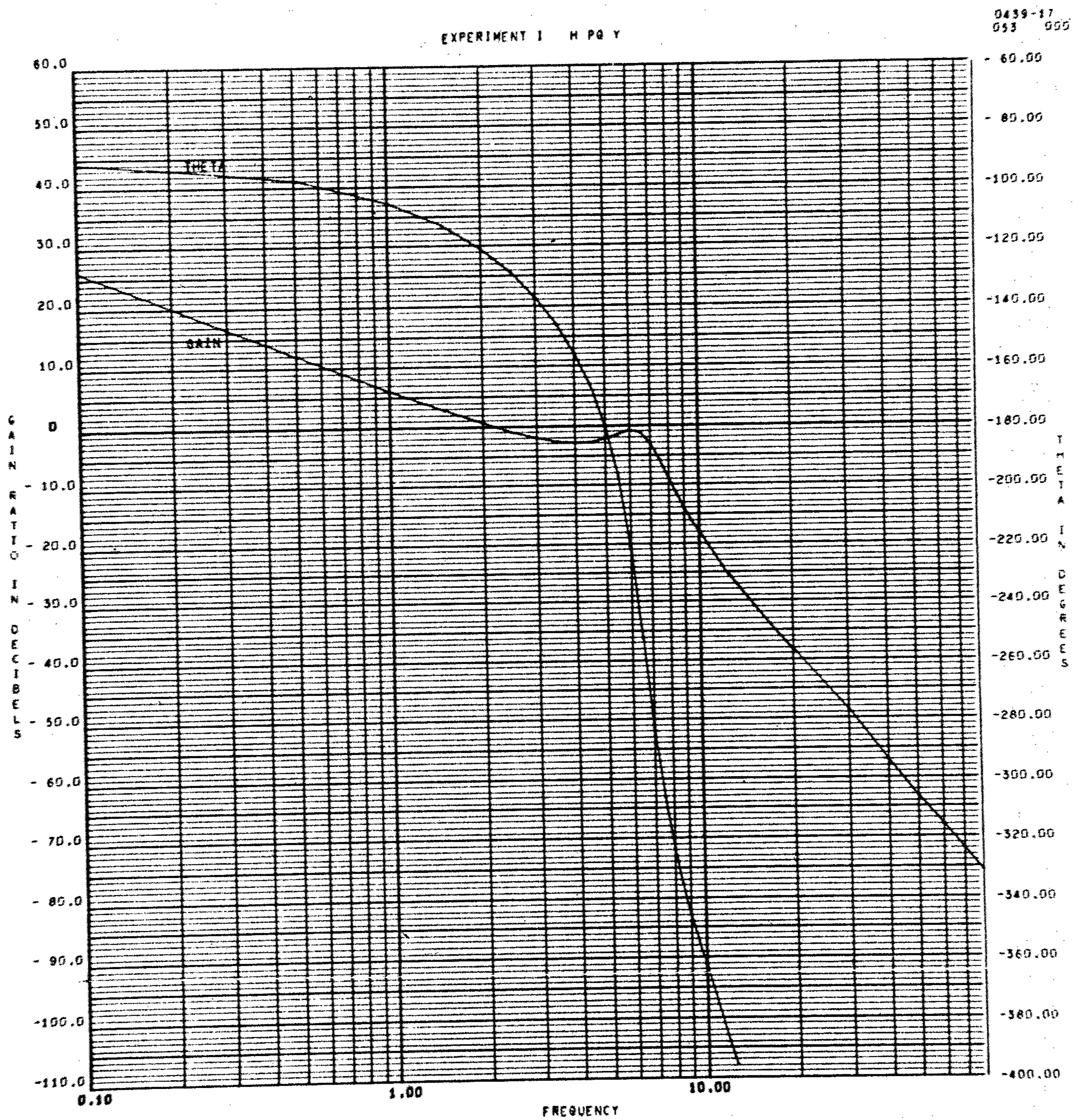

0439-17
043 000
EXPERIMENT I H PQ X
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
THETA
GAIN
0.10
1.00
10.00
FREQUENCY

Figure 73.



0439-17
053 000
EXPERIMENT I H PQ Y
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 74.

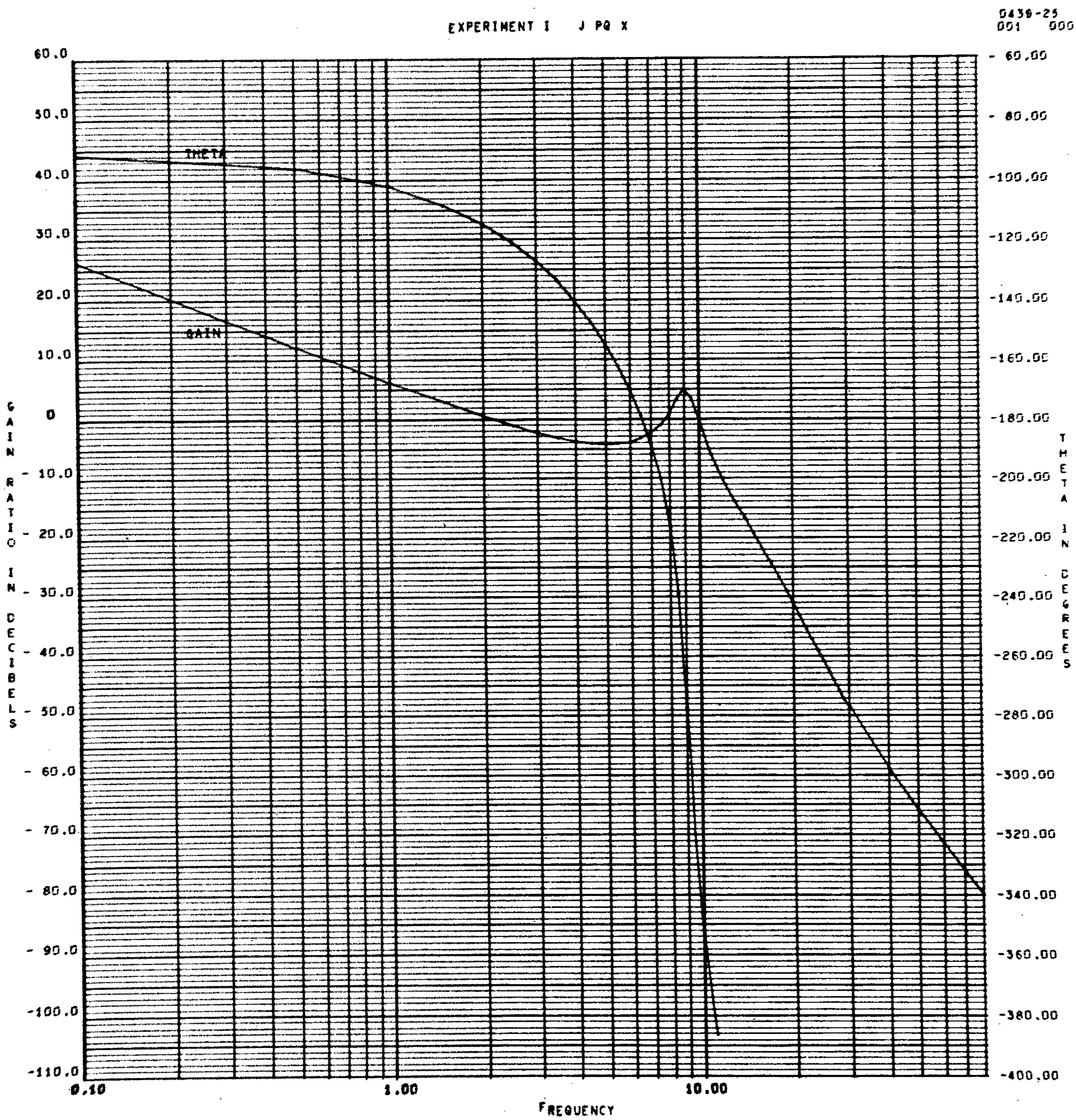

EXPERIMENT I J PQ X
0439-25
001 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 75.

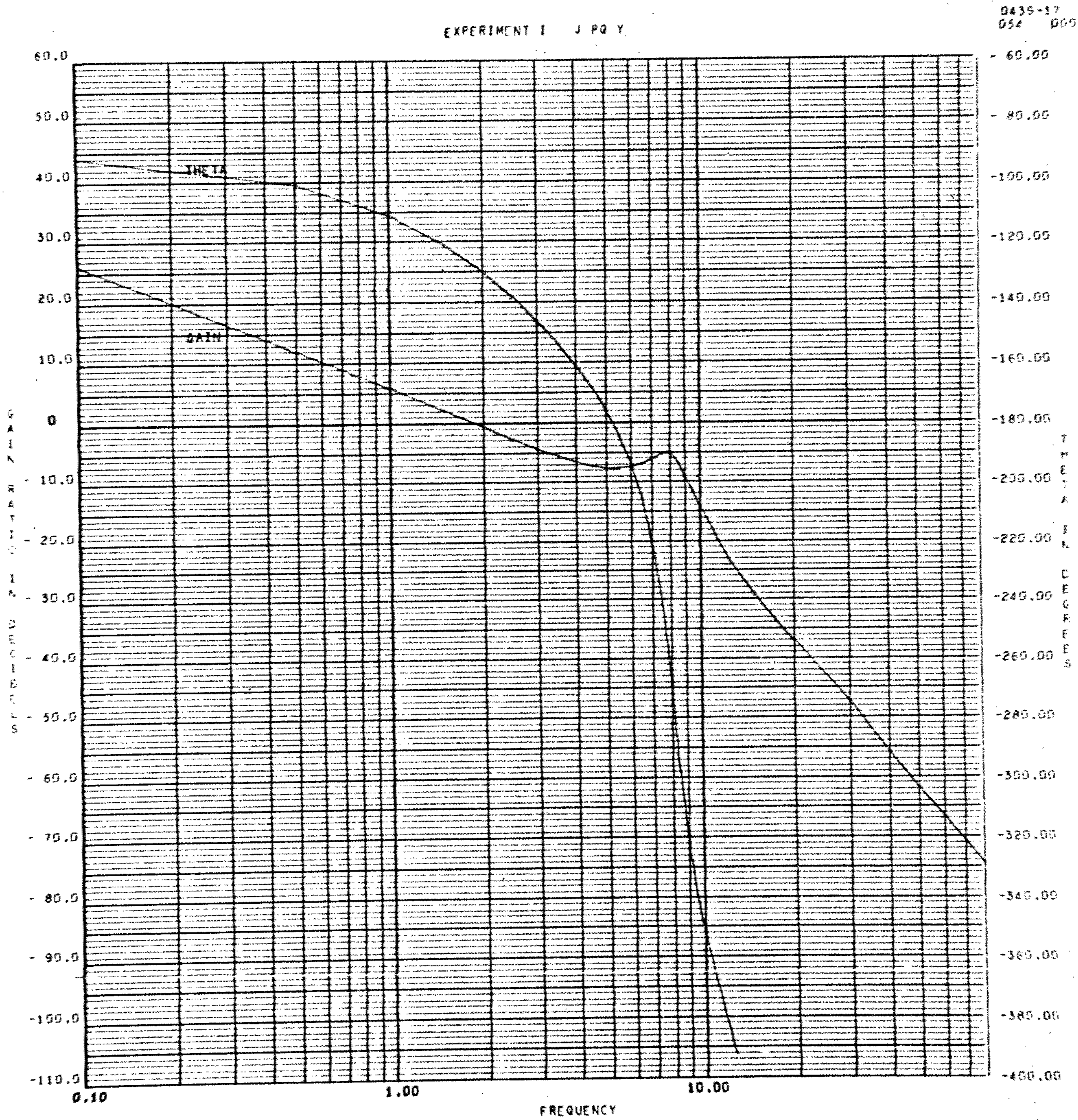

0439-17
054 DOO
EXPERIMENT I J PQ Y
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 76.

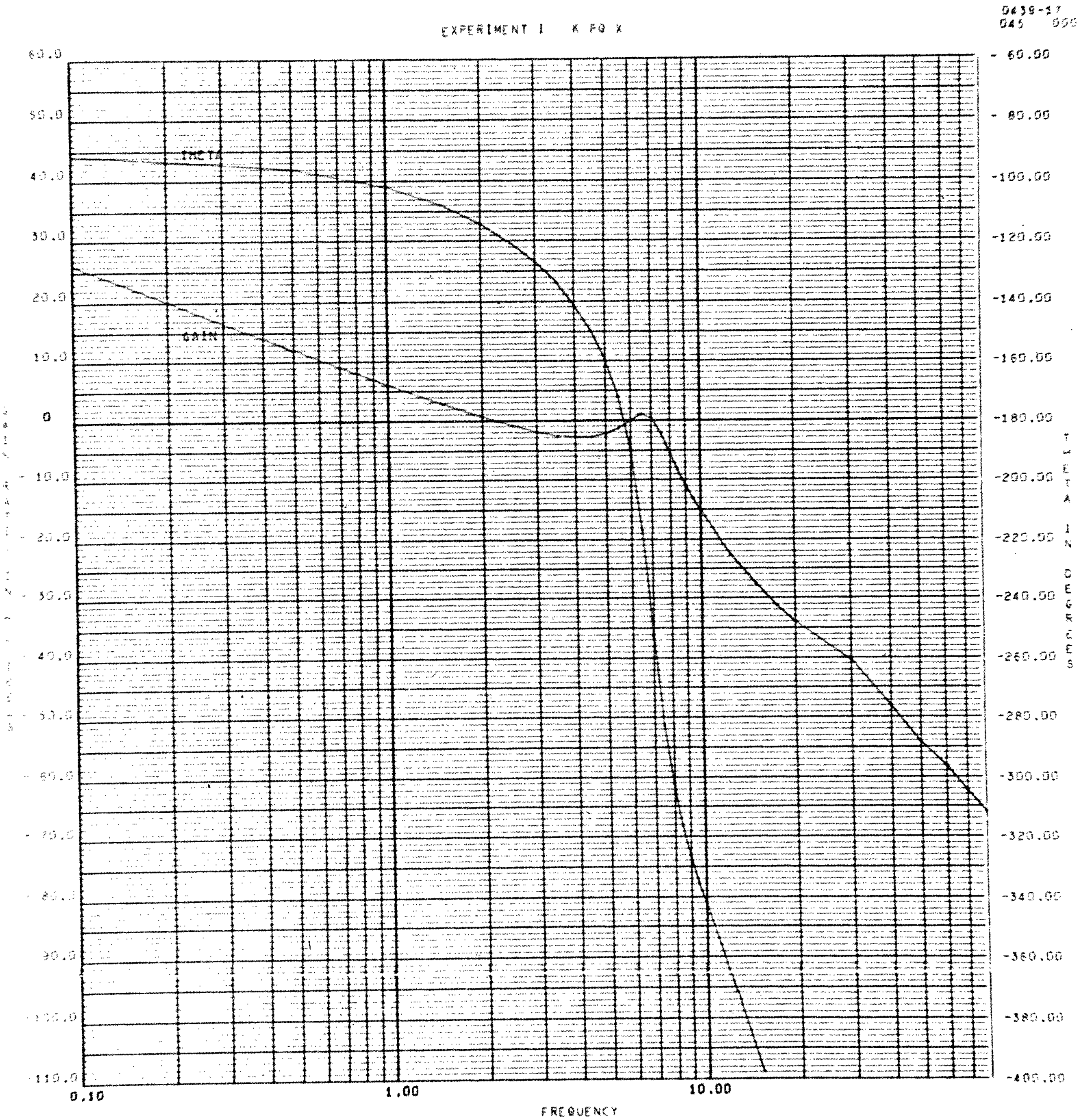

0439-17
045 000
EXPERIMENT I K PQ X
THETA
GAIN
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES

Figure 77.

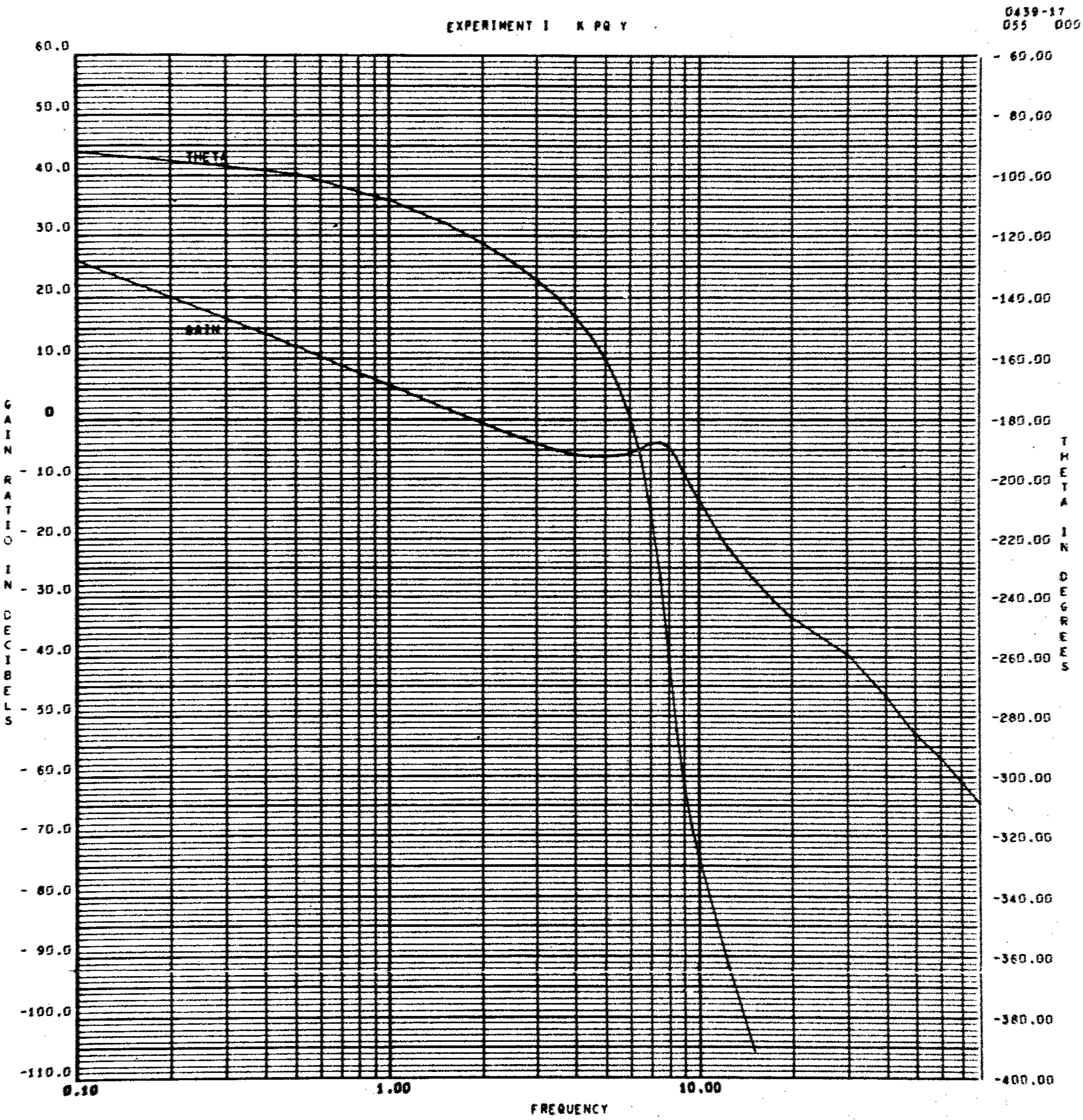

EXPERIMENT I K PQ Y
0439-17
055 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 78.

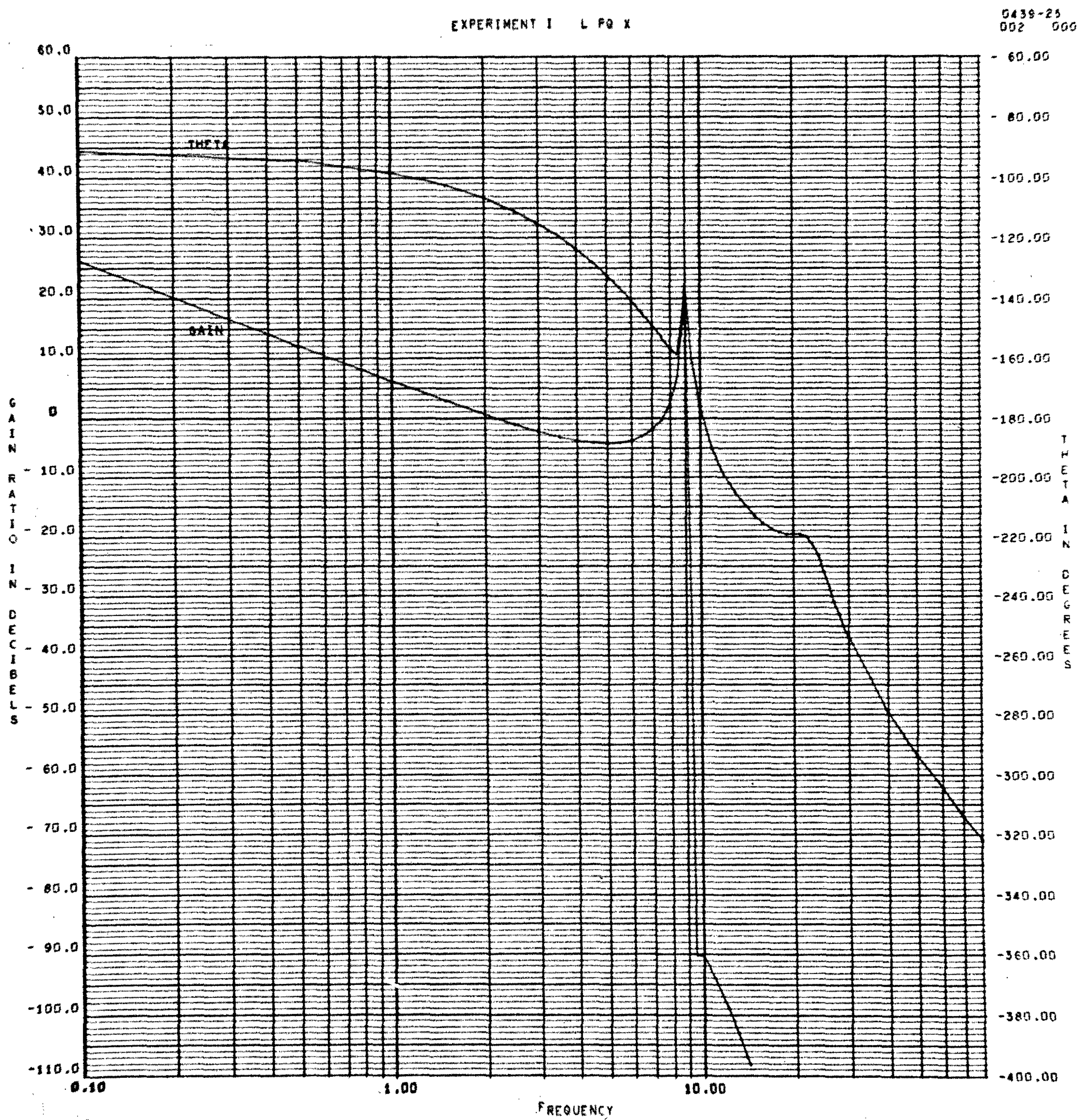
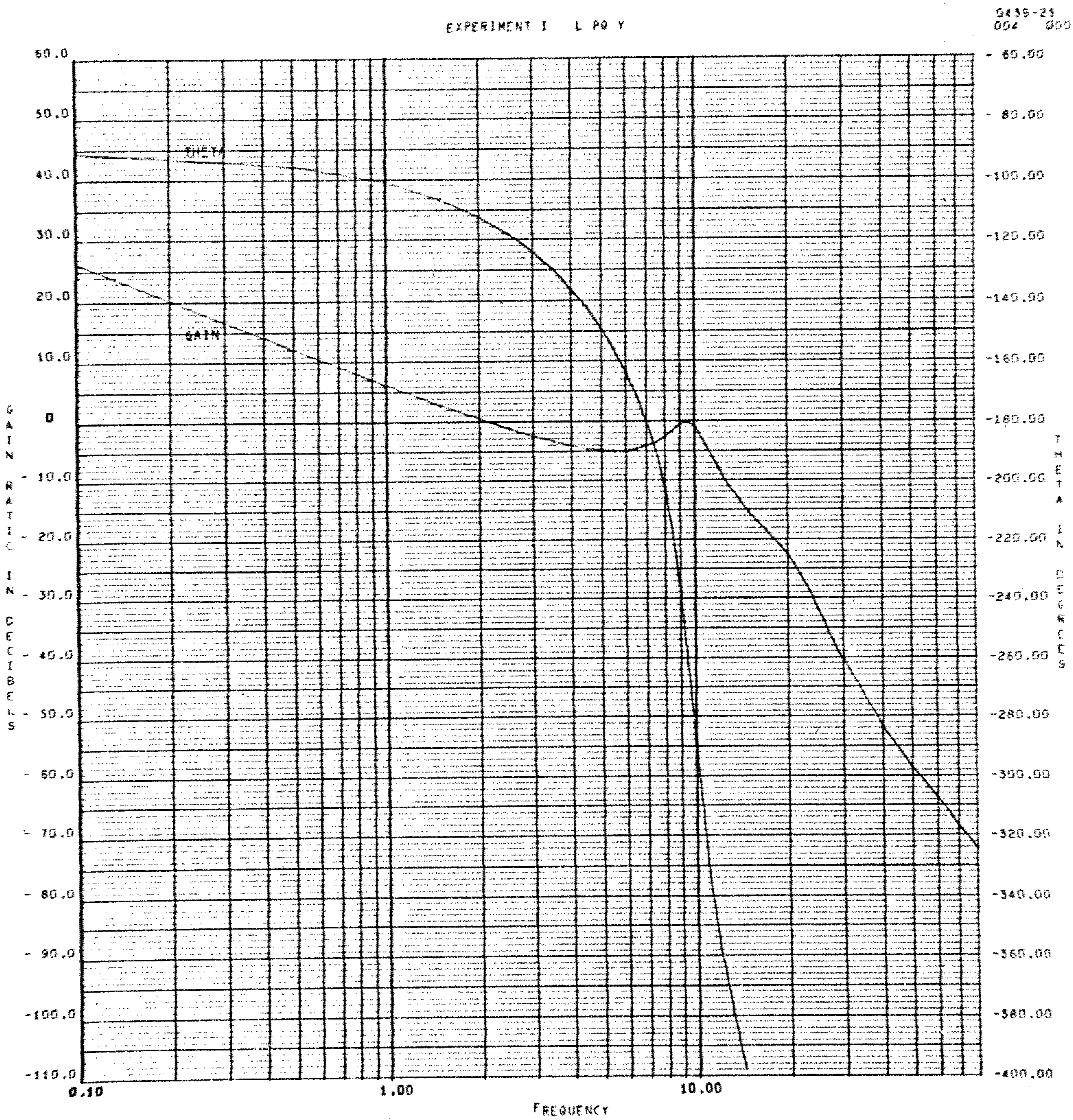
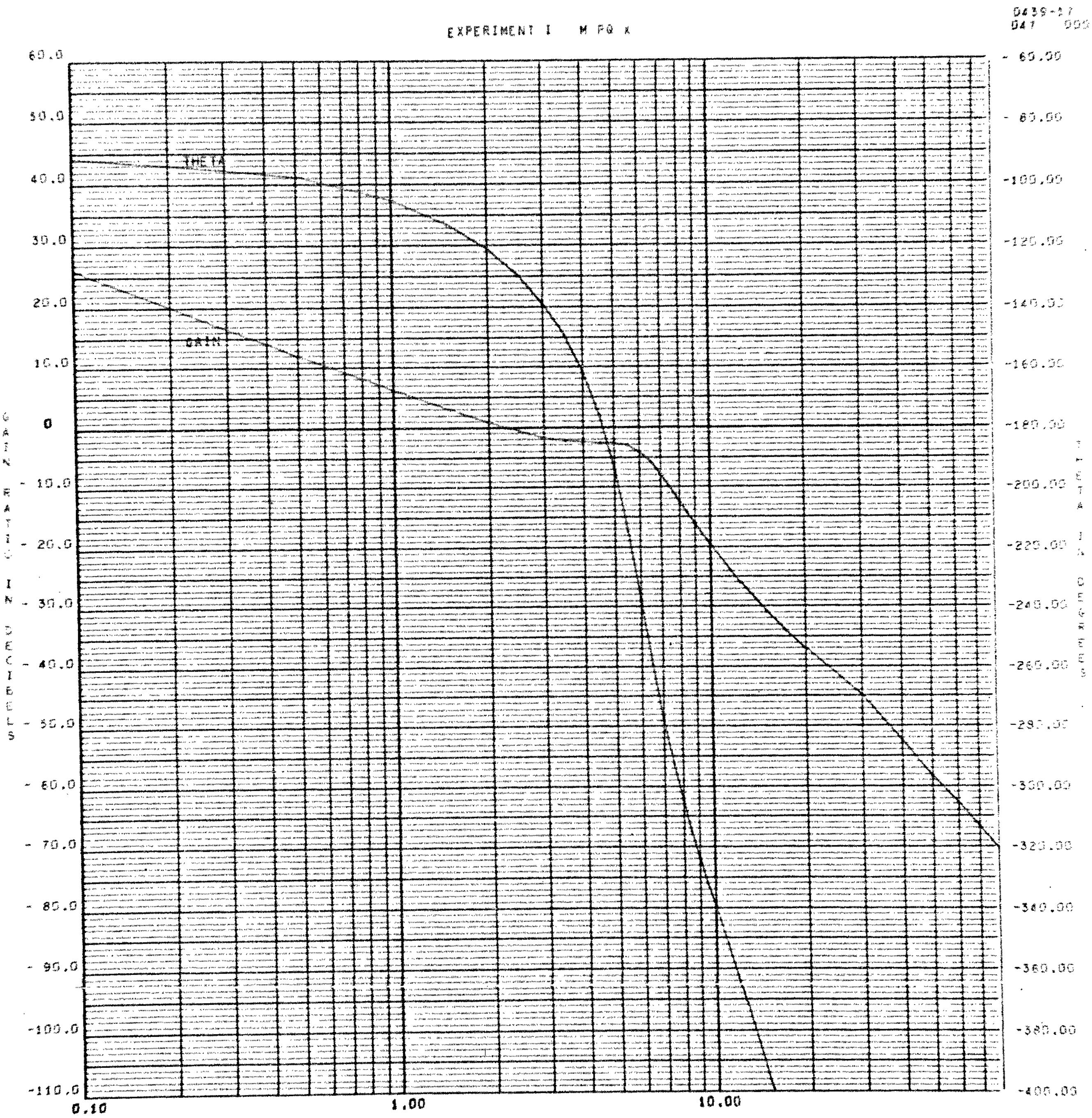

EXPERIMENT I L PQ X
0439-25
002 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 79.



EXPERIMENT I L PQ Y
9439-23
004 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00
FREQUENCY

Figure 80.



EXPERIMENT I M PQ X
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 81.

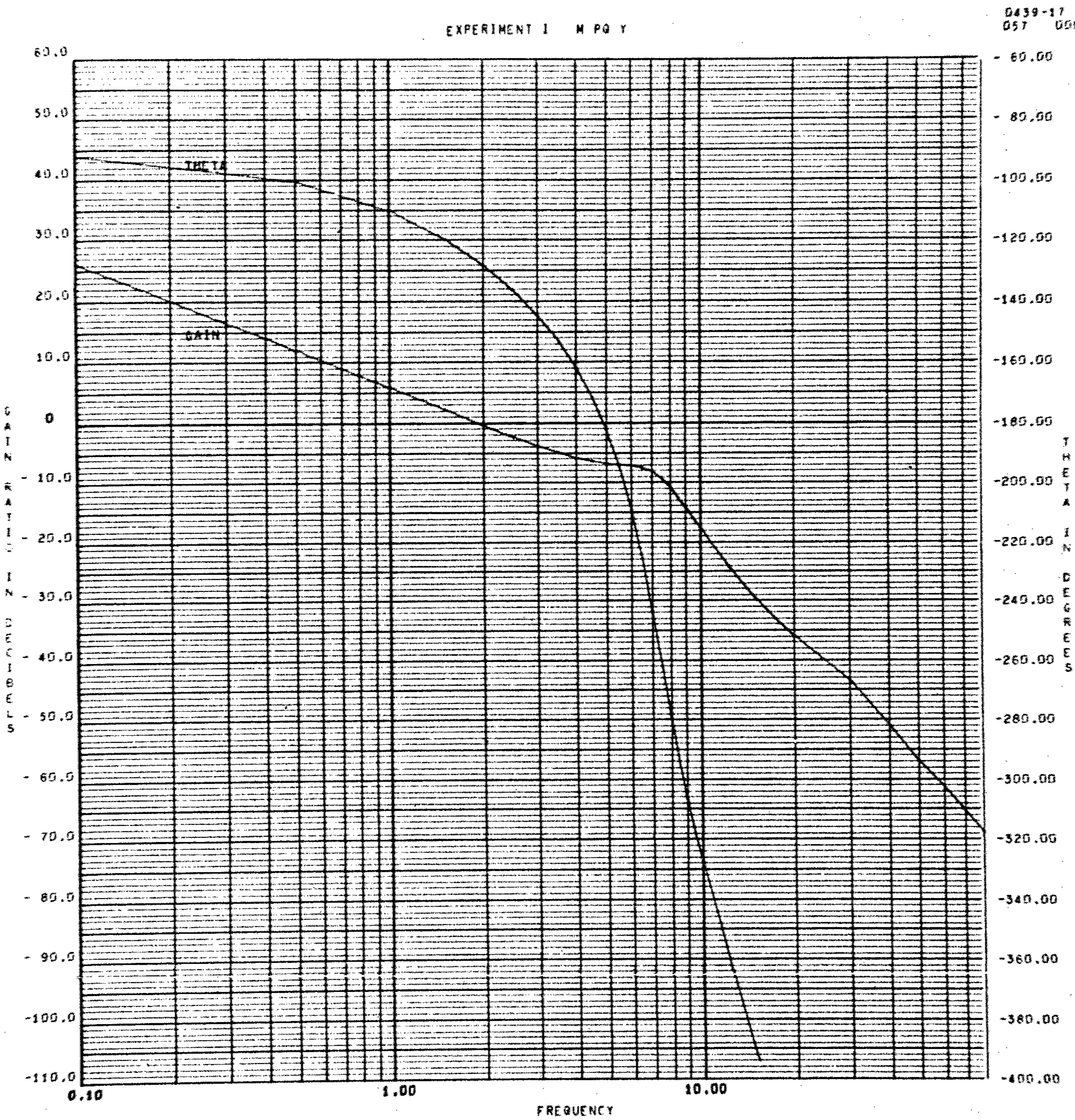
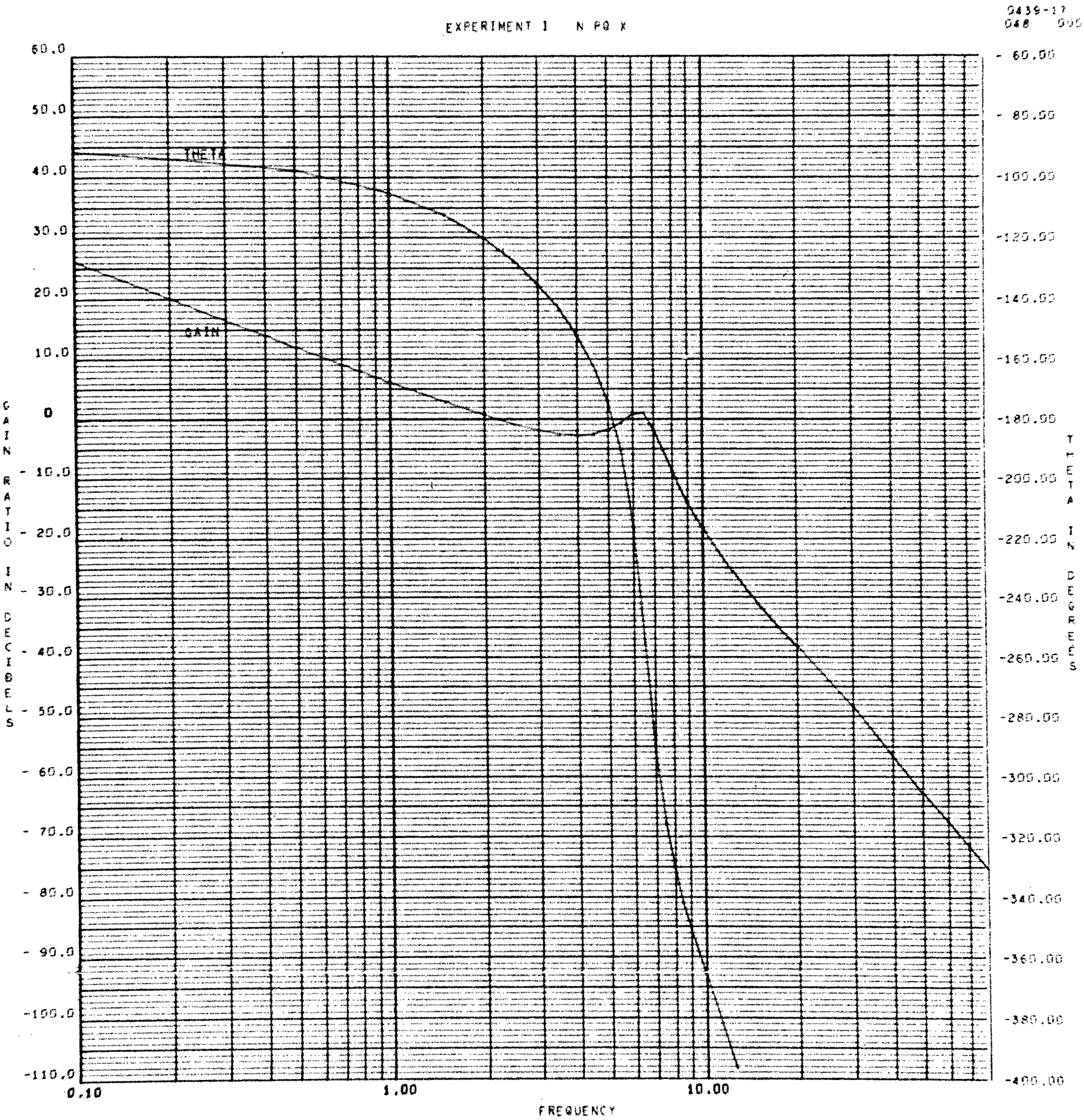

0439-17
057 000
EXPERIMENT I M PQ Y
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 82.



EXPERIMENT I N PQ X
0439-17
048 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY

Figure 83.

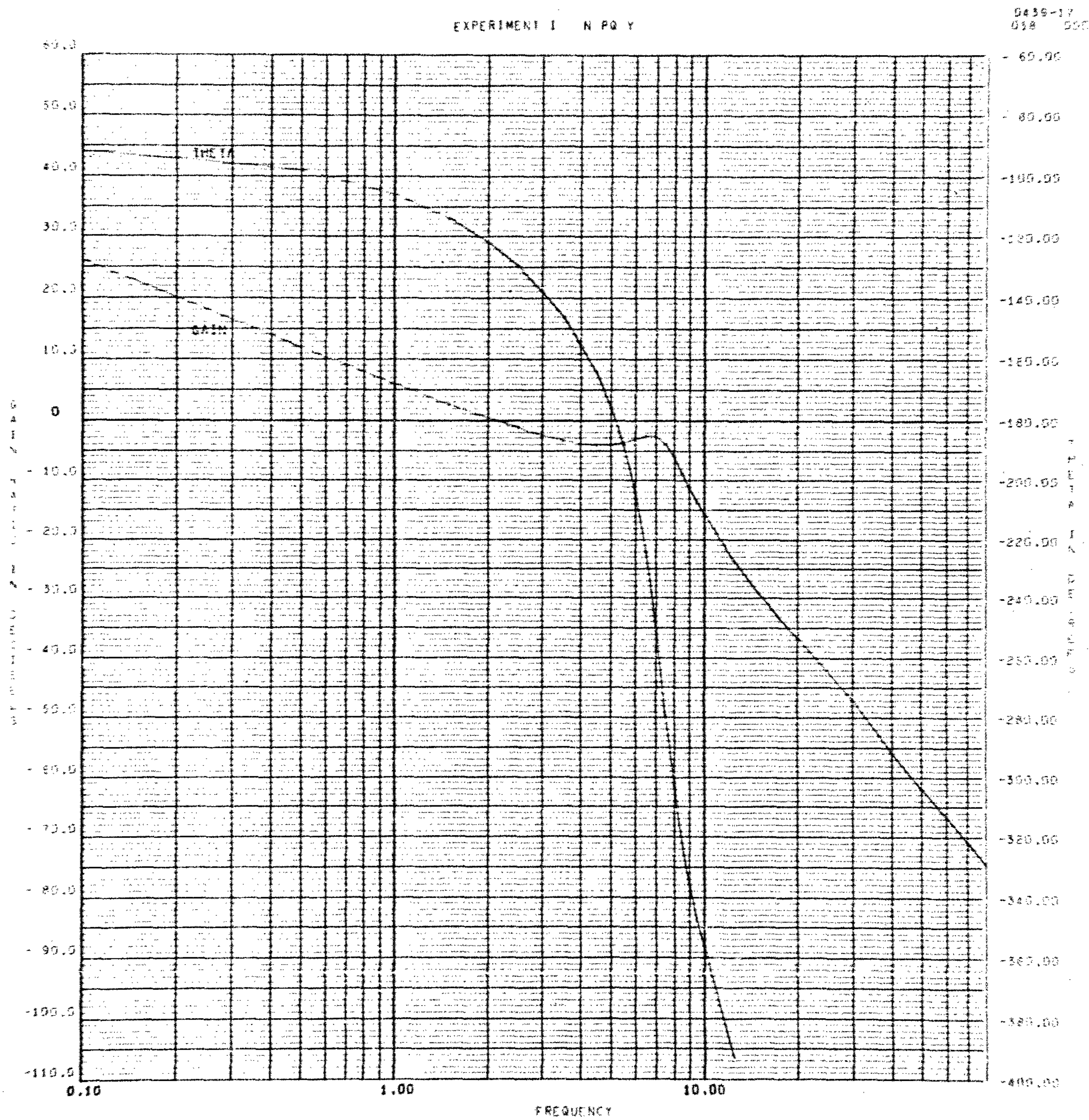
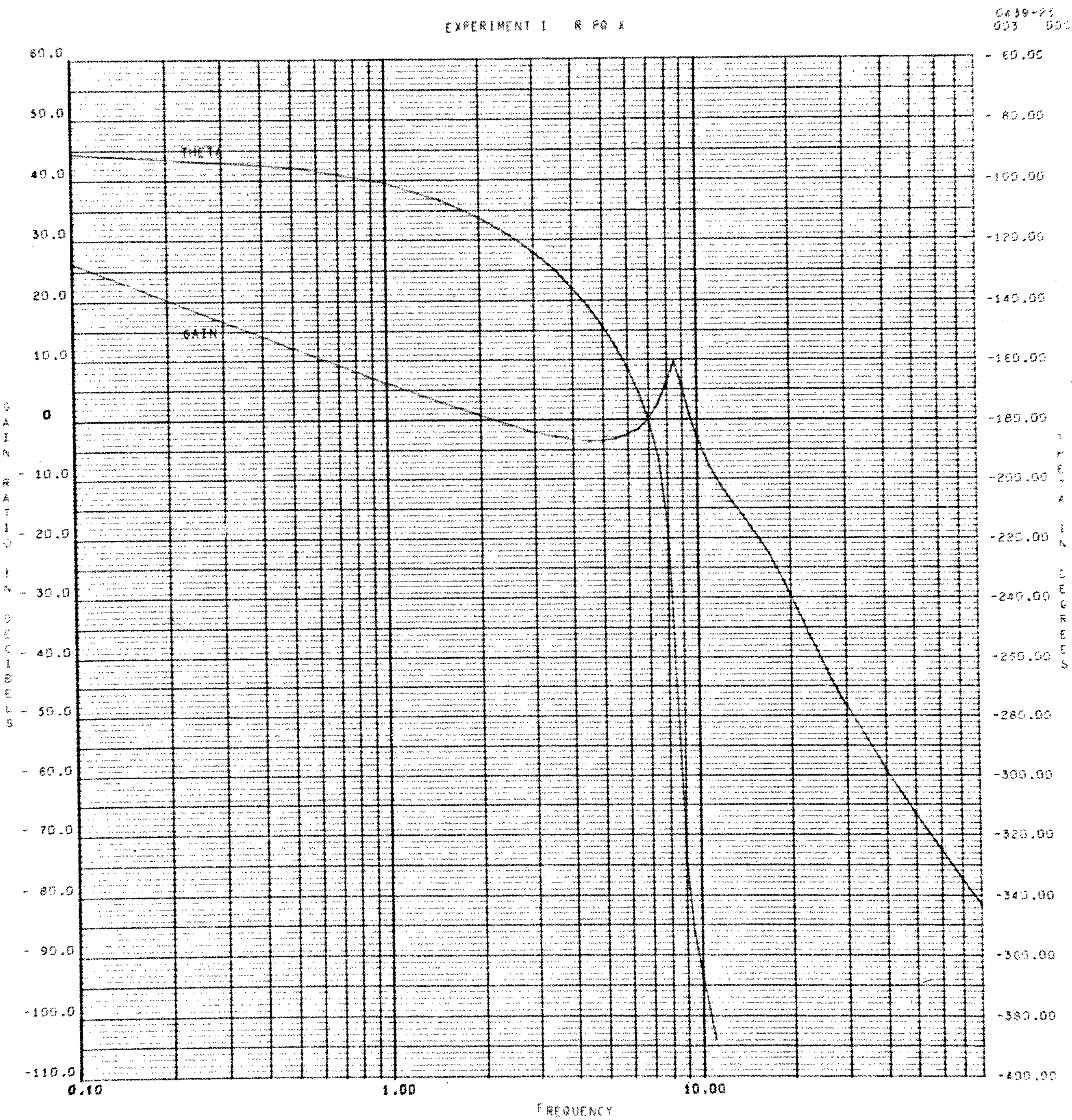


Figure 84.



EXPERIMENT I R PQ X
0439-75
003 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 85.

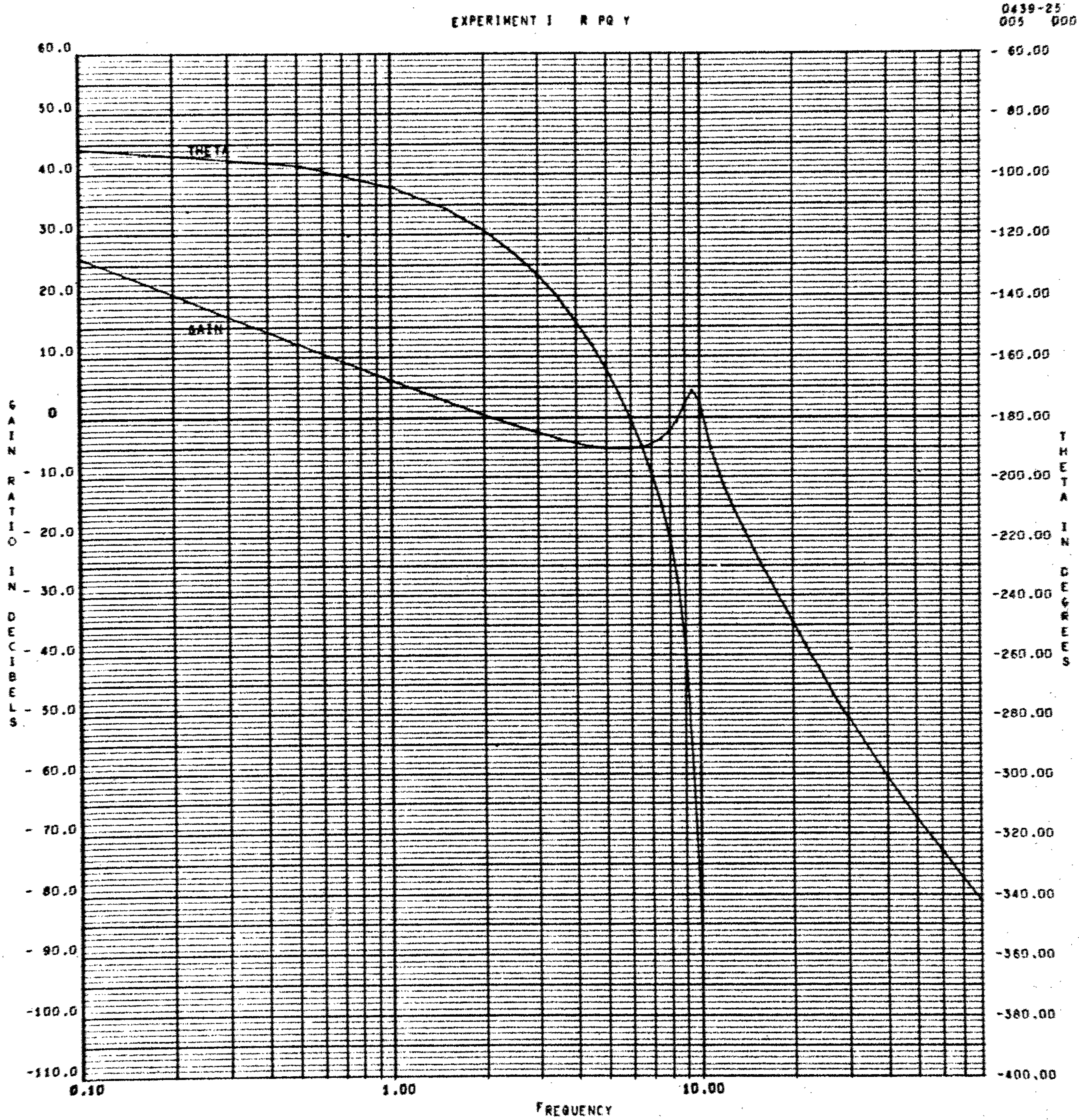

EXPERIMENT I R PQ Y
0439-25
005 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 86.

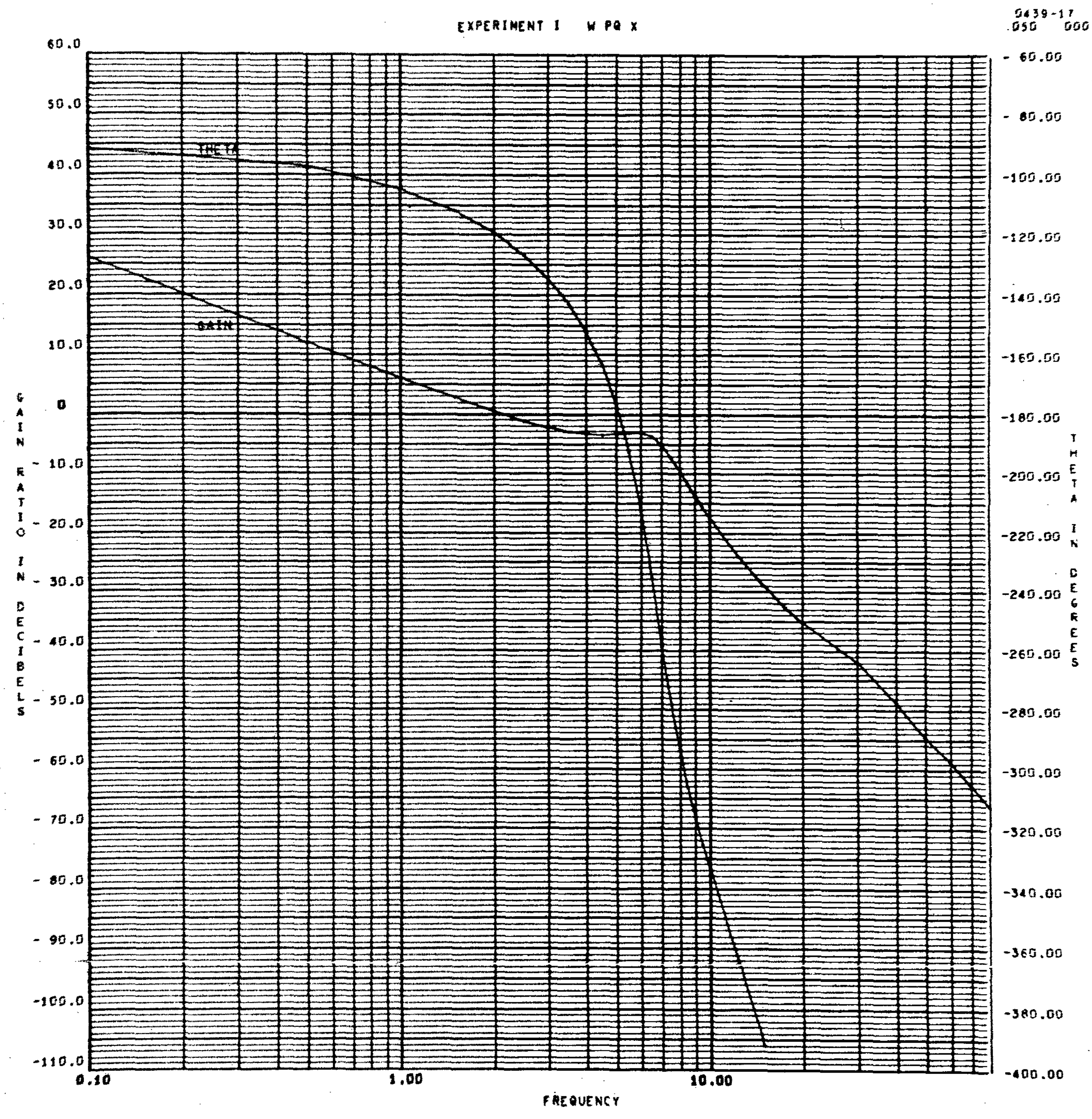
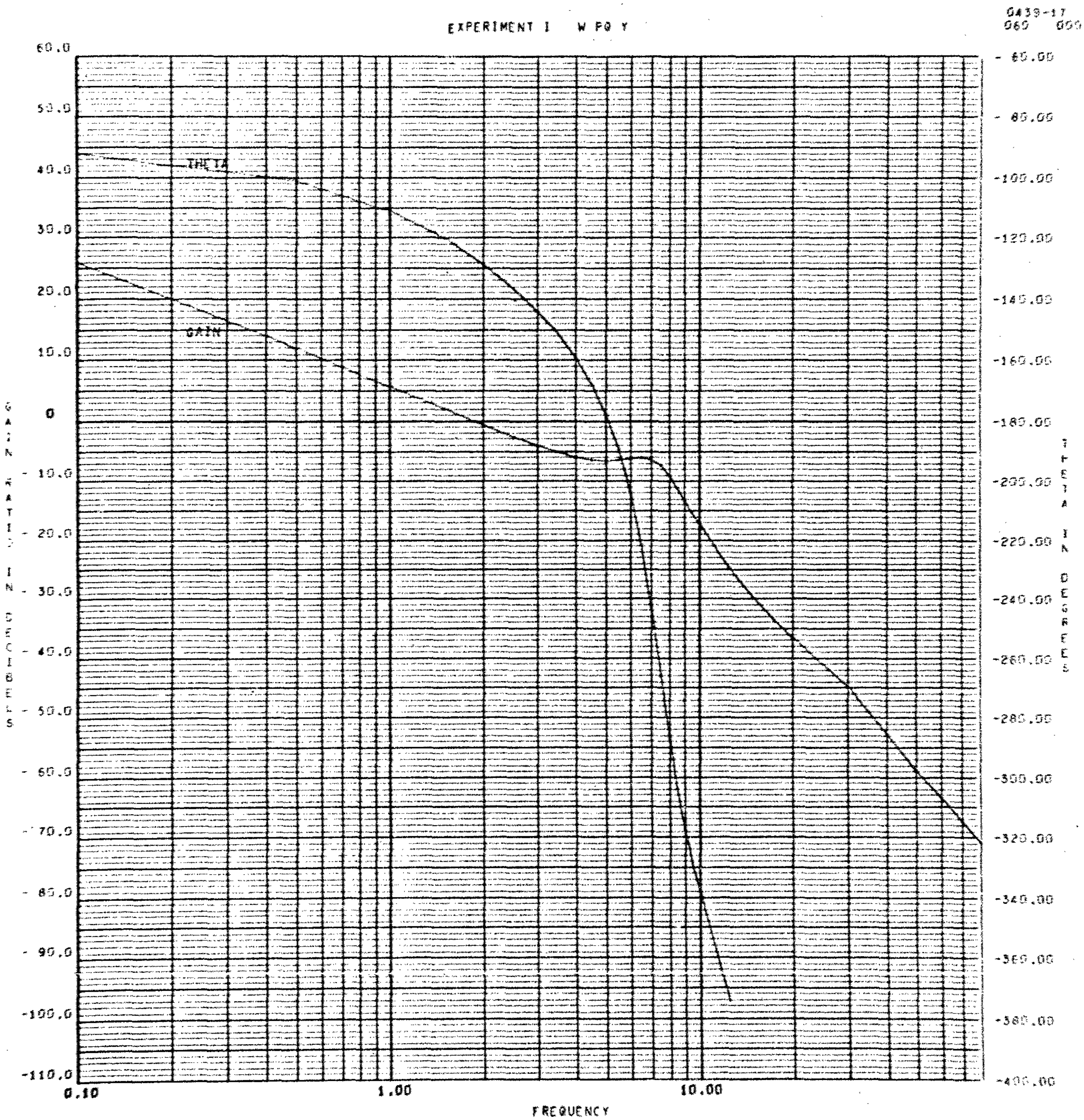
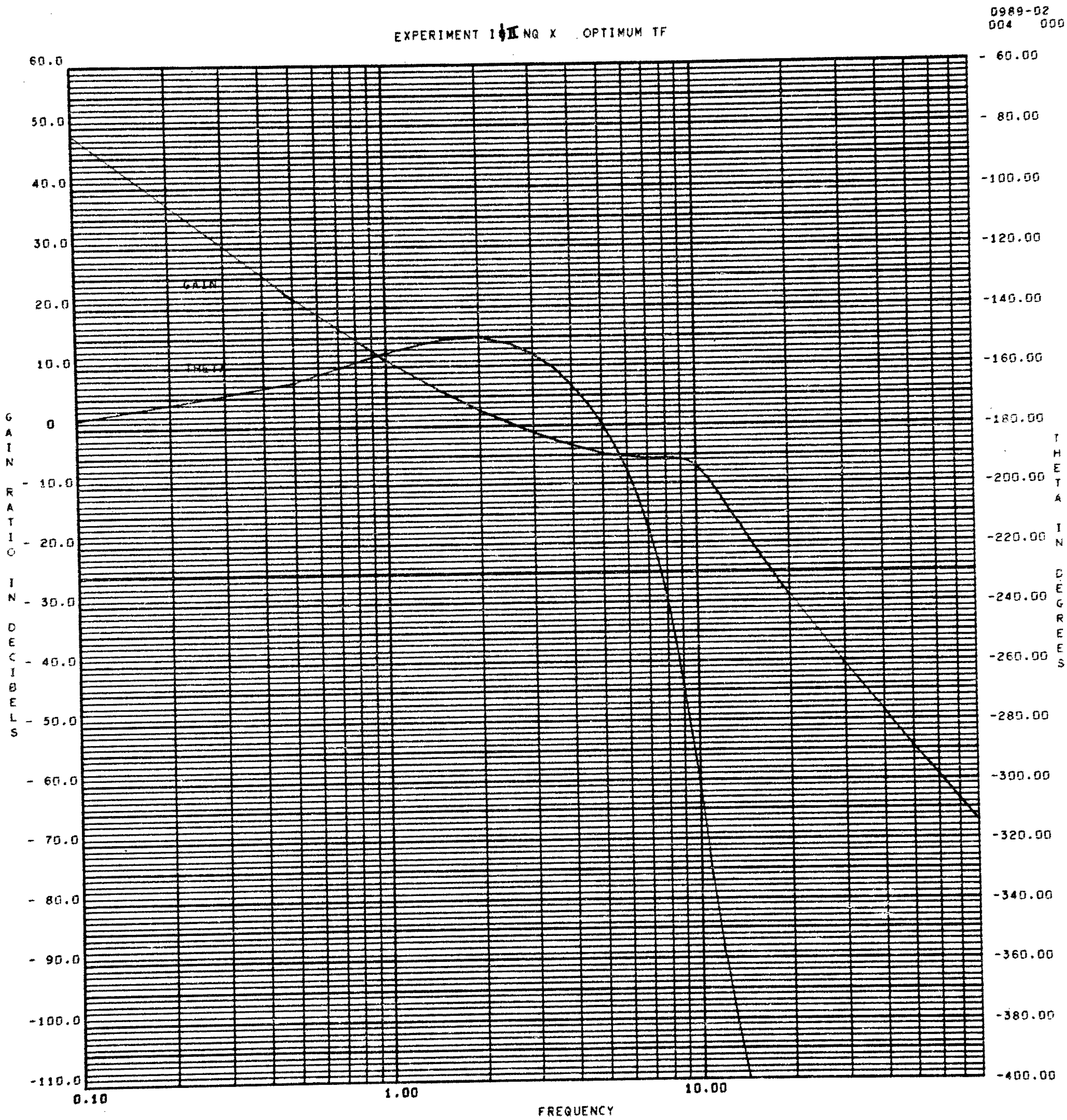

EXPERIMENT I W PQ X
9439-17
.050 000
THETA
GAIN
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
0.10
1.00
10.00
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 87.



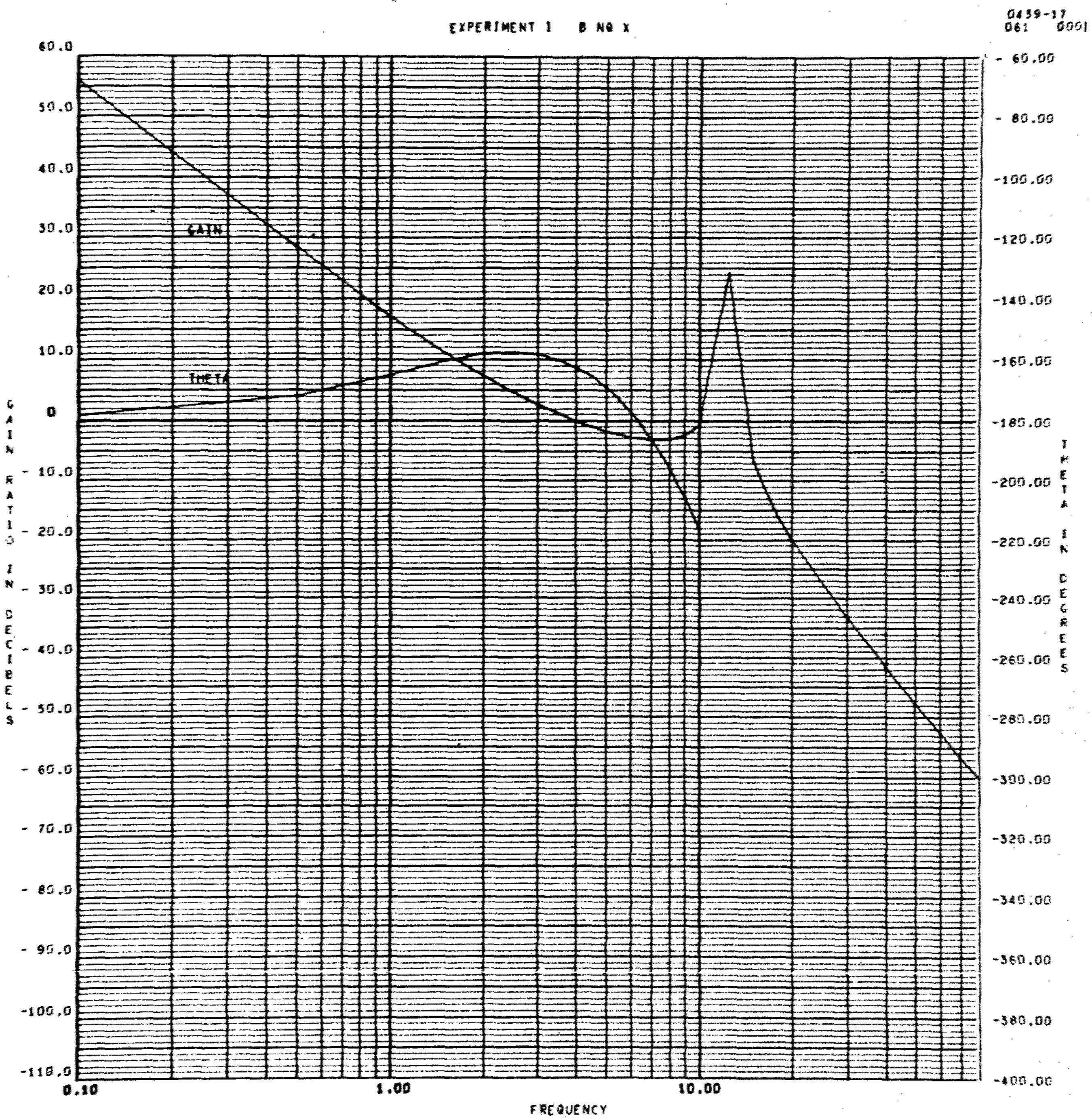
EXPERIMENT I W PQ Y
0439-17
060 000
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 88.



0989-02
004 000
EXPERIMENT I NQ X OPTIMUM TF
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 89.



EXPERIMENT I B NO X
0439-17
061 0001
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
GAIN
THETA
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 90.

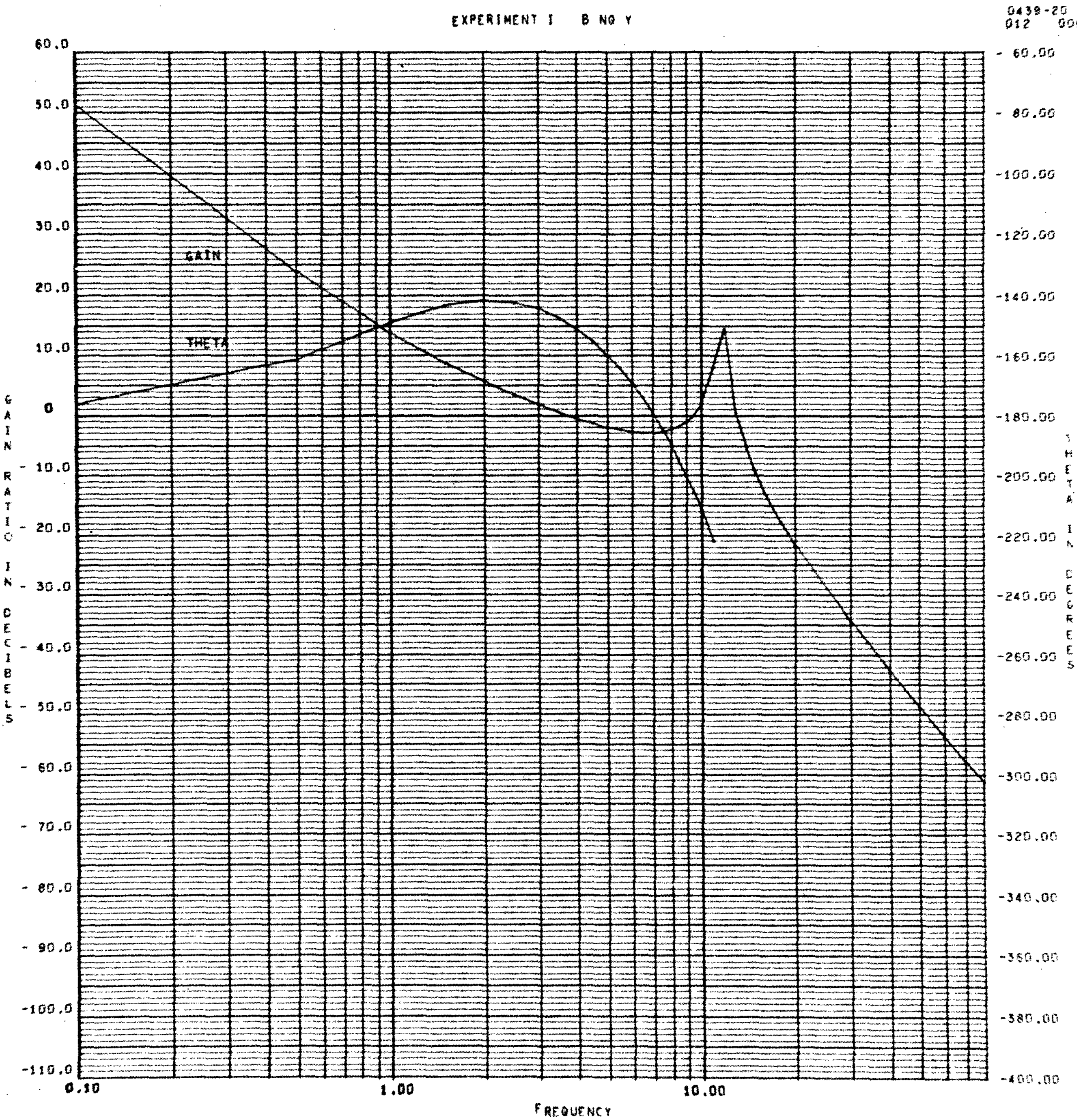

EXPERIMENT I B NO Y
0439-20
012 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 91.

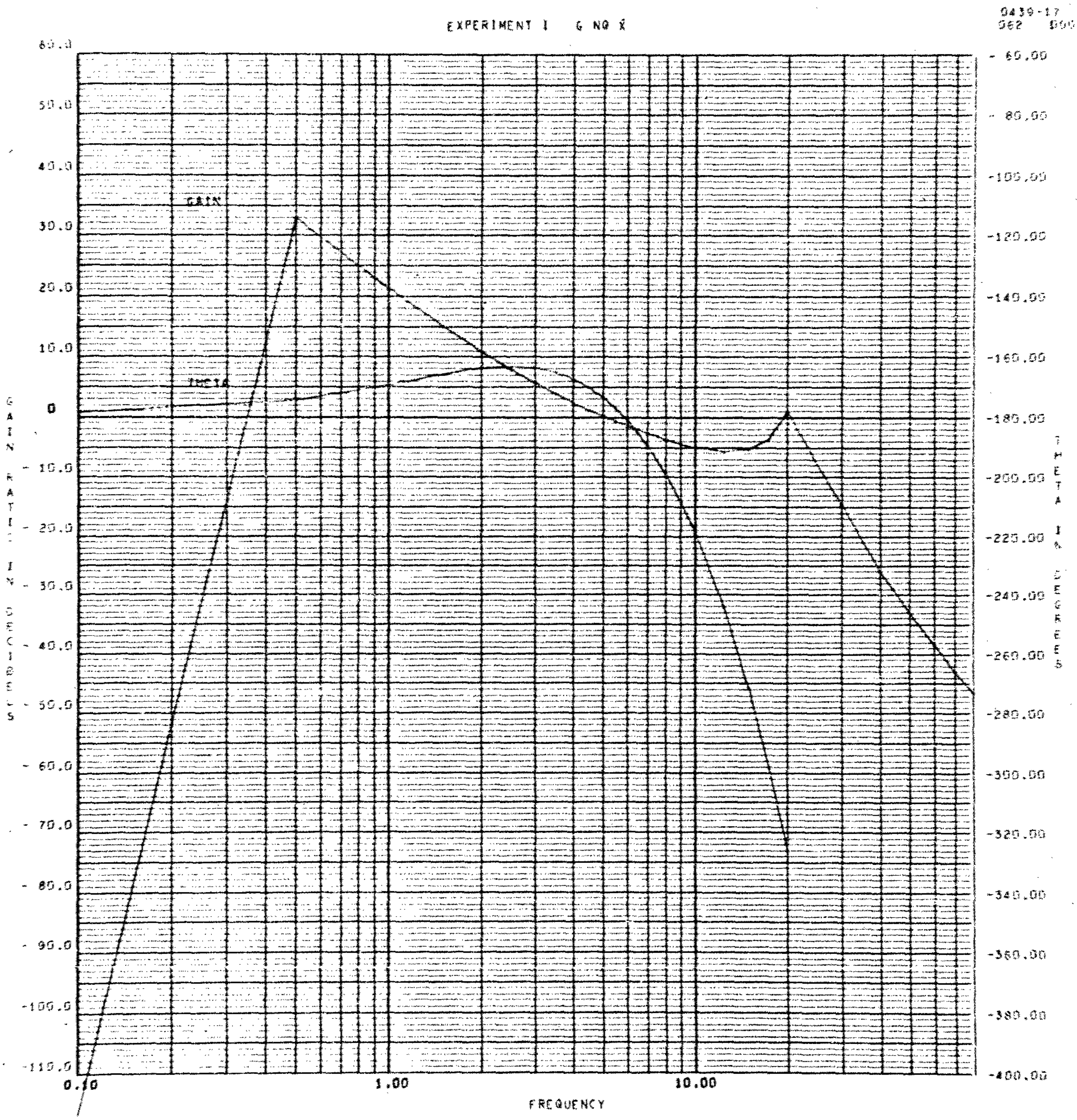

EXPERIMENT I G NO X
0439-17
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00

Figure 92.

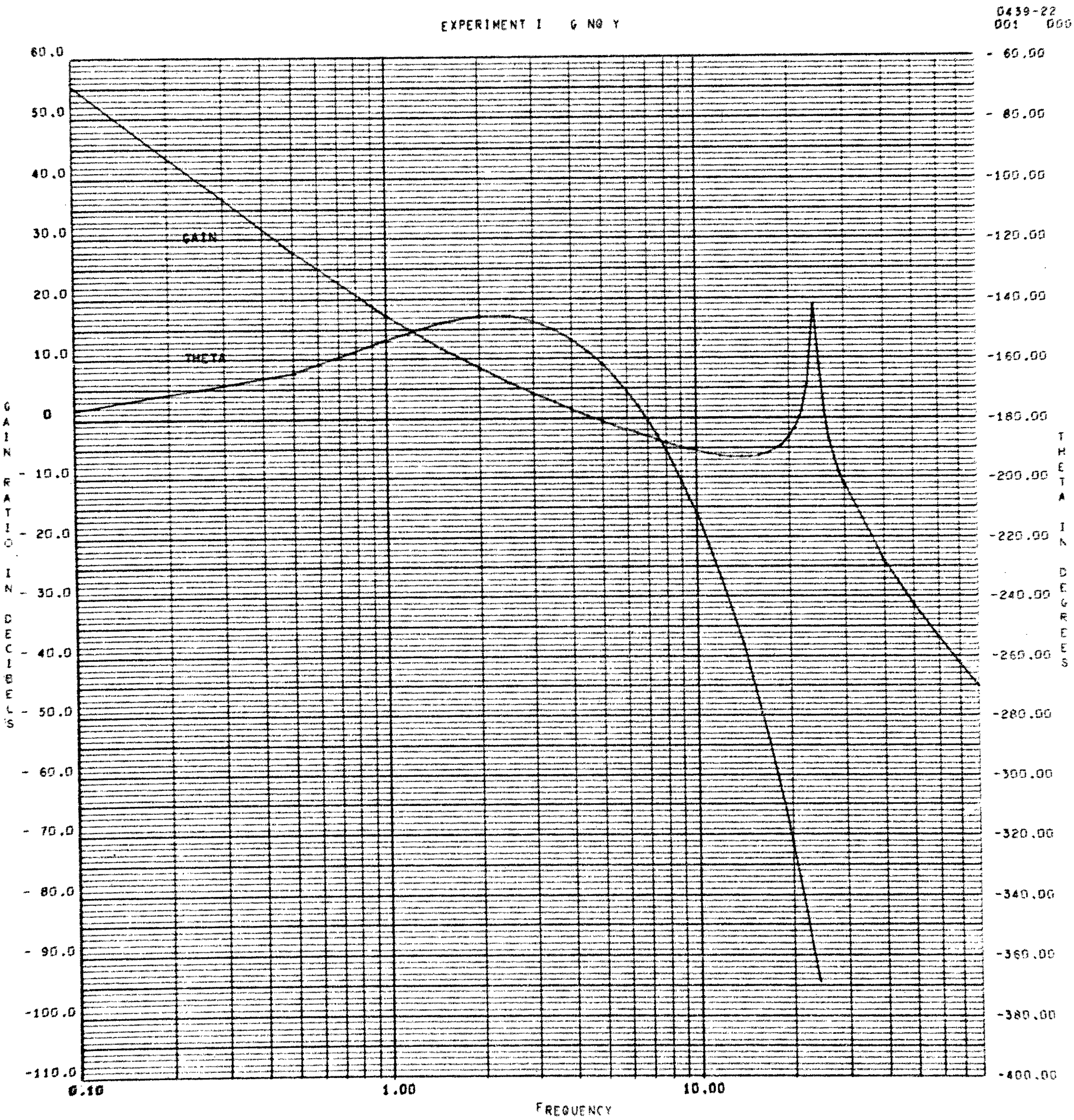
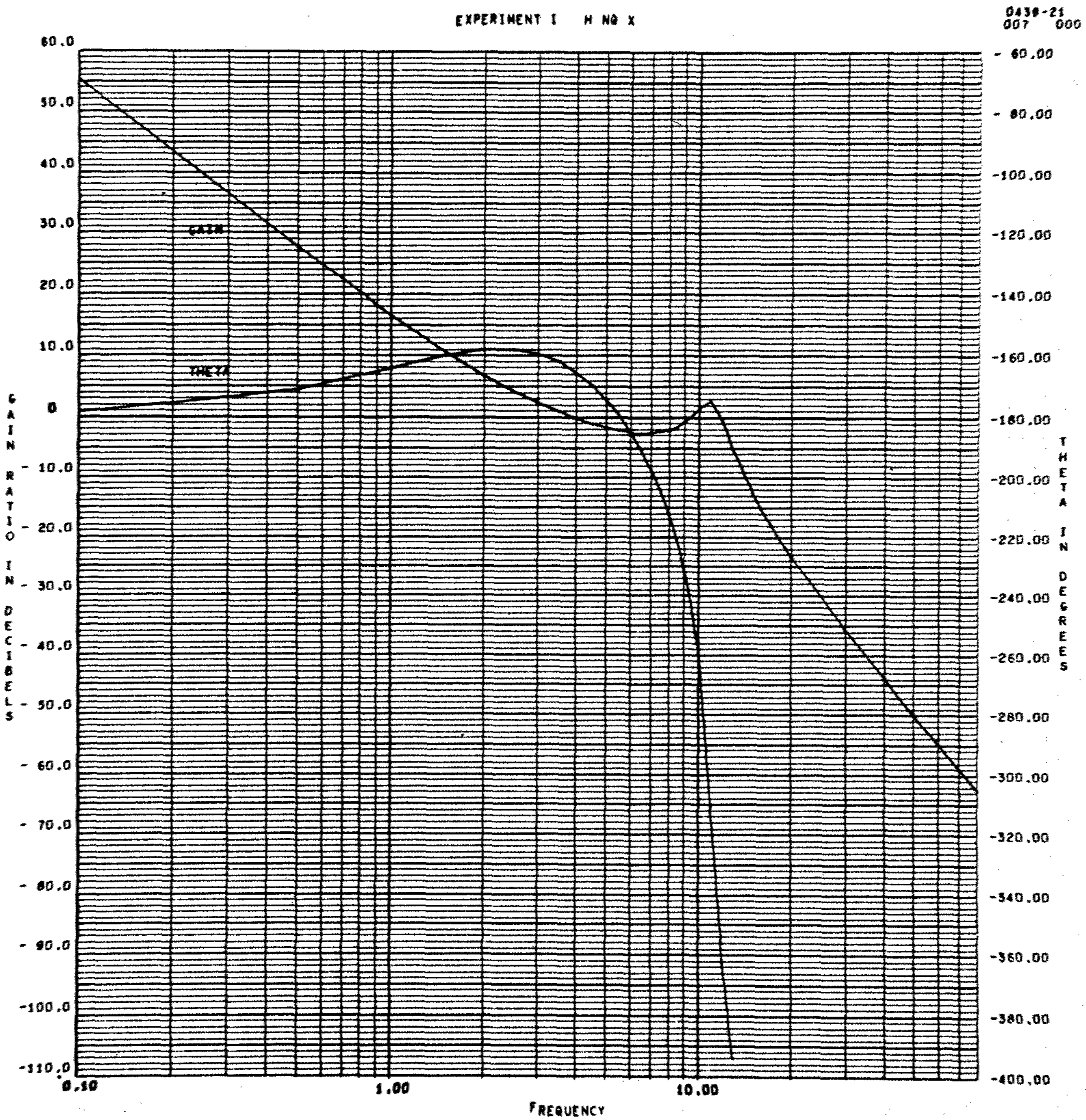
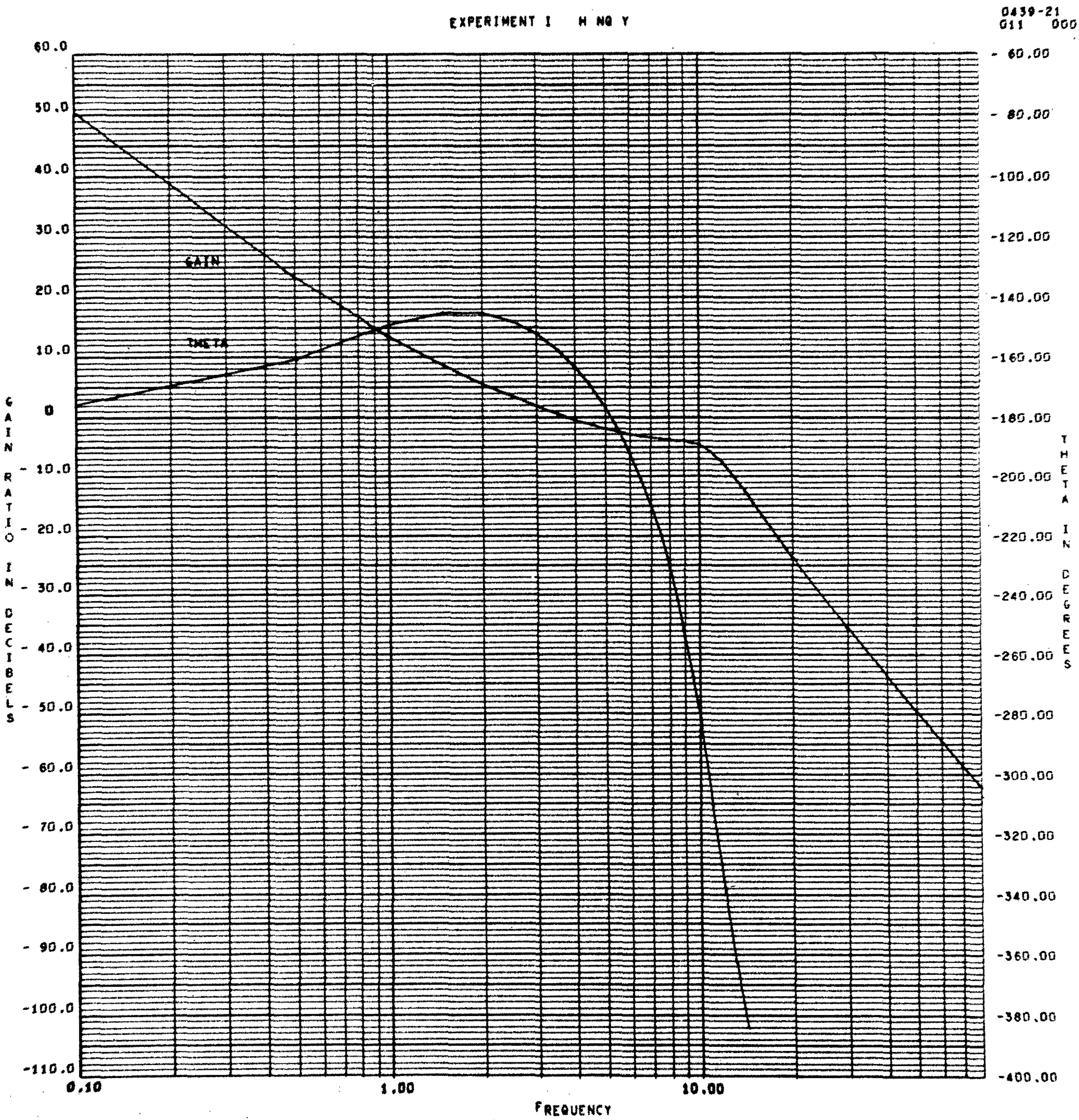

EXPERIMENT I G NQ Y
0439-22
001 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 93.



EXPERIMENT I H NO X
0439-21
007 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN
THETA
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 94.



EXPERIMENT I H NQ Y
0439-21
G11 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 95.

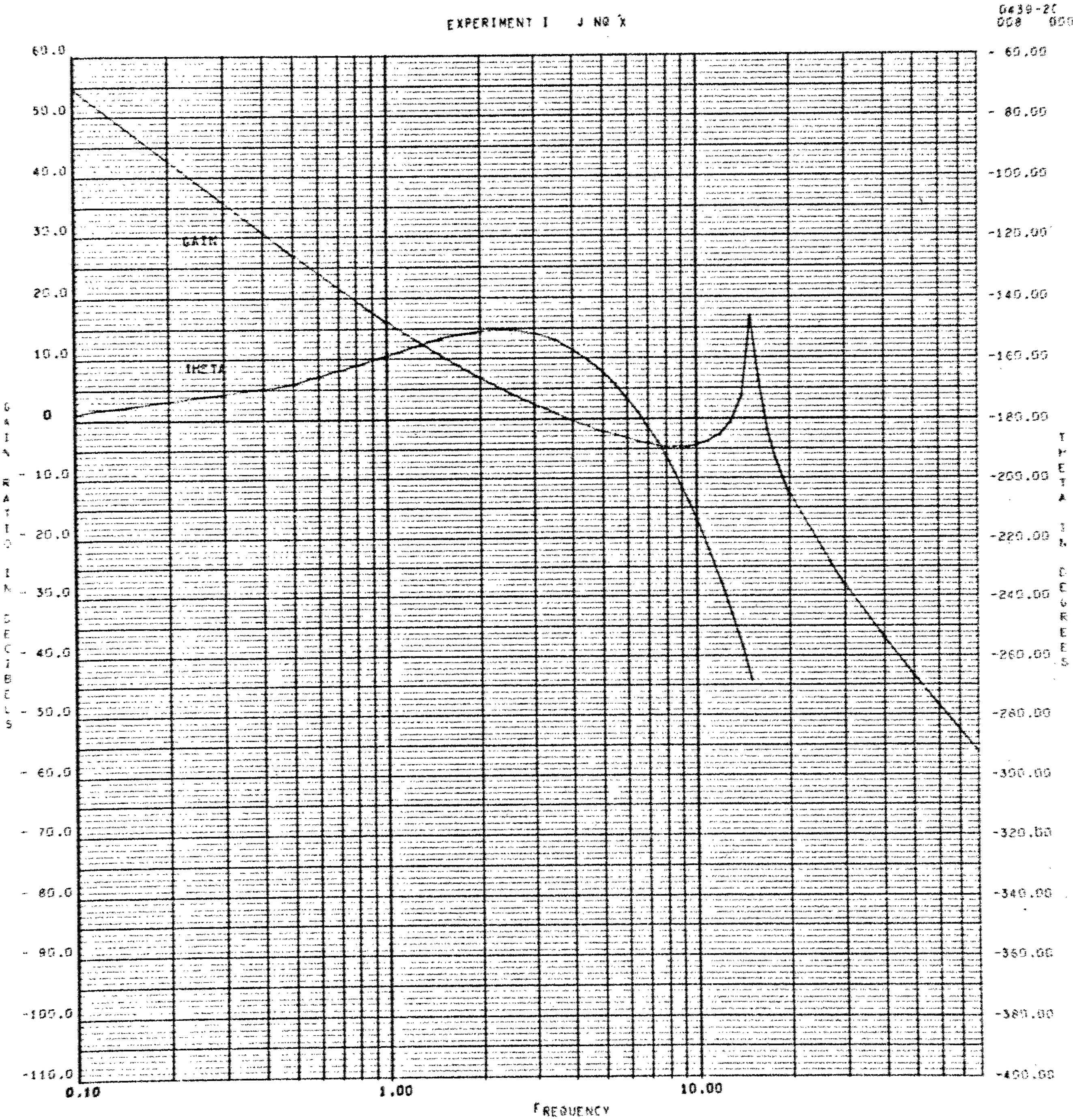
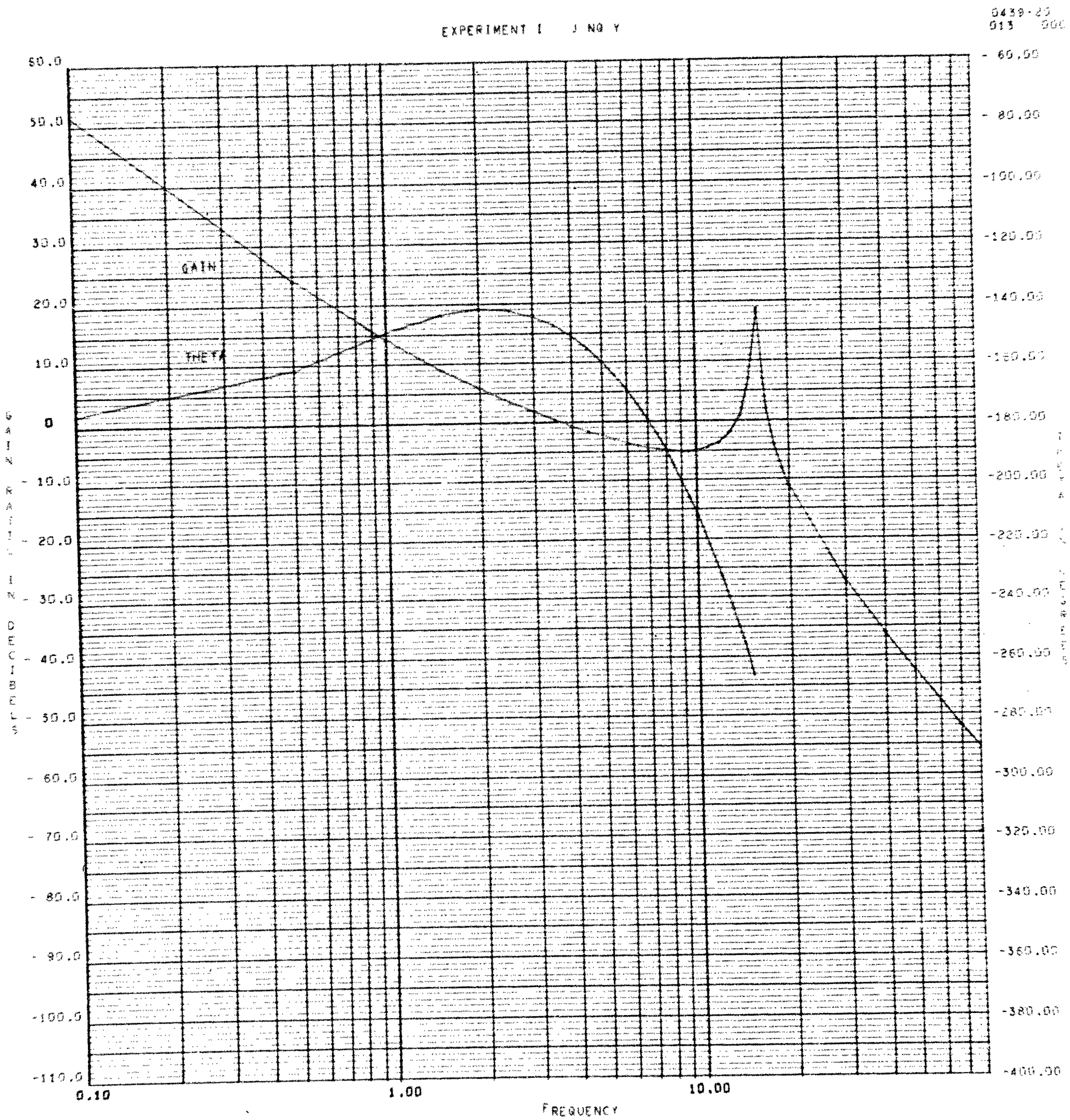
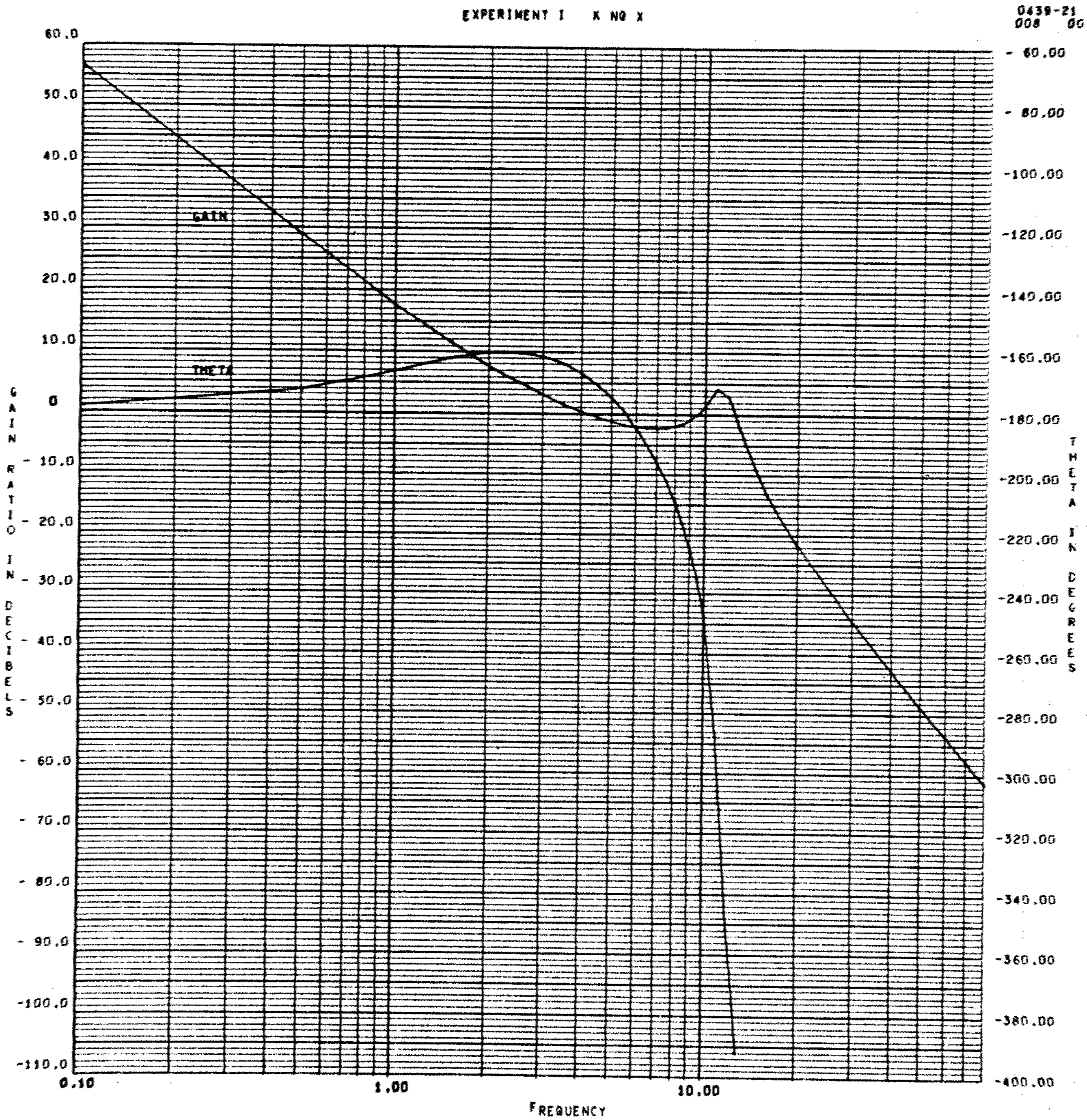

EXPERIMENT I J NO X
0439-20
008 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 96.



EXPERIMENT I J NO Y
0439-20
013 900
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
0.10
1.00
10.00
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 97.



EXPERIMENT I K NQ X
0439-21
008 00
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
0.10
1.00
10.00
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 98.

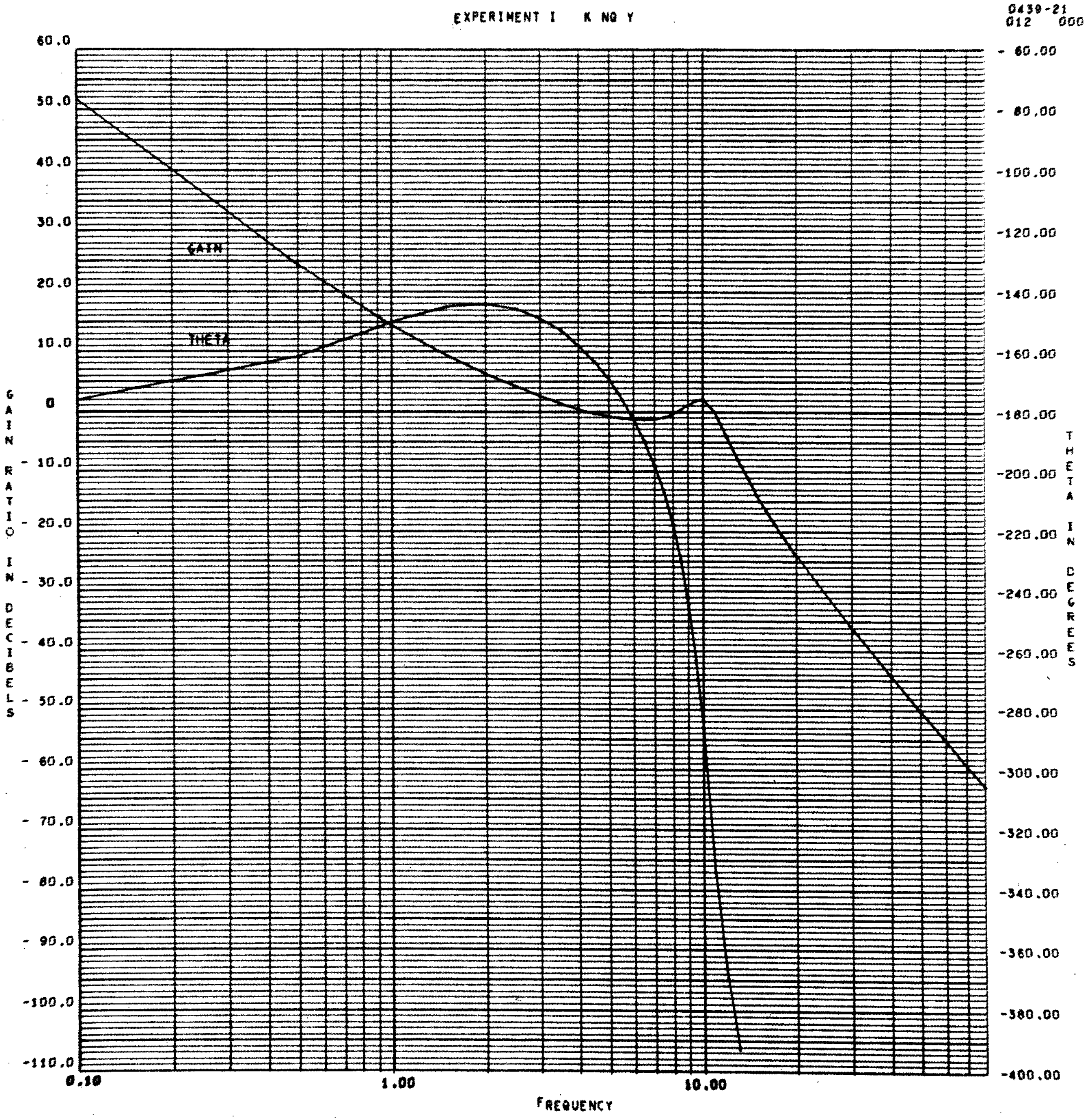
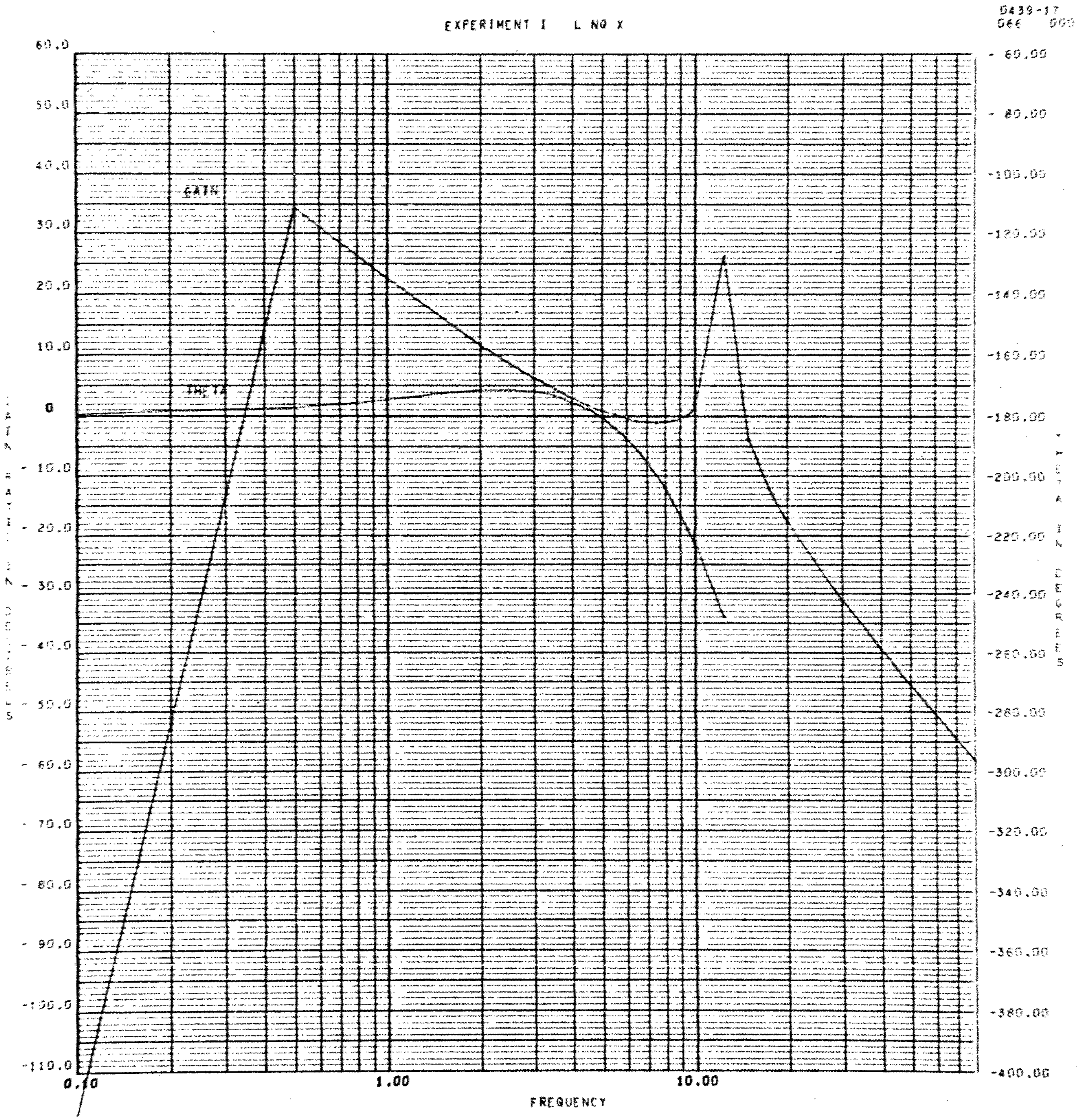
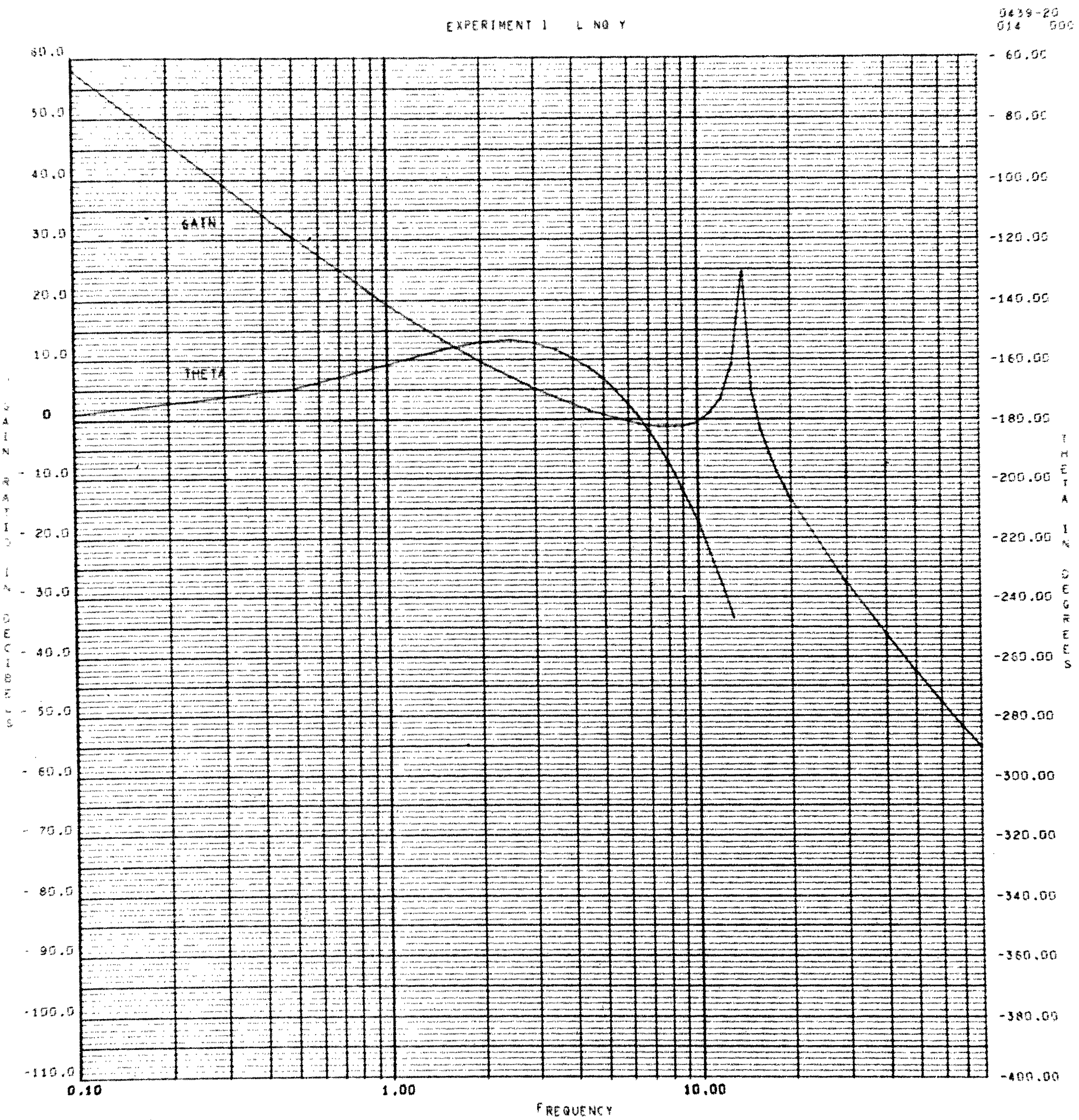

EXPERIMENT I K NQ Y
0439-21
012 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 99.



0439-17
066 000
EXPERIMENT I L NO X
GAIN
THETA
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES

Figure 100.



EXPERIMENT 1 L NO Y
0439-20
014 900
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 101.

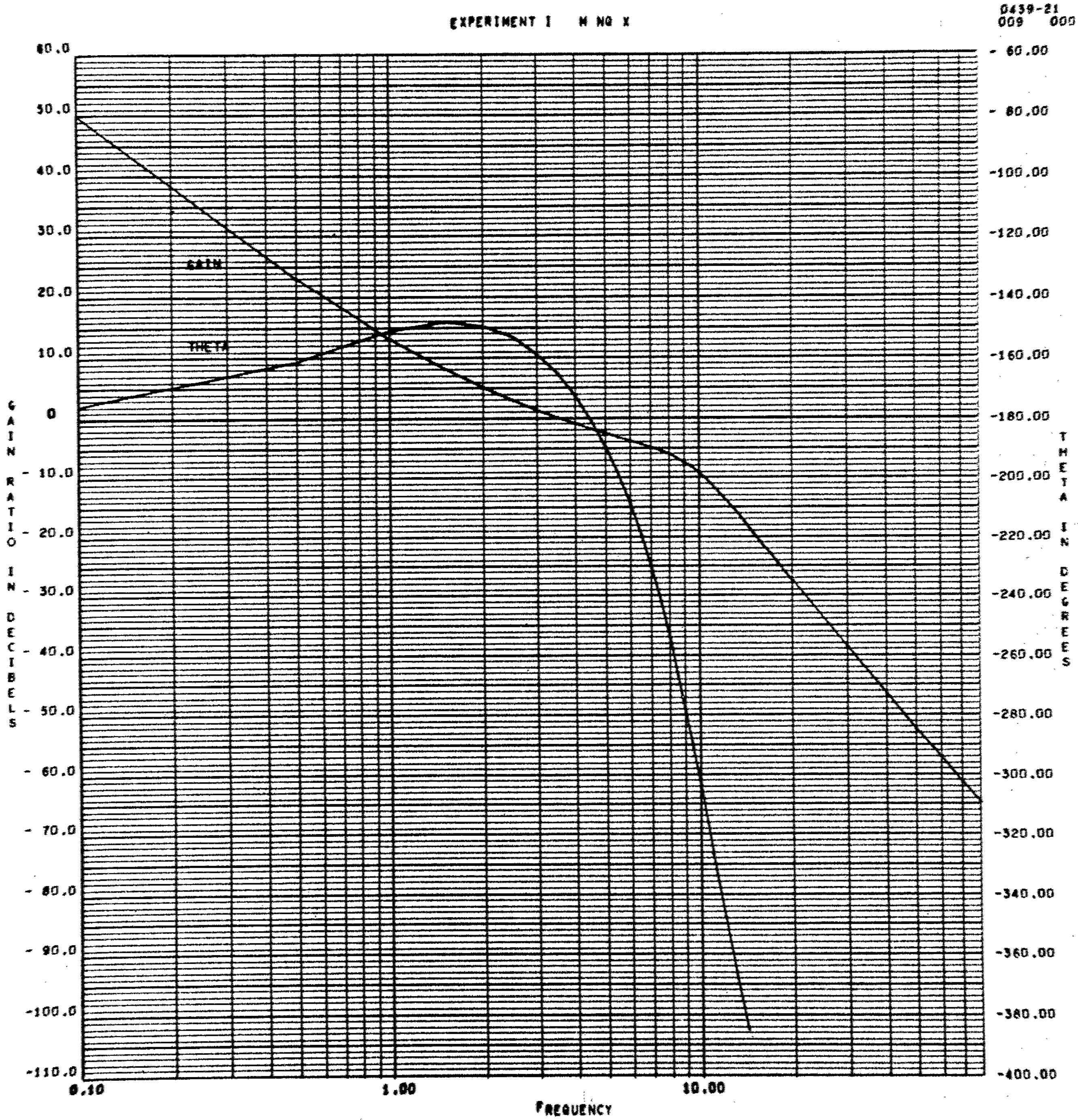
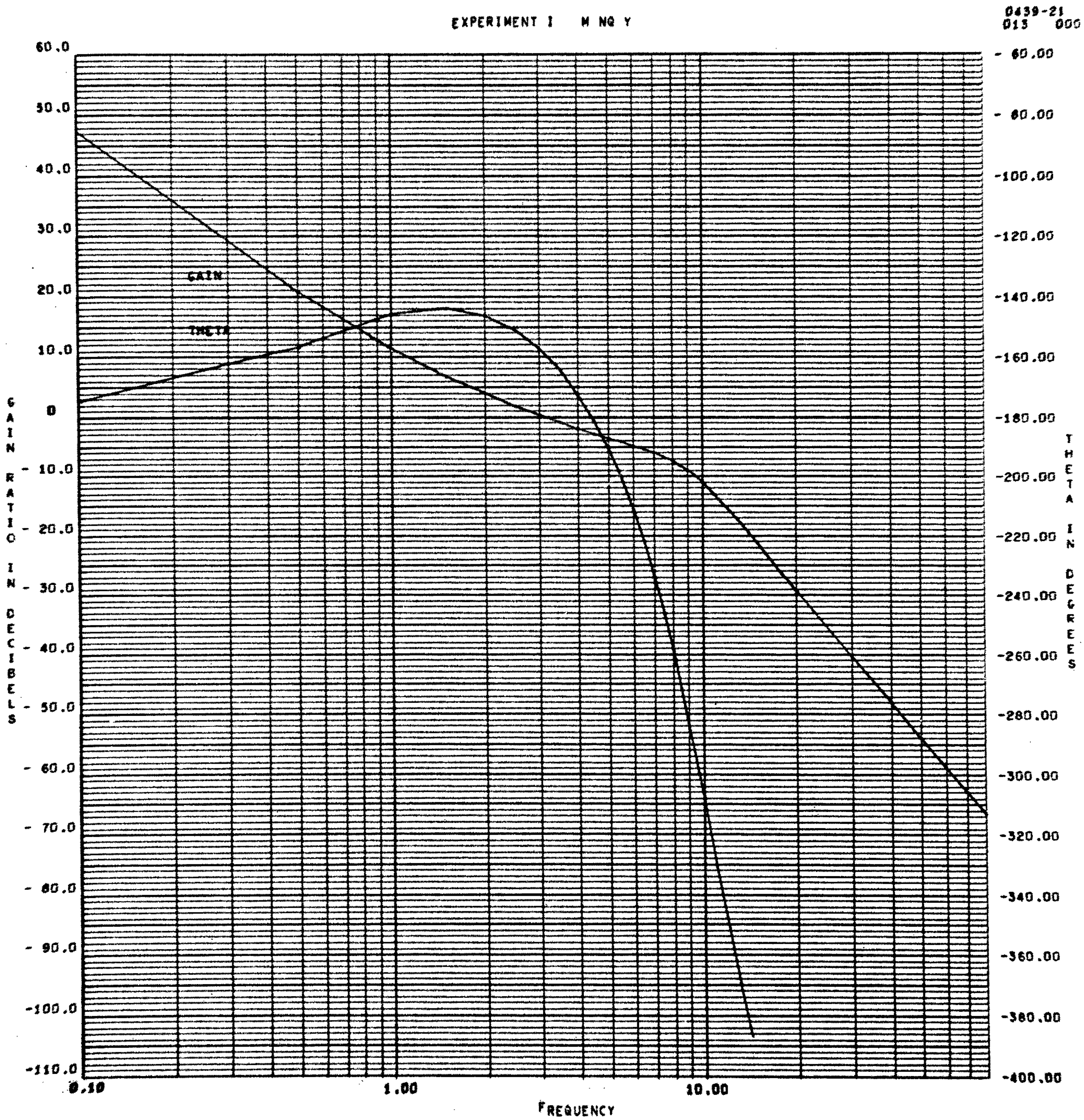

EXPERIMENT I M NO X
0439-21
009 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 102.



EXPERIMENT I M NQ Y
0439-21
013 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
GAIN
THETA
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 103.

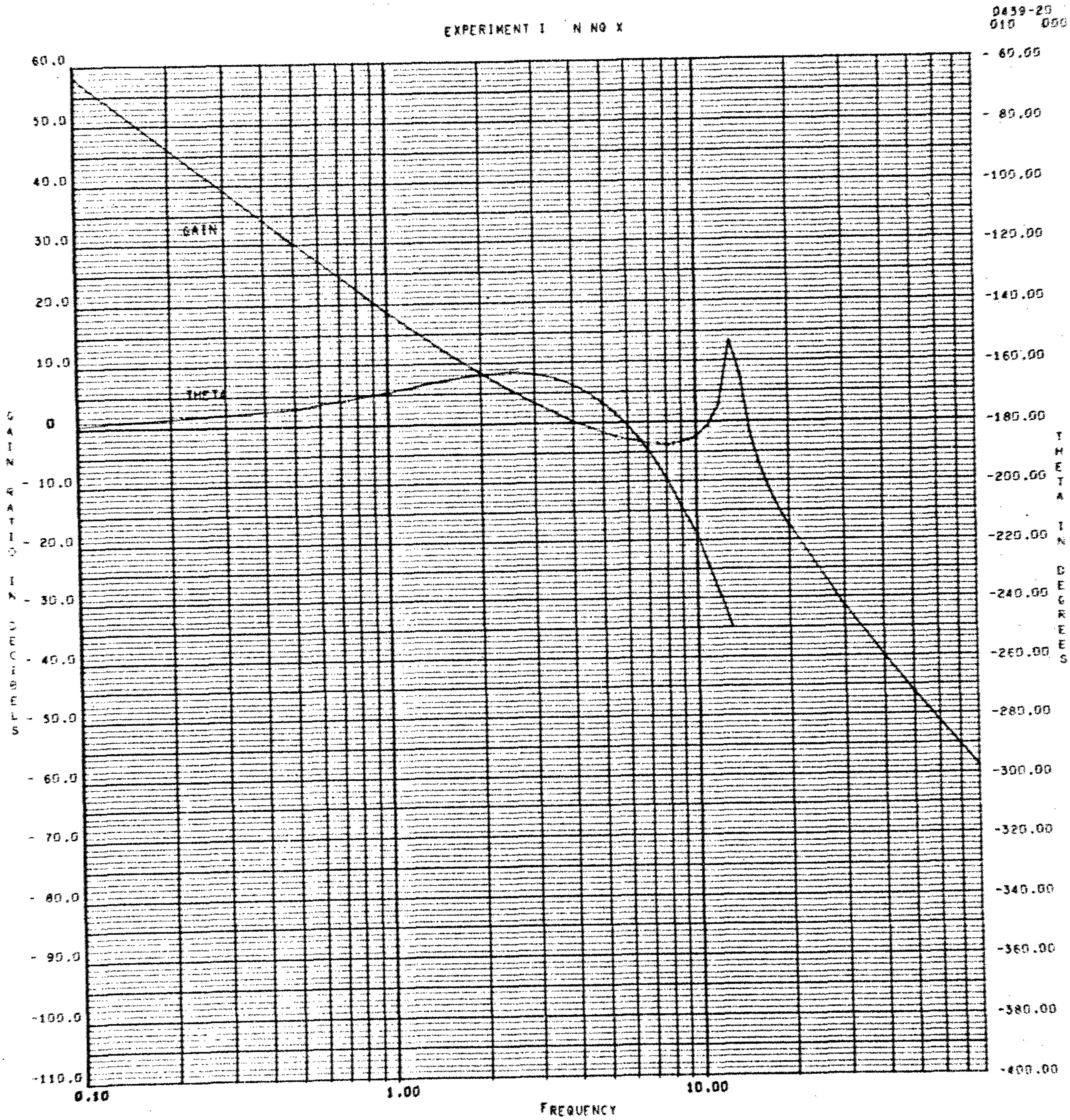

EXPERIMENT I N NO X
0439-20
010 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 104.

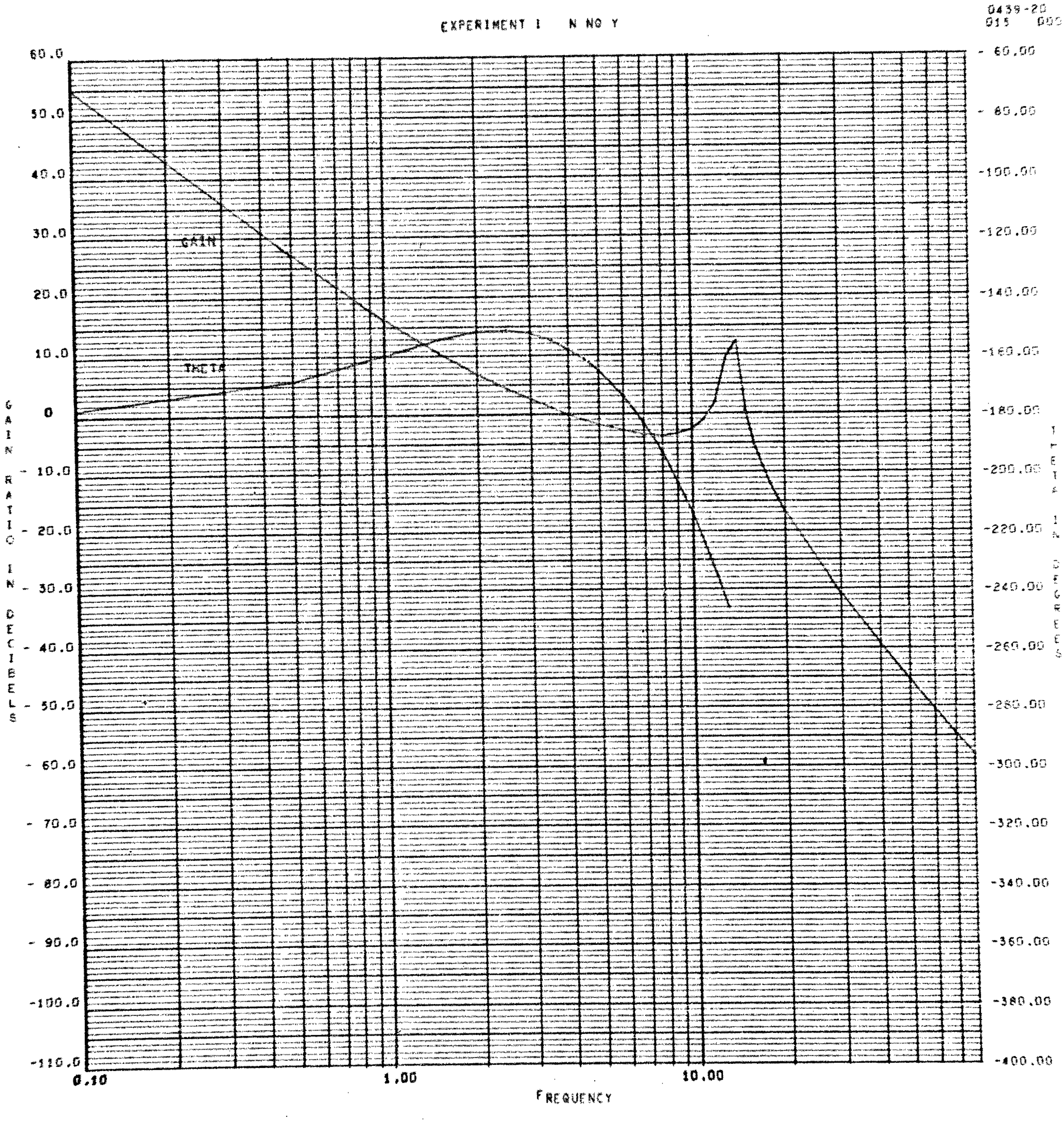
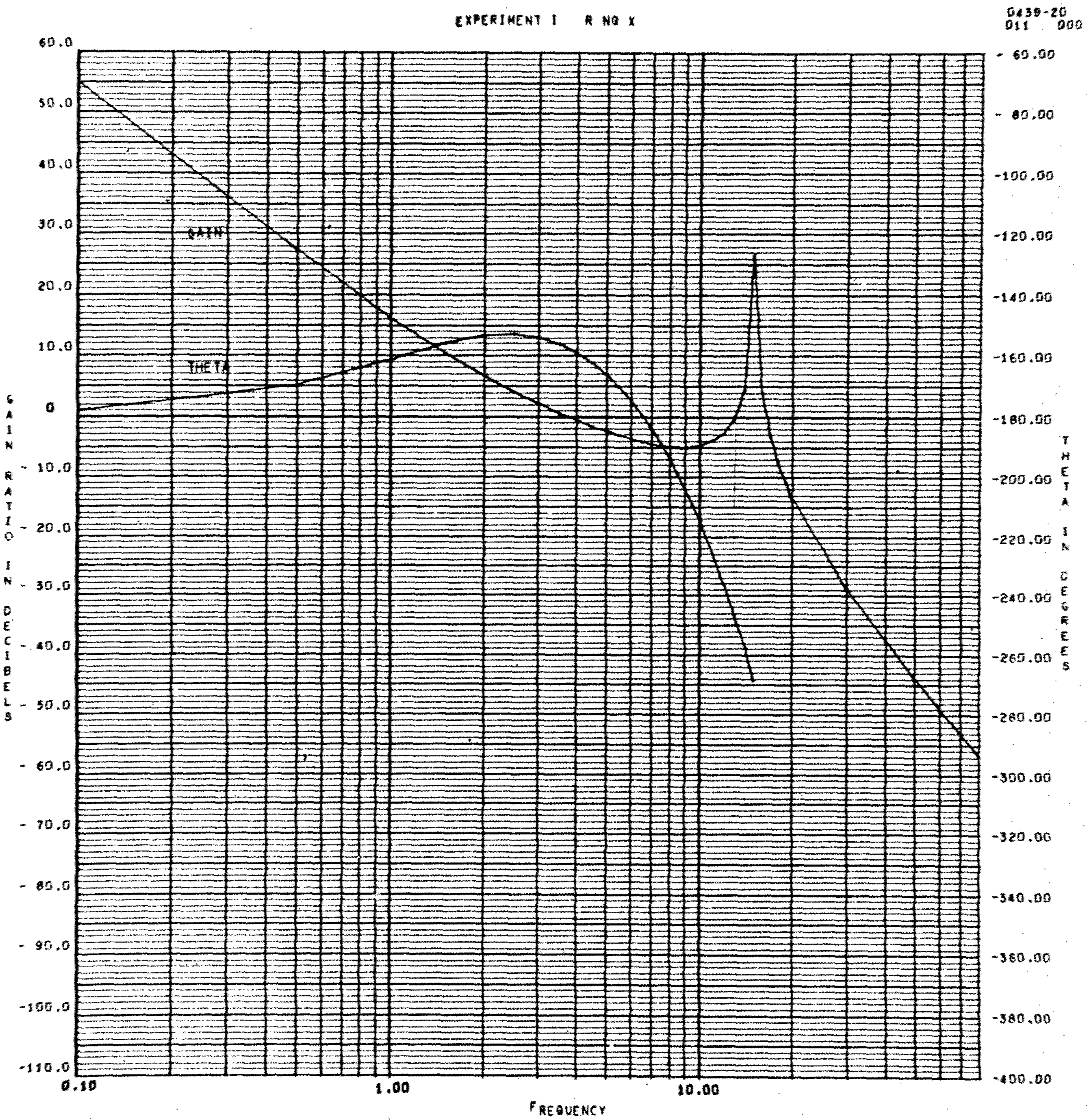
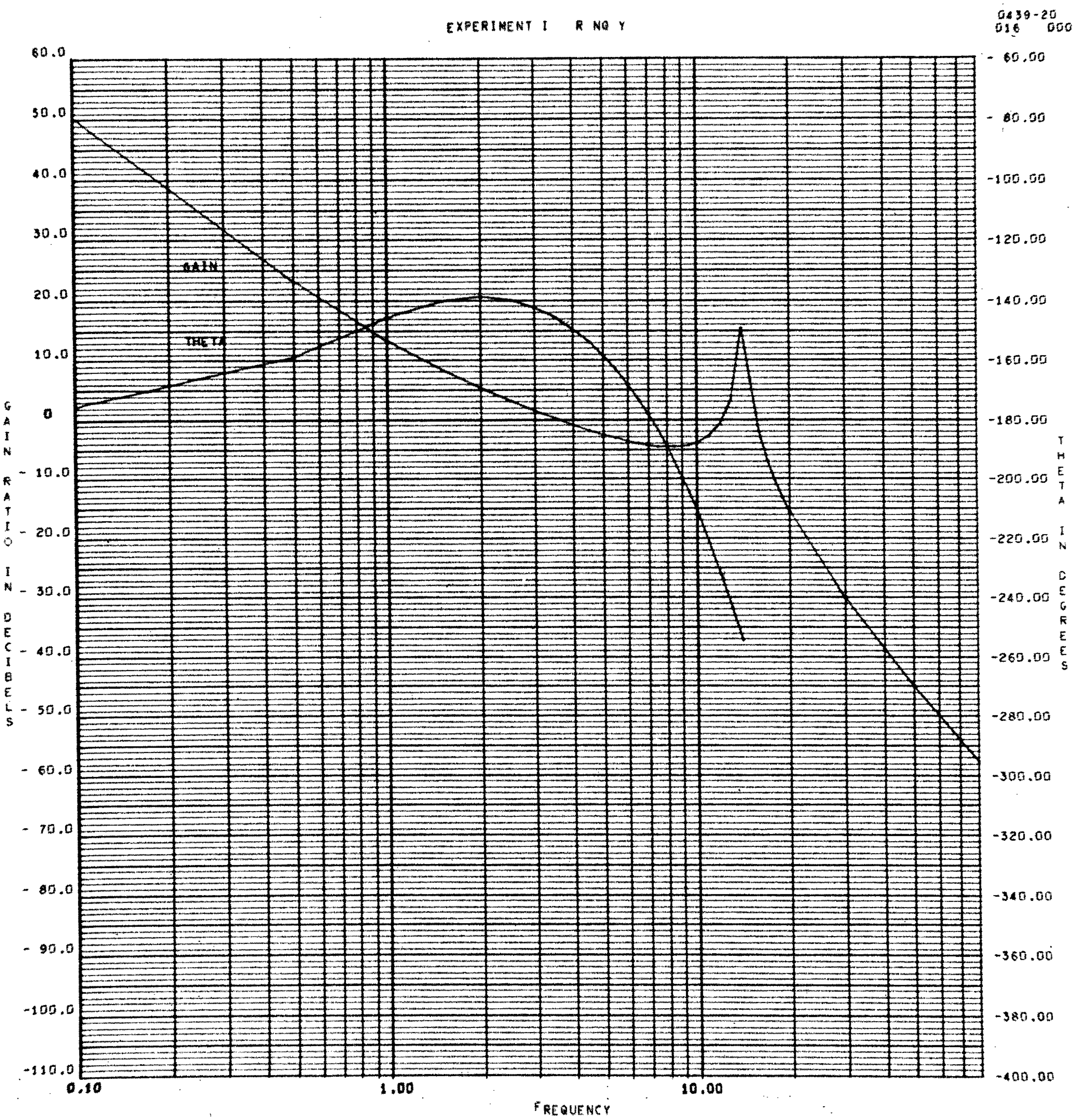

EXPERIMENT I N NO Y
0439-20
015 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
GAIN
THETA
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 105.



EXPERIMENT I R NO X
0439-20
011 900
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
GAIN
THETA
0.10
1.00
10.00
FREQUENCY

Figure 106.



EXPERIMENT I R NQ Y
0439-20
016 000
GAIN
THETA
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 107.

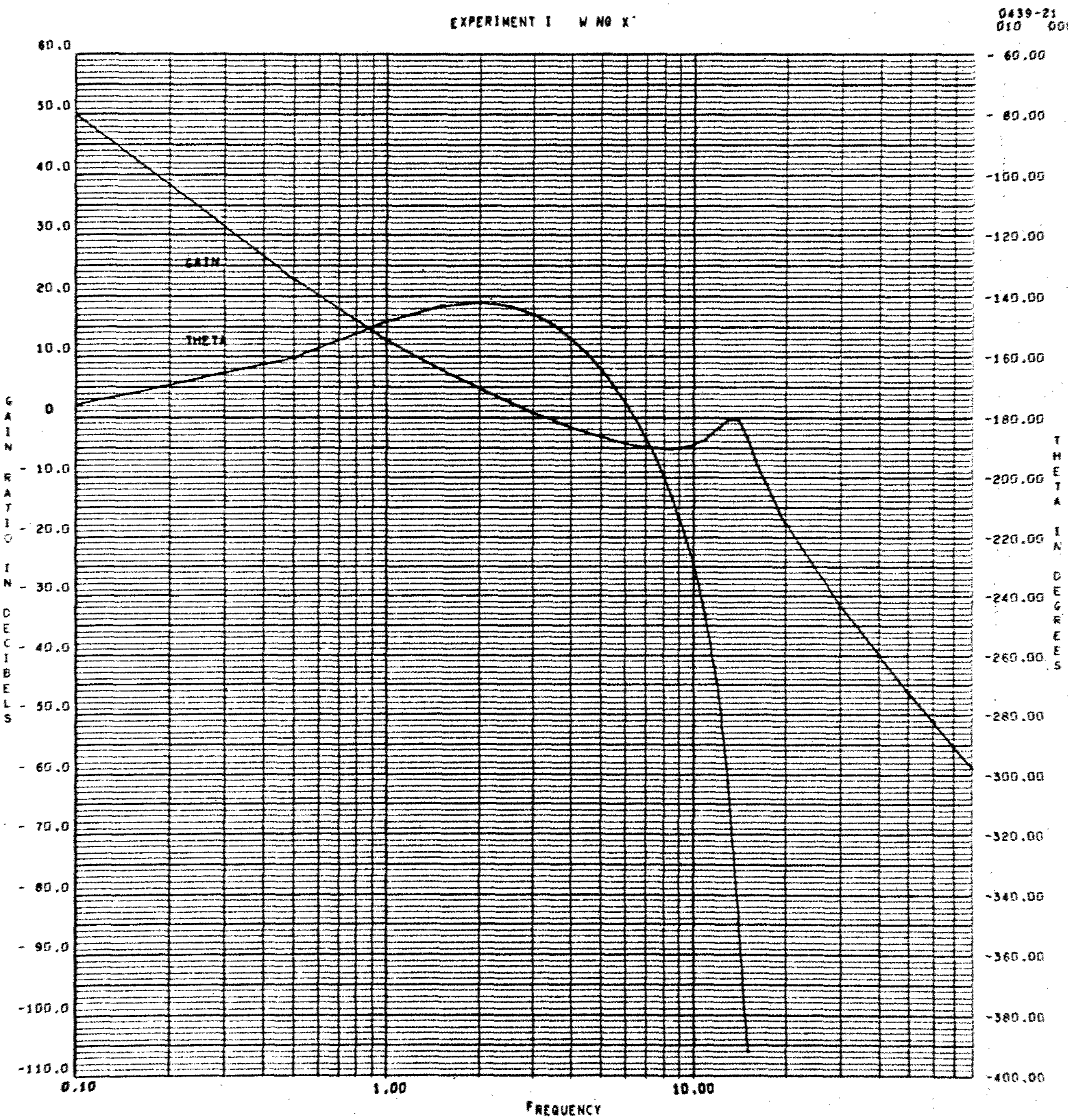
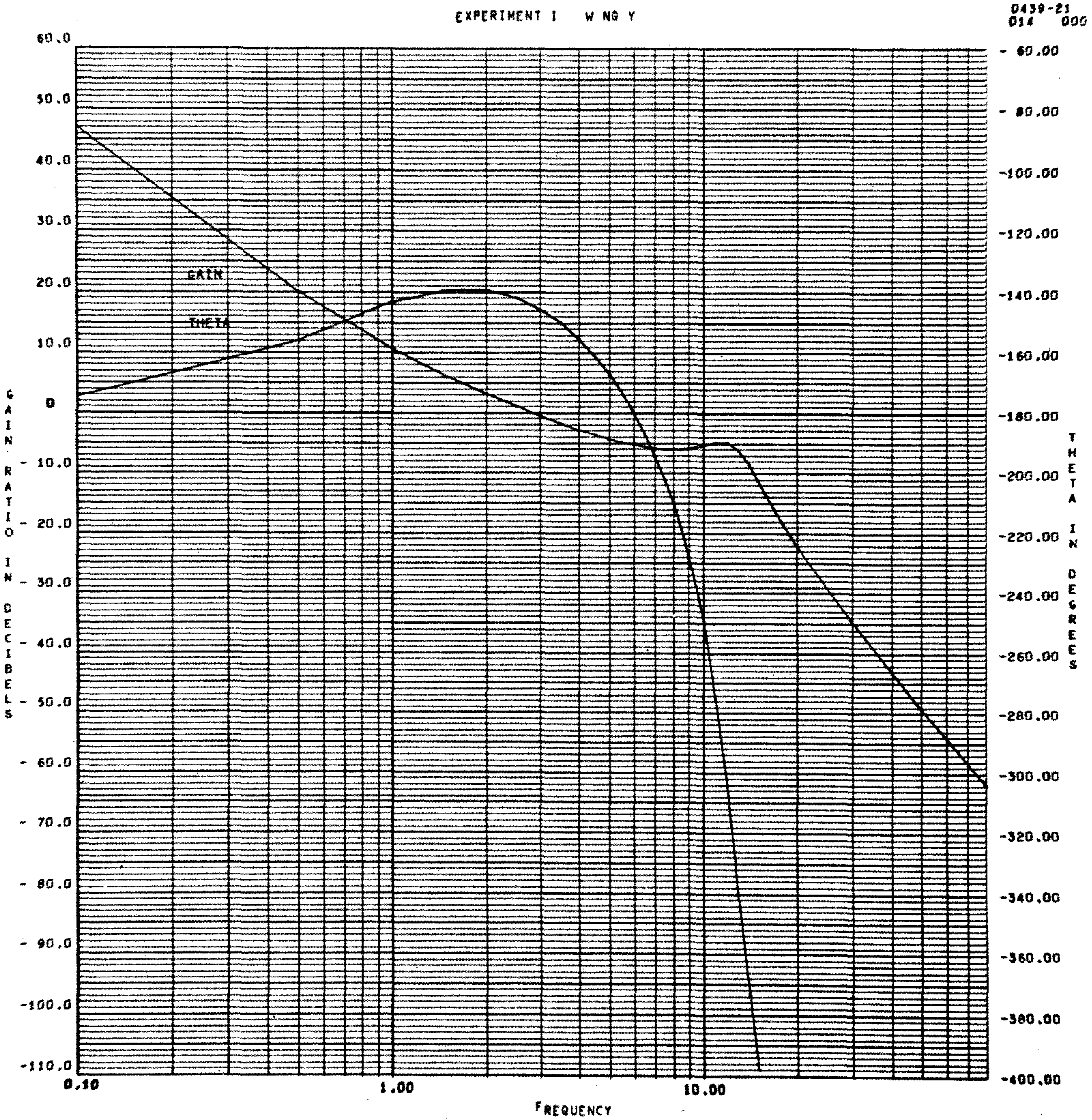

EXPERIMENT I W NO X
0439-21
010 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 108.



EXPERIMENT I W NQ Y
0439-21
014 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 109.

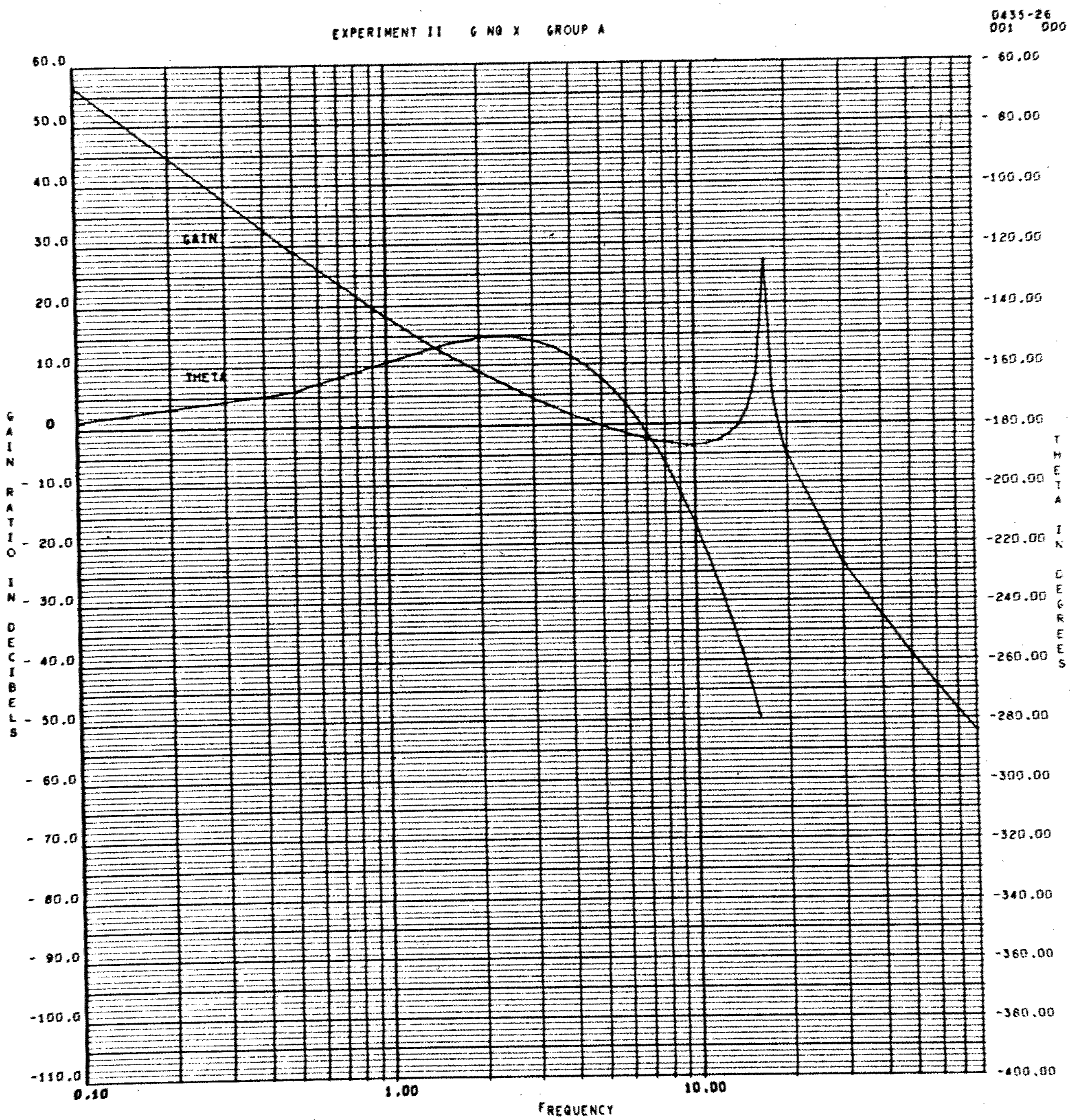

EXPERIMENT II G NO X GROUP A
0435-26
001 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 110.

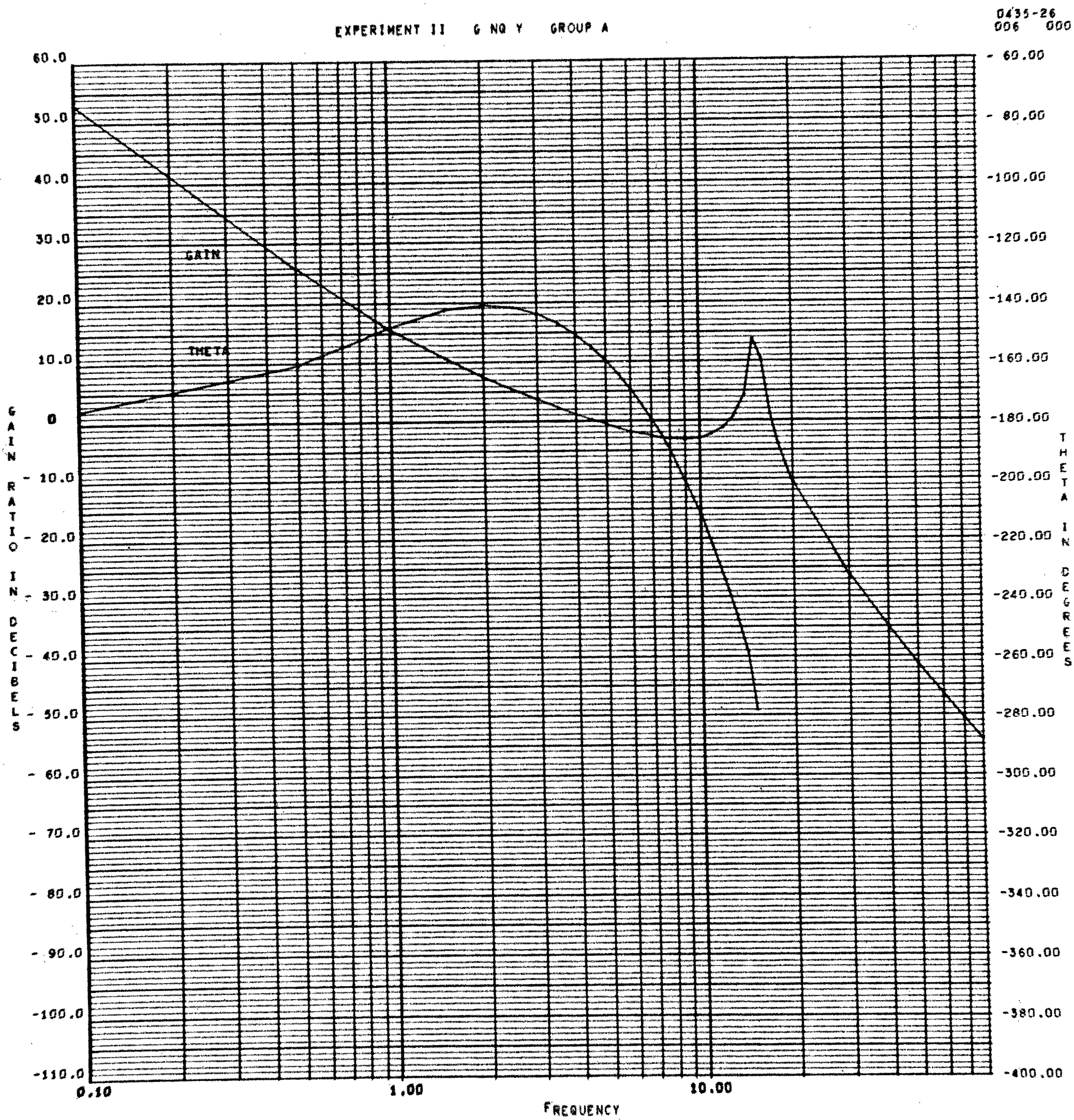
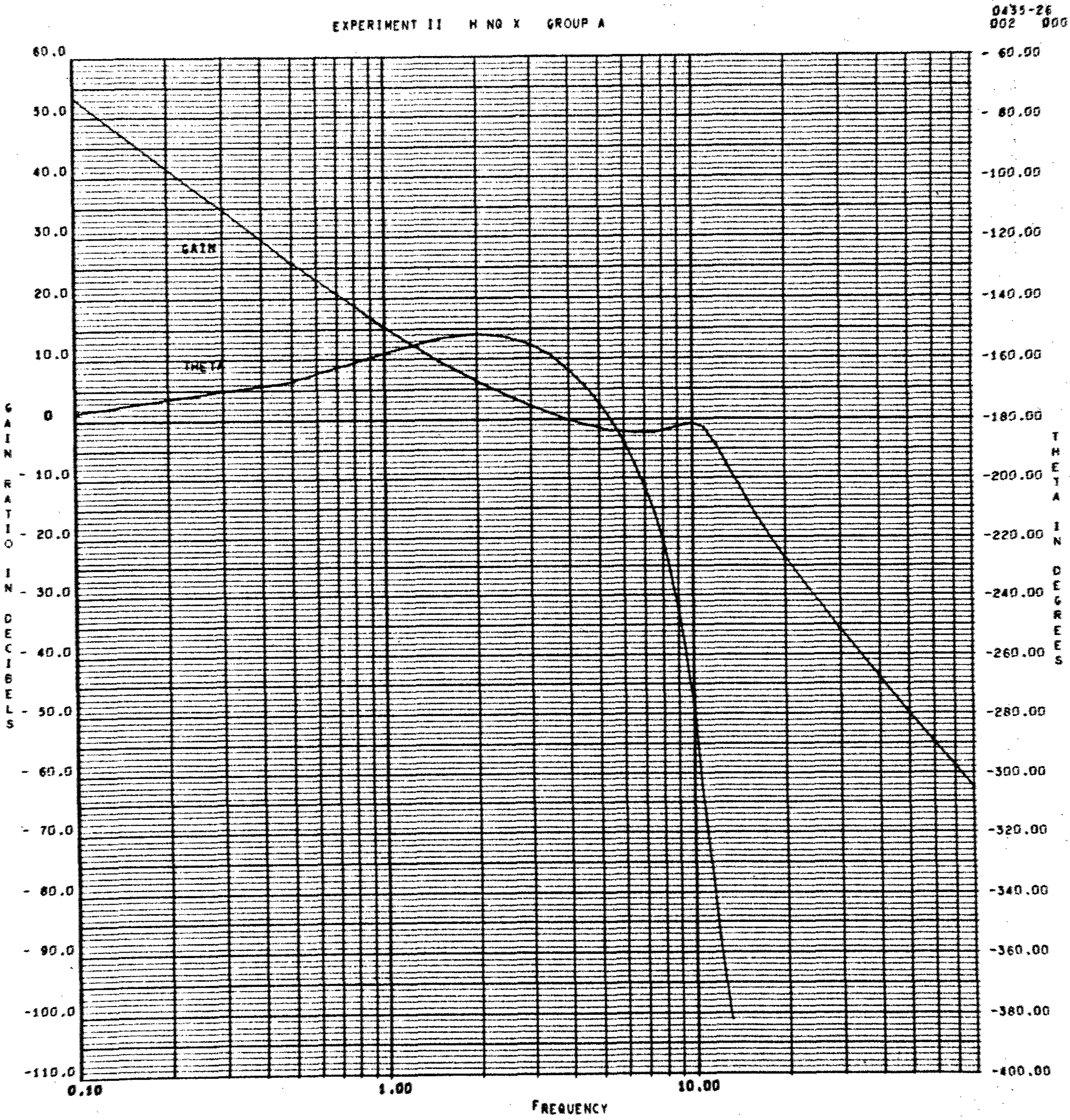
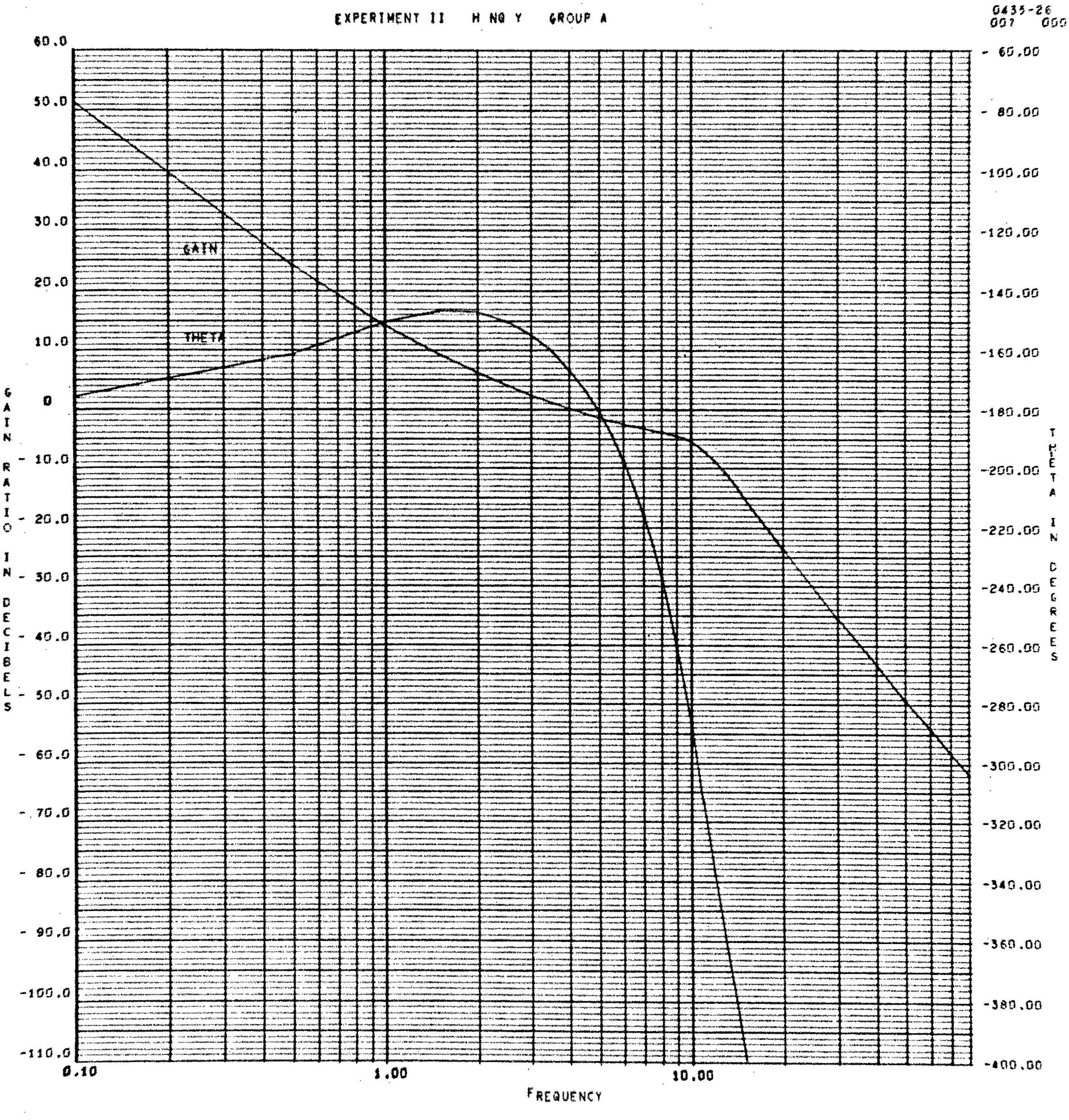

EXPERIMENT II G NQ Y GROUP A
0435-26
006 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
GAIN
THETA
0.10
1.00
10.00
FREQUENCY

Figure 111.



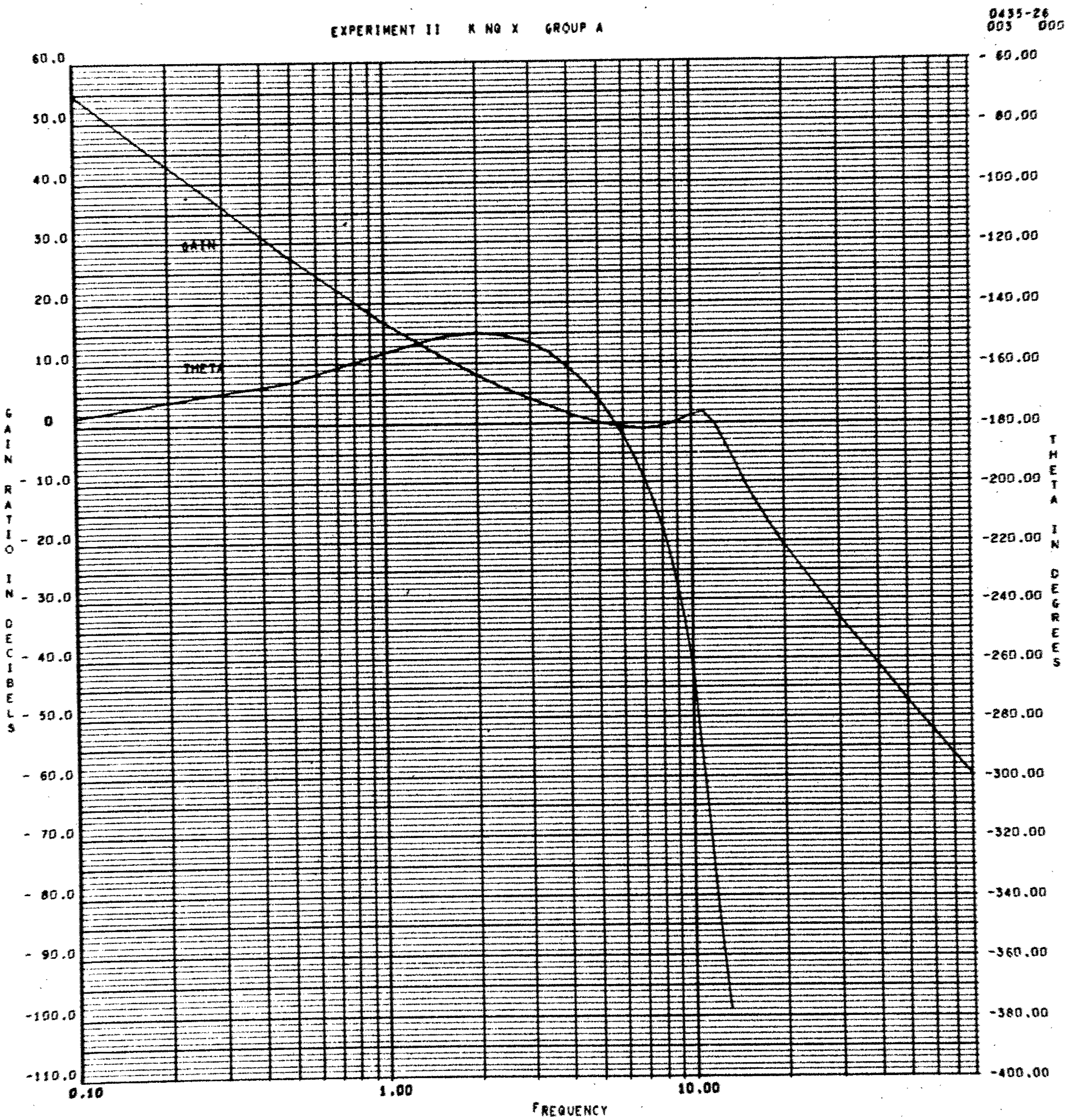
0435-26
002 000
EXPERIMENT II H NO X GROUP A
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 112.



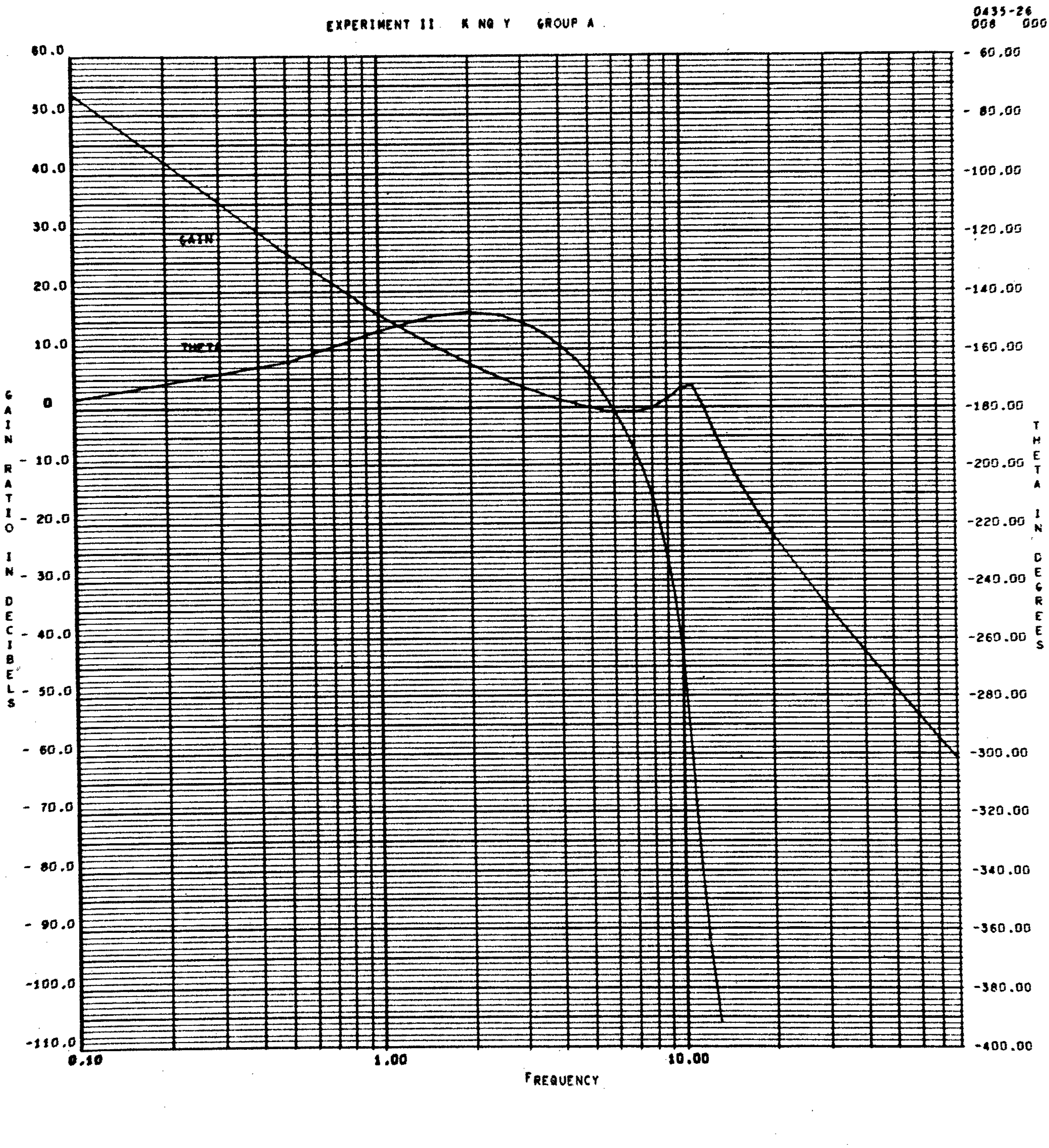
EXPERIMENT II H NQ Y GROUP A
0435-26
007 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
GAIN
THETA
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 113.



EXPERIMENT II K NQ X GROUP A
0435-26
003 005
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 114.



EXPERIMENT II K NQ Y GROUP A
0435-26
008 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 115.

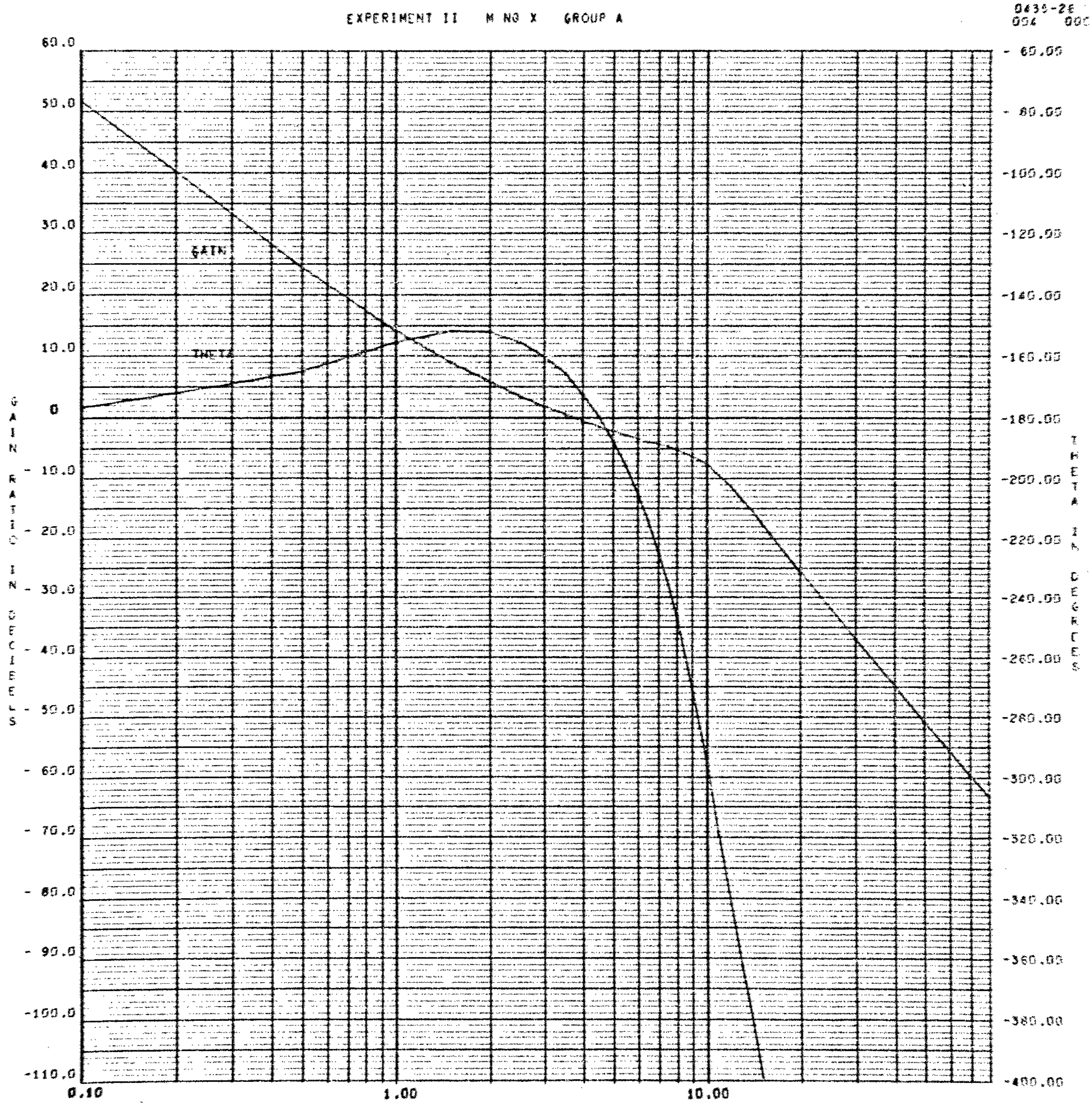

EXPERIMENT II M NO X GROUP A
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
0.10
1.00
10.00
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00

Figure 116.

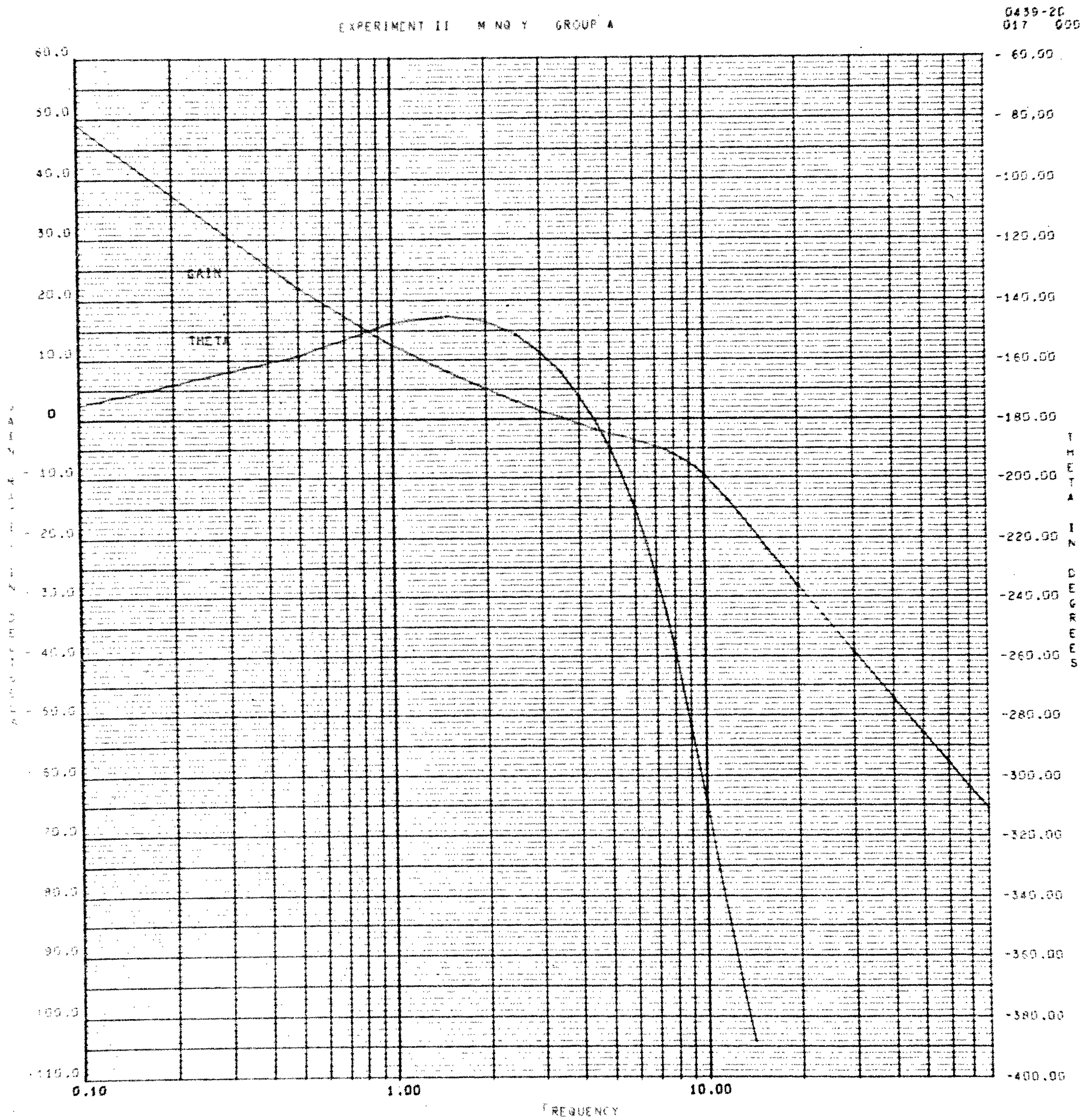

EXPERIMENT II M NO Y GROUP A
0439-20
017 000
GAIN
THETA
0.10
1.00
10.00
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
-110.0
-60.00
-80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES

Figure 117.

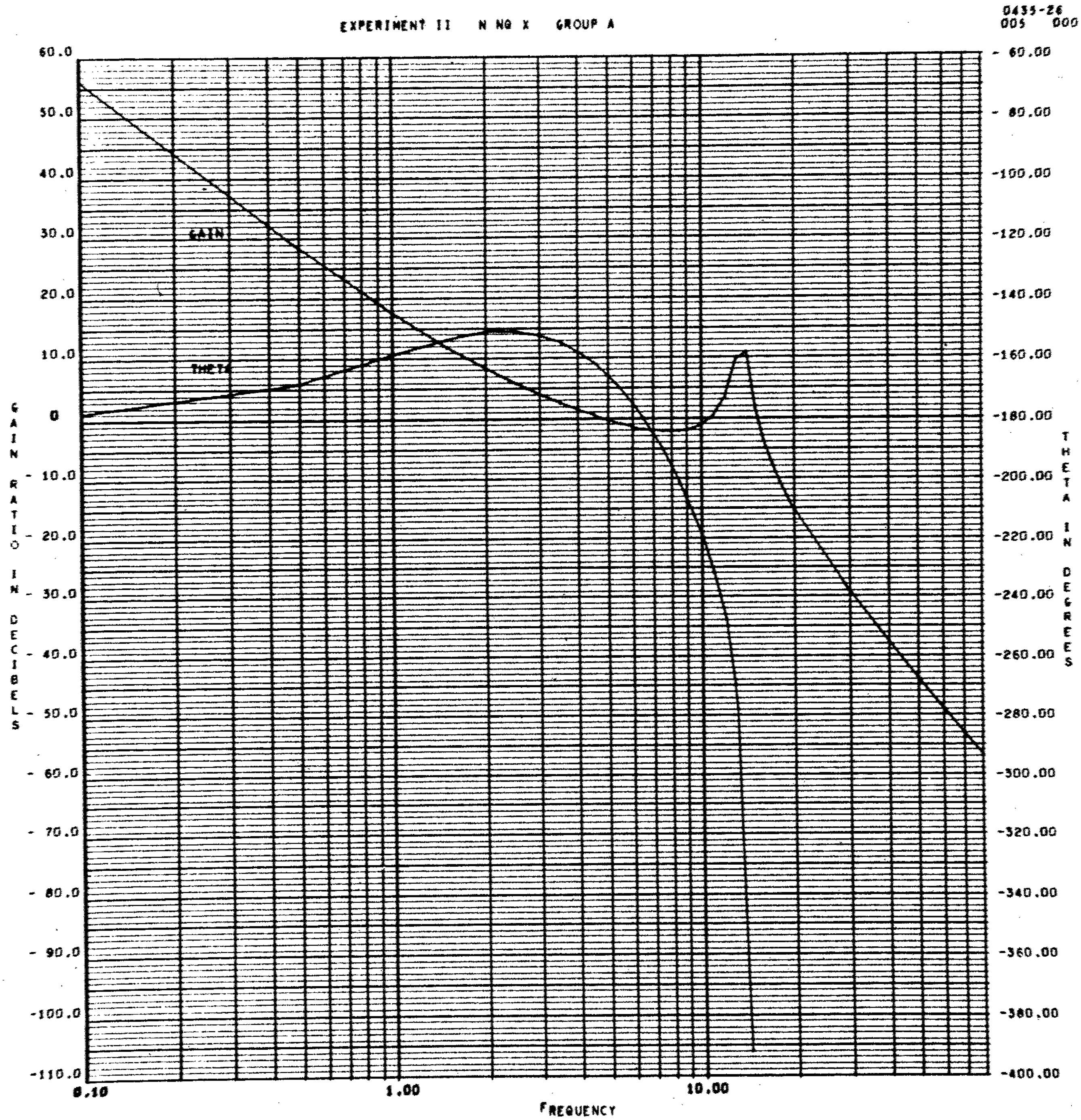

EXPERIMENT II N NQ X GROUP A
0435-26
005 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 118.

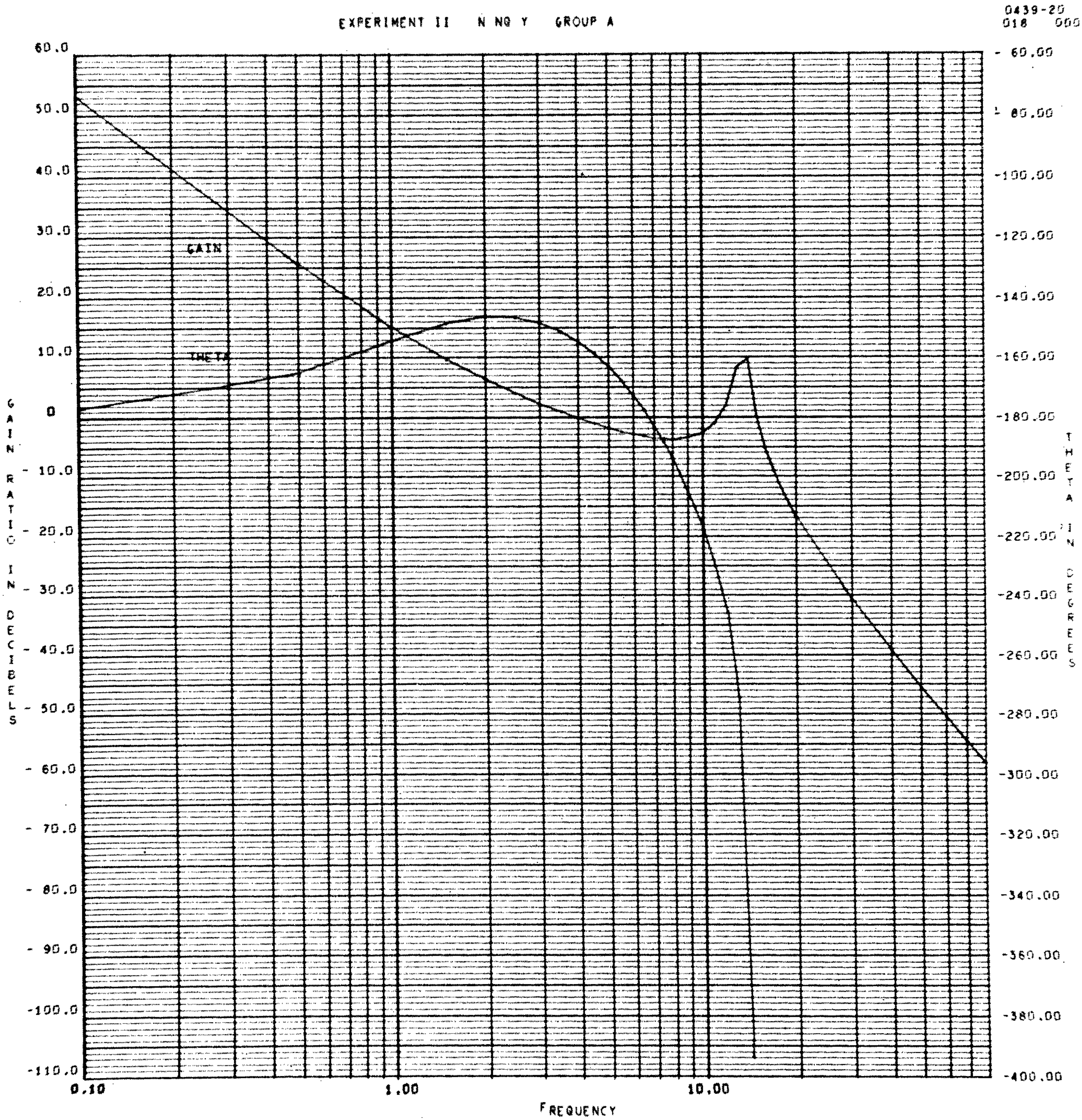

EXPERIMENT II N NQ Y GROUP A
0439-20
018 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 119.

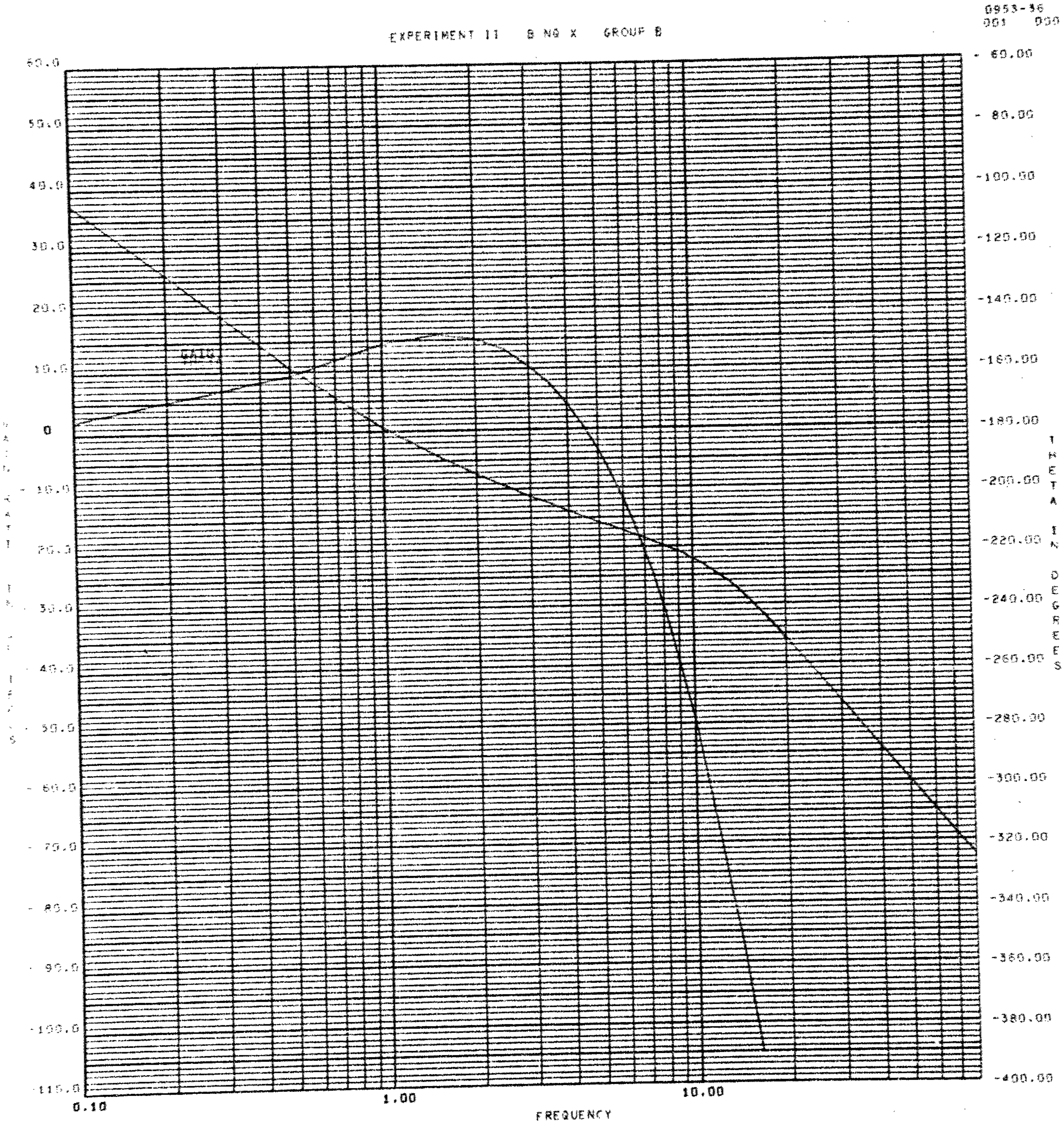
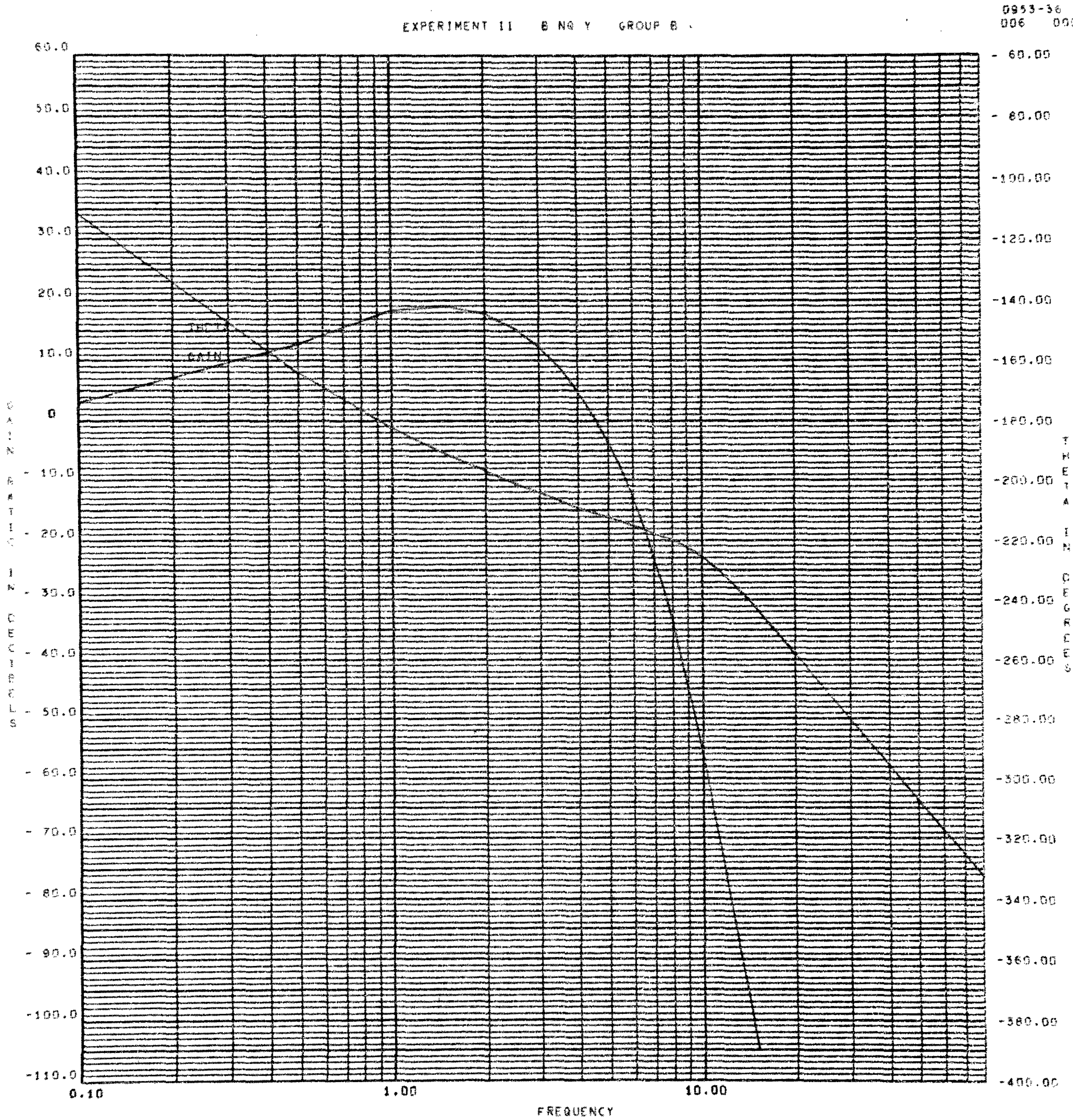

0953-36
001 000
EXPERIMENT II B NO X GROUP B
GAIN
FREQUENCY
THETA IN DEGREES

Figure 120.



0953-36
006 000
EXPERIMENT II B NQ Y GROUP B
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
GAIN
0.10
1.00
10.00
FREQUENCY

Figure 121.

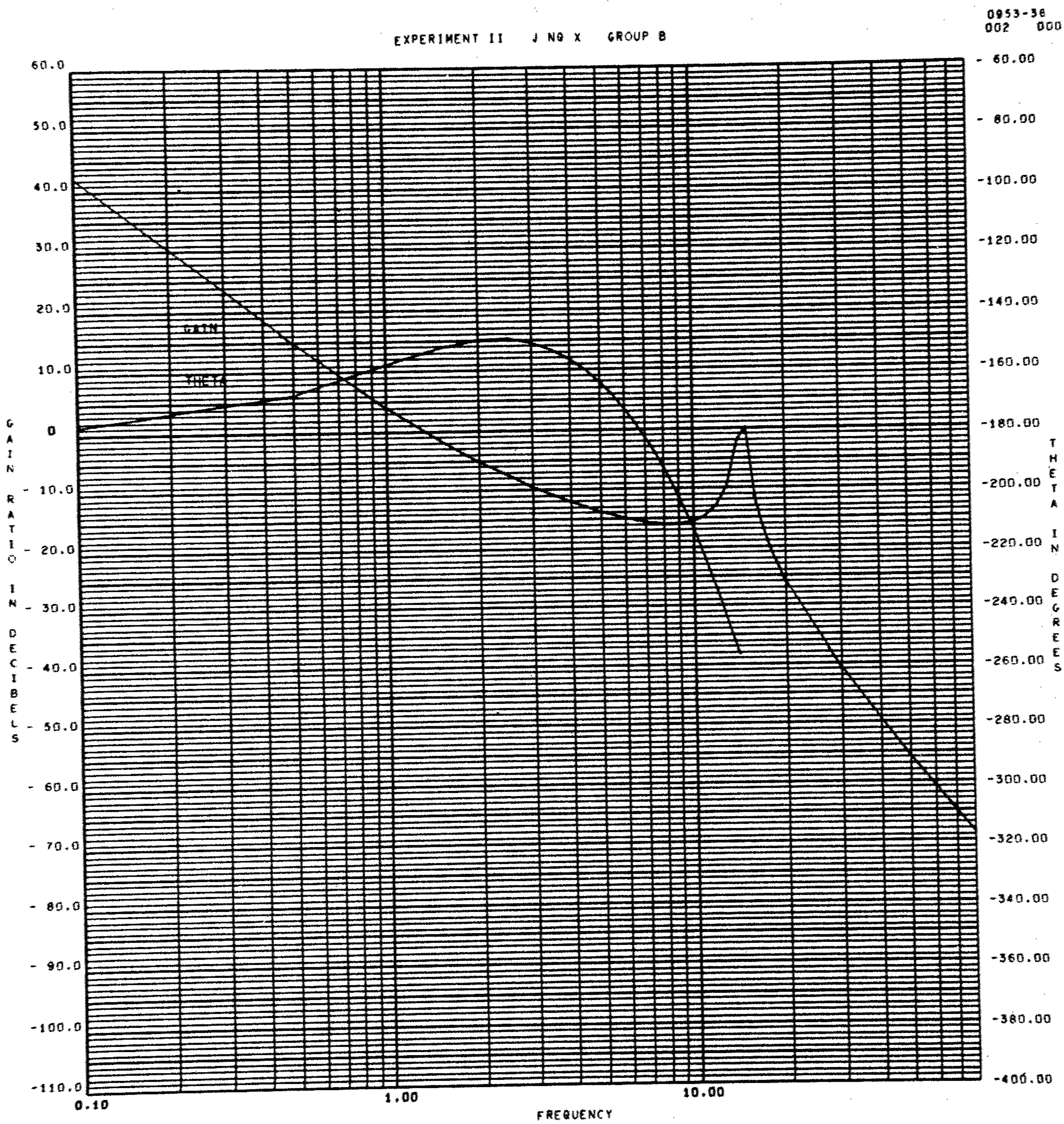
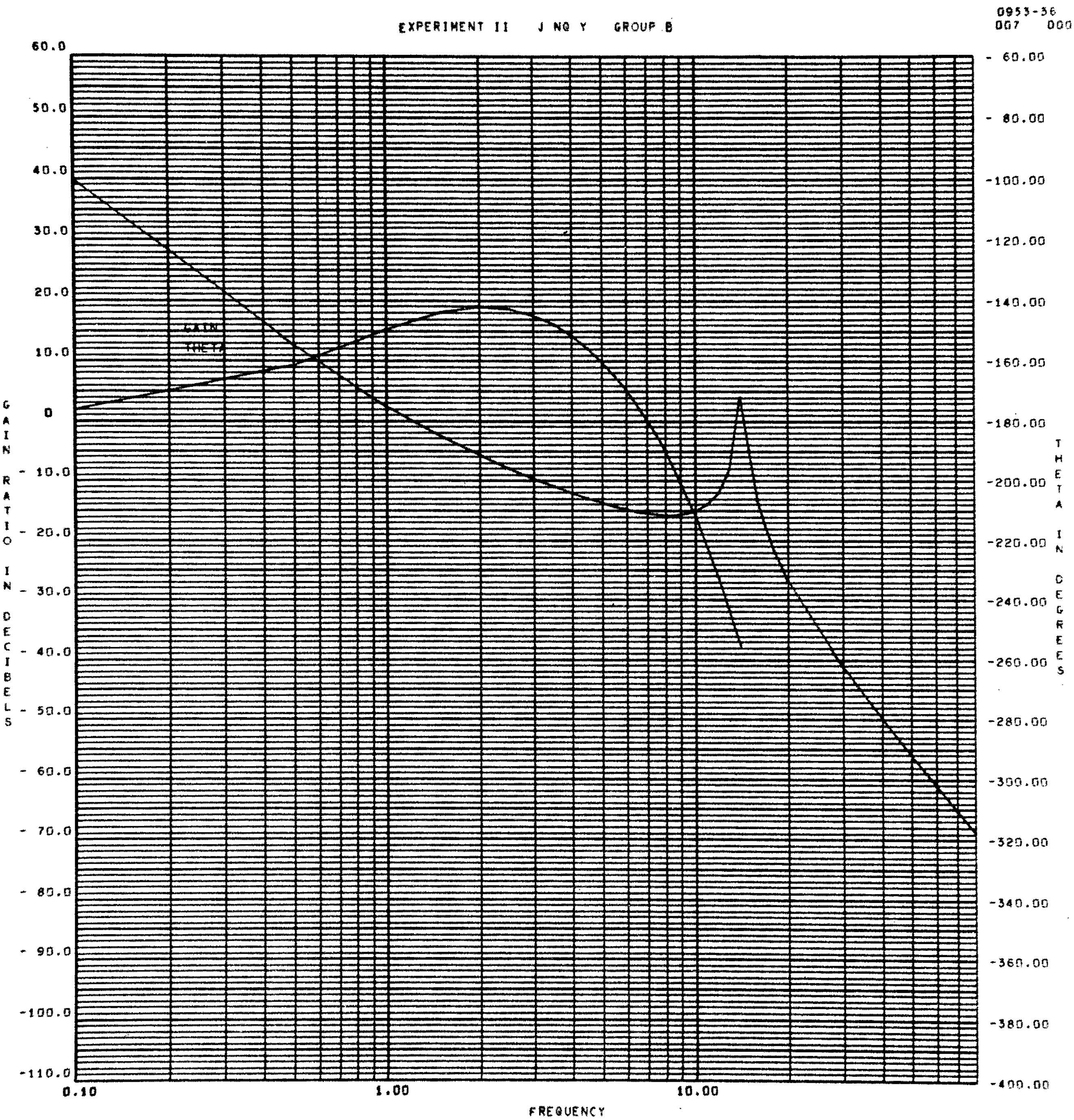
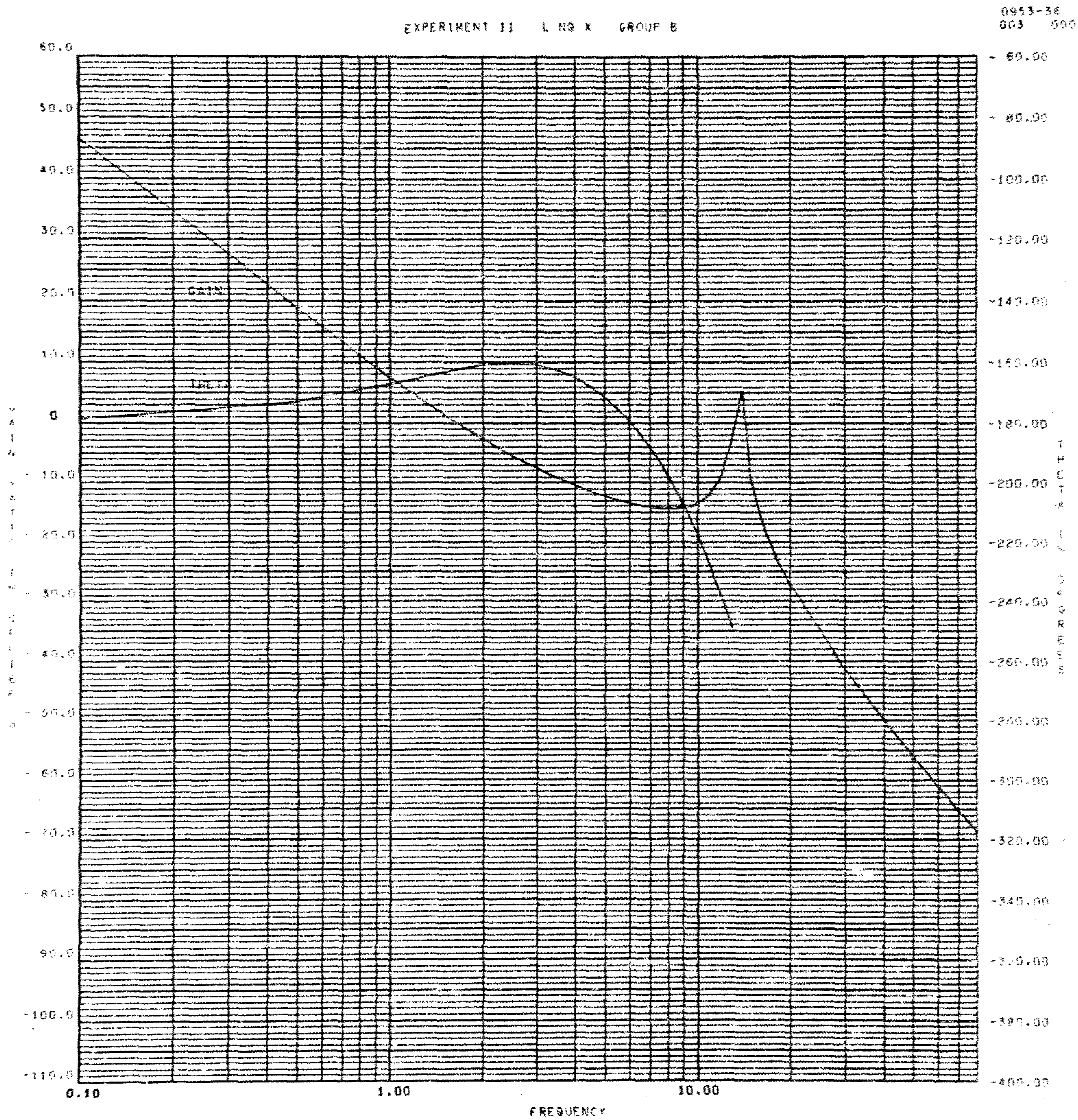

0953-36
002 000
EXPERIMENT II J NO X GROUP B
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
GAIN
THETA
0.10
1.00
10.00
FREQUENCY

Figure 122.



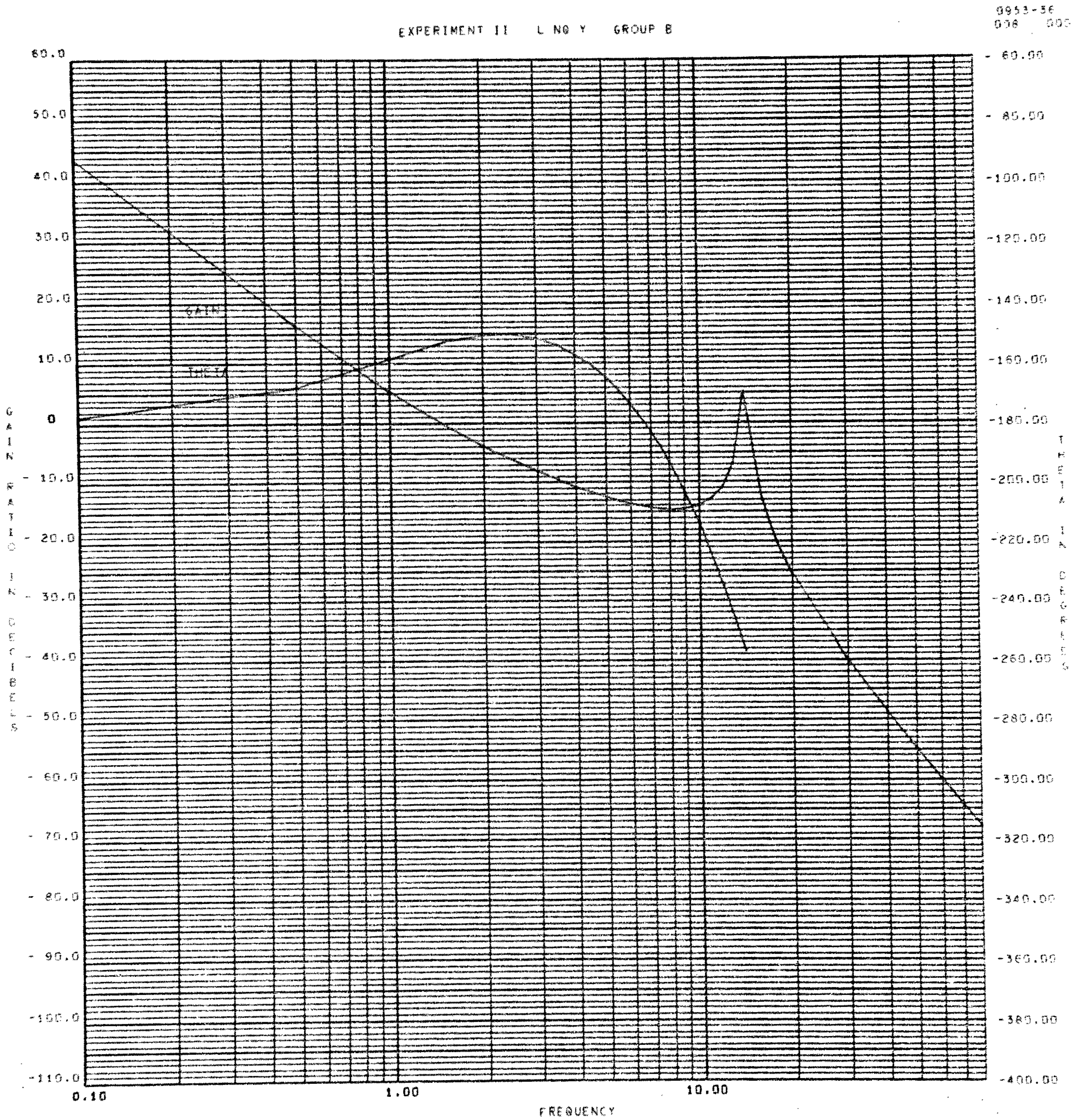
EXPERIMENT II J NQ Y GROUP B
0953-36
007 000
GAIN
THETA
GAIN RATIO IN DECIBELS
THETA IN DEGREES
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00
FREQUENCY

Figure 123.



EXPERIMENT II L NO X GROUP B
0953-36
003 000
GAIN
THETA
FREQUENCY
0.10
1.00
10.00

Figure 124.



0953-56
008 005
EXPERIMENT II L NO Y GROUP B
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
GAIN
THETA
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 125.

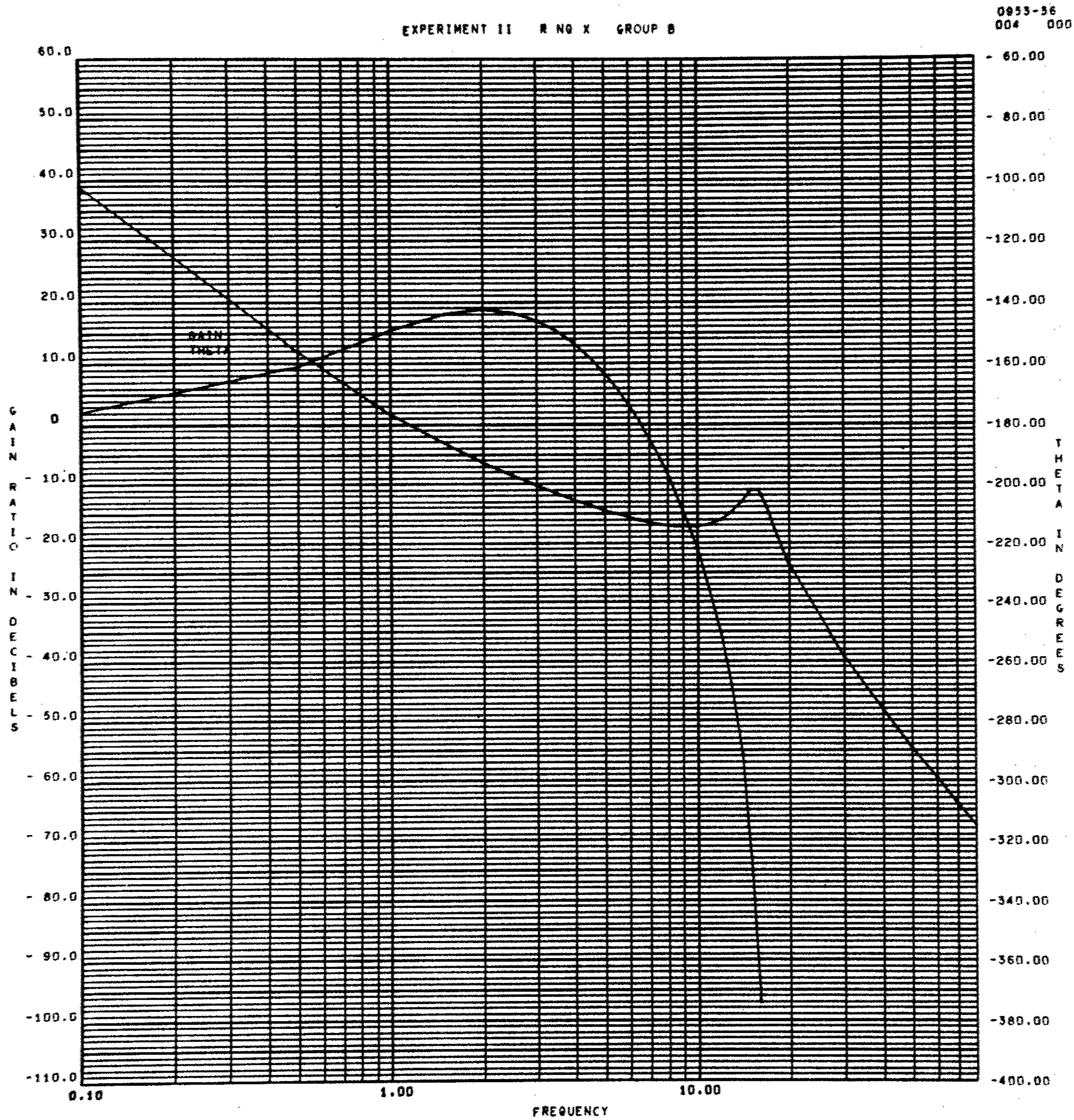
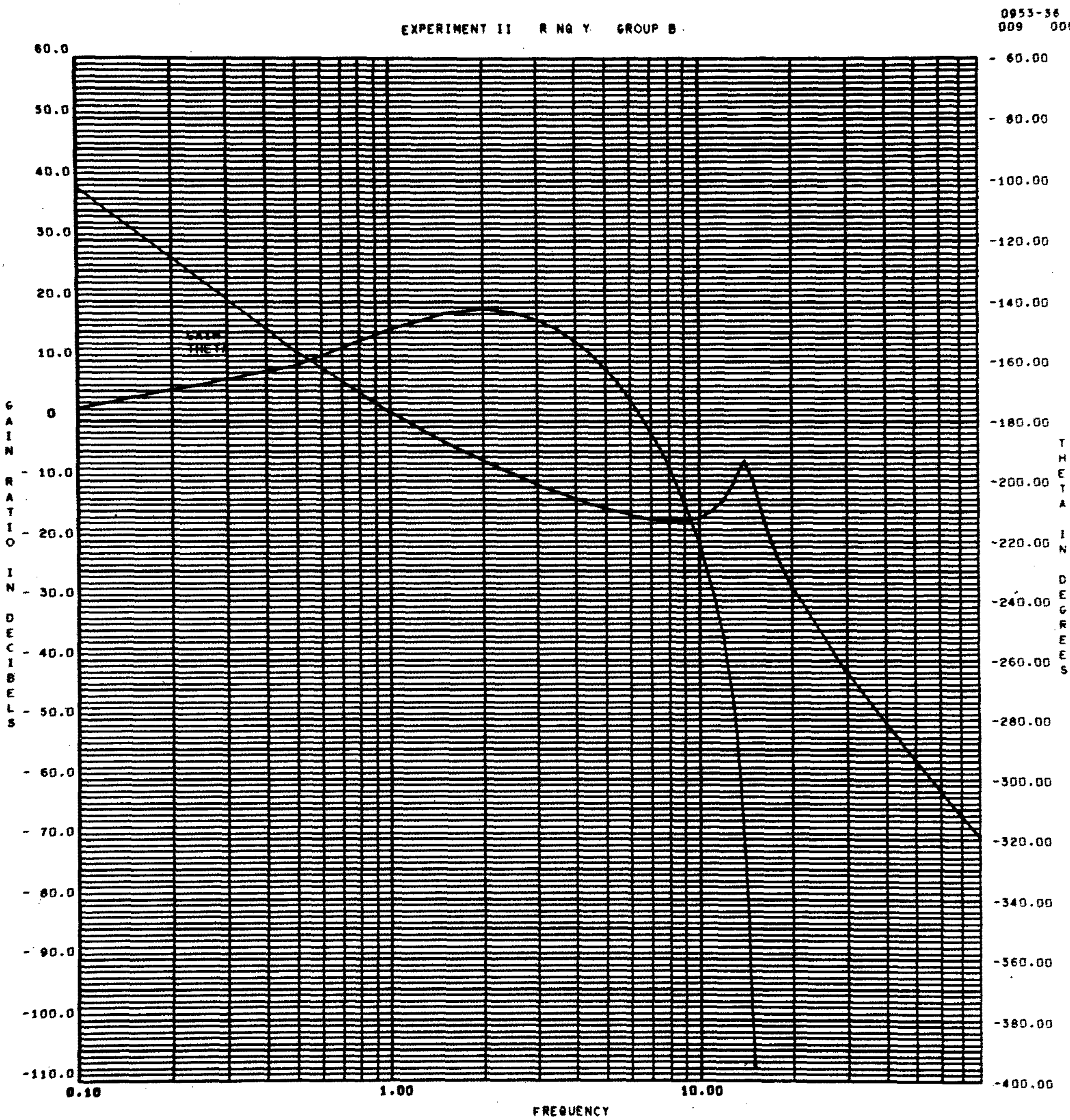
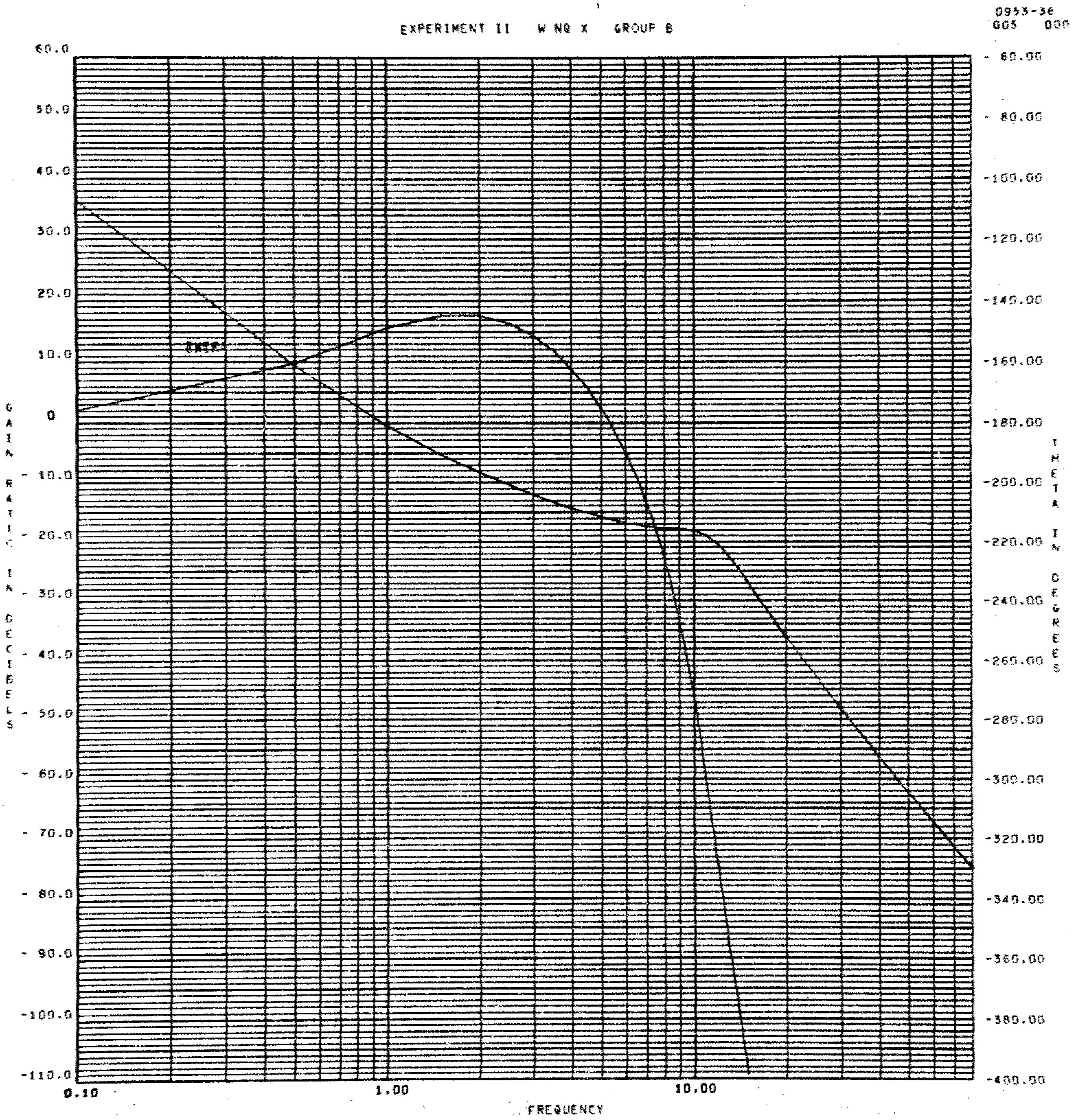

0953-56
004 000
EXPERIMENT II R NO X GROUP B
GAIN
THETA
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 126.



EXPERIMENT II R NQ Y GROUP B
0953-36
009 000
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 127.



0953-36
005 000
EXPERIMENT II W NO X GROUP B
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
GAIN RATIO IN DECIBELS
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
THETA IN DEGREES
0.10
1.00
10.00
FREQUENCY

Figure 128.

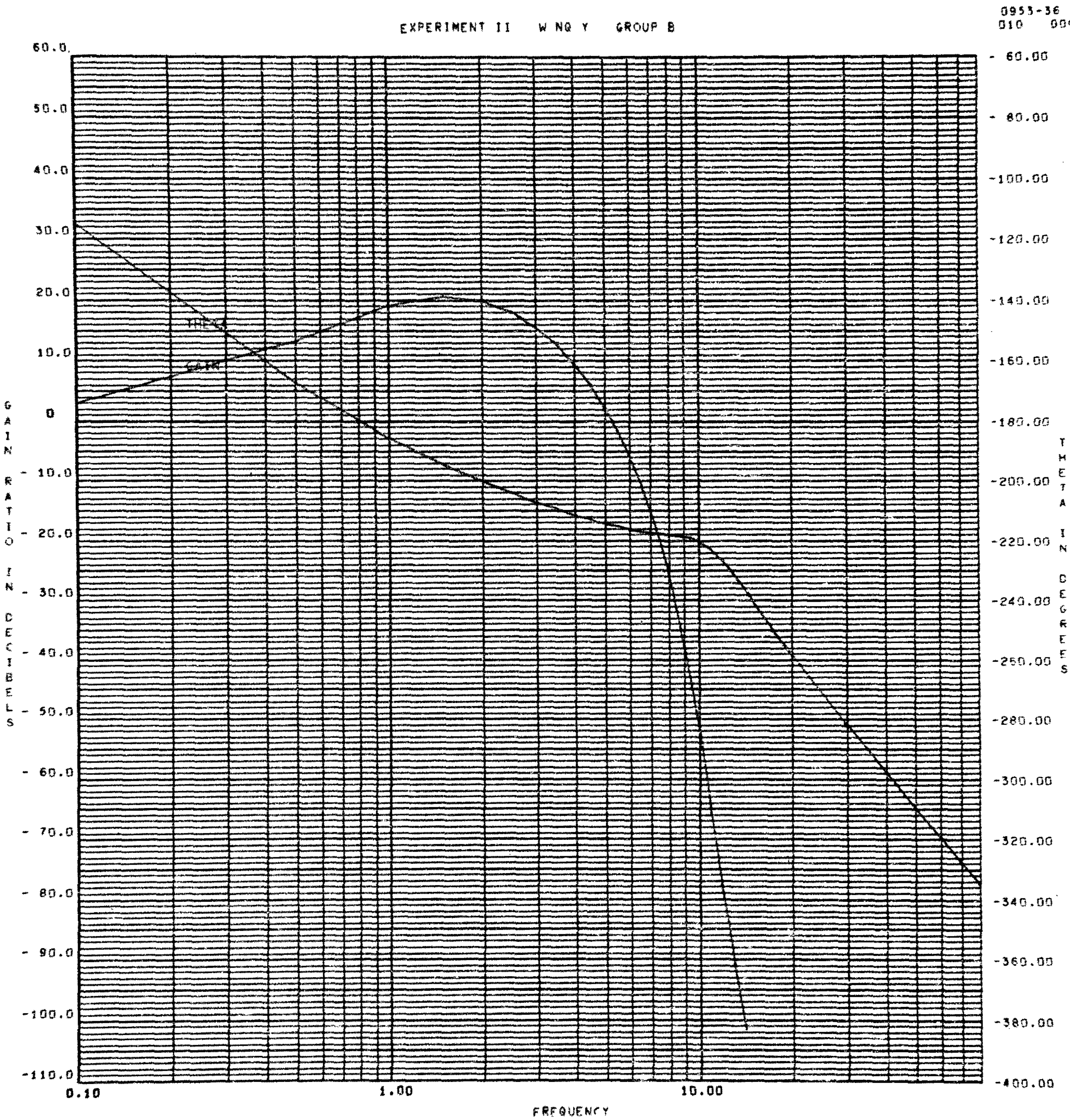

EXPERIMENT II W NQ Y GROUP B
0953-36
010 000
GAIN RATIO IN DECIBELS
THETA IN DEGREES
FREQUENCY
THETA
GAIN
60.0
50.0
40.0
30.0
20.0
10.0
0
- 10.0
- 20.0
- 30.0
- 40.0
- 50.0
- 60.0
- 70.0
- 80.0
- 90.0
-100.0
-110.0
- 60.00
- 80.00
-100.00
-120.00
-140.00
-160.00
-180.00
-200.00
-220.00
-240.00
-260.00
-280.00
-300.00
-320.00
-340.00
-360.00
-380.00
-400.00
0.10
1.00
10.00

Figure 129.

APPENDIX VII

TF PARAMETERS AS A FUNCTION OF
FORCING FUNCTION BANDWIDTH

APPENDIX VII

TF PARAMETERS AS A FUNCTION OF FORCING FUNCTION BANDWIDTH

The data of experiment I do not permit the determination of adjustment rules describing the relation of TF parameters to the bandwidth of the forcing function similar to those reported in reference 1. However, data from another study (ref 25) does permit such an investigation. Specifically, the reference study required that the man perform compensation tracking using apparatus identical to that of the present study with the exception of the forcing function. A set of 12 forcing functions ranging in bandwidth from 1.27 to 14.23 radians per second was used. Each signal was a composite of five sinusoids.

Signals 1-4 consisted of the summation:

$$\frac{8}{5}\left(\cos \omega_1 t - \cos \omega_2 t + \cos \omega_3 t - \cos \omega_4 t + \sin \omega_5 t\right) \tag{24}$$

while signals 5-12 were generated from:

$$\frac{8}{5}\left(\sin \omega_1 t + \sin \omega_2 t + \sin \omega_3 t + \sin \omega_4 t + \sin \omega_5 t\right) \tag{25}$$

The individual ω_i for each signal summation is listed in table XXIX.

Curves for the transfer function coefficients as a function of the highest frequency in each group are plotted in figures 130 through 133. An examination of these curves shows that the gain for the full quickening case behaves exponentially. That is, the gain as a function of frequency can be satisfied by the general expression

$$K = C_1 \epsilon^{-a_1\omega} + C_2 \epsilon^{-a_2\omega} \tag{26}$$

The gain for the partial quickening and no quickening cases suggests the same sort of phenomenon except that a sinusoidal component appears. This can be characterized by the general expression

$$K = C_1 \epsilon^{-a_1\omega} \sin b\omega \tag{27}$$

Both of these equations are solutions of the general second order linear differential equation

$$\frac{d^2K}{d\omega^2} + \beta_1 \frac{dK}{d\omega} + \beta_2 K = c \qquad (28)$$

A fit of this equation to the data was performed with the aid of an EAI analog computer and the results are shown in figures 134 through 136.

Table XXIX

FORCING FUNCTION FREQUENCIES

Signals	ω_1	ω_2	ω_3	ω_4	ω_5
1	1.27	.87	.59	.41	.19
2	2.51	1.49	.83	.43	.23
3	3.59	1.99	1.13	.53	.29
4	4.87	2.63	1.37	.67	.31
5	5.93	3.31	1.67	.79	.31
6	7.19	3.97	1.91	.89	.37
7	8.29	4.49	2.11	.97	.37
8	9.47	5.03	2.41	1.07	.37
9	10.69	5.63	2.71	1.13	.41
10	11.81	6.19	2.93	1.27	.43
11	13.07	6.91	3.17	1.37	.43
12	14.23	7.51	3.49	1.49	.47

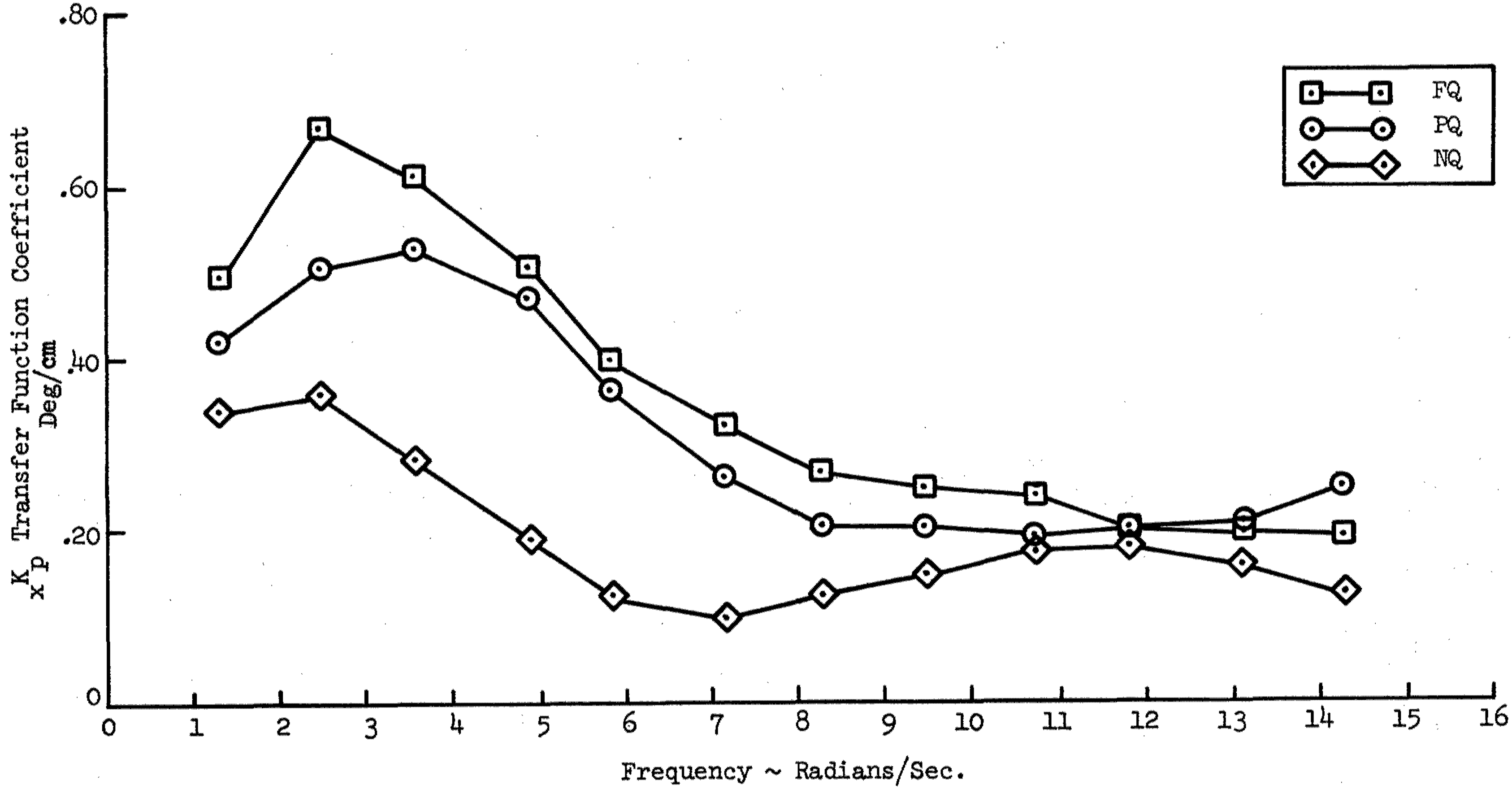


Figure 130. ${}_xK_p$ plotted as a function of frequency

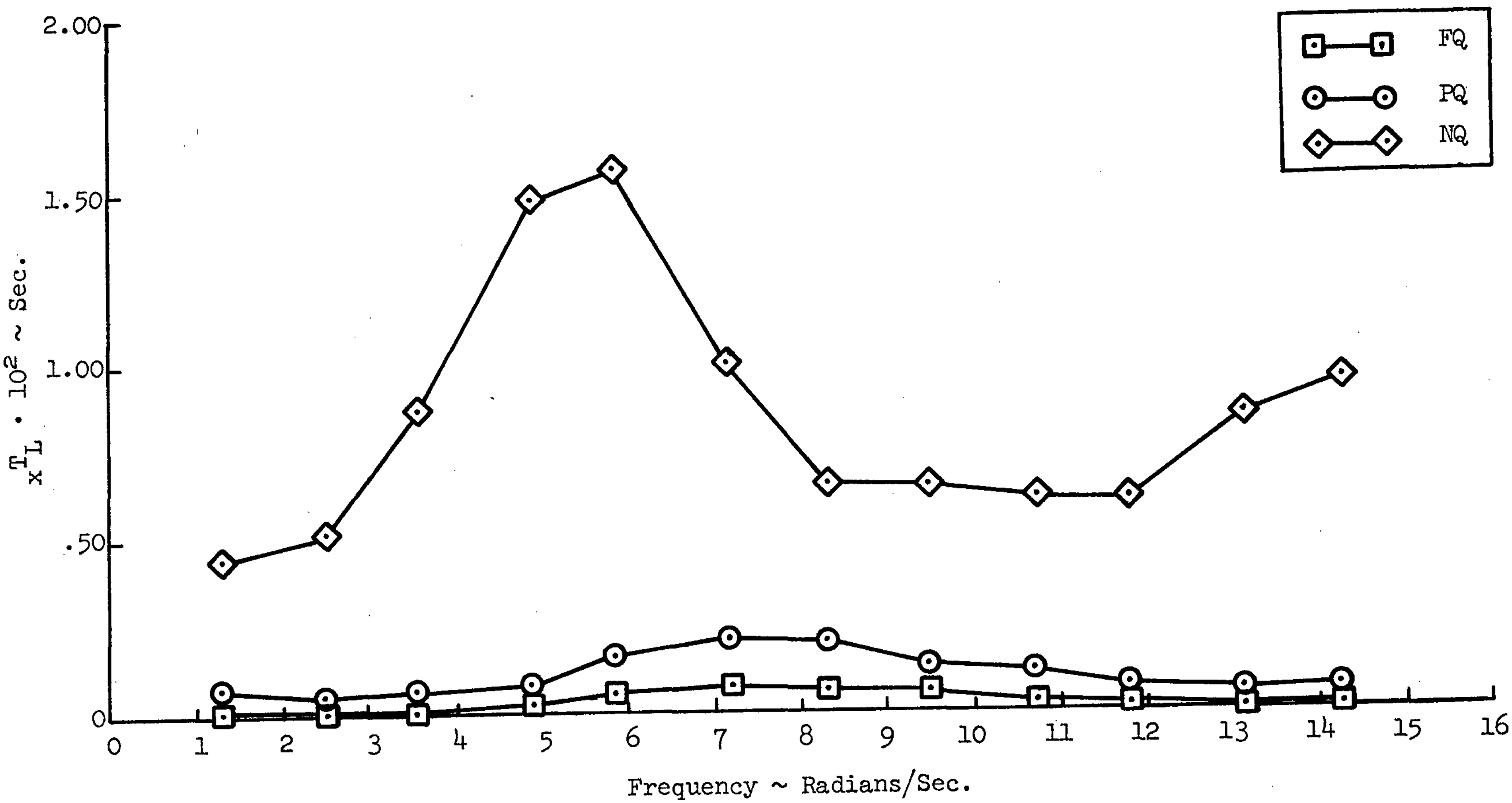


Figure 131. $_xT_L$ plotted as a function of frequency

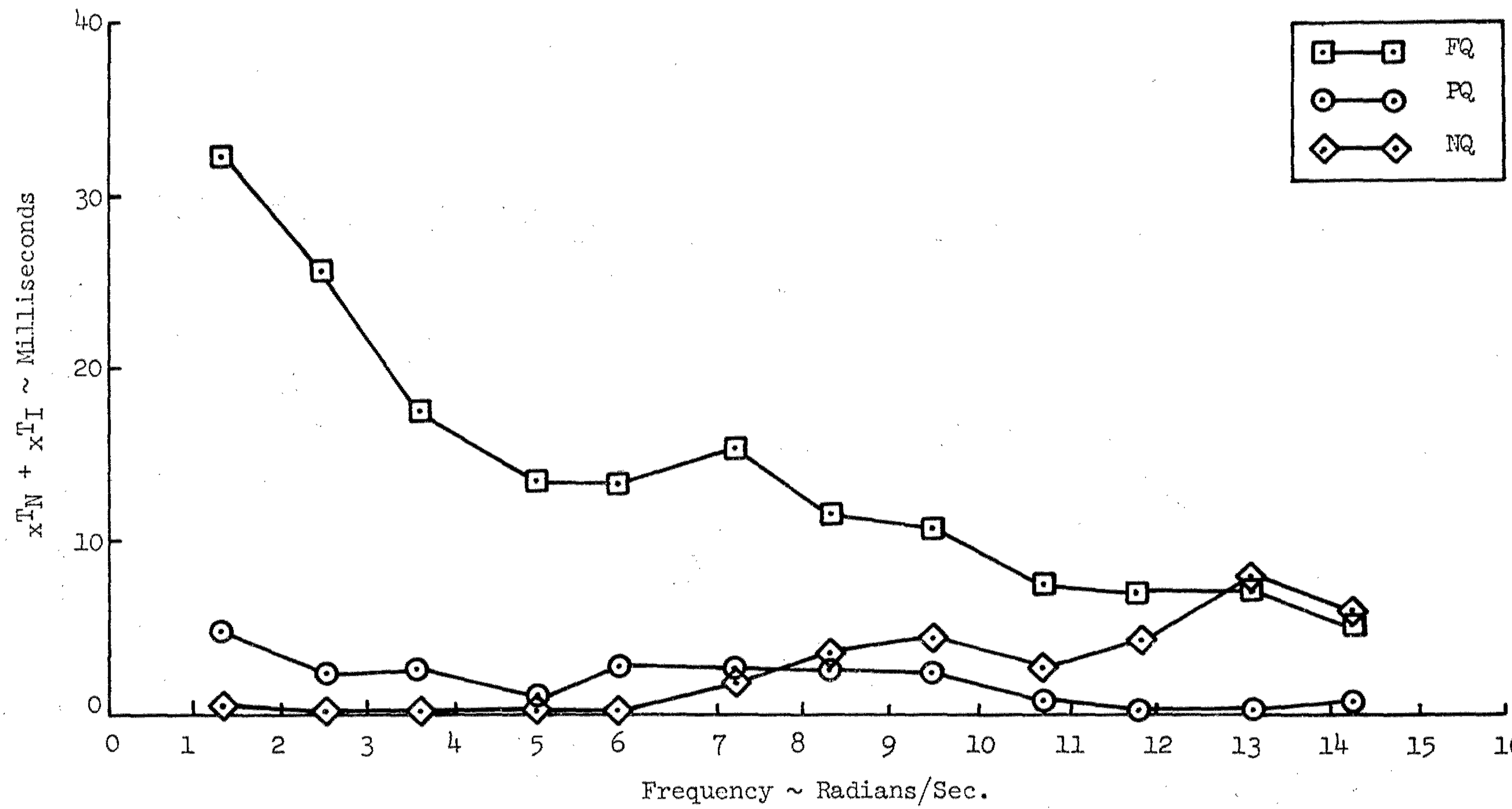


Figure 132. $_xT_N + {_xT_I}$ plotted as a function of frequency

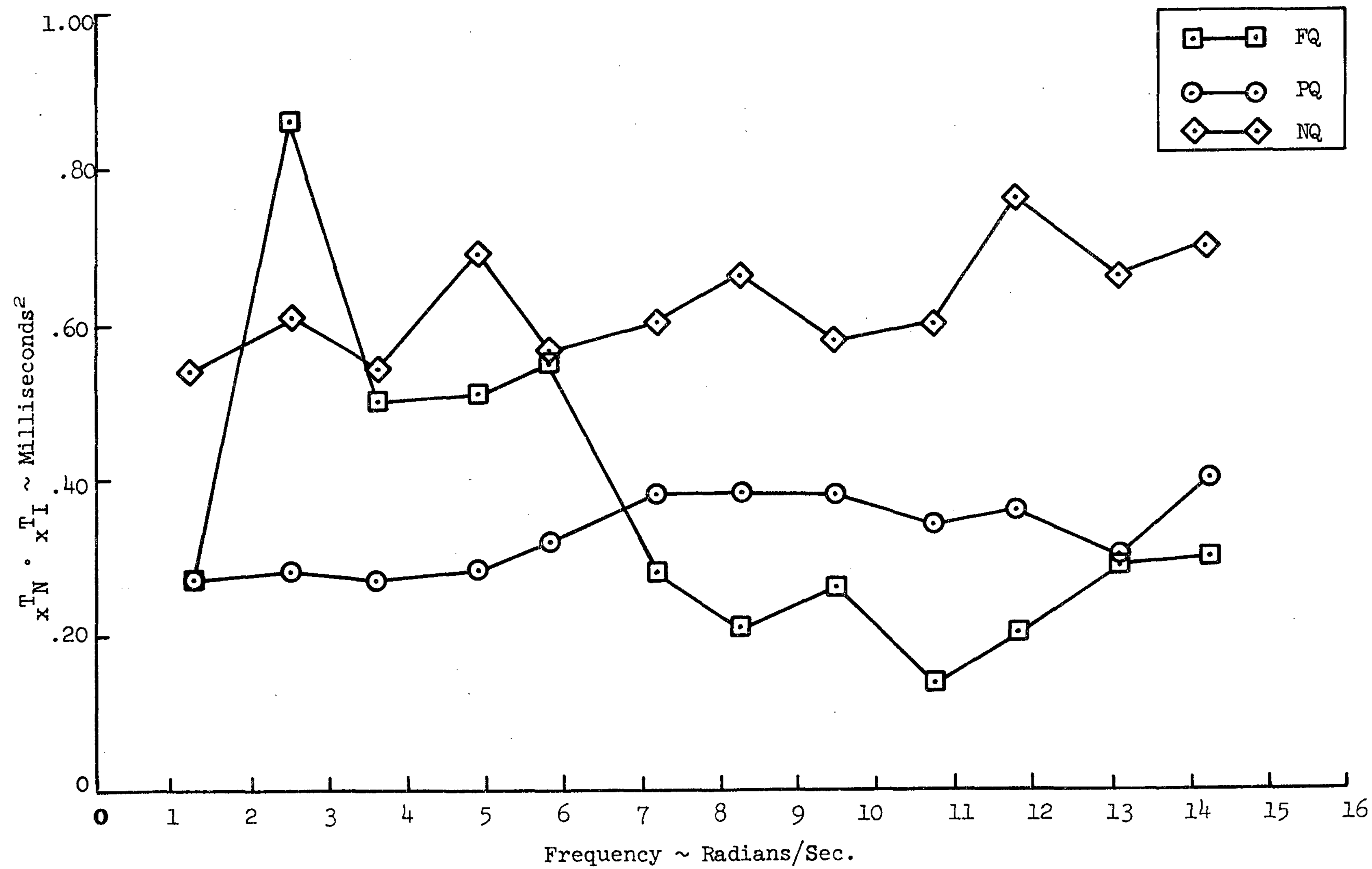


Figure 133. $x^T{}_N \cdot x^T{}_I$ Plotted as a Function of Frequency

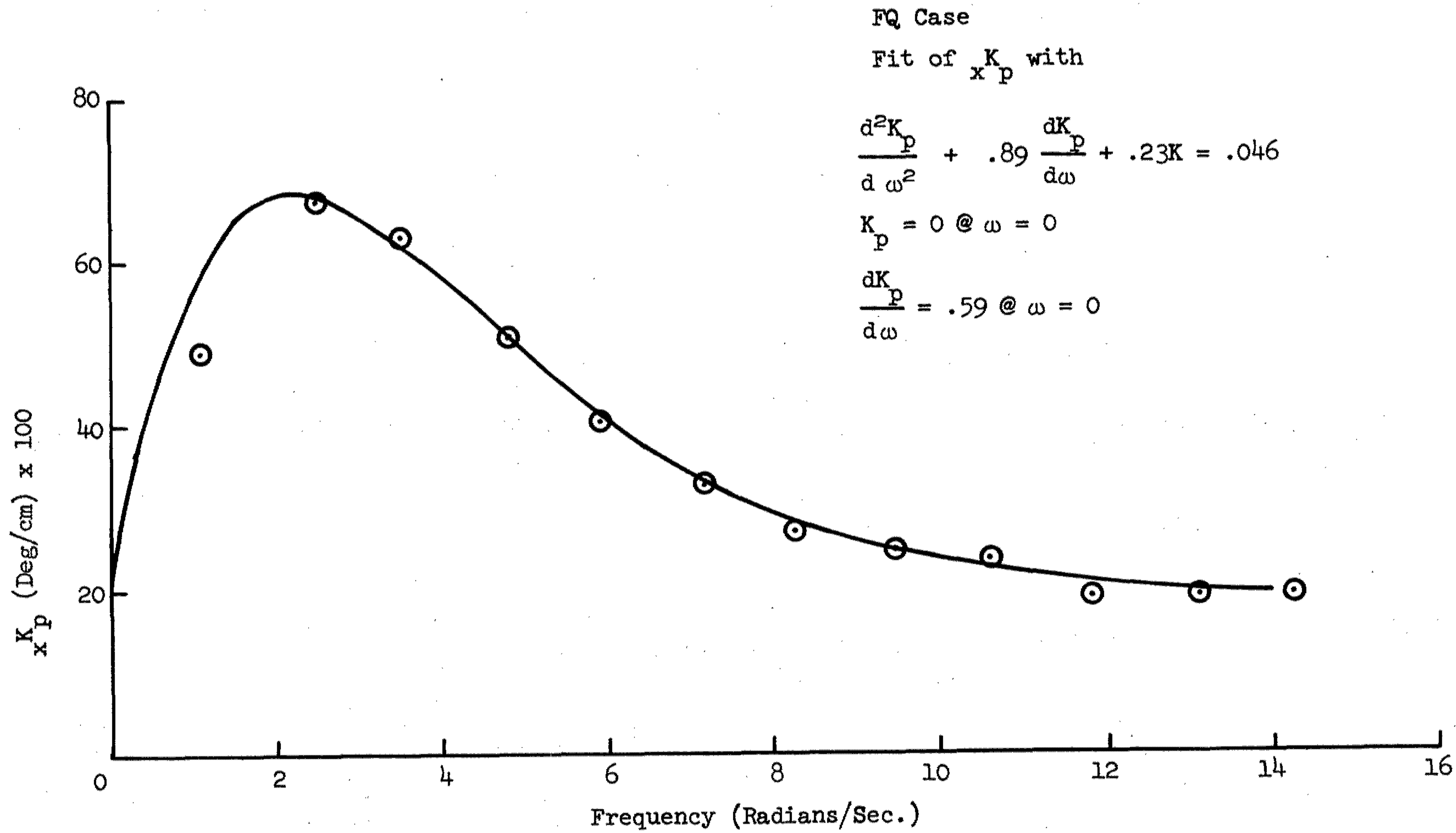


Figure 134. Second Order Linear Differential Equation Fit For $_xK_p$ Under FQ Condition

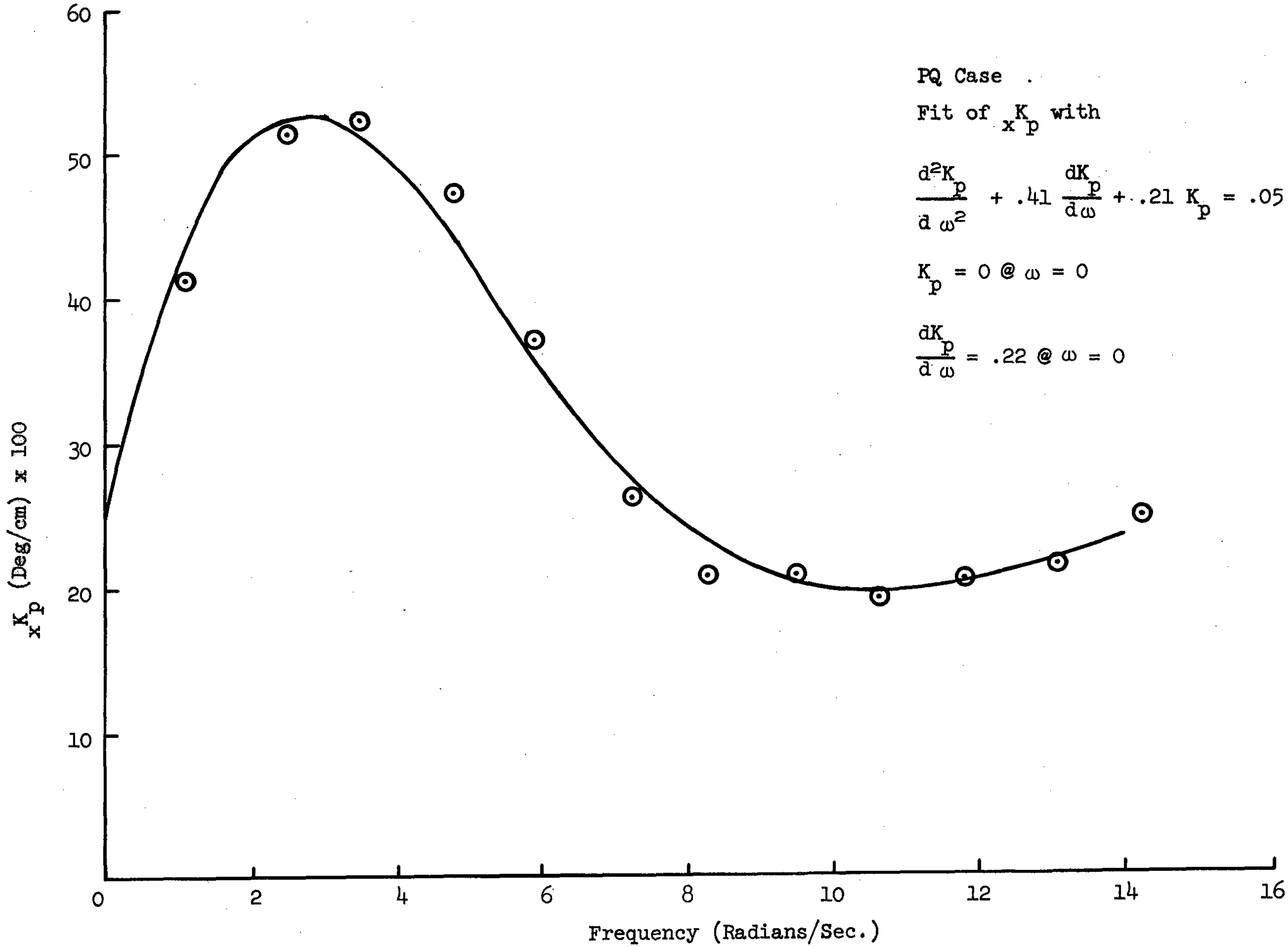


Figure 135. Second Order Linear Differential Equation Fit For $_xK_p$ Under PQ Condition

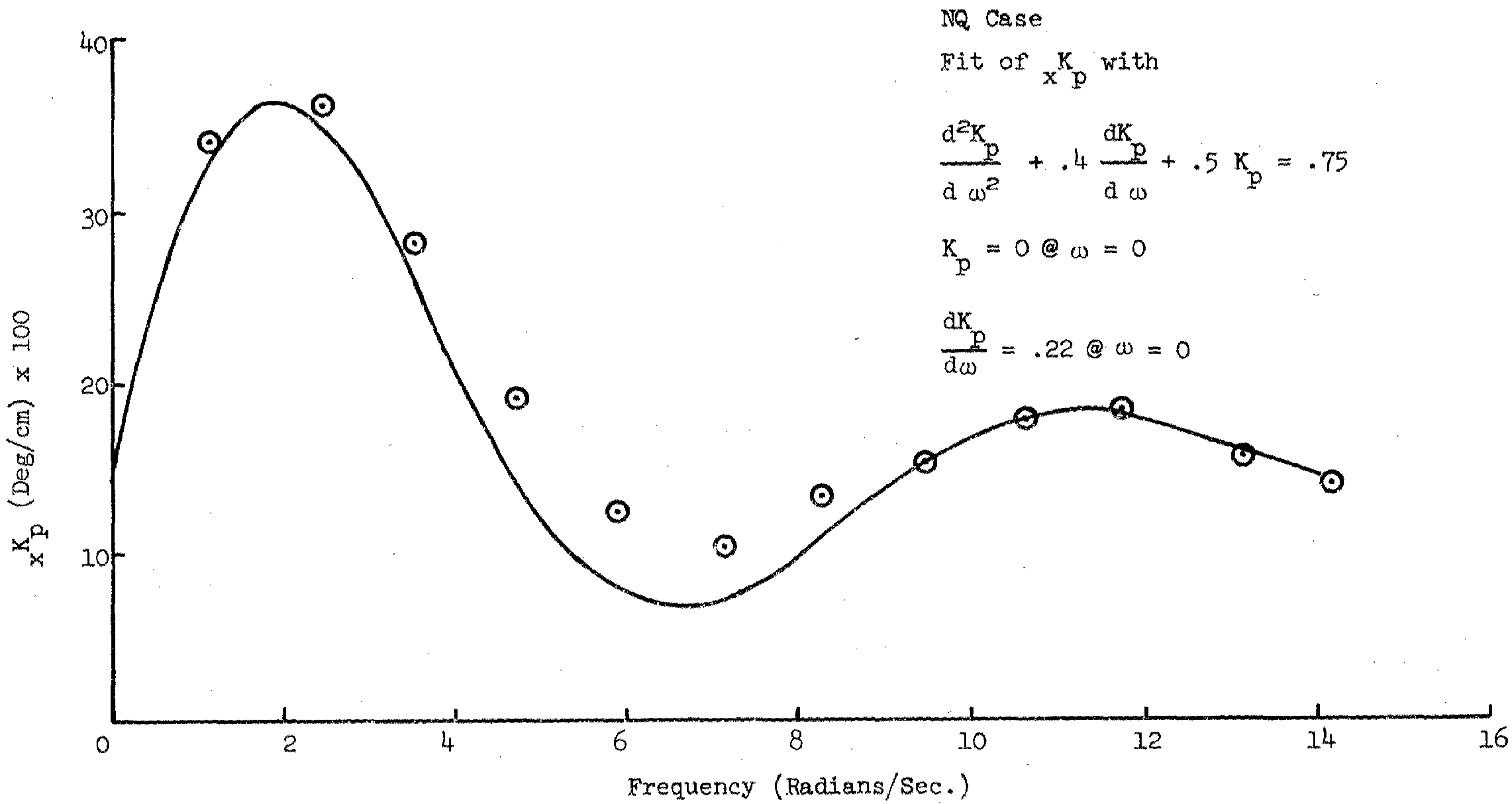


Figure 136. Second Order Linear Differential Equation Fit For $_xK_p$ Under NQ Condition

REFERENCES

1. Ashkenas, I. L. and McRuer, D. T., The Determination of Lateral Handling Quality Requirements from Airframe Human Pilot System Studies. WADC-TR-56-135 (AD-212-152), Wright-Patterson Air Force Base, Wright Air Development Center, June 1959.

2. Birmingham, H. P. and Taylor, F. V., A Human Engineering Approach to the Design of Man Operated Continuous Control Systems, NRL Report 4333 (AD 30879), Naval Research Laboratory, Washington, D. C., April 1954.

3. Chernikoff, R., Duey, J. W., and Taylor, F. V., Two-Dimensional Tracking with Identical and Different Control Dynamics in each Coordinate, NRL Report 5424, (AD 230 879), Naval Research Laboratory, Washington, D. C., November 1959.

4. Duey, J. W. and Chernikoff, R., The Use of Quickening in One Coordinate of a Two-Dimensional Tracking System, NRL Report 5428, (AD 230956) Naval Research Laboratory, Washington, D. C., November 1959.

5. Elkind, J. I., Further Studies of Multiple Regression Analysis of Human Pilot Dynamic Response: A Comparison of Analysis Techniques and Evaluation of Time-Varying Measurements. ASD-TDR-63-618 (AD 435686) Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, March 1964.

6. Fitts, P. M., Bahrick, H. P., Noble, M. E., and Briggs, G. E., Skilled Performance, Ohio State University Research Foundation Project 686, Parts I and II, 1959.

7. Flying Qualities of Piloted Aircraft, Military Specification No. MIL-F-8785.

8. Garvey, W. D. and Mitnick, L. I., An Analysis of Tracking Behavior in Terms of Lead-Lag Errors, NRL Report 4707, (AD 88106). Naval Research Laboratory, Washington, D. C., February 1956.

9. Helson, H. "Design of Equipment and Optimal Human Operation," Amer. J. Psychol., 1949, 62, 473-497.

10. Holland, J. G. and Henson, J. B., "Transfer of Training Between Quickened and Unquickened Tracking Systems," J. Appl. Psychol., 1956, 40, 362-366.

11. Hudson, E. M., "An Adaptive Tracking Simulator," IRE International Congress on Human Factors in Electronics, May 1962.

12. Jackson, A. S., "Synthesis of a Linear Quasi-Transfer Function for the Operator in Man-Machine Systems," IRE Wescon Convention Record, 1958, Part 4, 263-271.

13. Jex, H. R. and Cromwell, III C. H., Theoretical and Experimental Investigation of Some New Longitudinal Handling Qualities Parameters. ASD-TR-61-26 (AD 282879), Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, June 1962.

14. McCormick, E. J., Human Engineering, McGraw-Hill, New York, 1957.

15. McRuer, D. T., Ashkenas, I. L., Guerre, C. L., A Systems Analysis View of Longitudinal Flying Qualities WADD-TR-60-43, (AD 249386), Wright-Patterson Air Development Division, Wright-Patterson Air Force Base, Ohio, January 1960.

16. McRuer, D. T. and Krendal, E. S., Dynamic Responses of Human Operators, WADC-TR-56-524 (AD 110693), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, October 1957.

17. McRuer, D. T. and Krendal, E. S., "The Human Operator as a Servo System Element, Part II," JNL of the Franklin Institute, 1959, 267, 511-536.

18. Ornstein, G. N., Applications of a Technique for the Automatic Analogue Determination of Human Response Equation Parameters. Doctoral Dissertation, The Ohio State University, December 1960. Also, North American Aviation, Inc., Report NA61H-1, January 1960.

19. Ragazzini, J. R., Engineering Aspects of the Human Beings as a Servo Mechanism. Paper read at American Psychol. Association Meeting, Boston, September, 1948.

20. Rund, P. A., Birmingham, H. P., Tipton, C. L. and Garvey, W. D., The Utility of Quickening Techniques in Improving Tracking Performance with a Binary Display, NRL Report 5013 (AD 144895) Naval Research Laboratory, Washington, D. C., September 1957.

21. Searle, L. V., Psychological Studies of Tracking Behavior Part IV - The Intermittency Hypothesis as a Basis for Predicting Optimum Coded-Tracking Time Constants. NRL-TR-3872-1951 (AD 134251), Naval Research Laboratory, Washington, D. C.

22. Sakoda, J. M., Cohen, B. H. and Beall, G., "Test of Significance for a Series of Statistical Tests" Psychol. Bull. 1954, 51, 172-175.

23. Sweeney, J. S., Bailey, A. W., and Dowd, J. A., Comparative Evaluation of Three Approaches to Helicoptor Instrumentation for Hovering Flight, NRL Report 4954, Naval Research Laboratory, Washington, D. C., June 1957.

24. Tustin, A., "The Nature of the Operator's Responses in Manual Control, and its Implications for Controller Design." J. Inst. Elec. Engrgs. London, 94, 190-207.

25. Verdi, A. P., Human Information Processing During a Compensatory Tracking Task, Doctoral Dissertation, The Ohio State University, December 1964. Also, North American Aviation, Inc., Report NA64H-1129, December 1964.

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) North American Aviation, Inc., & Aerospace Medical 4300 East Fifth Avenue Research Labs., Columbus, Ohio Wright-Patterson AFB, O.	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

EFFECTS OF DISPLAY QUICKENING ON HUMAN TRANSFER FUNCTIONS DURING A DUAL-AXIS COMPENSATORY TRACKING TASK

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report May 1963 - June 1964

5. AUTHOR(S) (Last name, first name, initial)

Verdi, Angelo P., Ornstein, George N., Heydorn, Richard P., Frost, George

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1965	207	25

8a. CONTRACT OR GRANT NO. AF 33(657)-11102 b. PROJECT NO. 7184 c. Task No. 718402 d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AMRL-TR-65-174

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Aerospace Medical Research Laboratories Aerospace Medical Division, Air Force Systems Command, Wright-Patterson AFB, Ohio

13. ABSTRACT This research was concerned with the human's behavior in adapting his response mode to variations of certain conditions of a compensatory tracking task. The task conditions evaluated were quickening level, system gain, task load, and task complexity. The results of the studies show good agreement with the transfer function "adjustment rules" developed by other investigators. When quickening is introduced, the human adjusts his transfer function in a systematic and predictable manner in response to variations of the quickening level. As the amount of quickening increases the operator increases gain and lag but decreases lead. The human adjusts his equalizing parameters to achieve stable loop performance for all quickening levels. Man's ability to reduce the system error is significantly affected by the distribution of gains in the overall man-machine system. The human's transfer function for single and dual task load conditions probably differs. Tracking error was found to be least when the quickening level used in the second axis is identical to that in the axis of primary interest; error increased as the quickening levels for the two axes became more dissimilar. Display error scoring yielded an order of merit for quickening levels that was directly contradictory to that obtained with system error scoring. System error was greater for a quickened system than for an unquickened system. This finding provides strong support of the need for an antibias network in many applications of display quickening to vehicle control problems.

DD FORM 1 JAN 64 1473

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Display system, effectiveness						
Tracking, psychological factors						
Tracking, errors						
Control systems, human engineering						
Pilots performance						
Motor reaction, analysis						
Airplane, control system						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.