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Electro-Mechanical Actuator

DC Resonant Link Controller

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Electro-Mechanical Actuator Final Report

Contract NAS3-25799

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40 HP Electro-Mechanical Actuator Test Report — August 1993
NASA Contract: NAS325799, GDSS

40 HP EMA Hardware Documentation — November 1993
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Current Regulator Study - Report #44135 — June 1994
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Electro-Mechanical Actuator Final Report

1. INTRODUCTION

1.1 Scope

This report summarizes the work performed on the 68 HP electro-mechanical actuator (EMA) system developed on NASA contract NAS3-25799. The 70 HP system consists of a motor controller system and a linear actuator capable of up to 32,000 lbs loading. The system is designed to demonstrate the capability of large, high power linear actuators for applications such as Thrust Vector Control (TVC) on rocket engines. The baseline design is the Advanced Launch System (ALS) L vehicle preliminary concept. This system utilizes a resonant power converter that operates at a nominal frequency of 55 kHz.

2. SYSTEM DESCRIPTION

The electromechanical actuator system, shown in figure 1, consists of an input power source, a motor controller, a high efficiency induction motor, and an linear actuator. The EMA system is capable of forces up to 32,000 lb. at velocities up to 7.4 in/sec. The three phase induction motor is capable of up to 68 HP peak to accelerate the motor rotor and associated actuator and load inertias. The peak actuator output is 32.8 HP to the load.

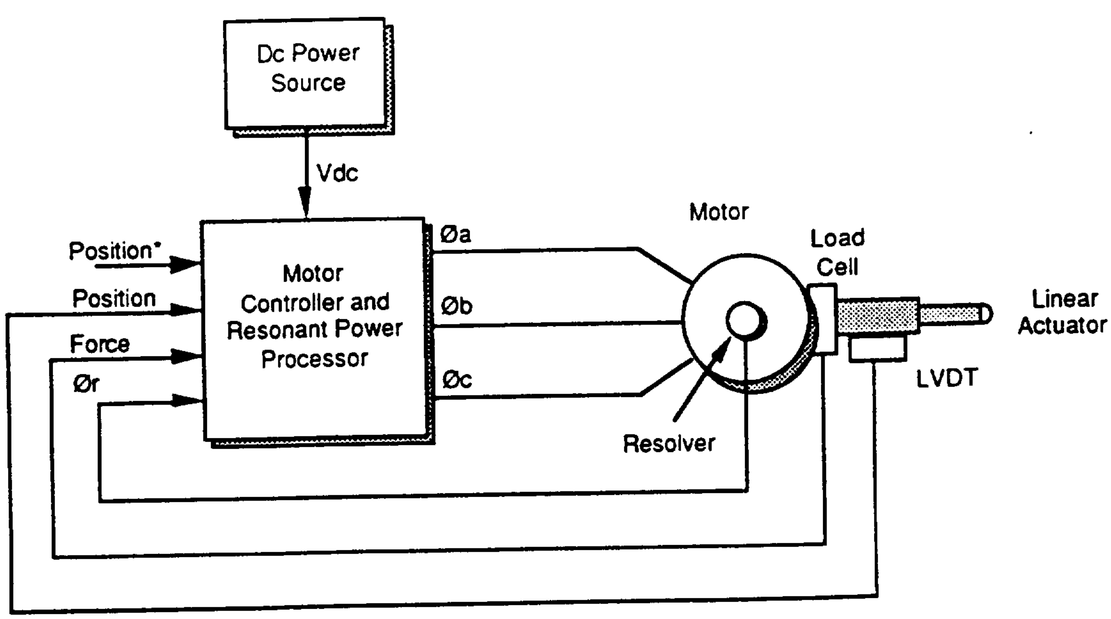


Figure 1. Electromechanical actuator

2.1 Actuator

The actuator was originally designed by Moog Aerospace under a Moog internal R&D program to meet the Space Shuttle Main Engine Thrust Vector Control (TVC) requirements. The actuator converts the rotary motion of the induction motor to linear motion and is capable of up to 48,000 lbs. of stall loading. Impulse loads of up to 100,000 lbs will not damage the unit. The design was modified to increase the maximum linear rate as required by the ALS system from 5.2 in/sec to 7.4 in/sec and likewise the maximum force required is reduced from 48,000 lbs. to 32,000 lbs. The 14,700 rpm top speed of the motor translates to the maximum 7.4 inches per second of linear motion. The range of motion is ±5.5 inches with a rated acceleration of 60 in/sec/sec. An LVDT (Linear Variable Displacement Transducer) is used to measure the linear motion of the actuator. The LVDT is mounted in the housing of the actuator and is connected to the motor controller by a dual twisted pair cable. The LVDT accepts a sinusoidal reference signal and returns a sinusoidal drive signal that varies in phase and amplitude, dependent on the linear position of the actuator. These signals are processed by the motor controller electronics. A load cell is also installed that will measure actuator compressive and tensile force.

2.2 Motor

The motor is a Sundstrand designed, AC induction motor capable of 68 peak HP. It was designed to provide a high power to weight ratio and attains about 3.5 peak HP per pound with a weight of 19.6 lbs. The motor is a six pole, 3 phase design with a maximum synchronous speed of 15,000 rpm. Cooling is achieved by conduction through the motor bearings and housing to the actuator body. The motor is designed to require no additional cooling when operating in its TVC environment for a typical 10 minute ALS mission. Forced air cooling may be used during extended laboratory testing by connecting two air fittings located on the top of the motor to filtered shop air. The motor's magnetics are constructed from Hyperco-50. A Harowe resolver (#21BRCX-335-512) is mounted on the motor to provide motor angular position. The resolver is a six terminal device with a reference frequency input and a sine and cosine output. The angular position of the rotor is determined by comparing the input reference with the output signals. There is also a thermocouple embedded in the motor's stator which may be used to measure motor temperature. The rotor's temperature may be measured through an access hole located on the motor's rear housing. A power output of 35 HP at 750 Hz is specified with an input current of 106 A/phase. The peak power output of 68 HP at 750 Hz is predicted with an input current of 210 A/phase.

2.3 Controller Hardware Description

The hardware configuration of the motor controller is shown in Figure 2. The hardware is divided into two subsections. The first section is a VME based card rack containing the computer processing elements. The second section is the power stage which contains the power components and the measurement and link control functions. Communication between the two sections is via two fiber optic lines.

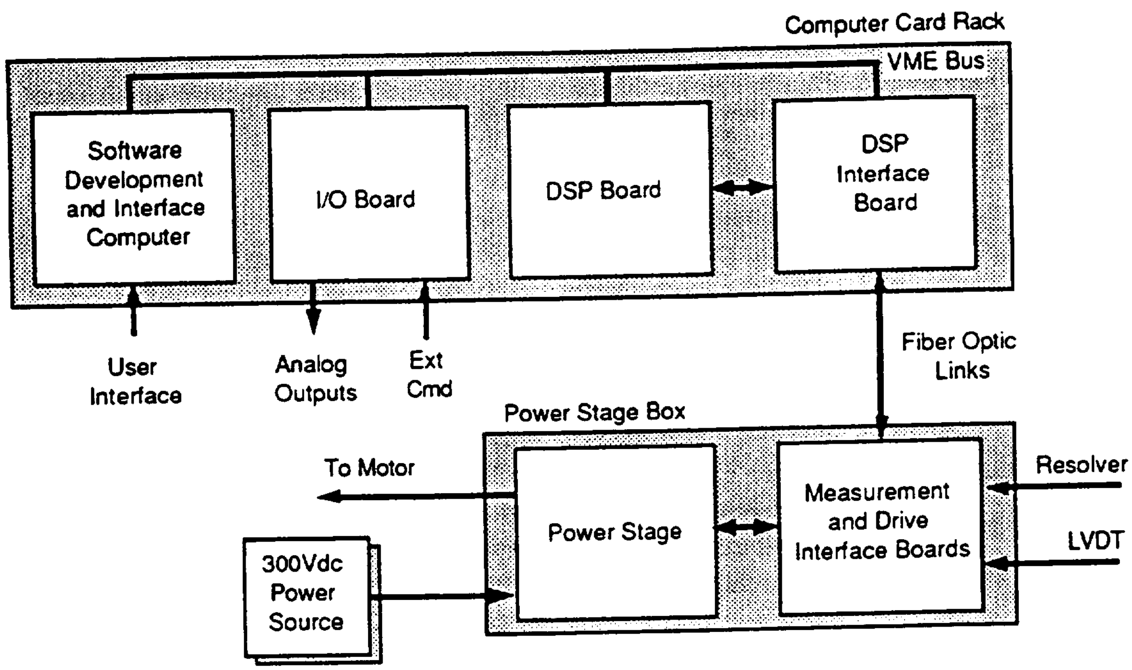


Figure 2. Controller hardware configuration

The **software development and user interface board** is a VME based '386 PC manufactured by Radysis. All 320C30 DSP software is developed on this PC and then downloaded to the DSP board over the VME bus. The PC also serves as the user interface that allows the user to issue commands and to vary controller gains and parameters. The PC then issues these commands to the DSP controller over the VME bus.

The **DSP board** is a stacked board set consisting of a motherboard and two daughter-boards. The motherboard contains a single 320C30 processor, the VME interface circuitry, high speed SRAM for the 320C30, and the VME dual ported memory. The first daughter-board contains another 320C30 processor and its associated SRAM while the second daughterboard contains a high speed digital I/O interface. The DSP board has been set up to be the VME bus controller and arbitrator with the PC being a slave. All motor controller functions, excluding resonant link control, are performed by the DSP board. The control provided by the DSP on the motherboard includes current regulation and command execution while the control provided by the DSP on the daughterboard includes position, rate, or torque regulation, and command function generation.

The **DSP interface board** contains the fiber optic interface to the power stage and the digital interface to the DSP board. The board takes the data from the fiber optic receiver and converts it to 32 bit data (the upper 16 bits are zero), which is then transferred to the DSP I/O board. The board also takes the switch output commands from the DSP I/O board and writes them to the fiber optic transmitter.

The **VME I/O board** contains an external analog command input and 4 analog output ports. The external command input is a ±6V signal that can be used for position, rate, or torque commands. The analog outputs are used for monitoring and testing the controller and can be set to look at a number of points in the system.

The **measurement board** in the power stage, along with the DSP board interface, is shown in figure 5. The measurement board contains two parallel A/D channels and associated signal conditioning, resonant link control circuitry, a switch output command interface, and resolver and LVDT converter circuits. At a fixed time before each zero voltage transition during the resonant cycle, motor, controller, and actuator sensor data is sampled and digitally converted, then is transmitted serially via a fiber optic cable. As soon as the data is received by the DSP board, the current regulator code is run on the primary DSP and the new switch commands are send back to the power stage via a second fiber optic cable. The switch commands are then sent to the switch drive board which provides the proper signal levels for the IGBT's. The current regulation function takes approximately 6.5 usec from the time that the currents are sampled to the time the new switch commands are issued.

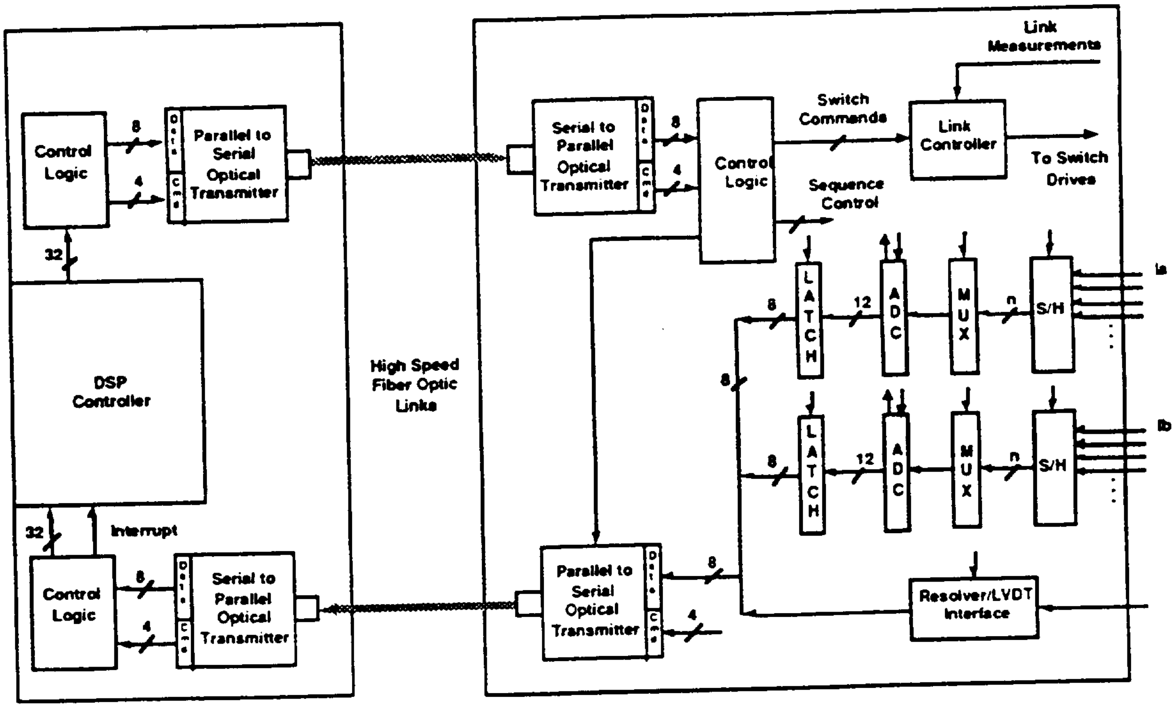


Figure 3. Measurement board and DSP interface

3. SYSTEM SOFTWARE

3.1 PC Interface Software

All software for the Radysis PC has been developed using Microsoft C version 6.0. The program is a menu driven text based program that is loaded into memory from the hard disk at run time. The modules that make up the program are listed below:

Module	Description
control.exe	The executable control program.
control.c	Main module that controls execution of the various program commands.
run.c	Executes the various controller commands.
error.c	Error checking of user inputs.
display.c	Displays data during run command.
param.c	Modifies parameters and gains.

utils.c	Collection of various control functions.
help.c	Displays help text.
system.c	Collection of various system functions.
menu.c	Controls menu creation and item display then returns selection.
window.c	Creates windows and keeps track of displayed windows.

The directories for the various files are as follows:

\dsp\pc_cntl\src	.C source files and CONTROL.MAK
\dsp\pc_cntl\obj	CONTROL.EXE and .OBJ files
\dsp\pc_cntl\inc	.H header files

To modify the program (i.e. control.exe) simply modify the appropriate module and/or header file and type ***make control*** at the command line while in the source code directory. This will run the Microsoft make utility NMAKE using the make file named **control.mak**.

3.2 DSP Software

Software for the 320C30 processors on the Pentek DSP board has been developed using TI C and assembly language version 4.1. C is used where timing is noncritical. The DSP control program is created in two separate modules for each of the two processors. The 4283 board is the motherboard and the 4244 is the coprocessor daughterboard. The modules that make up the program are listed below.

Module	Description
code83.out	The 4283 DSP compiled and linked code.
main83.c	Executes the various controller commands.
init83.c	Initialization for the 4283 board and code.
move83.c	Loads 4244 code from 4283 memory to 4244 memory.
creg83.s30	Motor current regulator.
code44.out	The 4244 DSP compiled and linked code.

main44.c	Looks for commands from the 4283 board.
init44.c	Initialization for the 4244 board and code.
timr44.c	Interrupt routines that control the internal software function generators.
pstn44.s30	Position, rate, and torque regulator interrupt routines.

The directories for the various files are as follows:

\dsp\dsp_cntl\src	.C and .S30 source files.
\dsp\dsp_cntl\out	.OUT files, .CMD link command files, and .MAP files.
\dsp\dsp_cntl\obj	.OBJ files
\dsp\dsp_cntl\include	.H header files

To modify the DSP program simply modify the appropriate module and/or header file. To compile and link all the modules type either ***make83*** or ***make44*** depending on which processor code is being modified. If you compile the file directly, then adding a ***-l*** to the ***make***** command will only link the **.obj** files and will not compile (e.g. ***make83 -l***). The ***make83*** and ***make44*** batch commands must be executed while in the source code directory.

Since there is no access to the 4244 program memory, the 4244 code must first be loaded into the 4283 memory and then the 4283 code will load the 4244 code. For this reason, the initialization address and size of the 4244 code must be determined from the **code44.map** file and then placed in the **move83.h** header file every time the 4244 code is modified. Since the **move83.h** header file is modified, ***make83 -l*** needs to be run which will automatically recompile **move83.c**. If only the 4283 code is modified, there is no need to run ***make44.***

After compiling and linking the DSP code it must then be loaded into program memory. This is done by typing ***load_dsp*** at the command line. It does not matter which directory you do this from. This batch file prompts the user to reset the DSP board, then loads the 4244 into memory, then prompts the user to reset the DSP board again, then loads the 4283 code, and finally runs the PC interface code. At this point the controller should be ready to run.

3.3 PC to DSP Communication

The PC communicates to the DSP board through VME shared memory. To issue a command to the DSP controller, the PC will write commands to the shared memory. To indicate that a command is available, the PC will write to a mailbox register in the shared memory. The DSP monitors this mailbox register to determine if there is a message from the PC. When a message is available, the DSP controller will get the commands from the shared memory, execute the command, and then clear the mailbox register to indicate that the command has been executed.

The DSP controller also communicates to the PC board through the shared memory. While the controller is running, data is continuously written to the shared memory. This data includes operating conditions and internal and external variables. The DSP controller only responds to commands from the PC and does not initiate commands.

4. THEORY OF OPERATION

4.1 Resonant DC Link Operation

The actively clamped resonant dc link converter circuit is depicted in Figure 4. Vdc is the power source voltage. Lres and Cres form the resonant tank in the circuit. The voltage clamp, which is comprised of Scl and associated flyback diode and the clamping capacitor Cclamp, prevents the link voltage from exceeding a preset value. The three phase bridge consists of switches S1-S6 with the associated flyback diodes.

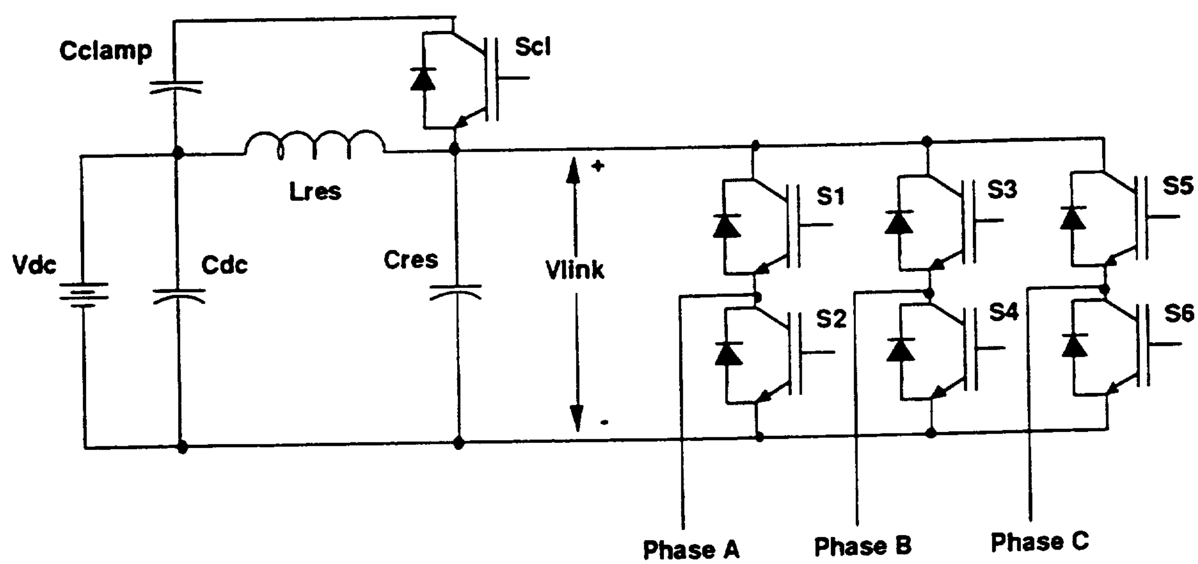
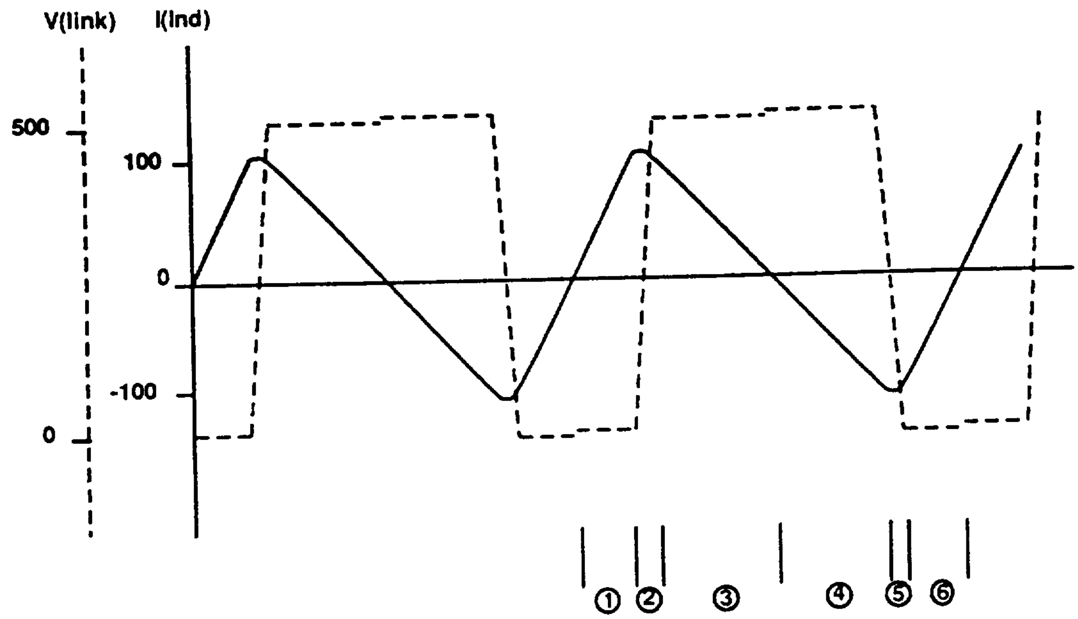


Figure 4. Actively clamped resonant dc link power processor

At time t1, as shown in figure 4, the voltage across the resonant capacitor Cres is 0. All bridge switches(S1-S6) are turned on, causing the current in the resonant inductor Lres to increase. At the end of the fixed shorting time, one switch in each of the three bridge legs is turned off according to the switch pattern selected by the current regulator. The switch pattern is selected in such a way to reduce the error between the commanded and actual motor currents. When the selected switches are opened in the bridge, the link short is removed and the current in the resonant inductor now flows in the resonant capacitor and increases the link voltage Vlink, shown as time t2. As



① Bridge switches conduct - build up inductor current

②⑤ Resonant rise/fall of link voltage

③ Clamp diode conducts - turn on clamp switch

④ Clamp switch conducts

⑥ Bridge diodes conduct - turn on bridge switches

Figure 5. Resonant link operation

the voltage across Cres increases, at time t3 the Scl flyback diode becomes forward biased and Cclamp begins charging. At the time that the Scl flyback diode conducts, Scl is also tuned on. Scl is left on until the current into the clamp capacitor through the diode is approximately equal to the current flowing back through Scl, shown as time t4, thereby maintaining the clamp voltage constant. Opening the clamp switch causes the current flowing back through the resonant inductor to discharge the resonant capacitor, time t5, and returns the link voltage to zero. The bridge diodes start conducting at time t6 when the link voltage is less than 0, thereby restarting the cycle again.

Parameters for the actively clamped resonant link controller are shown in table 1.

Parameter	Value	Description
Vdc	300V	Supply voltage
Cres	.47uF	Resonant capacitor
Lres	7.9uH	Resonant inductor
Cclamp	4400uF	Clamp capacitor
Cdc	4400uF	Input capacitor

Table 1. Actively clamped resonant dc link parameters

The torque, rate, or position control algorithm, depending on which mode is commanded, is run on a second DSP processor on the DSP board. Data transfer to the second DSP processor is coordinated by the primary DSP after completing the current regulation function. The primary DSP also handles the interface to the VME bus where command generation is initiated. The secondary DSP additionally handles all internal command function generation. Internal command functions include sine wave, square wave, triangle wave, sine sweep, and arbitrary waveforms. There is also a provision for an external command input via a VME interface card.

4.2 Motor Current Regulation

The control of the motor currents is performed with a discrete control algorithm called a modified adjacent state regulator. A discrete algorithm is required due to the discrete nature of the switching instants in the resonant voltage waveform. A switch state selector, as shown in figure 6, has seven possible switching states of the ordered triplet {Sa,Sb,Sc} where Sa =1 when S1 is on and S2 is off and Sa=0 when S1 is off and S2 is on in the bridge circuit.

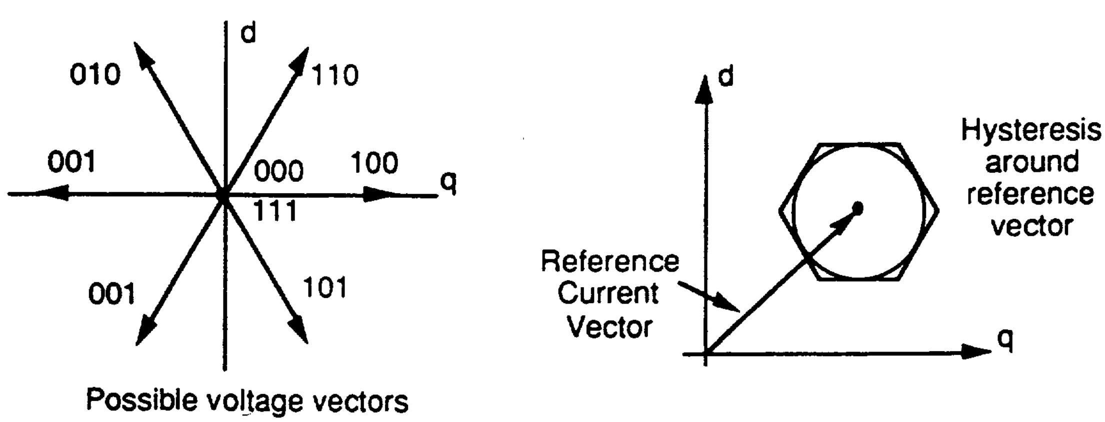


Figure 6. Possible switching vectors in adjacent state regulator

Selection of one of the possible states is accomplished as follows. At the instant that the currents are sampled and then sent to the DSP board, the phase errors are found by:

$i_{as}err = i^*_{as} - i_{as}$ (* = reference)

$i_{bs}err = i^*_{bs} - i_{bs}$

$i_{cs}err = -i_{as}err - i_{bs}err$ (wye connected machine)

If the magnitude of all the current errors is less than the hysteresis band (10A) then the zero state is chosen (000 or 111). If the current error magnitude of any phase is greater than the hysteresis band then the desired state for each phase is found by:

$Sx = 1$ for $ixserr >= 0$

or

$Sx = 0$ for $ixserr < 0$

When the desired state is found, then that state is selected if the desired state is adjacent to the current state. If the desired state is not adjacent to the current state then a zero state is chosen.

The chose between which zero state to select, state 0 or state 7, is made depending on the neutral count. The neutral count is found as follows:

$$Count\_new = 2(Sa + Sb + Sc) - 3 + Count\_old$$

If the zero state is selected then the (111) state is chosen when the new count is less than zero and the (000) state is chosen when the new count is greater than zero.

The reference currents for the current regulator are generated from the desired flux current, i^{e*}_{ds} and the torque output of the position regulator, i^{e*}_{qs} as follows:

$i^*_{as} = i^{e*}_{qs}\cos\varnothing_e + i^{e*}_{ds}\sin\varnothing_e$

$i^*_{bs} = i^{e*}_{qs}\cos(\varnothing_e - 2\pi/3) + i^{e*}_{ds}\sin(\varnothing_e - 2\pi/3)$

where $\varnothing_e$ is the sum of the rotor angle and the slip angle

4.3 Position Control

The control of the actuator position as shown in figure 7. The output of the position controller is a torque command that is used to generate the phase current reference commands. Motor rate is limited to ±14700 rpm with rate feedback obtained from the difference between rotor angle samples.

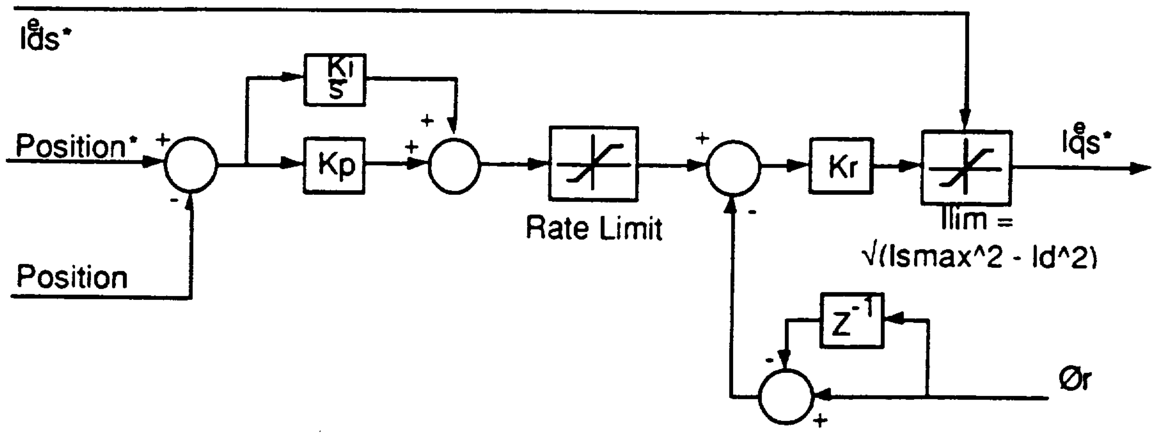


Figure 7. Position regulator block diagram

4.4 Rate Control

The control of the motor rate as shown in figure 8. The output of the rate controller is a torque command that is used to generate the phase current reference commands. Motor rate is limited to ±14700 rpm with rate feedback obtained from the difference between rotor angle samples.

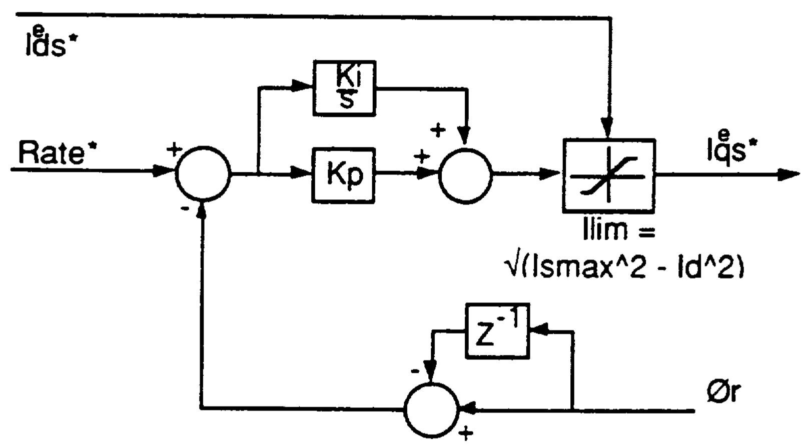


Figure 8. Rate regulator block diagram

4.5 Torque Control

The control of the motor torque as shown in figure 9. The output of the position controller is a limited torque command that is used to generate the phase current reference commands. Motor rate is unlimited so special care is needed to make sure motor rate does not exceed the maximum allowed.

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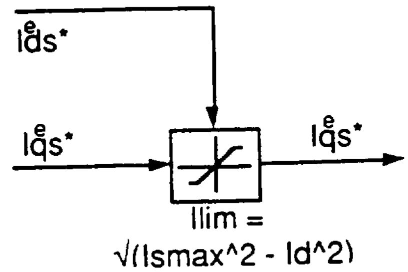


Figure 9. Torque regulator block diagram

5. SYSTEM OPERATION

5.1 System Setup

Connect the system as shown in figure 8.

Communication between the DSP controller and the power stage is via two fiber optic cables. These cables should be connected with Tx from the I/O board going to Rx on the power stage and with Rx on the I/O board going to Tx on the power stage. Control power is provided to the power stage by a separate box containing three power supplies, with +5V and ±15V going to the logic board through a 'D' connector and +15V going to the drive board through a circular connector.

Feedback from the actuator and motor comes through a 'D' connector into the control board in the power stage. This cable branches out to the LVDT, resolver, and force connectors. The connections to the motor and the DC power supply are made through circular connectors on the front of the power stage.

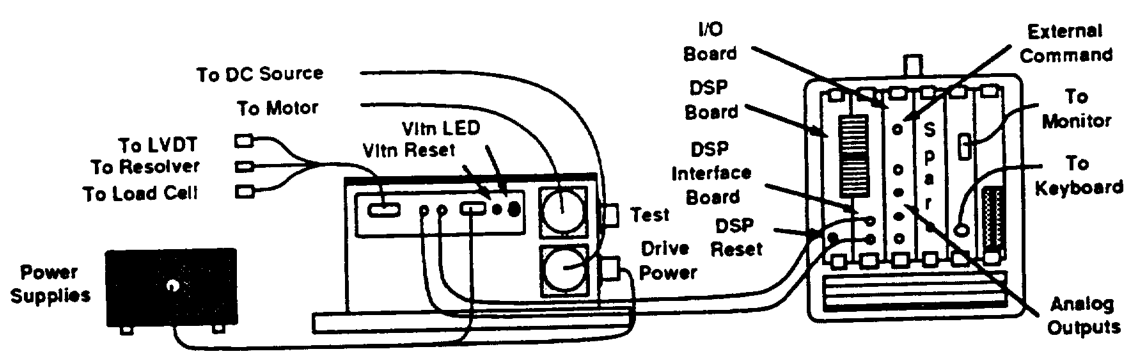


Figure 10. System connections

5.2 System Startup

After connecting the system as shown in figure 8, turn on power to the power supply box and the card rack. Be sure the controller is powered up before applying power from the high-voltage DC power source. The Vltn LED may be lit after powering up the system. This LED indicates a communications error between the power stage and the DSP board and may normally occur during power turn on. Reset the LED with the reset button next to the LED. If the LED is still lit then a problem is indicated, probably the fiber optic cables being crossed.

5.3 Loading Control and Interface Software

After powering up the controller, the software needs to be loaded. Type ***load_dsp*** at the command prompt. This command will load the code into the DSP and then start the PC interface code. You will be prompted to push the reset button on the DSP board during program loading. This button is located in the lower left hand corner of the DSP board. If the code successfully loads the message 'Controller Responded OK' will appear, otherwise an error message will appear.

5.4 Capacitor Precharging

Before starting the power stage, the clamp capacitor needs to be charged to approximately .4 times the input voltage. This can be done with an external lab power supply through a 100 ohm resistor. Be sure to disconnect the power supply before starting the controller.

5.5 Starting the Controller

Before starting the controller, make sure the controller gains and parameters are set to the appropriate values. The controller can be started through the ***run*** command in the main menu. If you try to start the controller when the clamp capacitor is not charged or is partially charged, the controller will not start and the software will need to be reloaded and the capacitor charged up to the correct value before trying to restart.

6. TEST CONFIGURATION

6.1 Test Article

The system under test includes the EMA motor controller, the Sundstrand AC induction motor, and the Moog actuator.

6.2 Test Equipment

Make	Model / Description	Control #
Fluke	8600A, Digital Voltmeter	X142994-00
Gould	CL-810231-01, Instrumentation Amp	E1040169-
Gould	RS3800, Strip Chart Recorder	E1040169-00

HP	43A8A, Milli-ohm meter	E142033-00
HP	3466A, Digital Voltmeter	145773
HP	3466A, Digital Voltmeter	E334007-00
Reliance	MC2512AT, Dynamometer Motor	01KA858302-PR
Tektronix	7A22, Differential Amp	HC51879
Tektronix	7A26, Dual Trace Amp	E1040181-00
Tektronix	11A34, 4 Channel Amp	E1040175-00
Tektronix	AM503, Current Probe Amp	147305
Tektronix	AM503, Current Probe Amp	147307
Tektronix	AM503, Current Probe Amp	E1040124-00
Tektronix	DSA602, Digitizing Scope	E1040250-02
Yokagawa	2533, Digital Power Meter	E1040160-00

6.3 Test Plan

Testing was performed in accordance with the "Task Order #14 System Test Plan" REV 4 dated 7-29-93.

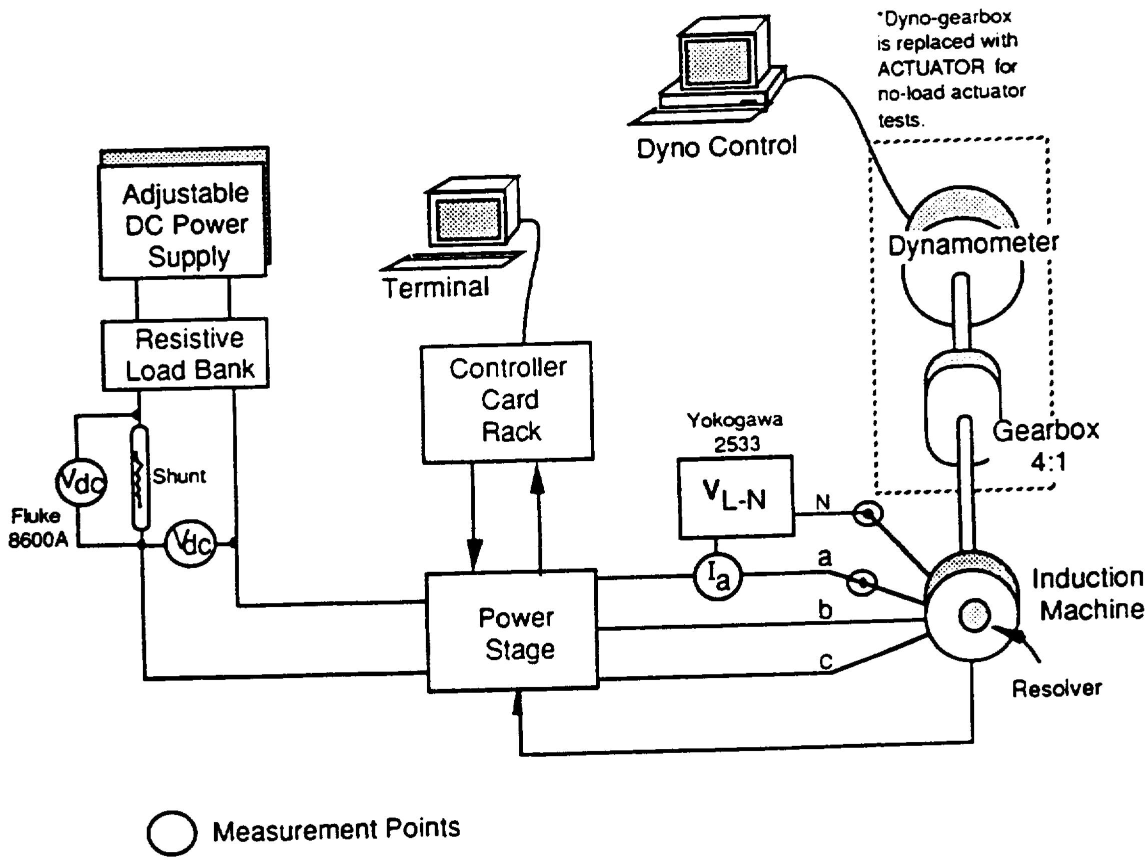


Figure 11. Test Measurement Configuration

7. TEST PROCEDURES AND MEASUREMENT TECHNIQUES

7.1 General

There are eight sets of tests that were performed on the system.

1) Motor Parameters
2) Motor Characteristic Curves
3) Steady State Power Loss and Efficiency
4) Motor Rate Step Response
5) No Load Actuator Tests
6) Inertial Load Test on SSME Test Stand at Moog
7) Force-Velocity Test on SSME Static Load Stand at Moog
8) Force-Velocity Test on SSME Static Load Stand at Marshall

Each of these areas required different test procedures and measurement techniques. The specifics are outlined in the test plan and summarized in the following sections.

7.2 Motor Parameters

The motor parameter tests were done under the 40 HP testing and the results are reproduced here. Two sets of tests were performed that determined the Sundstrand motor parameters. The first test is the blocked rotor test that determines leakage inductance and rotor and stator resistances. The second test is the unloaded motor test that determines the mutual inductance and resistance associated with magnetic core loss.

7.3 Motor Characteristic Curves

The motor characteristic curve measurements generate a set of torque/speed curves that are used to verify the Sundstrand motor simulation results and verify the controller operation. The test procedure requires that ids=constant for constant flux. Two values of ids were chosen: ids=85A, corresponding to full rated flux, and ids=42A, corresponding to 50% rated flux. The dynamometer is commanded to a set of speeds on the motor torque/speed curve and the stator frequency is maintained constant by increasing the torque output and slip frequency.

A Fluke 8600A digital multimeter was used to measure input dc voltage. The input dc current was obtained from a coaxial current shunt and the output of the shunt was read by a Fluke 8600A. A Yokagawa 2533 digital power meter was used to determine motor voltage, motor phase current, and power factor. A single phase was used to derive the total motor input power after verifying that all three phases were producing similar data. Motor output torque was read by the torque transducer and resolver associated with the dynamometer. The data points for each curve were taken at approximately the same stator temperature to minimize errors.

7.4 Steady State Power Loss / Efficiency Measurements

The steady state power loss/efficiency measurements are similar to the motor curve data with the exception that the controller is run in the rate regulation mode and the dynamometer is run in the torque mode. An additional set of points corresponding to 25% rated flux is also included in this set of data.

7.5 Motor Rate Step Response

The motor rate was commanded to run at 7500 rpm CCW and then a step to 7500 rpm CW was issued and the response was recorded. The motor is unloaded during this test and ids is set for full flux (85A).

7.6 No Load Actuator Test

The unloaded actuator test verifies the system operation and characterizes the system in preparation for the subsequent loaded testing at Moog. For the purpose of conducting the no load actuator tests, the motor was attached to the actuator which in turn was mounted on a table. The testing consisted of two sets of tests. The first test used a sine wave input signal to measure the system frequency response and phase shift. This was performed for amplitudes ranging from ±0.1″ to ±5.5″. The frequency was varied from 0.05 Hz to 8 Hz. A frequency sweep was also performed at ±0.1″ and ±0.25″. The step response of the system was measured in the second set of tests. A square wave input signal to the system was adjusted from ±0.25″ to ±5.5″ at 0.3 Hz and the actuator's output position was recorded on a strip chart recorder.

7.7 Inertial Load Test on SSME Test Stand

The inertial load actuator tests were performed on the SSME inertial test stand at the Moog facility in West Aurora, New York. The actuator was installed in the inertial test stand with one end of the actuator attached to the equivalent of the SSME inertial load and the other end of the actuator attached to the equivalent of the structure mounting attach point stiffness, thereby simulating actual load dynamics. The first test used a swept sine wave input from 0.1 Hz to 10 Hz at ±0.1″ and ±0.5″ peak . The gain and phase of the system was plotted for the two input commands at various values of controller gains. The step response of the system was measured in the second set of tests. A square wave input signal to the system was adjusted from ±0.25″ to ±5.5″ at 0.3 Hz and the actuator's output position was recorded on a strip chart recorder.

7.8 Force-Velocity Test on SSME Test Stand

The force-velocity actuator tests were performed on the SSME static test stand at the Moog facility in West Aurora, New York. The test actuator was installed in the force velocity test stand and actuator rate and load force were measured. Load force is provided by a regulated hydraulic piston that can be controlled in the extension and retraction mode. The hydraulic pressure regulator that controls the load is relatively slow and exhibits ringing at the application of the step command. This ringing dies down and the force and velocity measurements can then be made.

The test actuator is commanded to -5.5 inches before the test is to start. A command is then made to +5.5 inches with a given force commanded and then the position is commanded back to -5.5 inches. Actual force and linear rate are recorded in both directions. The commanded force is varied from no load (actually a test stand minimum of approx. 5000 lbs.) to full rated load. This test verifies the loading capability of the actuator and controller.

8. TESTS AND RESULTS

8.1 General

The test data gathered to satisfy the test plan is the culmination of many tests and verifications. In most cases the data was re-measured to confirm the results. This thorough measurement approach was necessary due to the complex nature of the test article and because of the opportunities for equipment error.

It is important to note that all of the motor testing at Sundstrand was performed with a sine wave motor drive, quite different from our PDM controlled motor voltage waveform. We have no error information from Sundstrand in regard to their measurements. References are also made to Sundstrand's "predicted performance" of the motor. These figures were generated by Sundstrand during the design phase of the motor and are included in the "ALS ACTUATOR INDUCTION MOTOR CRITICAL DESIGN REVIEW" dated April 4, 1991.

8.2 Motor Curves Test Results

The motor curves test data was gathered at two different values of flux: ids* = 50% rated flux(42A) and ids* = 100% rated flux(85A). The current, and thereby the slip, was selected to give representative data points on each curve with phase currents up to 120Arms. The motor curves are restricted to the area within the operational limits of the controller. For the condition of full rated flux, this limits the torque to well below the maximum torque output since this would imply operation at 100's of amps and approx. 150 hp. The area of interest is mainly the maximum torque per amp and maximum efficiency - both of which occur at significantly less than the peak torque.

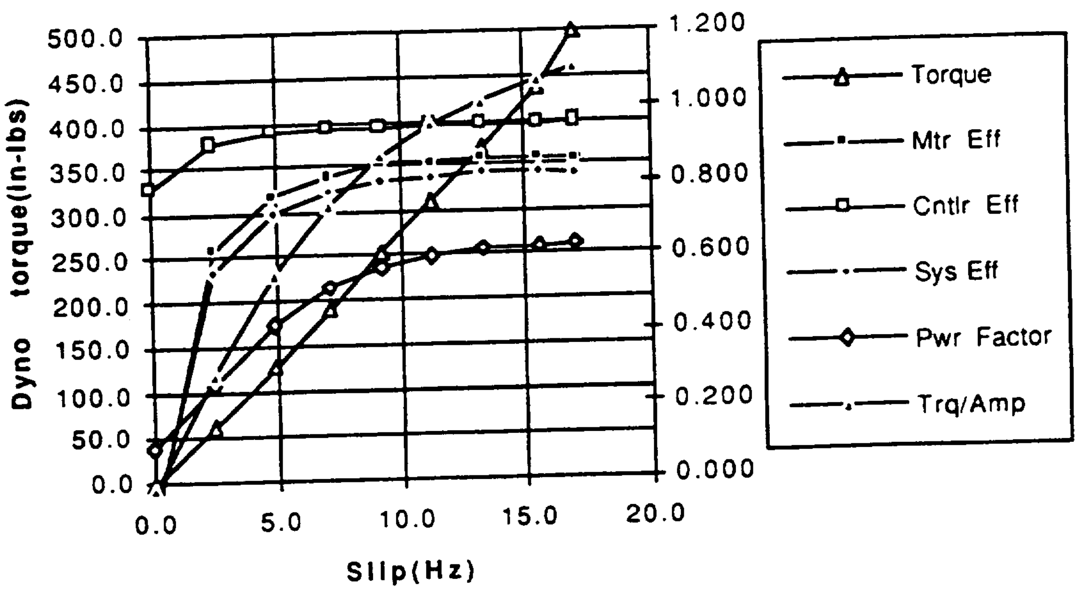


Figure 12. Typical motor curve test data (700Hz/Ids=85A)

The motor curves information is represented in tabular form as well as graphical form in Appendix D. The graphs or charts show the variations of torque, efficiency, and power factor relative to dyno torque. The following graphs are a summary of the data in Appendix D.

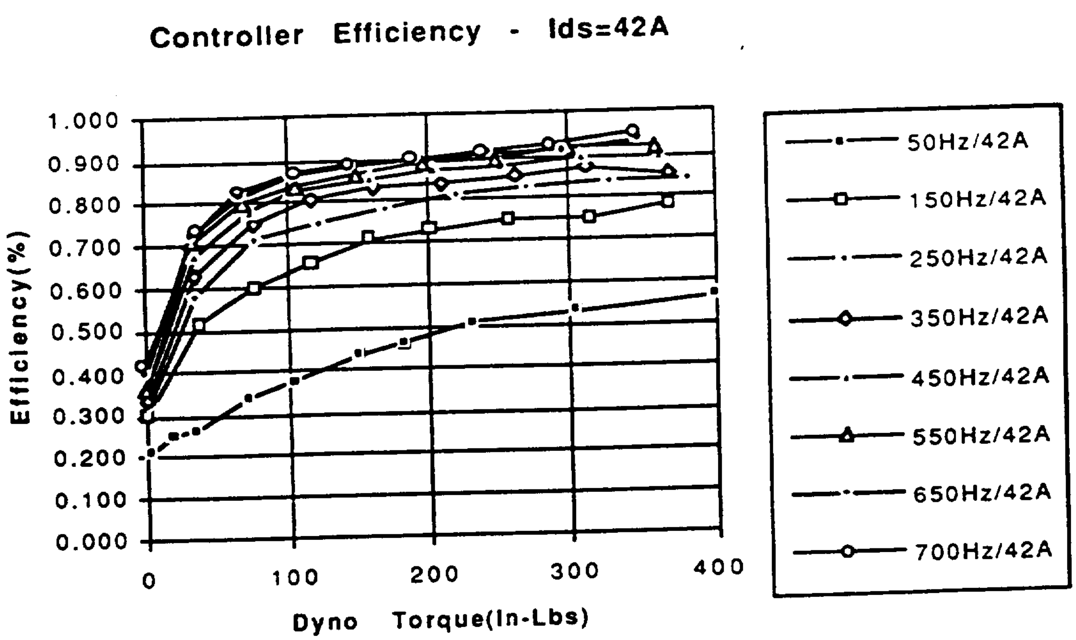


Figure 13. Controller Efficiency - (1/2 flux)

Controller Efficiency - Ids=85A

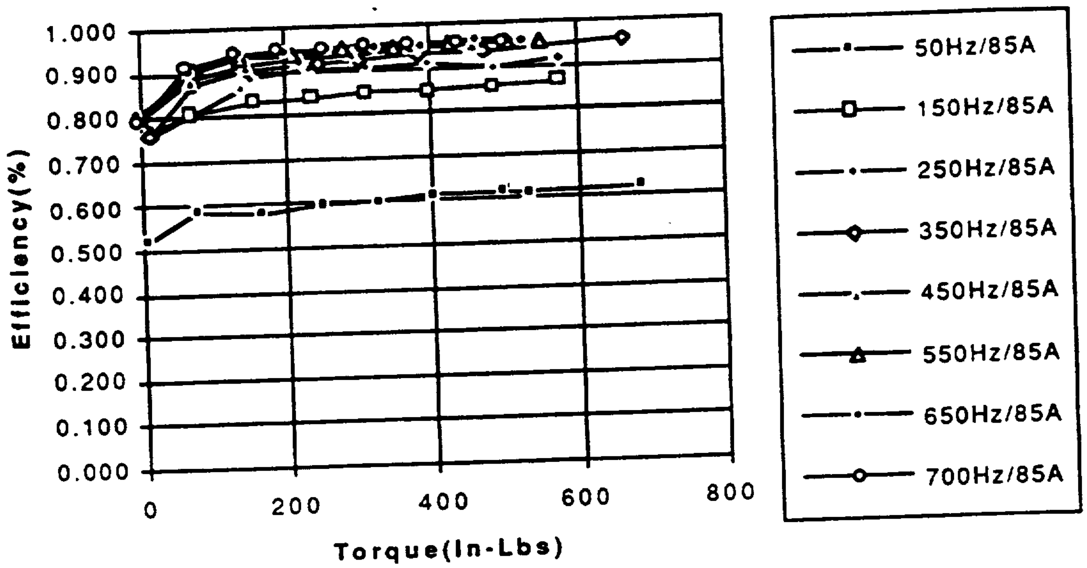


Figure 14. Controller Efficiency - (full flux)

The controller efficiency reaches a maximum of about 96% at 115 Amps per phase and 700 Hz. The controller reaches maximum efficiency at fairly low loads and then levels off. The controller shows higher efficiency at full-rated flux than at half-rated for any load. This is due to the fact that the higher rated flux means higher currents. As would be expected, the efficiency of the controller is a generally a function of current out of the controller and not as strong a function of power factor.

Motor Efficiency - Ids=42A

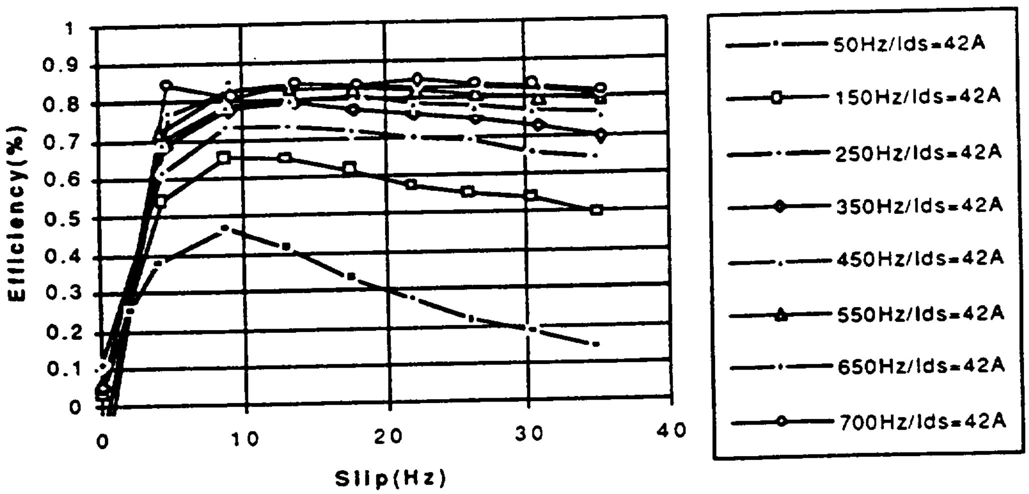


Figure 15. Motor Efficiency - (1/2 flux)

Motor Efficiency - Ids=85A

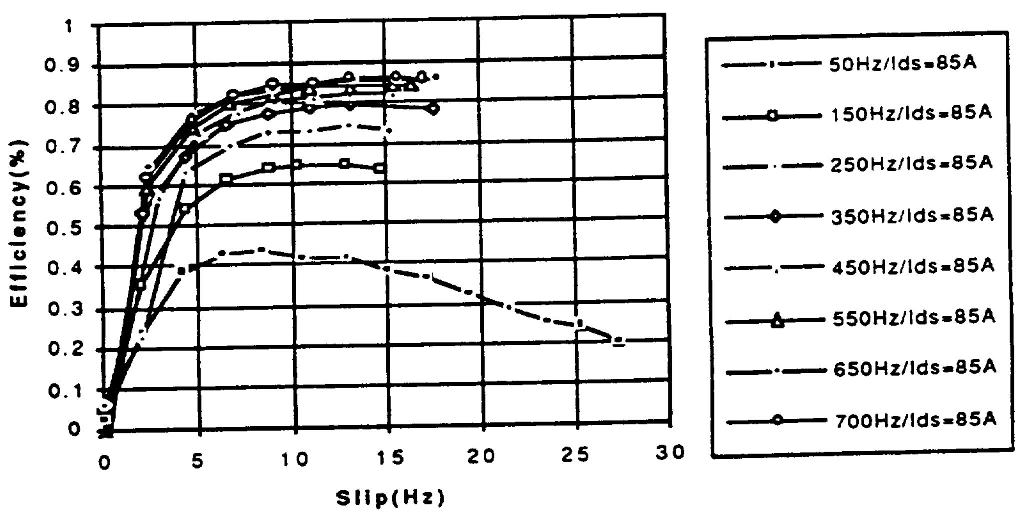


Figure 16. Motor Efficiency - (full flux)

The motor's efficiency reaches a maximum of about 86% at 115 Amps per phase and 14,000 rpm (700 Hz). The motor's top rated speed is 14,700 rpm, the point at which Sundstrand predicted 89.9% efficiency. We were unable to test the motor beyond 14,000 rpm due to limitations of the gearbox and dynamometer. The motor efficiency measurement error of ±10% is significant in this case, since the predicted motor efficiency falls within this window.

Overall Efficiency - Ids=42A

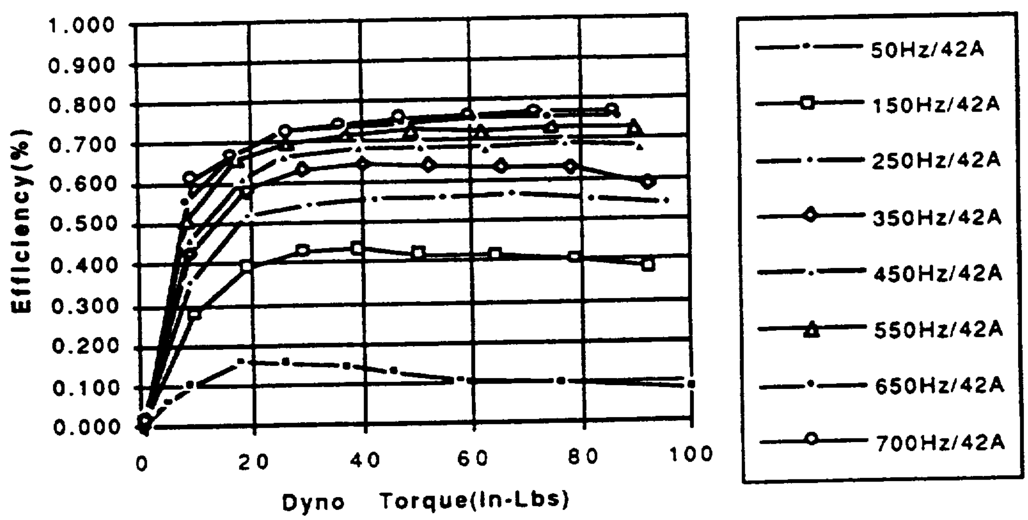


Figure 17. End-to-End Efficiency - (1/2 flux)

Overall Efficiency - Ids=85A

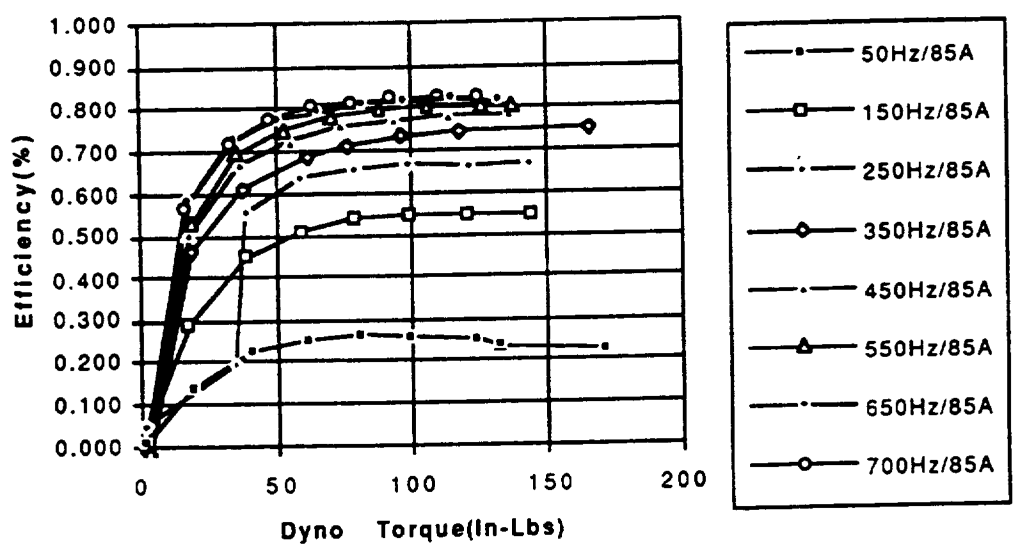


Figure 18. End-to-End Efficiency - (full flux)

The overall system efficiency reaches a maximum of over 80% for rated speed and rated flux. In general, the efficiency for one-half the rated flux is less than the efficiency for full-rated flux. However, the efficiency does show some improvement when operated at half-rated flux when the load torque is less than about 25 in-lbs. The strategy of lowering the flux for improved efficiency would only be advantageous if the motor spent long periods at low loads.

Sundstrand performed a simulation of the motor's capabilities as part of their design procedure. This data is used as a check on the motor data gathered. The simulation indicated the following operational maximums:

Efficiency (%)	89.9
Power Factor	0.85
Motor Rate	14,700
Torque (In-lbs)	148.4
Horsepower	34.6
Current per Phase	105.9

The measured efficiency does not reach the Sundstrand simulation data. A peak efficiency of 85.7% was measured at 125 in-lbs, 13,660 rpm, a phase current of 113Arms, and a power factor of .628, yielding 27.0 hp. The motor rate was limited to 14000 rpm due to the limitation of the dyno.

Motor power factor and efficiency measured lower in practice than the simulated data predicted. The maximum power factor achieved under test was 0.63 ±0.5%. Typical simulated values for the power factor fell into the 0.75 to 0.8 range. Some of the discrepancy in the predicted and measured power factor and efficiency may be explained by the low motor inductance. The low motor inductance causes higher current ripple in the motor currents which results in higher motor losses. Also the present current regulator is a "bang bang" regulator which depends on the motor inductance to perform the integration of the motor current. The circuitry is designed to respond to polarity of the error signal. A simulation performed by Krause and Associates for NASA LeRC indicates that with a low inductance, resulting in a large current ripple, a significant limitation in the torque output of the motor at higher speeds can be expected since the regulator is not able to limit the lower frequency harmonics, showing up also as poorer power factor.

8.3 Steady State Power Loss / Efficiency Test Results

For the purpose of these tests the slip constant (Ks) was adjusted to 8 Hz/A/A, the average value that produces the most efficient operation under typical operating conditions. The data sheets and associated charts in Appendix G illustrate this fact. The system efficiency scale (on the right of the chart) represents the % system efficiency. i^{e*}_{ds} and i^{e*}_{qs} are scaled on the left side of the chart. The lower torque values for a given motor speed provide a better picture of the efficiency vs. ids/iqs because there are more data points. The higher torque levels prevent the system from maintaining the commanded torque without higher currents and consequently fewer data points.

Table 2. System test data (Ids = 85A)

Vdc (Volts)	Idc (Amps)	Motor Current (Arms)	HP	Motor Speed (RPM)	Motor Eff	Cntlr Eff	Overall Eff
301.5	11.8	66.8	2.30	2992	56.5	85.3	48.2
301.5	18.8	84.6	4.18	2992	63.8	86.2	55.0
301.3	25.8	103.1	5.86	2992	64.3	87.5	56.2
301.2	18.2	67.2	4.68	5992	70.3	90.6	63.7
301.0	29.4	85.1	8.23	5996	75.2	92.2	69.4
300.8	41.0	105.7	11.58	5992	76.0	92.1	70.0
300.9	25.2	67.7	7.33	8984	76.9	93.7	72.1
300.7	41.6	87.1	12.79	8988	81.3	93.8	76.3
300.1	56.8	107.7	17.56	8964	81.0	94.9	76.9
300.8	31.2	66.4	9.50	11984	80.1	94.3	75.5
300.5	52.0	87.6	16.54	11984	83.1	95.0	79.0
299.9	72.8	111.9	23.33	11980	84.1	94.8	79.7
300.6	36.0	66.5	11.35	13980	82.3	95.1	78.2
300.1	58.4	88.5	18.93	13996	84.4	95.5	80.6
299.6	83.0	115.4	27.72	13952	85.7	97.0	83.2
299.6	90.0	121.4	29.44	13904	84.8	96.1	81.5

Total system efficiency exceeds 80% for the full flux commands at the higher motor speeds. The controller and motor also peak in efficiency at around the same point. As the current is increased beyond this point, saturation of the current regulator due to the series inductor begins and the efficiency starts decreasing. As seen from the data in Appendix E, the area where an efficiency advantage is gained for reducing the flux occurs only at the very small loads - probably for loads less than 10% of the full load torque.

8.4 Motor Dynamic Response

The motor responded to a 7500 rpm to -7500 rpm step in 110 msec. This corresponds to an acceleration of 148,920 rpm/sec or 2482 rev/sec^2.

8.5 No Load Actuator / System Test Results

As specified in the No Load Actuator Test Procedure (Appendix I), the frequency response was measured using a sine wave input and a sine sweep input. The step response was measured using a square wave input.

The frequency response of the system is best determined by identifying the frequency at which the phase delay is equal to 90 degrees. The command/position phase shift changes quickly approaching the pole in this second order system. The sine sweep data shows that the 90 degrees phase shift occurs at 5.0 Hz and ±0.1" amplitude with an amplitude gain of 0.6. The response of the system falls off rapidly at frequencies above 5.0 Hz. At larger amplitudes and lower phase currents the cutoff frequency is lower.

The step response for the unloaded actuator is 1.56 sec for a step of 11 inches(-

5.5 in to 5.5 in). This is mostly a rate limited response as it takes just over 100 msec to go from 0 to 15000 rpm.

The control loop constants may be adjusted to achieve optimum system response for differing conditions. For a second order system, which the unloaded actuator closely approximates, the classic solutions can be used (i.e. a larger value for K_p improves the small signal response by increasing w_n and decreasing zeta, thereby decreasing damping, while an increase in K_r increases zeta, thereby increasing damping). The values selected give an w_n of 20 radians/sec and a zeta of .95.

8.6 Force-Velocity Stand / System Test Results

The horsepower requirements for this system were 32.8 HP at 32,000 lbs. The maximum output power that was demonstrated was 31 HP at 32,000 lbs of force. The torque output of the motor is reduced at the higher stator frequencies due to the effects of the motor inductance as mentioned in Section 8.2. Also to reach the 31 hp, a higher value of motor current was required. This results in lower efficiency due to the decreased torque per amp output.

8.7 Inertial Test Stand / System Test Results

The control loop constants may be adjusted to achieve optimum system response for a given set of requirements. For a second order system, a larger value for K_p increases wn and decreases zeta, thereby decreasing damping and improving rise time, while an increase in K_r increases zeta, thereby increasing damping. However, the response of the system on the inertial test stand is more complicated. The addition of the load inertia and the structure spring makes calculation of the correct gains extremely difficult. The methods that are normally used are computer simulation and trial and error. The gains we had initially selected during the simulation did not give us the desired results on the test stand, so we had to adjust the gains while running the system on the stand. These adjusted gains, while giving adequate response, are not the optimum values.

The test data on the inertial test stand at MOOG showed some interesting results. The simple second order system of the unloaded actuator and the dyno loaded motor was no longer valid. The load inertia and the effective spring of the attach point structure increased the complexity of the overall system. The gains which directly controlled the natural frequency and damping of the system were now indirectly controlling the system. This meant that finding the proper control gains was a matter of trial-and-error. The data presented is the result of this process and did not necessarily result in the optimal gains for this system. As can be seen from the gain-phase plots of the system, there is a load resonance around 8 Hz. This load resonance resulted in a gain that was too high at the 180 degree crossover point of the phase, thereby resulting in a potentially unstable system. At the larger command input(5%), the load resonance was amplified to a point that resulted in overspeed operation of the motor, and large amounts of regenerated power. To remedy this, additional compensation needs to be added to increase the gain and phase margin.

9. MEASUREMENT ERROR

9.1 Principle Sources Of Error

Torque Measurement Error (at motor)	±3 in-lbs
Yokagawa 2533 Power Meter Accuracy (Tested at GDSS)	±2% of full scale
AC Voltage Measurement Error	±0.37% of input + 0.03% of range
DC Voltage Measurement Error	±0.02% of input + 0.008% of range
DC Current Measurement Error	±0.1% of input + 0.01% of range
Motor Speed Measurement Error	Negligible
Motor Fundamental Frequency Voltage Error	±5% of measured value
Temperature Measurement Error	±1 degree C

9.2 Error Assessment

The assessment of error in determining system efficiency values is complex. The magnitude of the errors depends on several factors. The measurement error changes with the operating point of the system because the Yokagawa power meter for example, specifies accuracy as a percentage of the range. The range changes during the measurements depending on the magnitude of the voltage and current. But for a given range, the measurements made on the low end of the range have a greater error associated with them. Power is particularly difficult to measure with a high level of accuracy. The available test equipment is capable of making real power measurements to an accuracy of between 2% and 20% in our test application. This is due to both the range in which the voltage and current magnitudes fall and the poor power factor environment in which many of the measurements were made. At the low power factors, power factor measurement error increases to about 4% on the Yokagawa 2533.

Some of the measurements have errors specified to a percentage of the measured value as well. The digital multi meter's errors are specified in this way. This requires a multi-step process when determining the total measurement error.

Another important consideration is the number of arithmetic calculations that are performed using the data. Each successive calculation accumulates the errors from the preceding computations. The very nature of the motor parameter determination requires numerous calculations to arrive at the end values, which consequently have large error uncertainties.

There are two types of error sources; Random Errors and Guarantee Errors. Random errors are the result of unknown or unpredictable forces that result in measurements varying from reading to reading on a given instrument. These types of errors may be analyzed using statistical methods. Guarantee errors are errors attributed to the capabilities of a piece of test equipment. Providing that the equipment is properly calibrated, all measurements will be within a specified error range. In determining the error associated with each measurement or calculation, these errors are treated differently. Random errors may be added using the root-sum-square techniques available in statistical theory while guarantee errors must be added algebraically.

The analysis of our data has revealed a potentially high variance of the values due to errors. It is important to keep in mind that these error numbers are a worst case calculation dictated by the standards of error analysis. This is not the likely error as it is improbable that all error components will be in their worst case condition at the same instant. In fact the actual error is a probably a fraction of the worst case scenario. Examples of the worst case error analysis are included in Appendix H.

9.3 Torque Transducer

The Eaton model 1105 torque transducer and it's associated Daytronic 3178 signal conditioner are integrated into the dynamometer assembly. They measure and transmit the motor's torque output (after a 4:1 gear reduction) to the dyno control terminal. There are several sources of error in this equipment. The torque transducer error is made up of nonlinearity, hysteresis, and repeatability errors of ±0.1%, ±0.1%, and ±0.05% of full scale, respectively. The full scale measurement capability of the torque transducer is 5000 in-lbs. The Daytronic signal conditioner has an error of ±0.05% of full scale. The torque transducer errors are considered random errors and consequently the total error is determined from their root sum square (RSS= 0.15). Including the signal conditioner error, the sum of these errors is ±0.2%, corresponding to ±10 in-lbs accuracy in the dyno torque measurement. The motor torque measurement error is ±2.5 in-lbs (The 4:1 gearbox separating the dyno from the motor results in a corresponding reduction in motor torque measurement error). Additional error is introduced in measuring the motor torque due to the gearbox nonlinearities. The total accuracy in measuring motor torque is ±3 in-lbs including these gearbox variations.

9.4 Power Measurement Meter Accuracy

The Yokagawa model 2533 digital power meter has a voltage, current and power measurement accuracy of ±2% of the range up to frequencies of 20 kHz, as specified by Yokagawa. The manufacturer has not measured the accuracy above this frequency, so we measured the voltage and current frequency response of the unit up to 400 kHz. Those measurements were within ±2% of our calibrated reference signal. The power factor accuracy is specified as ±0.5% at a 0.5 PF and 60 Hz. The power factor measurements were verified at several frequencies ranging from 100 Hz to 700 Hz on the Tektronix DSA 602 oscilloscope. At low power factors, however, Yokagawa relaxes this specification to ±4% (PF=0.1). The power measurement accuracy is based on the selected range of the measurement instrument. For our tests the current range was always 155 A, dictated by a current transformer used with the test set up. The voltage range changed depending on conditions. The following is a summary of the voltage, current and power measurement errors attributed to the Yokagawa 2533 voltage range setting.

Voltage Range (V)	Voltage Error (V)	Current Error (A)	Power Error (VA)
30	±0.6	±3.1	±93
60	±1.2	±3.1	±186
100	±2.0	±3.1	±310
150	±3.0	±3.1	±465
600	±12.0	±3.1	±1860

The accuracy of the power measurements included in the data are on average good to about 10%. The error is higher than 10% on low power factor measurements and those power measurements made on the low end of the range of the instrument. The error is heavily dependent on the voltage range selection because the power error numbers given above are fixed relative to a given range. For example, if power is measured as 3000 watts with the voltage range set to 600 volts, the error is 3000 watts ±1860 W or ±62%. Due to this limitation all measurements are performed with the instrument's range adjusted to minimize this error. In certain low power, high voltage situations, however, this result is unavoidable.

9.5 Digital Meter Accuracy

The digital voltmeters used in the DC measurements were highly accurate relative to the AC power meter capabilities. In practice the DC input power to the inverter was measured using a Fluke 8600A DVM in the DC voltage mode. Input current was measured as a voltage on the 200 mV range by using a precision 0.0004949 ohm shunt resistor. The inverter input voltage was measured on the 1200 volt DC scale. These measurements are accurate to

±0.02% of input +0.008% of the range.

9.6 No Load Actuator Test Error

The measurements involved in performing the No Load Actuator Tests are relatively simple and not subject to large errors. Two signals are measured; the command amplitude, phase and frequency, and the actuator position amplitude, phase and frequency. These measurements are performed and documented on the strip chart recorder, and verified on the DSA602 scope. The DSA602 is also used to plot the position / command, X-Y plots. The source of the signals are identical D/A converters located in the motor controller card cage. These D/A converters monitor both the input command voltage and the actuator position. The D/A converters were calibrated to one another prior to the testing to an accuracy of ±5 mV. Most of the measurements were in the ±1.0 v to ±10.0 v range so the D/A accuracy is negligible. The small signal measurements in the 150 mV range were more susceptible to random noise present in the environment. This is noticeable on the X-Y plots as random data points. The strip chart recorder was particularly adept at reducing environmental noise. Its differential inputs and noise filters effectively eliminated this noise from the plots. The steps that are noticeable in the small signal position traces are caused by the 5 m/Sec update time of the D/A converters. The total error associated with the no load actuator tests is about ±3%.

9.7 Cumulative Calculation Errors

Appendix H, Worst Case Error Analysis, contains examples of the error analysis applied to the experimental data. These calculations demonstrate the large errors that result from the cumulative affect of errors in successive calculations. These error margins should be considered as a worst case probability only, when evaluating the test data. The realistic value for error margins is significantly less than the worst case error analysis indicates. Measurements made at low powers, high voltages relative to range and low power factors have greater maximum errors. In general, most of the calculated values are accurate to within 10% of their stated values.

10. SUMMARY OF TEST DATA

The Sundstrand induction motor for this project was designed for minimum losses and low inertia. A byproduct of these general design goals is low leakage inductance in the motor. Low inductance is a common characteristic of high horsepower motors where a current source converter would typically be used instead of a voltage source converter to drive the low inductance motors. Since the controller used here is a voltage source, as are most PWM type controllers, the current rate of rise in the windings is equal to the applied input voltage minus the back EMF voltage divided by the leakage inductance. When the motor inductance is low, the rate of rise of current is high, and therefore the current ripple is large. To reduce the ripple, an inductor can be added to the motor windings, or the switching frequency could be increased, or an alternate converter topology could be used. Since the second two solutions would mean considerable redesign, the motor inductance was increased by the addition of an inductor in series with the motor windings. Some actual phase current waveforms are shown in Appendix I.

The full scale system has been verified for operation up to about 31 HP. At motor rates below 8000 rpm, full torque capability has been demonstrated. At motor rates above 8000 rpm the controller starts saturating and the actual current does not follow the current reference. Testing revealed that the system is not producing the motor torque it should, based on predictions from the motor's manufacturer. Simulations performed by Krause and Associates for NASA, identified this as a potential problem due to limitations in the current regulator caused by insufficient motor voltage. Since an inductor has been placed in series with the motor phase windings to decrease the large ripple currents by increasing the controller output impedance, the voltage is also lowered across the motor windings by the voltage drop in the series inductors. The current regulator therefore starts saturating at the higher commanded motor voltages. The applied motor voltage is proportional to motor input frequency, resulting in an increase in current error and in an accompanying increase in lower frequency harmonics at the higher motor rates, and therefore reduced power output. A value of 50uH is a compromise between higher ripple currents and output voltage saturation.

During preliminary testing in San Diego, a power switch in the motor bridge failed. The failure occurred at 200 Arms/phase and is the result of exceeding the maximum allowed junction temperature. The current reached the commanded value but failed shortly afterward. To eliminate this failure mode the heat load or the plate temperature must be reduced. To reduce the heat load, the present power switches could be replaced by the lower vsat switches. Replacing the switches would reduce the average vsat from 3.5 volts to 2.7 volts, resulting in a 23% decrease in the conduction losses, the main contributor to overall losses. To lower the base plate temperature, the cold plate temperature could be lowered or the interface could be redesigned. The power stage base plate, whose base is a flat plate that measures 12" by 18", is attached to a cold plate with machine screws. Thermal compound is spread between the surfaces to eliminate any voids that may result. It is difficult to get even pressure at the metal to metal contact between the two large flat plates, resulting in higher thermal impedance. The thermal calculations originally done on the box interface were based on ideal interface conditions, which could not be achieved with the present design. The cold plate temperature was therefore lowered from around 27 degrees C to around 15 degrees C. This temperature is just above the condensation point here, though this needs to be watched for varying climatic conditions. No other similar failures have been observed since decreasing the cold plate temperature.

The overall system efficiency was tested at a maximum of about 83%. The motor efficiency peaked at 86%. The controller power stage efficiencies measured as high as 97% respectively. In general, the efficiency calculations are good to approximately ±5%, although worst case analysis indicates about ±10%. All of these efficiencies are in the range anticipated for the system. Power loss analysis of the controller power stage predicted > 90% efficiencies.

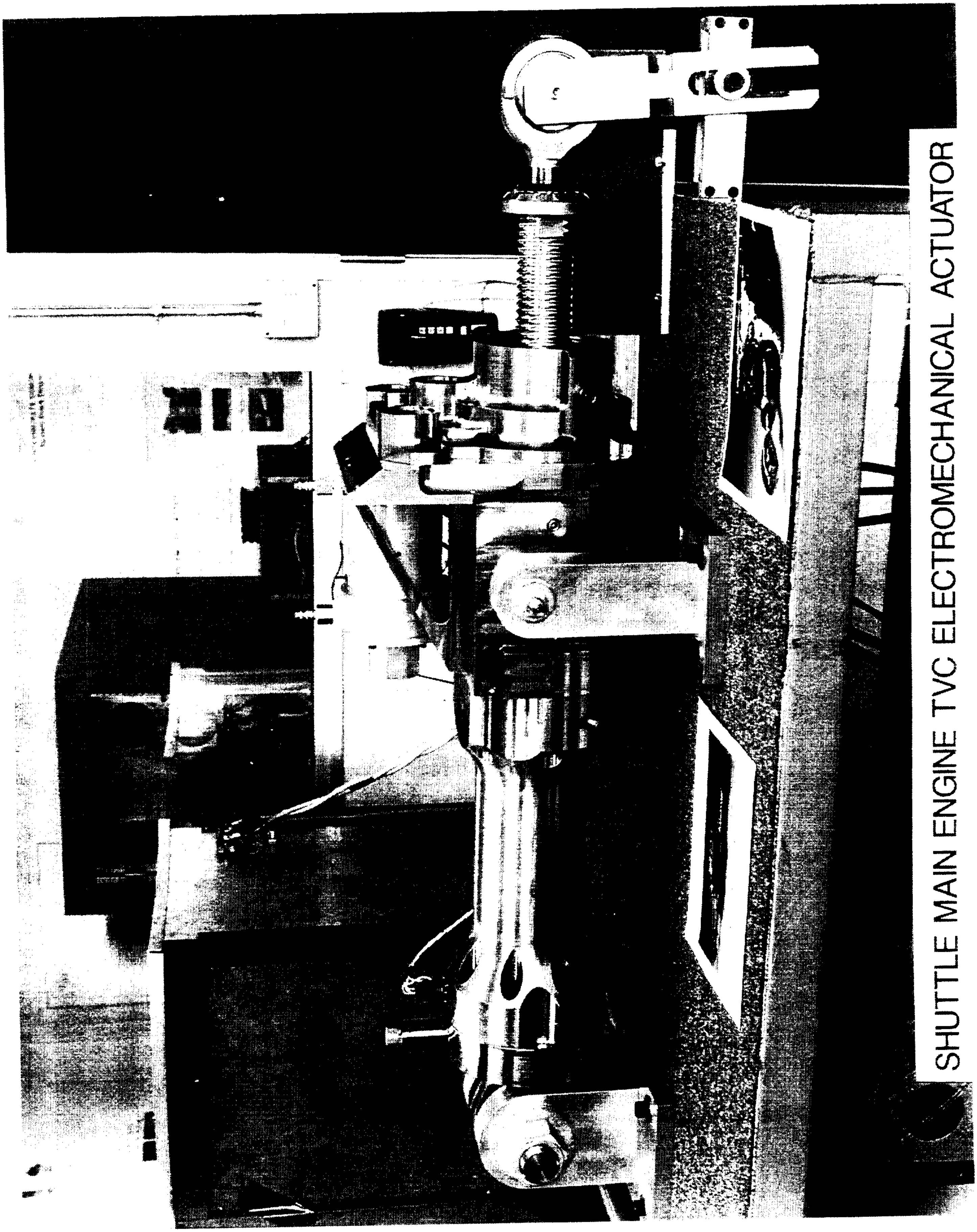
The step response of the loaded actuator is 770mSec for a 10 inch step. The large signal step is not really indicative of the controller bandwidth, as the motor spends most of the transition time with the motor revs limited.

The inertial load actuator tests indicated a system frequency response of approximately 4 Hz for the 2% input command (±0.1") at 200 A/phase with a strong resonance showing up at around 9 Hz. As can be seen from the gain-phase plots, the controller gain is not sufficiently down by the 180 degree crossover point of the phase, thereby presenting stability problems for the controller. The frequency response of the system is less at higher amplitudes or lower phase currents. The frequency response of the system may be adjusted by changing the control constants or the phase currents as demonstrated by the test data. Adjustment of these parameters is available via the computer terminal interface. The actuator test data is accurate to, at worst, about ±3%.

The worst case error analysis revealed potentially large deviations in the measured motor data. The errors may be attributed to two areas. The first is the relative inaccuracy of the AC power measurements. The available test equipment (Yokagawa 2533) is specified as 2% accurate at full scale and high power factors. Our system often operates at lower power factors and fractions of the full scale meter readings. This results in potential errors of about 10% of the measured values.

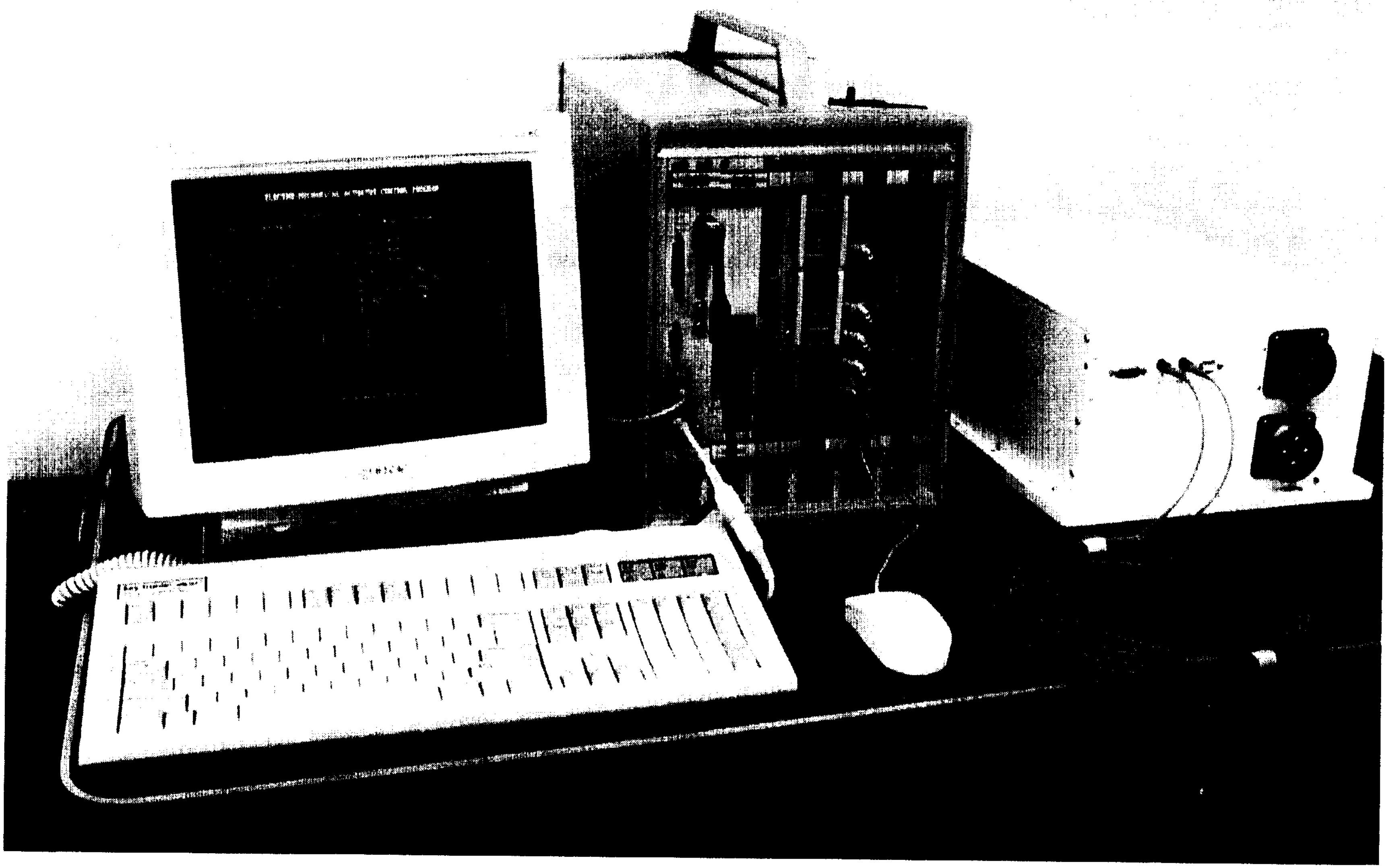
APPENDIX A

DRAWINGS

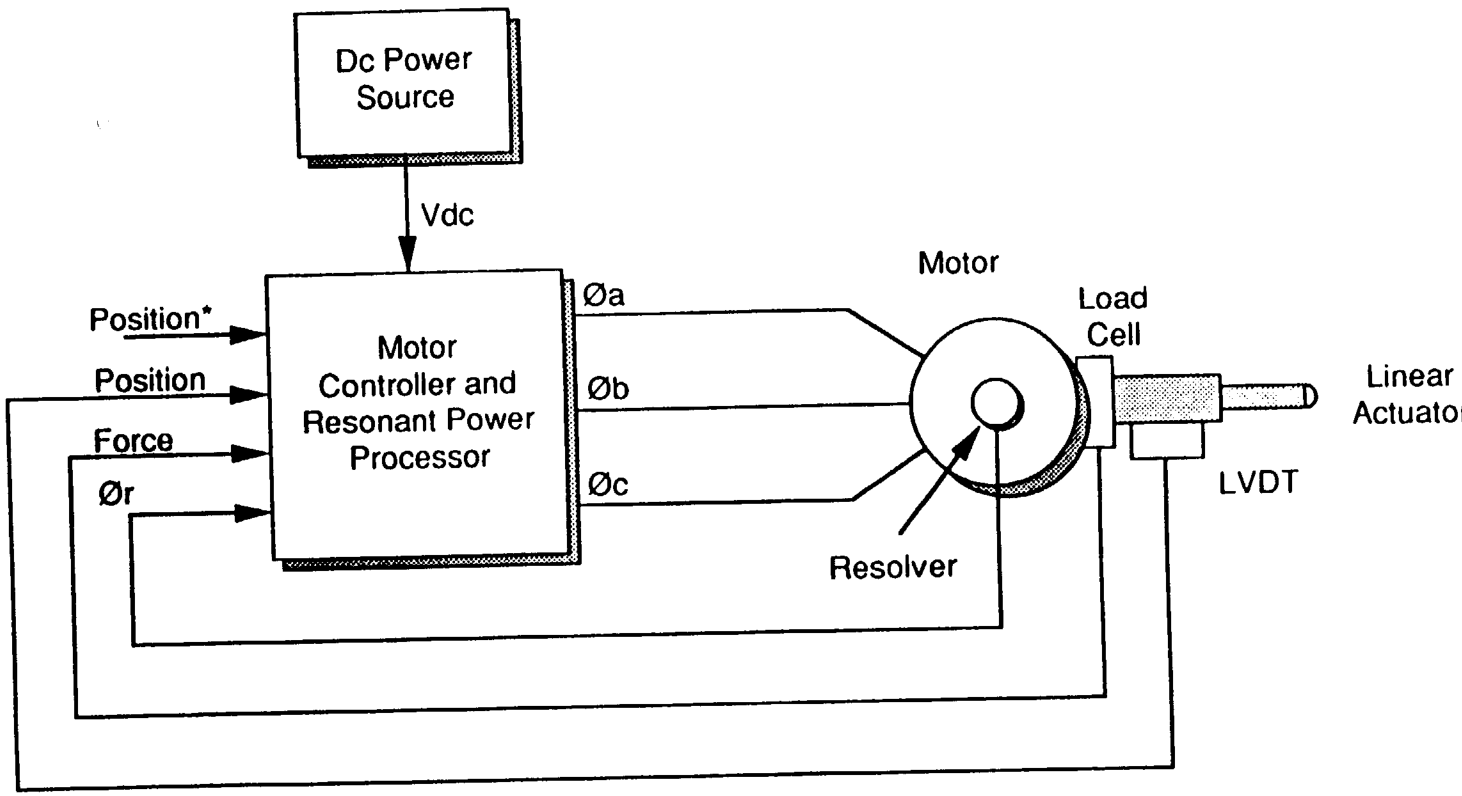


SHUTTLE MAIN ENGINE TVC ELECTROMECHANICAL ACTUATOR

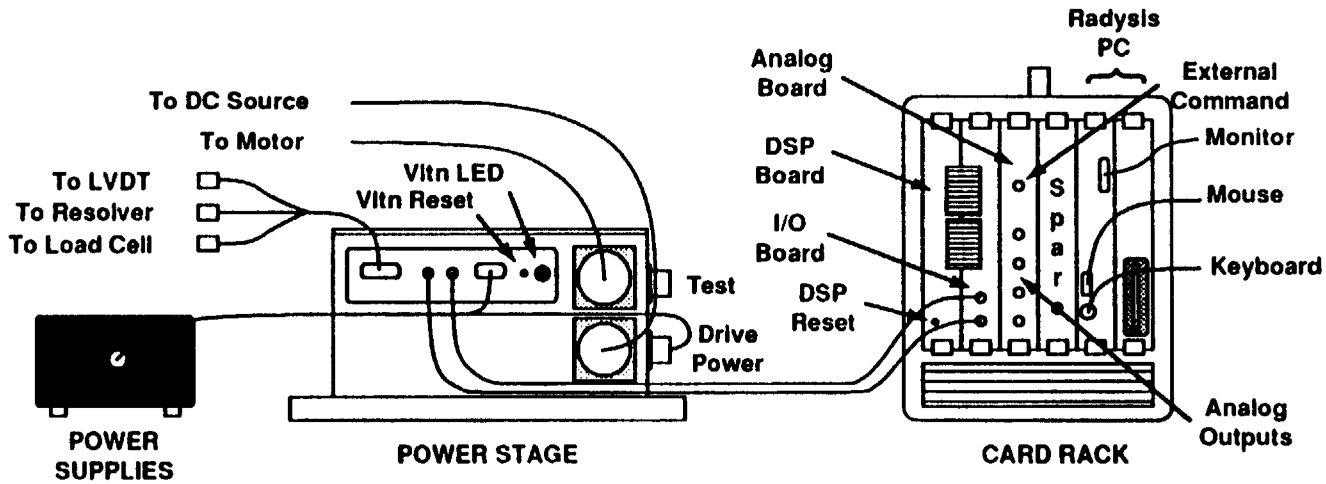
C-93-05000



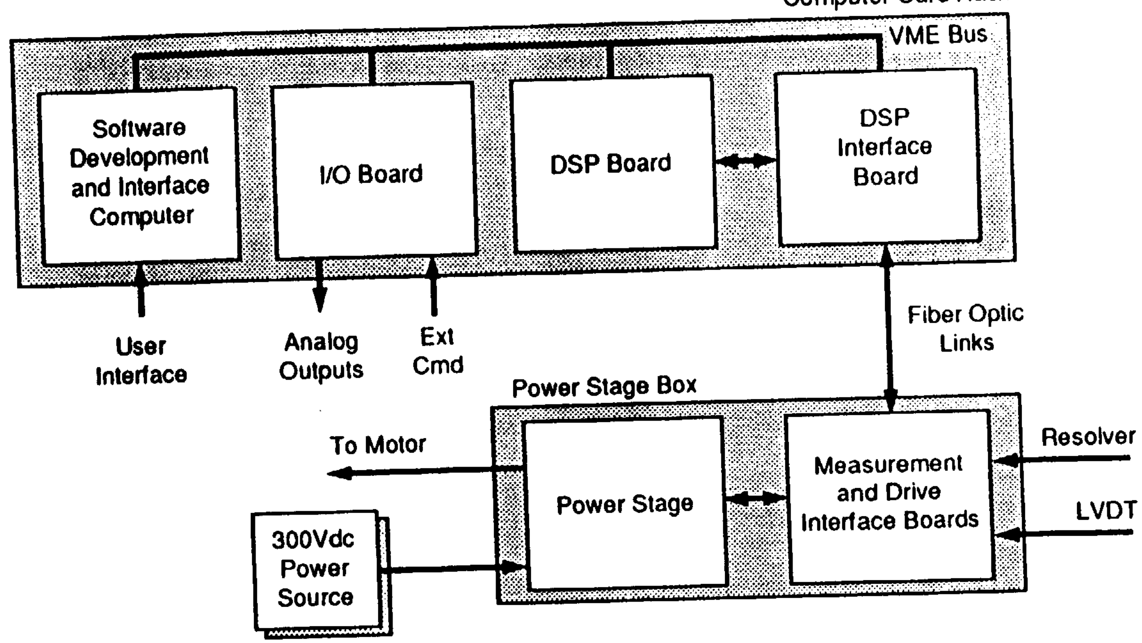
70Hp DC RESONANT LINK ELA CONTROLLER



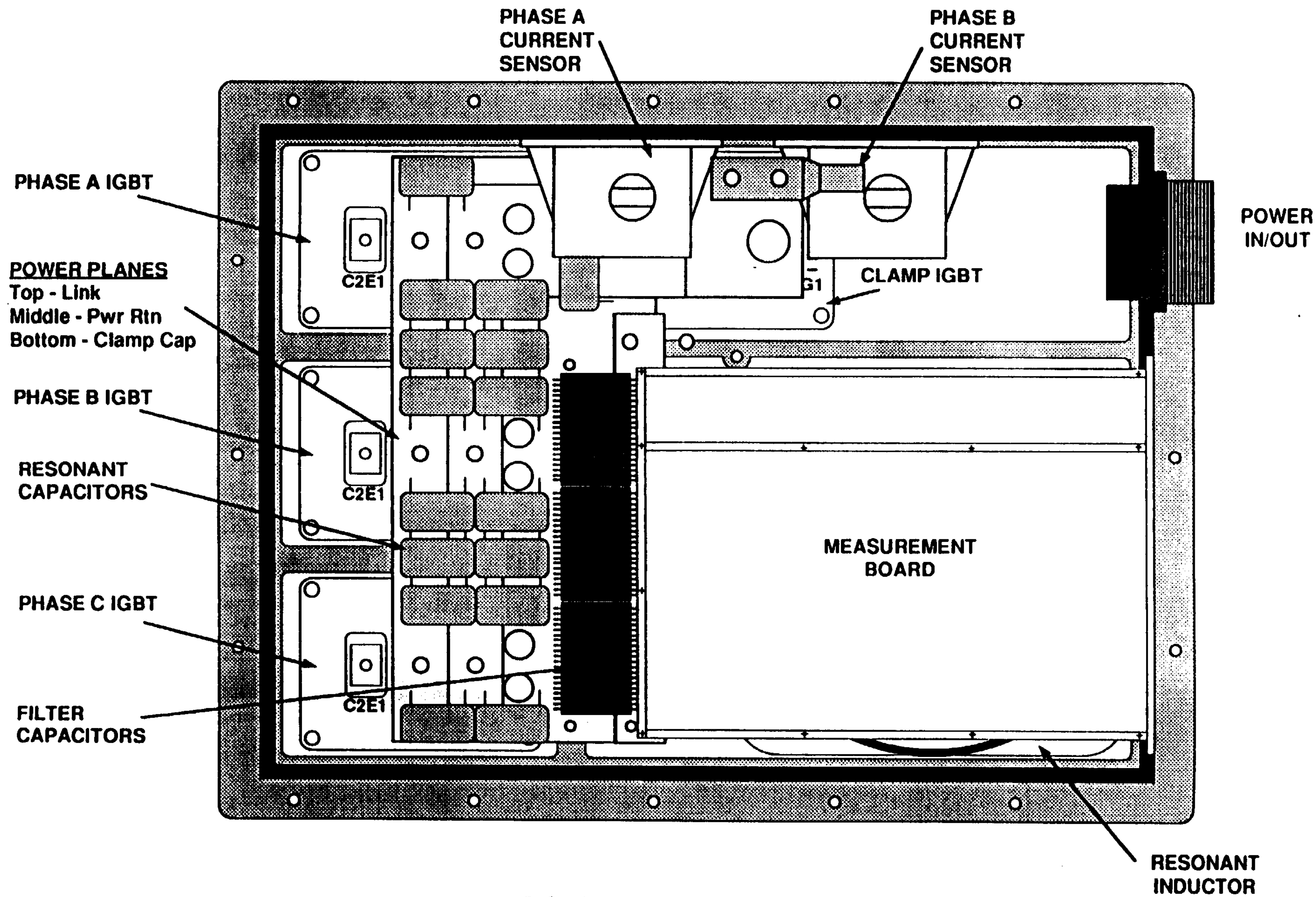
70 HP ELECTROMECHANICAL ACTUATOR SYSTEM DIAGRAM



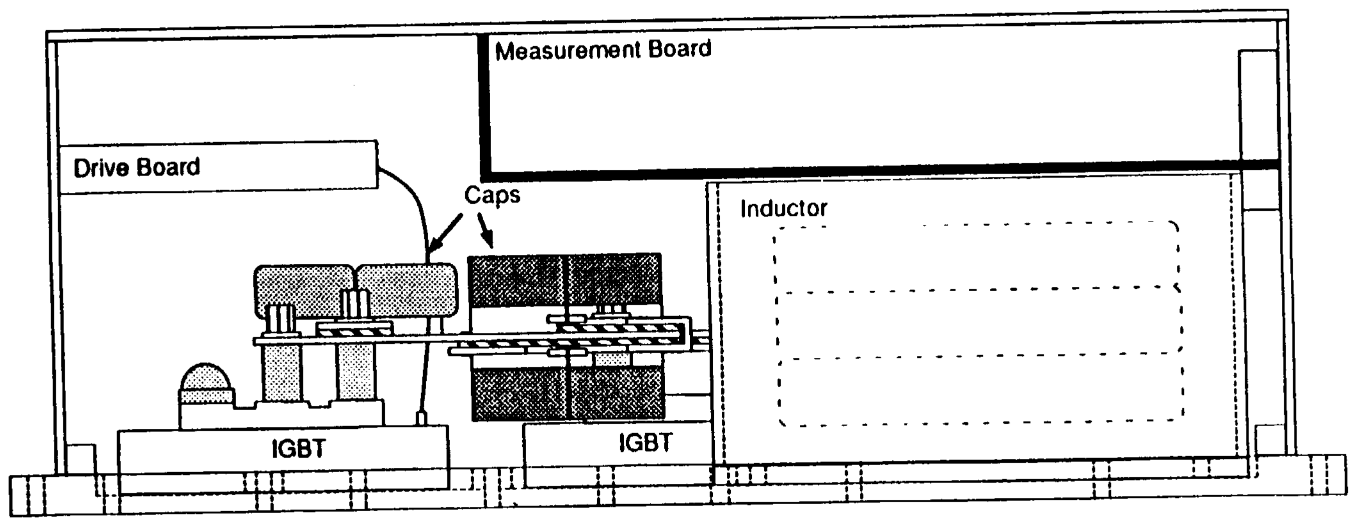
MOTOR CONTROLLER SYSTEM CONFIGURATION



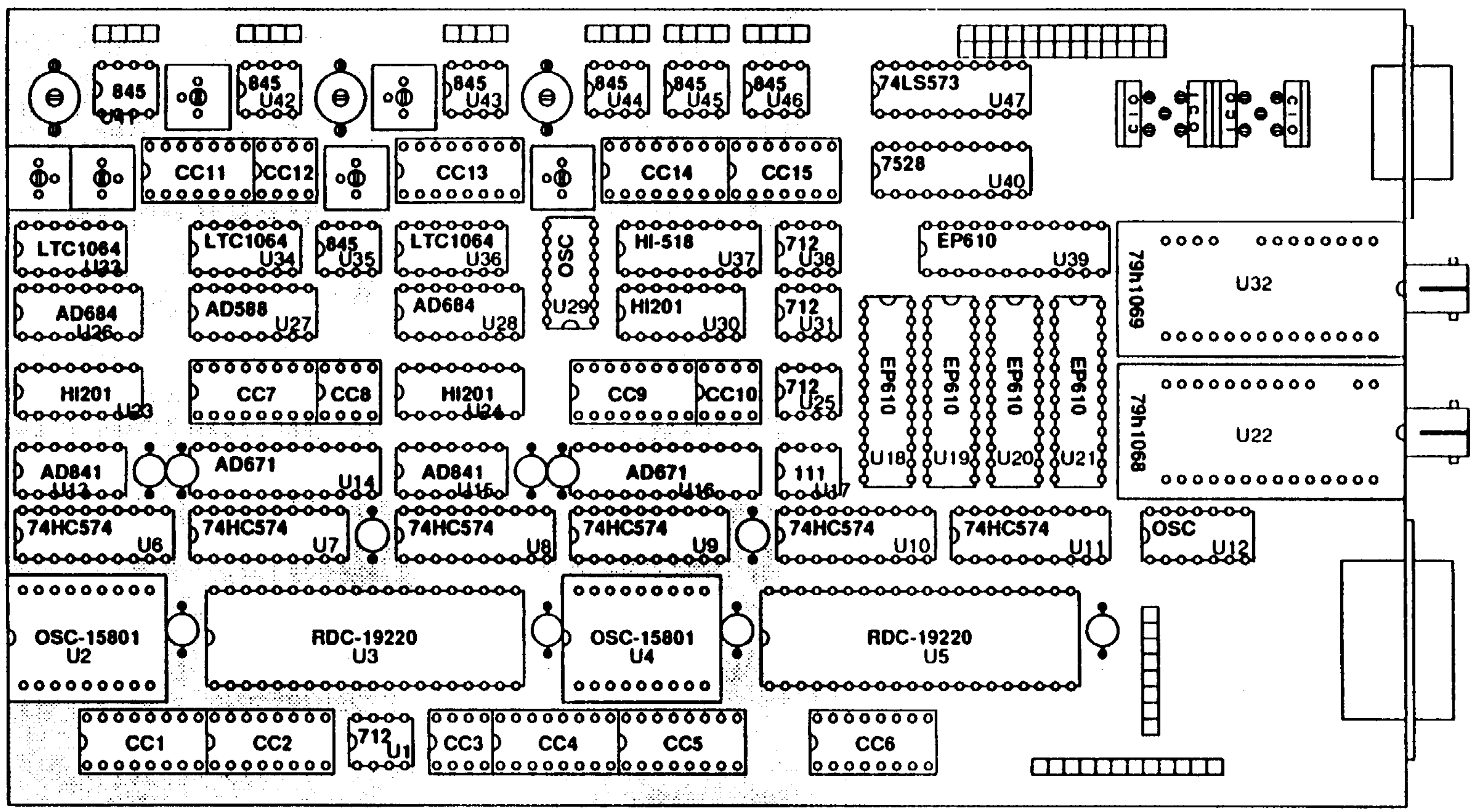
COMPUTER AND POWER STAGE INTERFACES



POWER STAGE LAYOUT



POWER STAGE LAYOUT - SIDE VIEW



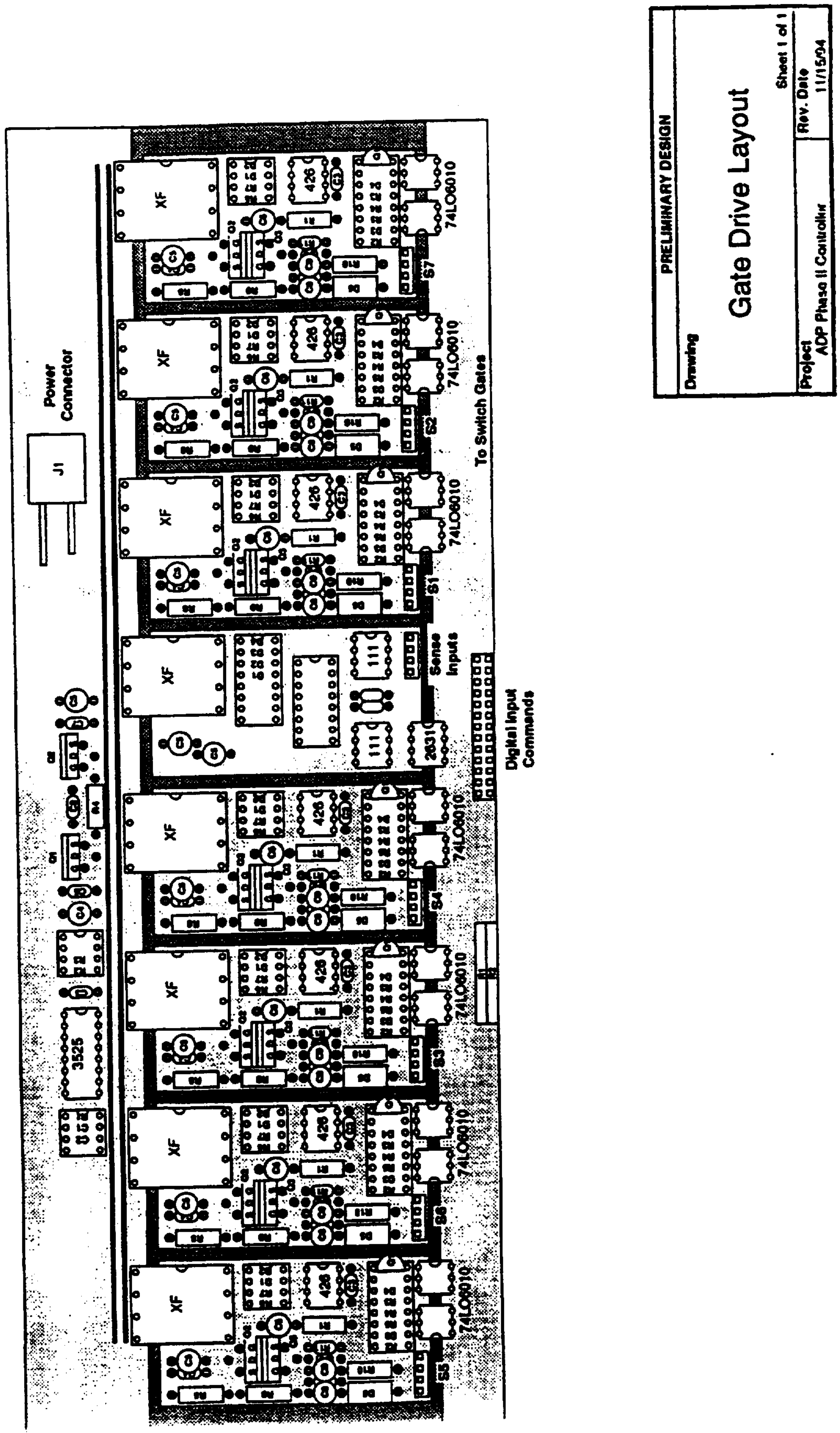
PRELIMINARY DESIGN

Drawing

Measurement Bd Layout

Sheet 1 of 1

Project	**Rev. Date**
ADP Phase II Controller	11/15/94


PRELIMINARY DESIGN
Drawing
Gate Drive Layout
Sheet 1 of 1
Project
ADP Phase II Controller
Rev. Date
11/15/94
Power Connector
J1
To Switch Gates
Sense Inputs
Digital Input Commands
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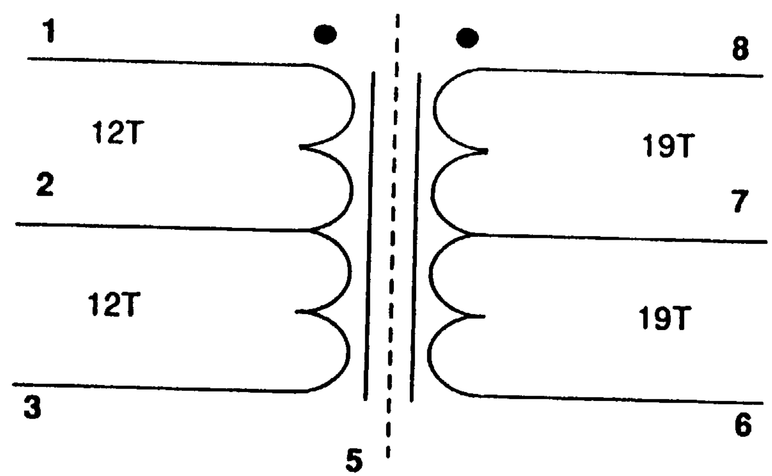
ELECTRICAL



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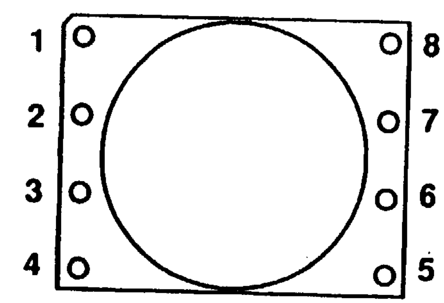


PRELIMINARY DESIGN

Drawing

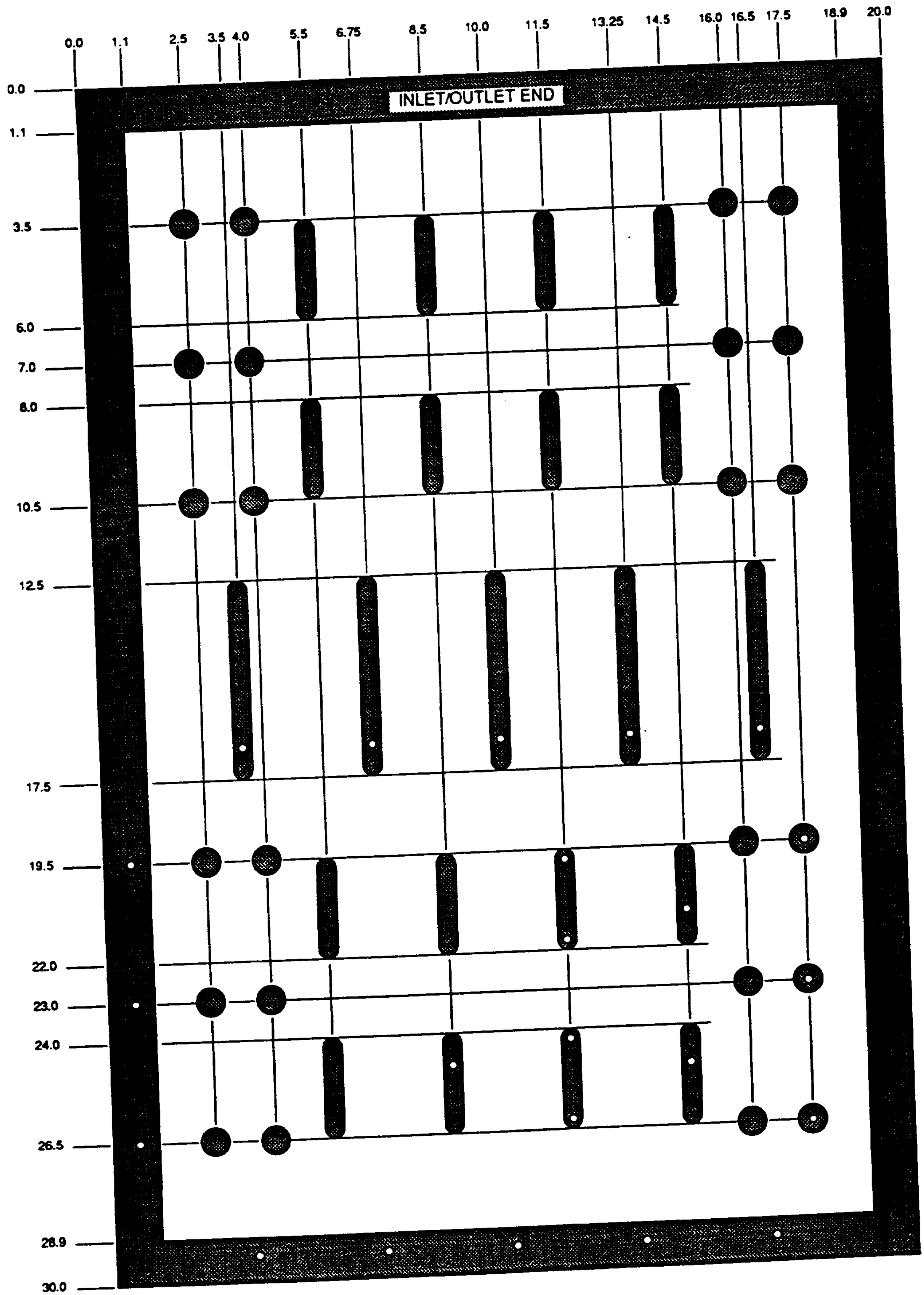
Gate Drive Transformer

Sheet 1 of 1

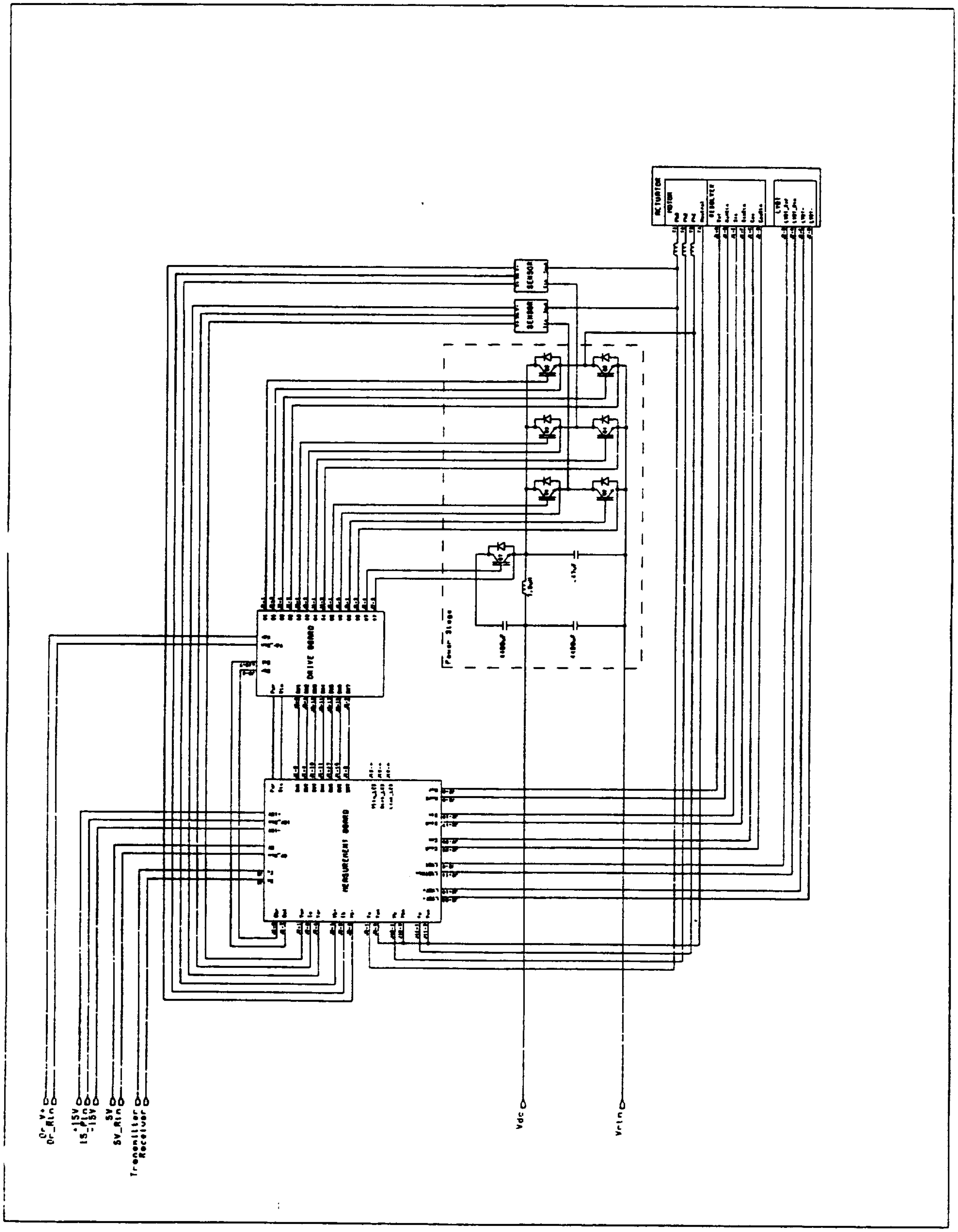
Project
ADP Phase II Controller

Rev. Date
[illegible]7/92

COLD PLATE DRILL PATTERN



Round mounting posts are 0.75" dia.
Mounting ribs are 0.5" wide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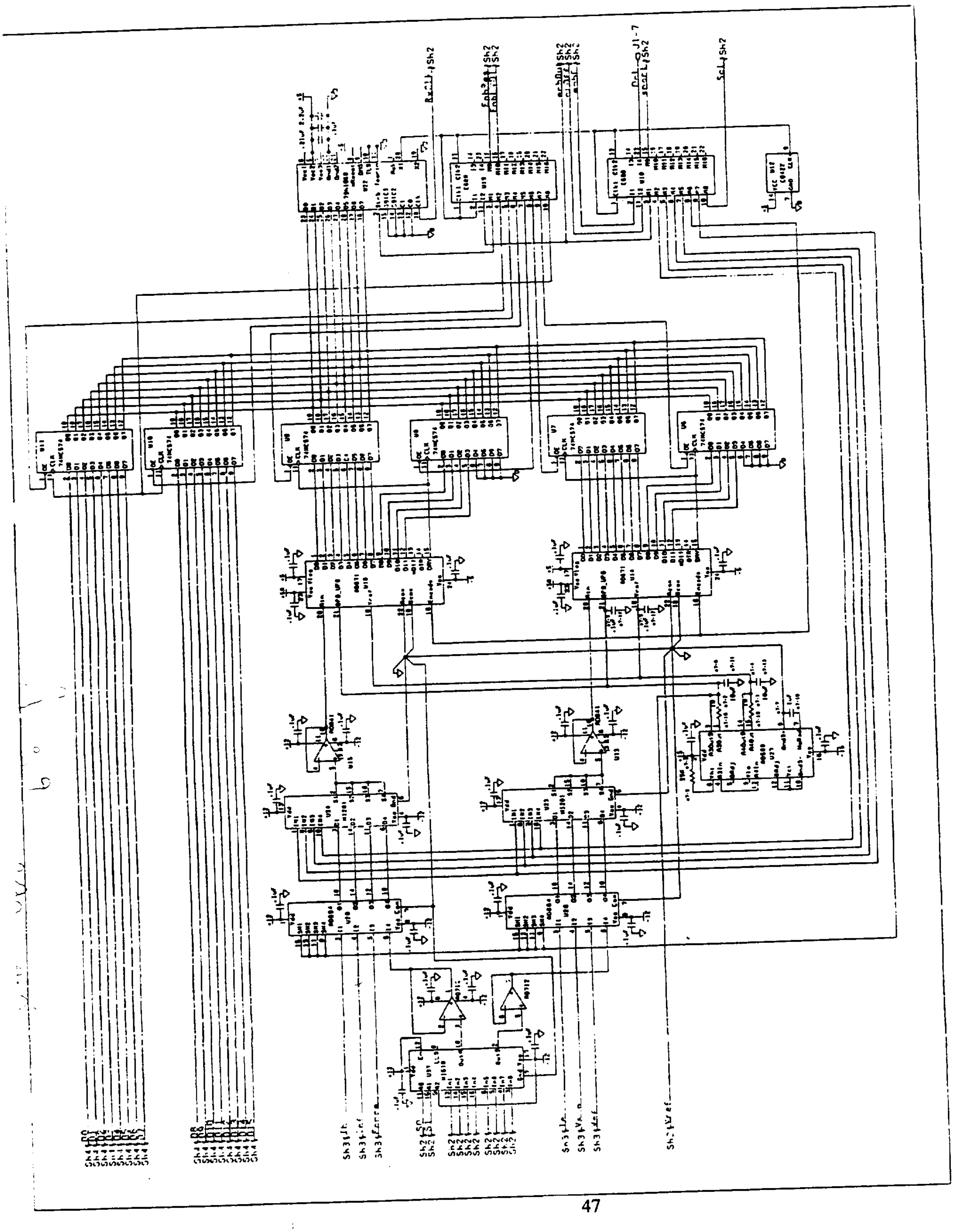
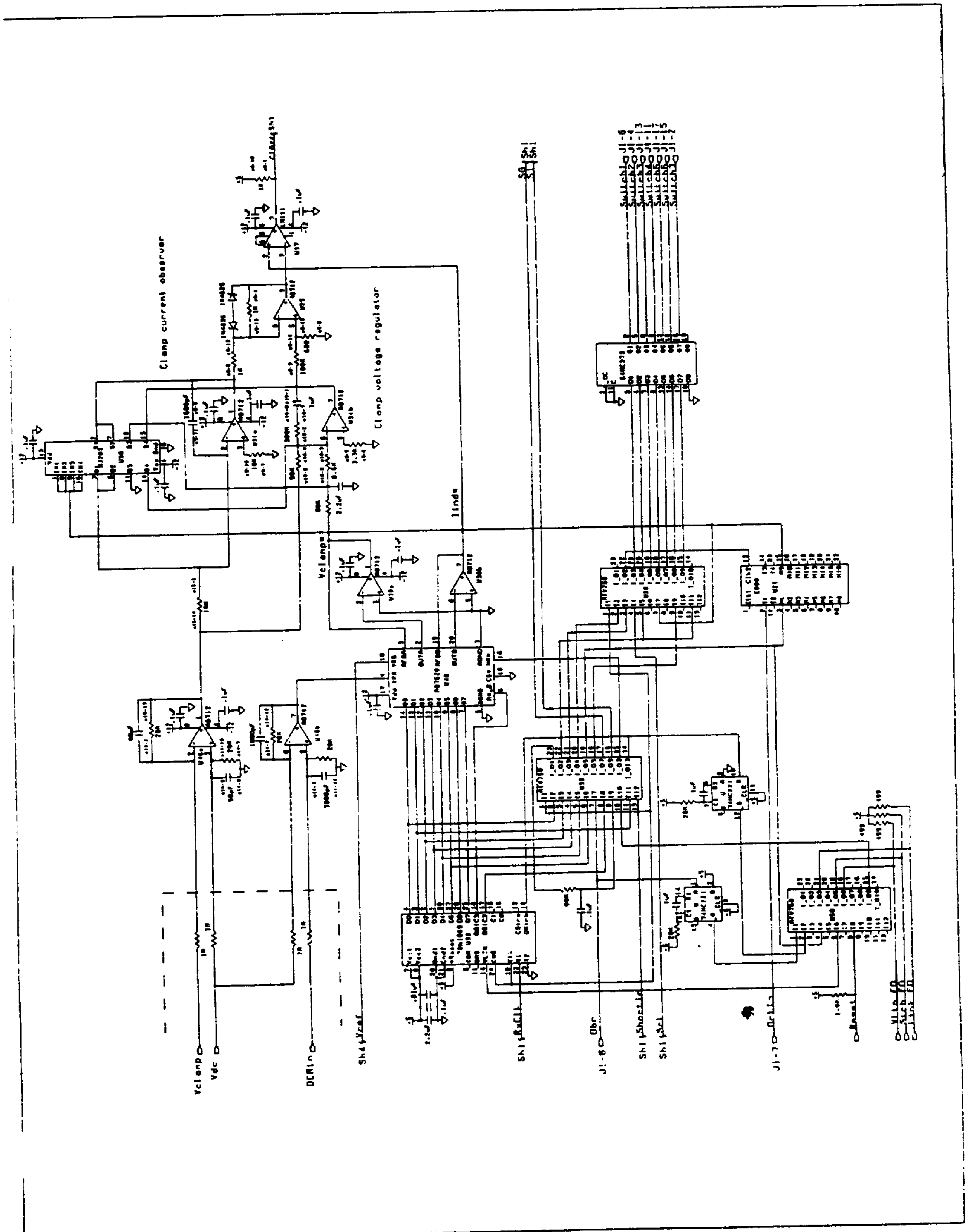
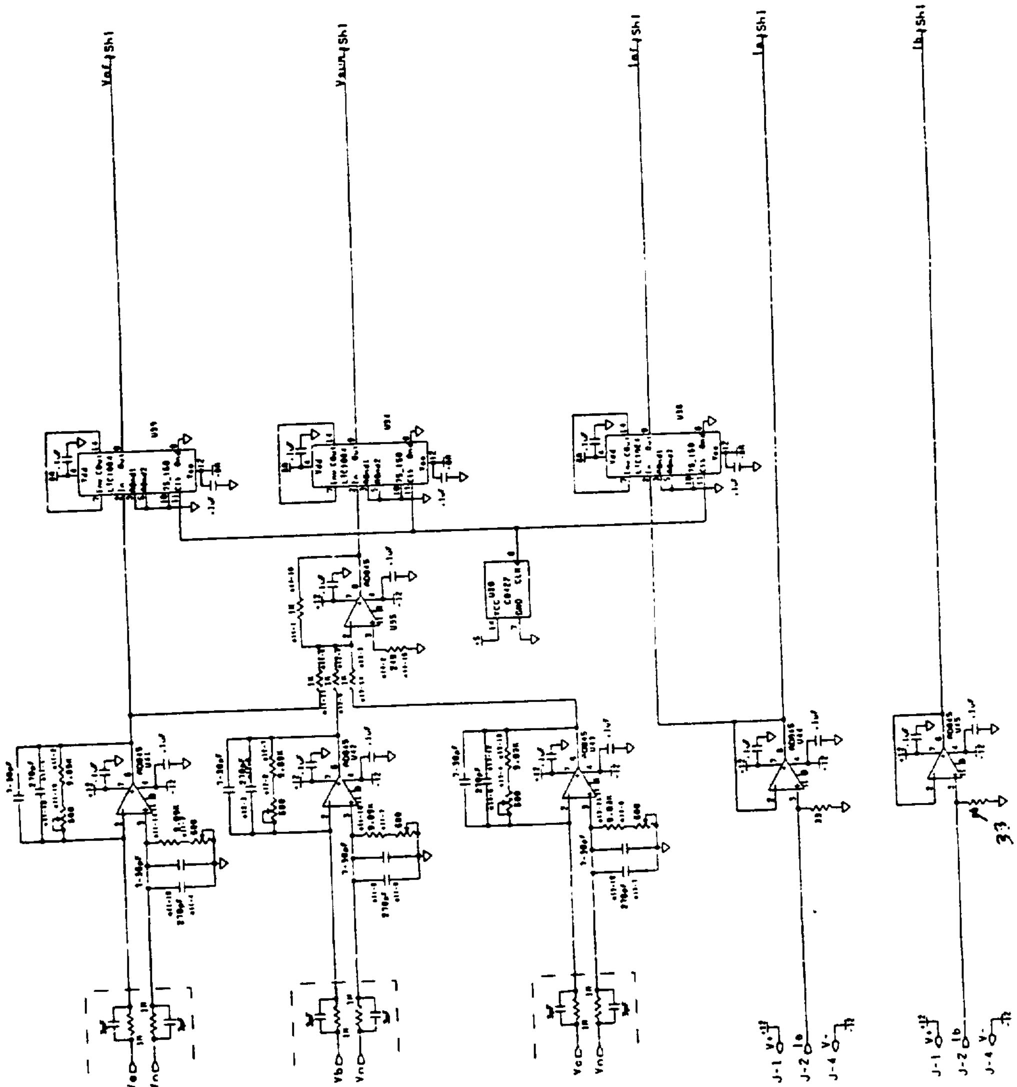
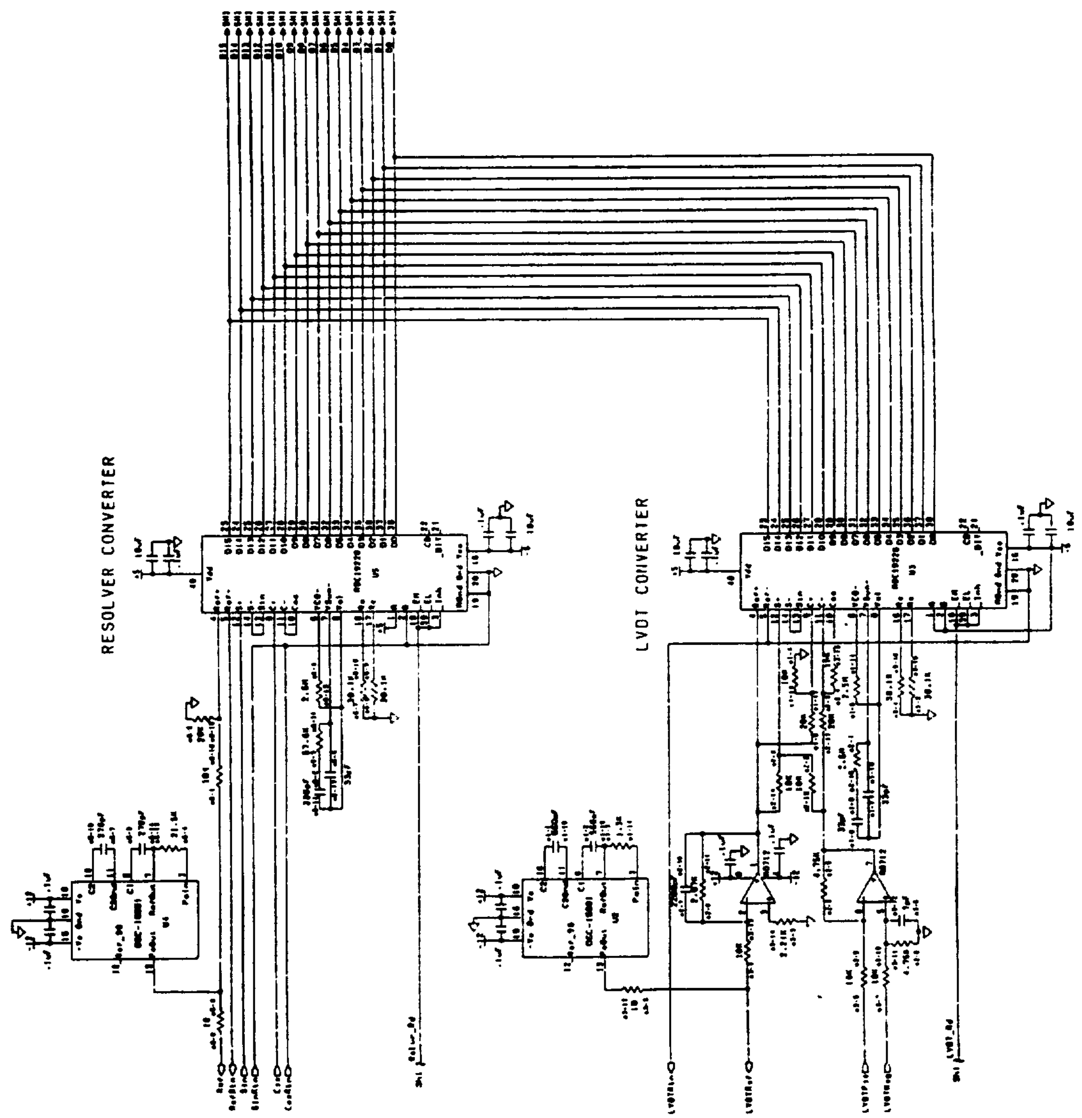
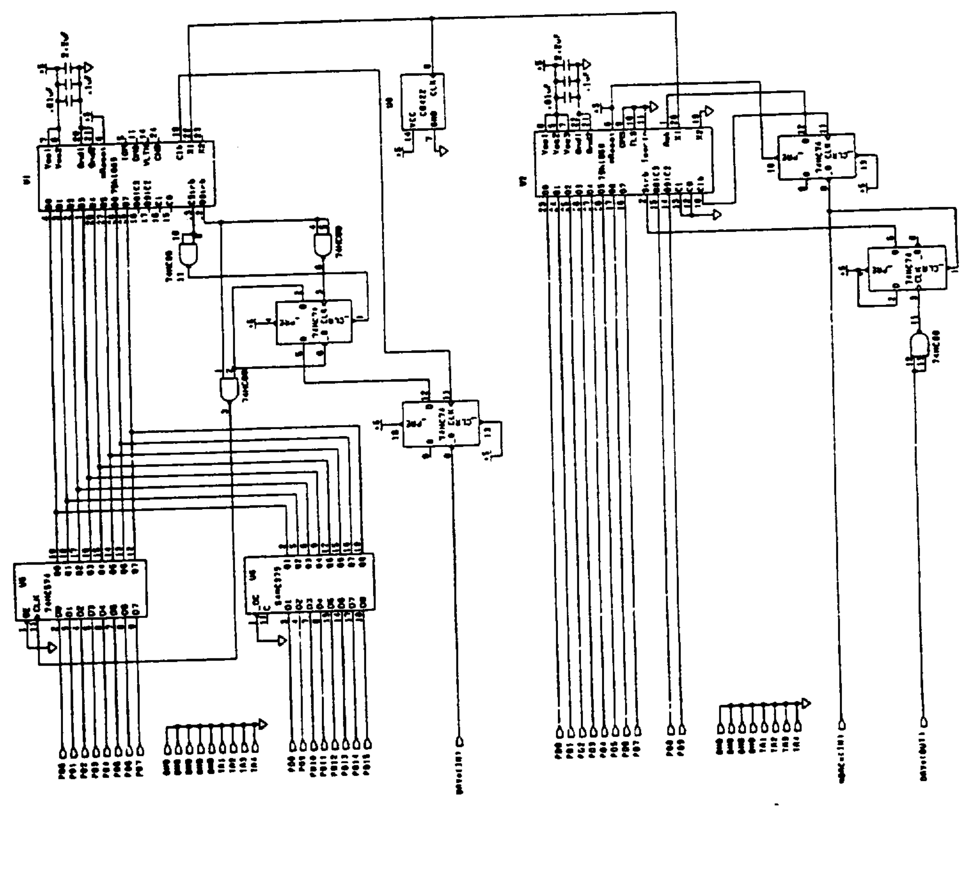
MOTOR
RESOLVER
LVDT
SENSOR
SENSOR
Power Stage
DRIVE BOARD
MEASUREMENT BOARD
Vdc
Vrin
Transmitter
Receiver

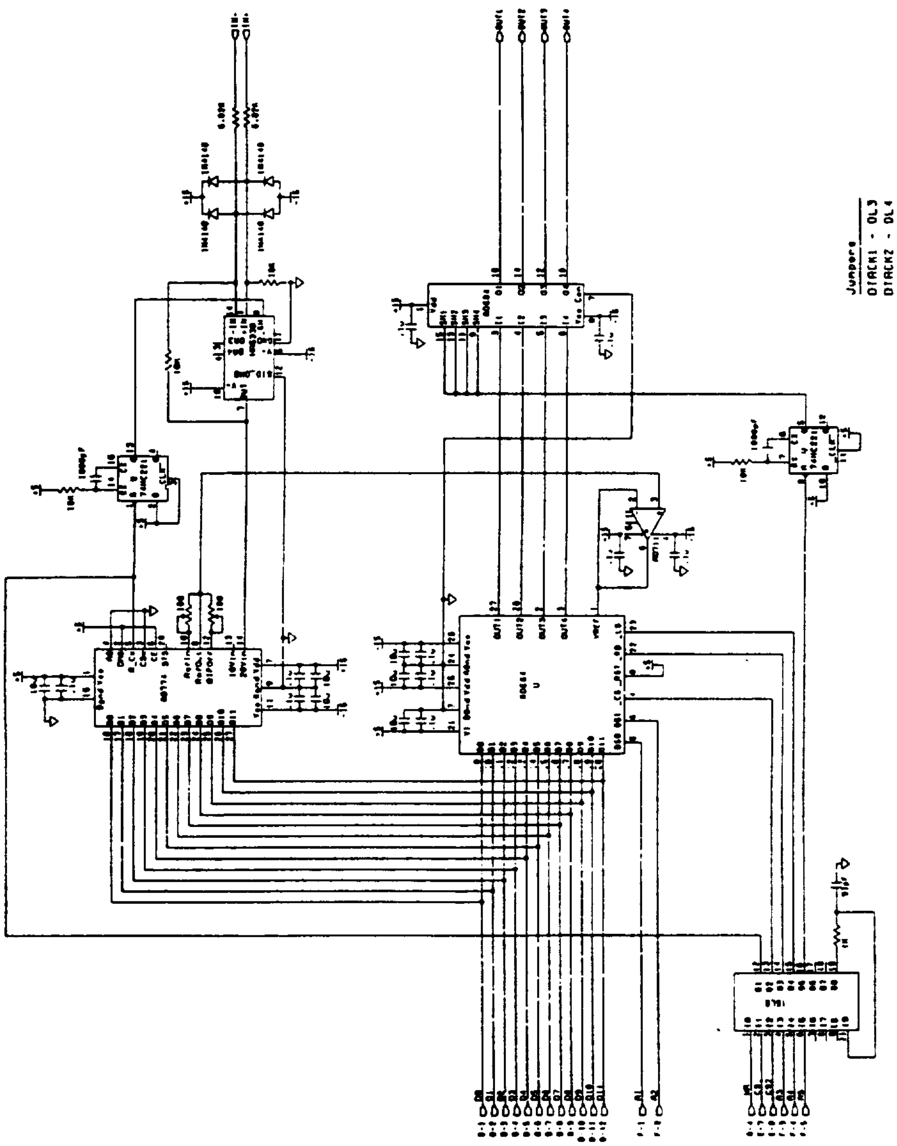


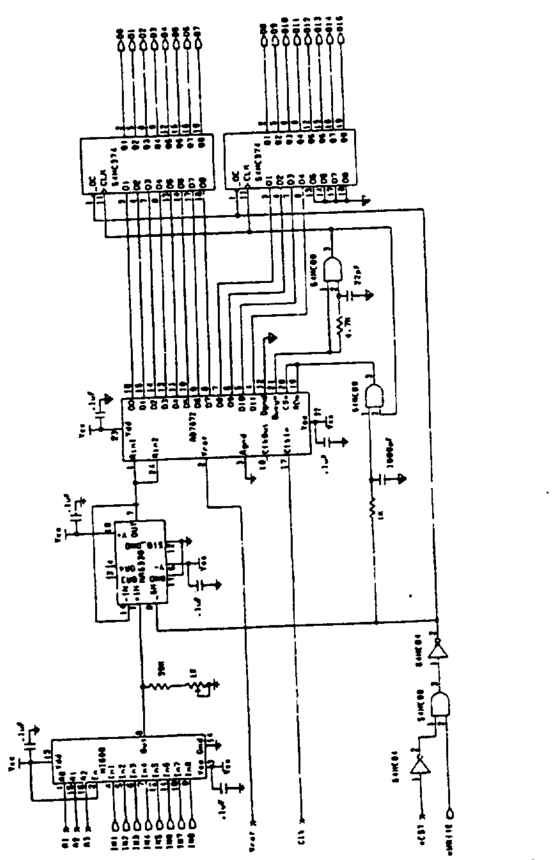

Clamp current observer
Clamp voltage regulator
Vclamp
Vdc
DCRin

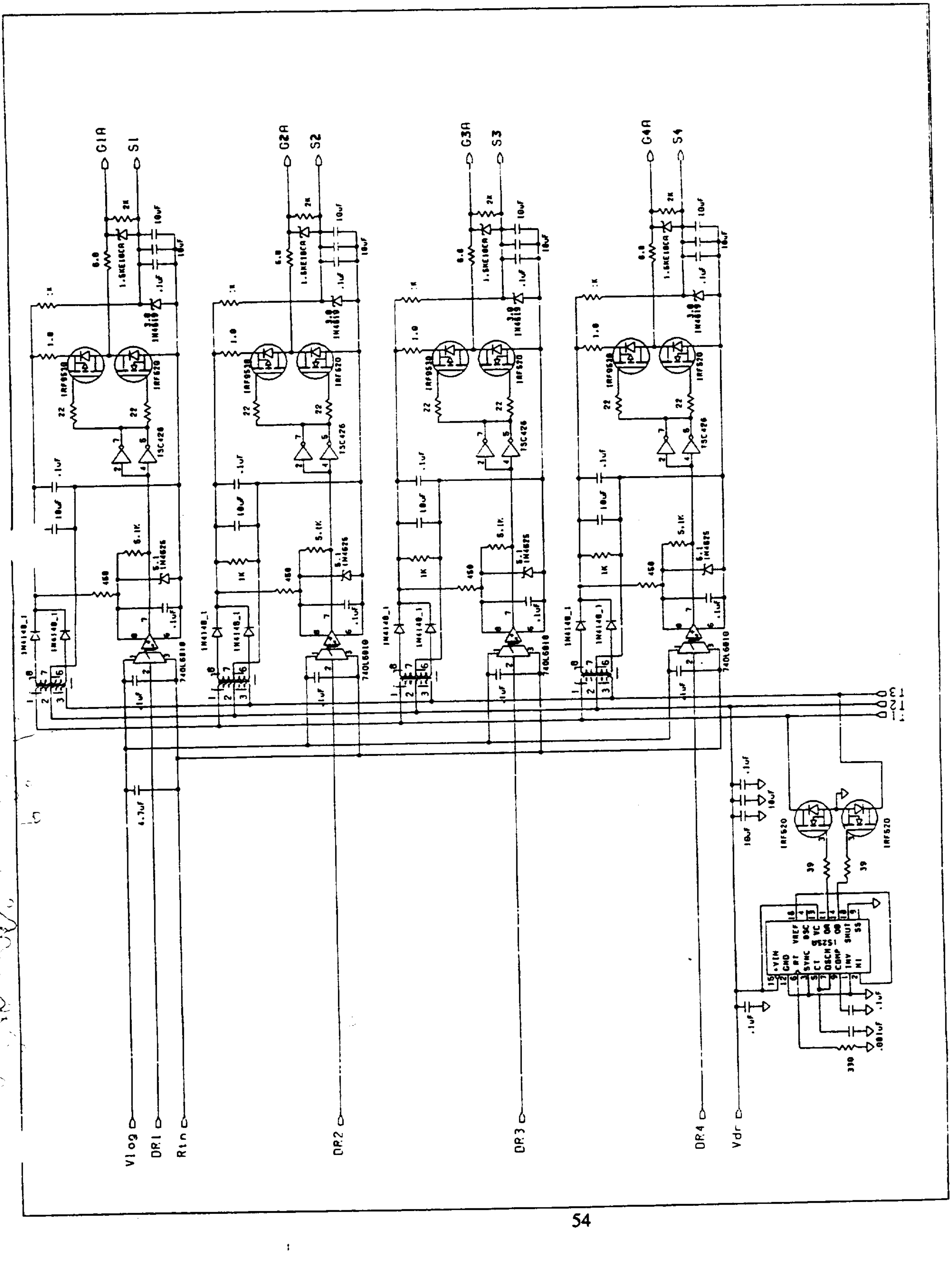


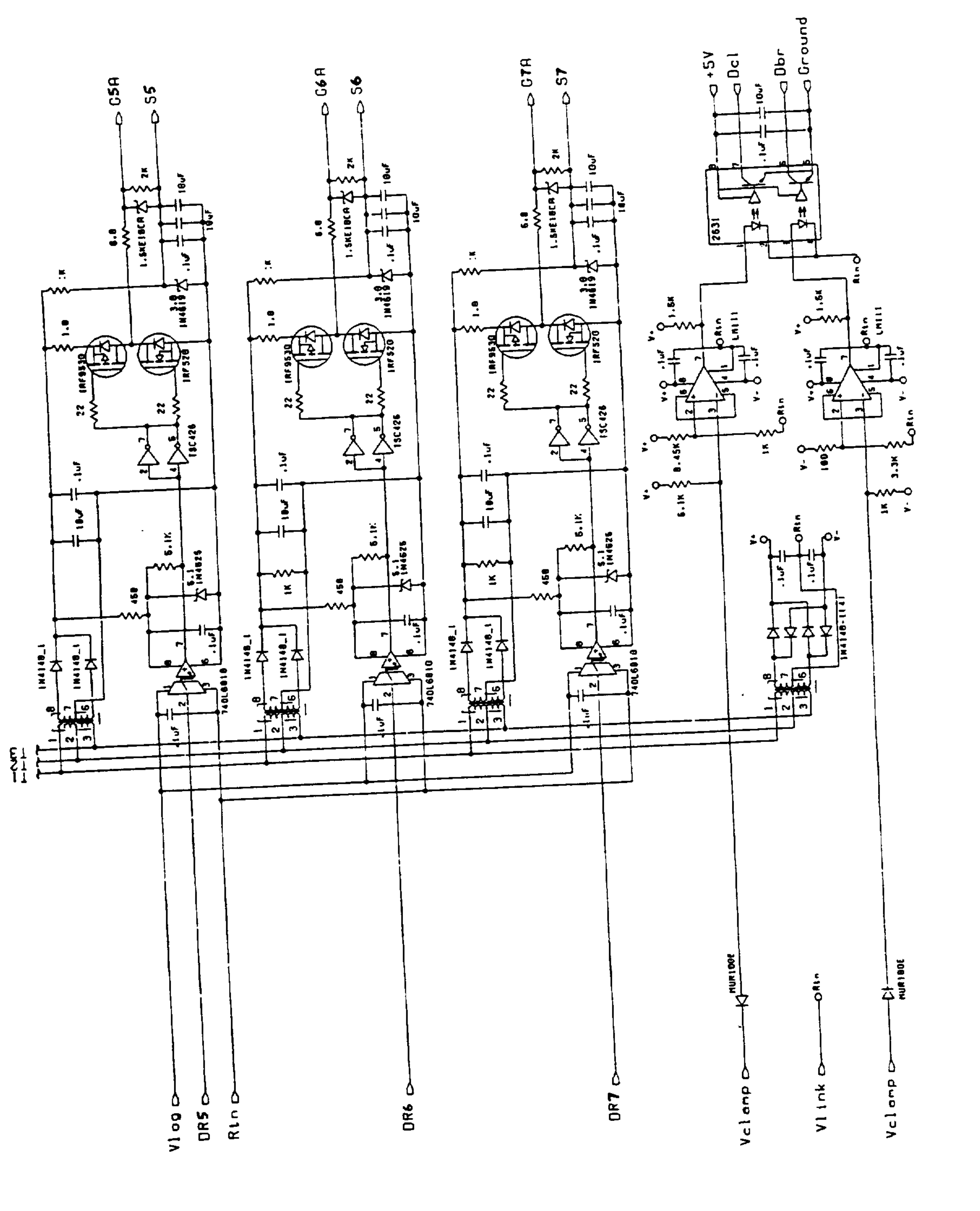

RESOLVER CONVERTER
LVDT CONVERTER




Jumpers
DTACK1 - DL3
DTACK2 - DL4




G1A
S1
G2A
S2
G3A
S3
G4A
S4
IRF9530
IRF520
1.5KE18CA
1N4619
TSC426
1N4148_1
1N4625
Vlog
DR1
Rtn
DR2
DR3
DR4
Vdr
VREF
OSC
SYNC
GND
+VIN
CT
RT
COMP
INV
NI
SHUT
SS


G5A
S5
G6A
S6
G7A
S7
+5V
Dcl
Dbr
Ground
Vlog
DR5
Rtn
DR6
DR7
Vclamp
Vlink
Vclamp

APPENDIX B

Motor Parameters Test Data; GDSS and Sundstrand

The tables containing the measured data have column headings defined below:

Heading	Definition
Core Loss Resistance (Ohms)	The calculated core loss resistance of the induction motor.
Current (A) One Phase	The measured stator current amps per phase.
Current (A) Single Phase	The measured stator current amps per phase.
FREQ Hz	The stator drive frequency.
Ids (A)	The commanded value of Ids.
Impedance Single Phase (Ohms)	The impedance of the motor at its fundamental frequency.
Iqs Ids (A)	The commanded value of Iqs and Ids in amps.
Leakage Inductance (Henries)	The calculated leakage inductance of the motor in Henries.
Magnetizing Inductance (Henries)	The calculated magnetizing inductance of the induction motor in Henries.
Power (W) One Phase All Harm.	The real power into a single phase of the motor.
Power (W) Single Phase	The real power into a single phase of the motor.
Rotor Resistance (Ohms)	The calculated rotor resistance in ohms.
Stator Resistance (Ohms)	The measured stator resistance in ohms.
Temp, Mtr Deg. F	The temperature of the motor's stator in Degrees Fahrenheit.
Volts L-N All Harm.	The motor voltage from line to neutral including all harmonics.
Volts L-N Fund	The motor voltage from line to neutral of the fundamental stator drive frequency.
Volts L-N Harmonics	The motor voltage from line to neutral including all harmonics.
Volts L-N	The motor voltage from line to neutral including all harmonics.

NO LOAD 5-.. .93; GDSS

V Fund. Measured w/TEK 602 Scope, Filtered Diff Amp + Avg (8)						Vlink = 350			
All Harmonic V, I, Power w/Yokogawa 2533; No Load									
FREQ	Ids	TEMP, MTR	Volts	Volts	Current (A)	Power (W)	Core Loss	Impedance	Magnetizing
Hz	(A)	Degrees F	L-N	L-N	Single Phase	Single Phase	Resistance	Single Phase	Inductance
			Fund.	Harmonics			(Ohms)	(Ohms)	(Henries)
150	30	150	9.6	23	28	99	5.34E+00	3.43E-01	3.89E-04
150	40	150	12.8	27.5	36.8	163	4.64E+00	3.48E-01	3.99E-04
150	50	150	15.5	35	45.8	249	4.92E+00	3.38E-01	3.86E-04
150	60	150	18	42.7	54.9	350	5.21E+00	3.28E-01	3.71E-04
225	30	150	14.1	24.7	28.1	107	5.70E+00	5.02E-01	3.89E-04
225	40	150	18.8	31.9	37.3	188	5.41E+00	5.04E-01	3.93E-04
225	50	150	22.9	37.5	46.5	285	4.93E+00	4.92E-01	3.87E-04
225	60	150	27	47.1	55.8	390	5.69E+00	4.84E-01	3.74E-04
448	30	150	30.6	38.2	28.5	158	9.24E+00	1.07E+00	4.32E-04
448	40	150	40.6	49	37.6	267	8.99E+00	1.08E+00	4.36E-04
448	50	150	49	59.3	46.4	400	8.79E+00	1.06E+00	4.27E-04
448	60	150	56.8	69.1	55.8	553	8.63E+00	1.02E+00	4.10E-04

NO LOAD

FREQ	Ids	TEMP, MTR	Volts	Volts	Current (A)	Power (W)	Core Loss	Impedance	Magnetizing
Hz	(A)	Degrees F	L-N	L-N	Single Phase	Single Phase	Resistance	Single Phase	Inductance
			Fund.	Harmonics			(Ohms)	(Ohms)	(Henries)
585	30	150	36.1	43	27.7	180	1.03E+01	1.30E+00	4.06E-04
585	40	150	47.1	54.8	36.7	285	1.05E+01	1.28E+00	3.98E-04
585	50	150	58.6	66.8	46.4	450	9.92E+00	1.26E+00	3.94E-04
585	60	150	68.3	77.7	55.7	620	9.74E+00	1.23E+00	3.82E-04
730	30	150	44.9	51.5	28.4	215	1.23E+01	1.58E+00	3.96E-04
730	40	150	58.9	65.8	37.3	345	1.25E+01	1.58E+00	3.94E-04
730	50	150	73.1	80.1	46.7	525	1.22E+01	1.57E+00	3.92E-04
730	60	150	85.1	92.2	54.9	695	1.22E+01	1.55E+00	3.87E-04
				Vlink=350	Ks=0.07				

Blocked Rotor [illegible]/93: GDSS

V Fund. Measured w/TEK 602 Scope, Filtered Diff Amp + Avg (64) Vlink = 350

All Harmonic V, I, Power w/Yokogawa 2533; Blocked Rotor

FREQ	Iqs	Temp, Mtr	Volts	Volts	Current (A)	Power (W)	Stator	Rotor	Impedance	Leakage
Hz	Ids	Deg. F	L-N	L-N	One Phase	One Phase	Resistance	Resistance	Single Phase	Inductance
	(A)		Fund.	All Harm.		All Harm.	(Ohms)	(Ohms)	(Ohms)	(Henries)
150	30	150	3.1	24.9	38.2	93.00	0.05	1.37E-02	8.12E-02	5.33E-05
150	40	150	3.8	34.6	50	164.00	0.05	1.56E-02	7.60E-02	4.07E-05
150	50	150	4.7	43.7	62.5	256.00	0.05	1.55E-02	7.52E-02	3.91E-05
150	60	150	5.8	50.9	74.2	356.00	0.05	1.47E-02	7.82E-02	4.66E-05
225	30	150	3.1	25.9	38.3	98.00	0.05	1.68E-02	8.09E-02	3.23E-05
225	40	150	4.6	35.3	50.6	171.00	0.05	1.68E-02	9.09E-02	4.36E-05
225	50	150	5.8	44.2	63	270.00	0.05	1.80E-02	9.21E-02	4.39E-05
225	60	150	6.8	51.7	74.5	367.00	0.05	1.61E-02	9.13E-02	4.45E-05
488	30	150	6.8	27.6	38.7	113.00	0.05	2.54E-02	1.76E-01	5.18E-05
488	40	150	8.9	36.3	50.9	191.00	0.05	2.37E-02	1.75E-01	5.17E-05
488	50	150	11.2	46.7	63.2	307.00	0.05	2.69E-02	1.77E-01	5.21E-05
488	60	150	13.2	53	74.4	415.00	0.05	2.50E-02	1.77E-01	5.25E-05
585	30	150	7.9	29.1	38.6	119.00	0.05	2.99E-02	2.05E-01	5.13E-05
585	40	150	10.7	37.5	51.3	206.00	0.05	2.83E-02	2.09E-01	5.26E-05

Blocked Roto 5/93: GDSS

FREQ Hz	Iqs Ids (A)	Temp, Mtr Deg. F	Volts L-N Fund.	Volts L-N All Harm.	Current (A) One Phase	Pov. (W) One Phase All Harm.	Stator Resistance (Ohms)	Rotor Resistance (Ohms)	Impedance Single Phase (Ohms)	Leakage Inductance (Henries)
585	50	150	13.1	47.8	63	320.00	0.05	3.06E-02	2.08E-01	5.22E-05
585	60	150	15.5	53.2	74.9	435.00	0.05	2.75E-02	2.07E-01	5.22E-05
730	30	150	9.6	29.8	38.6	126.00	0.05	3.46E-02	2.49E-01	5.10E-05
730	40	150	12.9	38.9	50.8	216.00	0.05	3.37E-02	2.54E-01	5.23E-05
730	50	150	16	48	63	336.00	0.05	3.47E-02	2.54E-01	5.22E-05
730	60	160	19	55.8	75.3	464.00	0.051	3.08E-02	2.52E-01	5.21E-05

NO LOAD Sundstrand

FREQ	Volts	Current (A)	Power (W)	Core Loss	Impedance	Magnetizing	Power Factor
Hz	L-N	Single Phase	Single Phase	Resistance	Single Phase	Inductance	
				(Ohms)	(Ohms)	(Henries)	
This test data was supplied by Sundstrand. Testing performed with sine wave drive voltages and currents.							
166	1.48	3.67	1.43	1.53E+00	4.03E-01	5.25E-04	0.26
166	4.9	11.8	6	4.00E+00	4.15E-01	4.44E-04	0.10
166	10.07	24.4	21.7	4.67E+00	4.13E-01	4.34E-04	0.09
166	19.74	49.92	78.3	4.98E+00	3.95E-01	4.12E-04	0.08
166	30.54	105.2	292	3.19E+00	2.90E-01	3.06E-04	0.09
500	4.19	3.72	4.4	3.99E+00	1.13E+00	5.00E-04	0.28
500	10.59	8.61	10	1.12E+01	1.23E+00	4.40E-04	0.11
500	30.13	24.2	47	1.93E+01	1.25E+00	4.24E-04	0.06
500	50.58	41.74	120	2.13E+01	1.21E+00	4.09E-04	0.06
500	71.99	59.52	220	2.36E+01	1.21E+00	4.06E-04	0.05
500	90.74	98.89	450	1.83E+01	9.18E-01	3.08E-04	0.05
750	4.15	3.59	3.33	5.17E+00	1.16E+00	3.16E-04	0.22
750	14.5	8.04	18	1.17E+01	1.80E+00	4.53E-04	0.15
750	23.3	12.7	31	1.75E+01	1.83E+00	4.35E-04	0.10
750	40.88	22.29	72	2.32E+01	1.83E+00	4.23E-04	0.08

NO LOAr ..dstrand

..·EQ Hz	Volts L-N	Current (A) Single Phase	Power (W) Single Phase	Core Loss Resistance (Ohms)	Impedance Single Phase (Ohms)	Magnetizing Inductance (Henries)	Power Factor
750	79.8	45.14	213	2.99E+01	1.77E+00	3.99E-04	0.06
750	121.3	78.25	463	3.18E+01	1.55E+00	3.46E-04	0.05
750	130.7	87.53	540	3.16E+01	1.49E+00	3.33E-04	0.05

BLOCKED ROTOR-Sundstrand

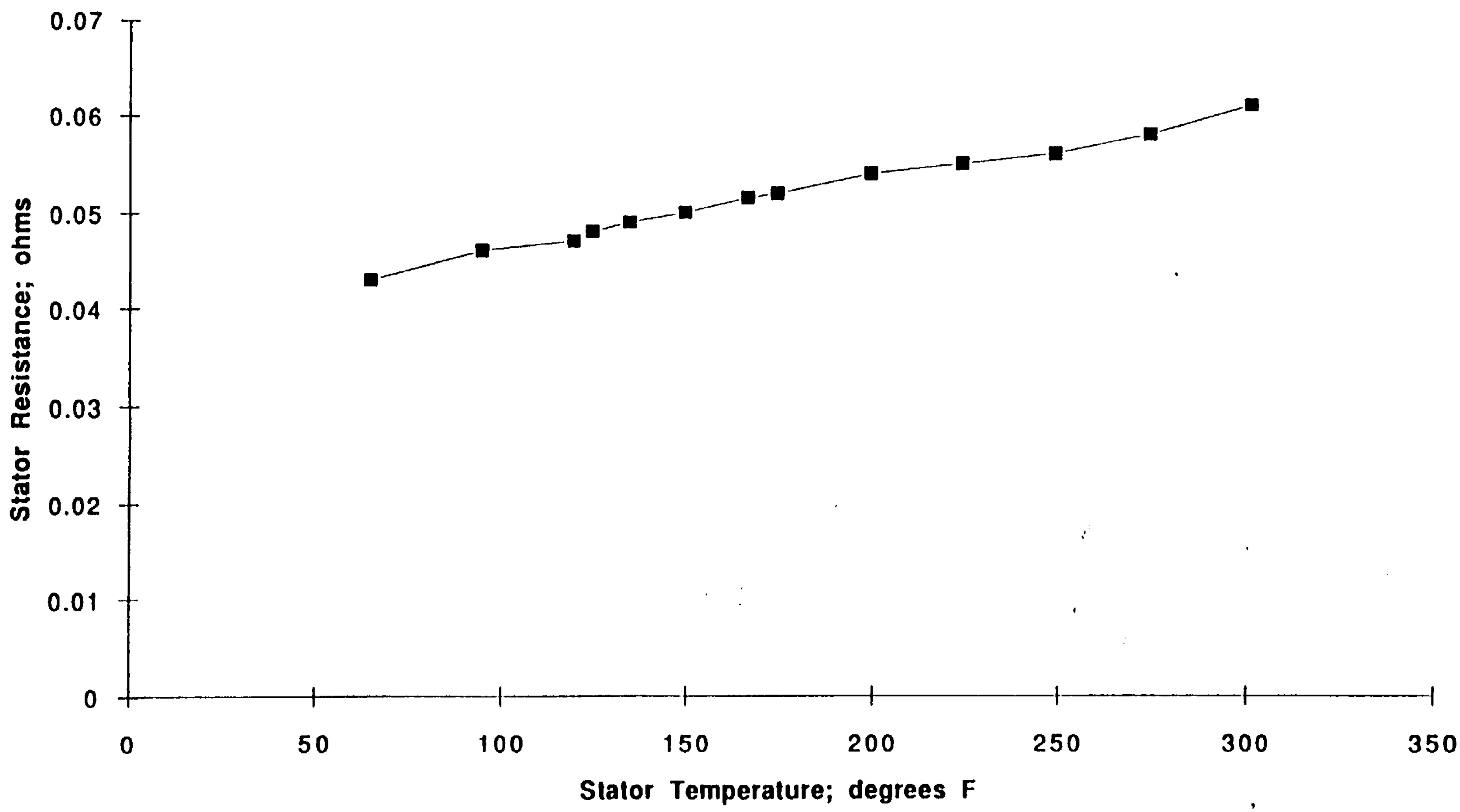
FREQ	Volts	Current (A)	Power (W)	Stator	Rotor	Impedance	Leakage	Power Factor
Hz	L-N	Single Phase	Single Phase	Resistance	Resistance	Single Phase	Inductance	
				(Ohms)	(Ohms)	(Ohms)	(Henries)	
This test data was supplied by Sundstrand. Testing performed with sine wave drive voltages and currents								
50	2.19	30.45	38.3	0.016	2.53E-02	7.19E-02	1.88E-04	0.57
50	5.22	74.15	228	0.016	2.55E-02	7.04E-02	1.81E-04	0.59
50	7.65	108.8	499	0.016	2.62E-02	7.03E-02	1.79E-04	0.60
50	9.83	131.8	787	0.016	2.93E-02	7.46E-02	1.89E-04	0.61
500	3.21	17.3	15	0.016	3.41E-02	1.86E-01	5.69E-05	0.27
500	4.86	26.55	35	0.016	3.37E-02	1.83E-01	5.61E-05	0.27
500	15.14	83.6	355	0.016	3.48E-02	1.81E-01	5.54E-05	0.28
500	25.35	135	1000	0.016	3.89E-02	1.88E-01	5.72E-05	0.29
750	4.04	15.79	12.7	0.016	3.49E-02	2.56E-01	5.32E-05	0.20
750	9.84	39.15	77	0.016	3.42E-02	2.51E-01	5.23E-05	0.20
750	14.79	58.88	177	0.016	3.51E-02	2.51E-01	5.22E-05	0.20
750	24.7	97.44	506	0.016	3.73E-02	2.53E-01	5.26E-05	0.21
750	34.76	133.43	1057	0.016	4.34E-02	2.61E-01	5.39E-05	0.23

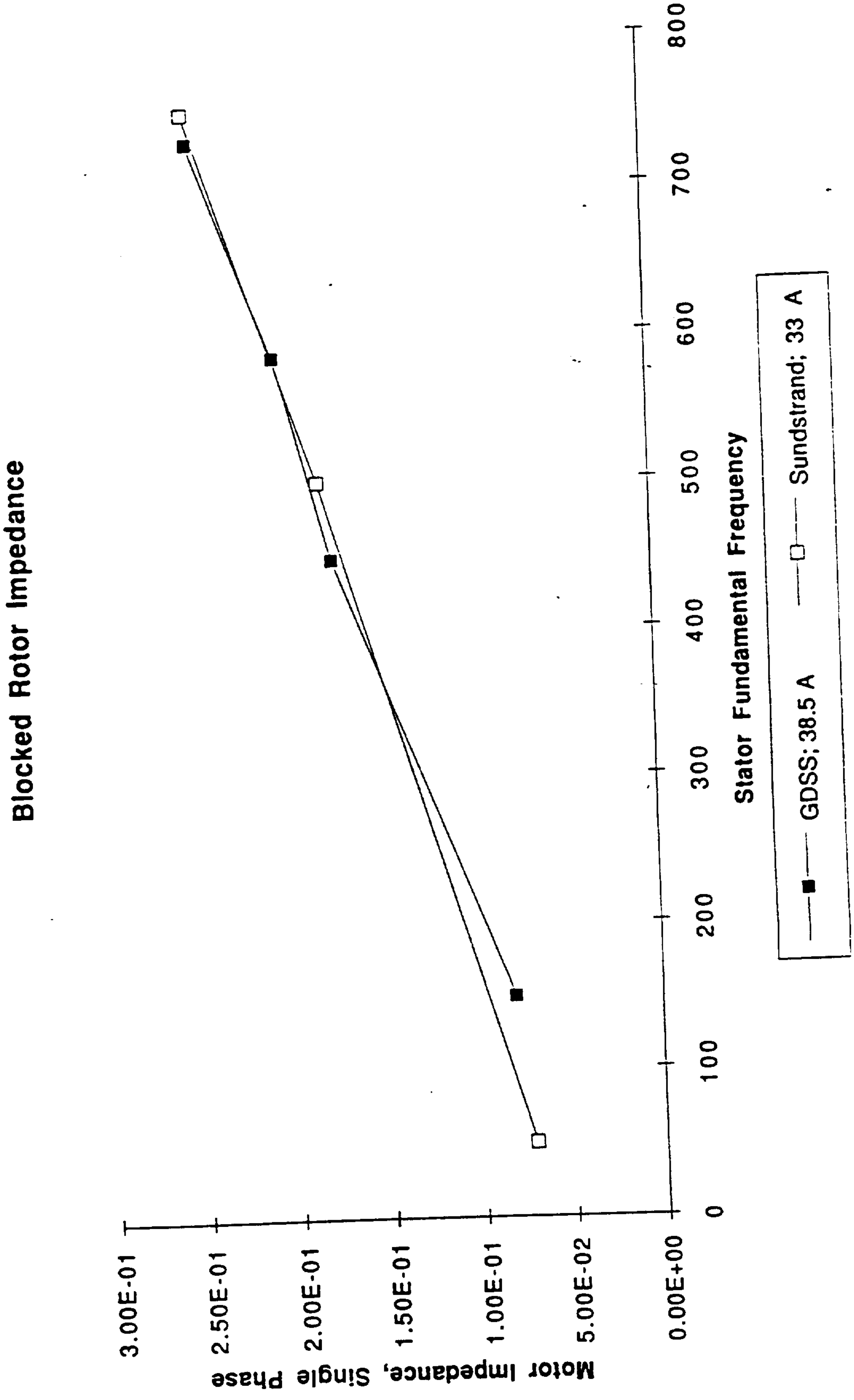
Stator Temp vs Rs #2

Temperature	Stator Resistance
Degrees F	*Ohms L-N*
65	0.043
95	0.046
120	0.047
125	0.048
135	0.049
150	0.05
167	0.0515
175	0.052
200	0.054
225	0.055
250	0.056
275	0.058
302	0.061

Stator Resistance vs Temp #2

Stator Resistance vs Temperature




Blocked Rotor Impedance
Motor Impedance, Single Phase
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
0
100
200
300
400
500
600
700
800
Stator Fundamental Frequency
GDSS; 38.5 A
Sundstrand; 33 A

APPENDIX C

Motor Parameter Test Procedure and Test Data

Reproduced from 40 HP Electro-Mechanical Actuator Test Report
NASA Contract: NAS325799 - August 1993

Appendix . , Motor Test Procedure

Measuring Induction Motor Parameters:

Measuring induction motor parameters with a Pulse Density Modulated (PDM) motor controller requires specialized test procedures. The procedures outlined here are required to achieve accurate measurements of the Stator Leakage Inductance (Ls), Rotor Leakage Inductance (Lr), Magnetizing Inductance (Lm), Rotor and Stator resistances (Rr and Rs), and Core Loss Resistance (Rm). The high harmonic content of the drive voltage and to a lesser extent, the drive current that are characteristic of a PDM drive make the following test procedure necessary.

Blocked Rotor Testing:

The goal of Blocked Rotor Testing is to identify the leakage inductances of the motor and the rotor/stator resistances. With the rotor blocked (held motionless) the single phase induction motor model reduces to only equivalent resistances and leakage inductances. This occurs because when the slip goes to 1 (with the rotor blocked), the magnetizing resistance and inductance are effectively shorted out by the small values of rotor resistance and leakage inductance.

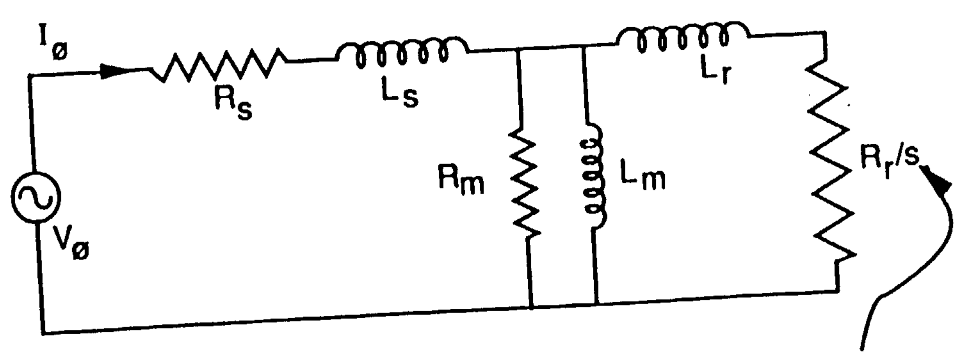


Figure 1

When S = 1 model reduces to:

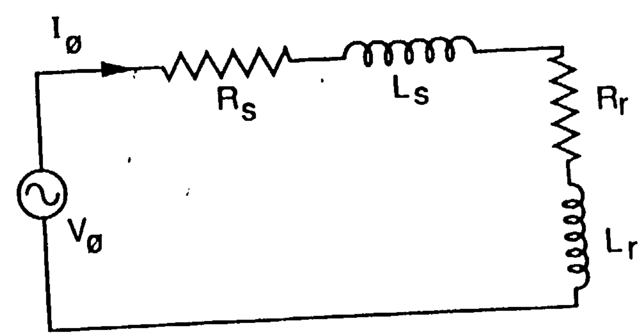


Figure 2

Appendix A; Motor Test Procedure

Blocked Rotor Measurements:

1) Measure the stator resistance (Rs) with a resistance bridge or milliohm meter. The measurement should be performed on all three phases of the induction motor from Line to Neutral, at different temperatures.

2) Measure the Real or Effective Power and the current into the motor on a per phase basis. These measurements should be made over a range of input currents and drive frequencies. Using the data gathered in this test the equivalent resistance ($R_{eq} = R_r + R_s$) may be calculated. This measurement should be made with test equipment capable of reading the entire harmonic spectrum produced by the PDM controller.

$$R_{eq} = \frac{\text{Real Power}}{I^2}$$

Then to calculate Rr: $R_r = R_{eq} - R_s$

3) Leakage Inductance: This measurement requires that the per phase voltage and current be determined at the motor's fundamental test frequency. This is necessary because the leakage inductance is measured indirectly using the blocked rotor impedance and then computed from the following formulas:

A) Calculate the Blocked Rotor Impedance Zbr. $Z_{br} = \frac{V}{I}$

B) Calculate the inductive reactance (X_L) from Zbr. $X_L = \sqrt{Z_{br}^2 - R_{eq}^2}$

C) Calculate the equivalent leakage inductance $L_{eq} = L_r + L_s$: $L_{eq} = \frac{X_L}{2 \pi F}$

Note: The voltage and current measured in step (A) must be the motor drive fundamental frequency. With a PDM controller the fundamental frequency component of the voltage is difficult to measure because the voltage is a series of pulses. Signal filtering or signal processing is necessary to identify the magnitude of the fundamental voltage component.

No Load Testing:

The goal of No Load Testing is to identify the magnetizing inductance and the core loss resistance of the motor. When the motor is running with no load the slip becomes very close to zero. The magnetizing inductance and core loss resistance are predominant in the motor model under these conditions because they are magnitudes larger than the leakage inductances and rotor/stator resistances.

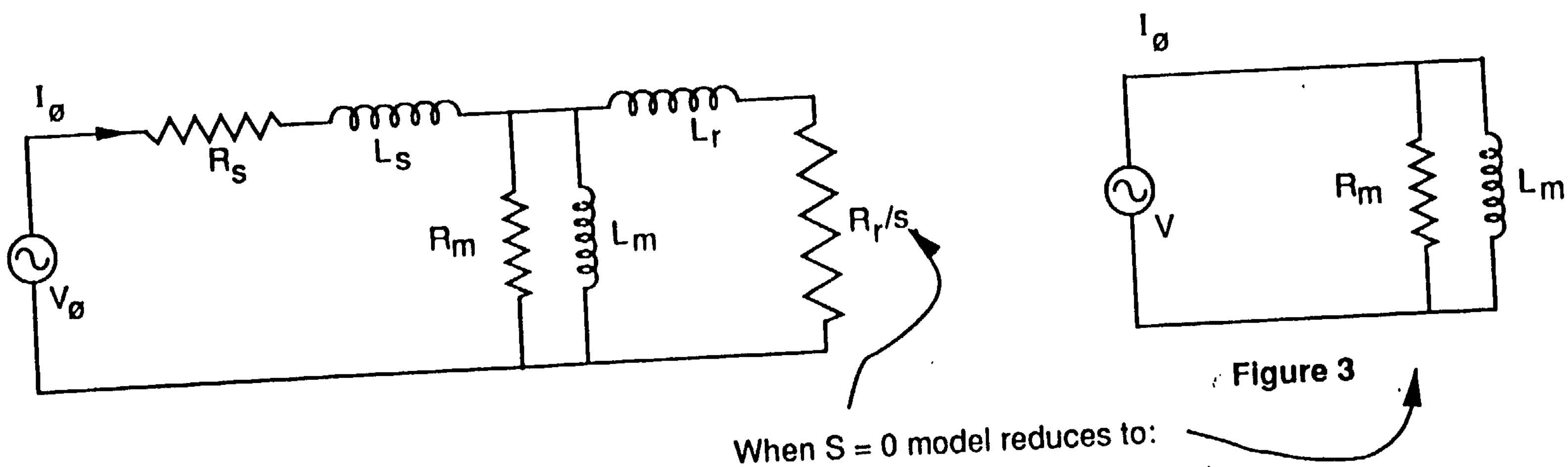


Figure 3

Appendix A; Motor Test Procedure

No Load Measurements:

1) Measure the Real or Effective Power and the voltage at the motor Line to Neutral terminals on a per phase basis. These measurements should be made over a range of voltages and drive frequencies. Using the data gathered in this test the core loss resistance (Rm) may be calculated. This measurement should be made with test equipment capable of reading the entire harmonic spectrum produced by the PDM controller.

$$Rm = \frac{V^2}{Power_R}$$

2) Magnetizing Inductance: This measurement requires that the per phase voltage and current be determined at the motor's fundamental test frequency. This is necessary because the magnetizing inductance is measured indirectly using the no load impedance and then computed from the following formulas:

A) Calculate the No Load Impedance Znl: $Znl = \frac{V}{I}$

B) Calculate the magnetizing reactance (X_M) from Znl: $\frac{1}{X_M} = \frac{1}{Znl} - \frac{1}{Rm}$

C) Calculate the equivalent magnetizing inductance: $Lm = \frac{X_M}{2 \pi F}$

Note: The voltage and current measured in step (A) must be the motor drive fundamental frequency. With a PDM controller the fundamental frequency component of the voltage is difficult to measure because the voltage is a series of pulses. Signal filtering or signal processing is necessary to identify the magnitude of the fundamental voltage component.

APPENDIX D

Motor and Unloaded Actuator Test Procedure

NASA CONTRACT: NAS3-25799

DC RESONANT LINK CONTROLLER

SYSTEM TEST PLAN

Principal Engineer:____________________
Ken Schreiner

Program Manager:____________________
Pat Klement

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

f_e = Stator Excitation Frequency
GR = Gear Ratio Of Motor To Dynamometer Speed
I_a = Phase A Current
i_a^* = Commanded Phase A Stator Current
I_{AC} = Measured 20 KHz AC RMS Current
i_{af} = Phase A Feedback Current
i_b^* = Commanded Phase B Stator Current
i_{bf} = Phase B Feedback Current
i_c^* = Commanded Phase C Stator Current
I_c = Phase C Current
I_{dc} = DC Measured Current
$i^e{}_{ds}^*$ = d-Axis Current In Synchronous Frame
$i^e{}_{qs}$ = Calculated q-Axis Current In Synchronous Frame
$i^e{}_{qs}^*$ = Commanded (Limited) q-Axis Current In Synchronous Frame
I_i = Measured Inverter Output Peak Current
L_m = Mutual Inductance
L_r = Rotor Inductance
p = Number Of Poles
R_m = Mutual Resistance
RPM_{dyno} = Dynamometer Rotational Speed
R_r = Rotor Resistance
s = rotor slip
T = Electromechanical Torque
V_{ab} = Measured AB Phase-to-Phase Voltage
V_{AC} = Measured 20KHz AC RMS Voltage
V_{bc} = Measured BC Phase-to-Phase Voltage
V_{dc} = DC Measured Voltage
V_i = Measured Inverter Output Peak Voltage
V_{l-n} = Measured Motor Line to Neutral Voltage
$\lambda^e{}_{dr}^*$ = Commanded Motor Flux
ø = Power Factor Angle
$Ø_r$ = Actual Rotor Angle
$Ø_s^*$ = Commanded Rotor Slip Angle
ω^* = Rotor Commanded Frequency
ω_r = Rotor Frequency
ω_s = Slip Frequency

* Commanded Values

1.0 SYSTEM DESCRIPTION

This Electro-Mechanical Actuation system utilizes a DC resonant motor controller and an induction motor powered linear actuator capable of up to 70 HP output. The system's power source is either a 300 VDC power supply, used for laboratory testing, or a 300 VDC battery. Control of the system is accomplished via a computer terminal which is an integral part of the system. The EMA Monitor Program controls all aspects of the systems operation. System testing is performed on a dynamometer when determining maximum power output, or on an actuator test stand for determination of frequency and phase response.

1.1 CONTROLLER

This controller utilizes field oriented control to determine the phase current values necessary to drive the induction machine to a commanded speed value. The controller also requires two position feedback sensors when used with a linear actuator. The first is a rotary position sensor which is mounted on the motor shaft and provides rotor angle and speed feedback. The second is a linear position sensor which determines the amount of actuator extension or retraction.

Field-oriented control relies on equations generated from a d-q (direct-quadrature) axis model of the induction machine. Figure 1-1 illustrates the equivalent circuit of the induction machine. When the rotor flux is aligned with the d-axis, the d-axis component of the current, i^e_{ds}, is decoupled and becomes the flux producing current. At this point the q-axis component, i^e_{qs}, may be used to control torque or speed as illustrated by the following equations:

$$T = \frac{3}{4}\frac{p L_m \lambda^{e*}_{dr}}{L_r} i^{e*}_{qs} \qquad \omega_s = \frac{R_r L_m}{L_r \lambda^{e*}_{dr}} i^{e*}_{qs} \qquad \lambda^{e*}_{dr} = L_m i^{e*}_{ds}$$

: assumes i^{e*}_{ds} constant.

The user definable variable needed to calculate these formulas are:

R_r = Rotor Resistance
L_m = Mutual Inductance
L_r = Rotor Inductance
P = Number Of Poles
$i^e_{ds}{}^*$ = d-Axis Current In Synchronous Frame

Figure 1-2 shows the block diagram of the system. A comparison of the commanded actuator position to the actual actuator position produces an error signal. This error signal is used by the software algorithms to generate the required field oriented control motor currents that move the motor/actuator and eliminate the position error. The rotor angle feedback and the actuator force feedback signals are used by the algorithms to determine the appropriate command signals. Motor current regulation is performed using computer software by comparing the actual motor currents from phase A and B feedback currents to the commanded phase currents. The resulting current error is used to determine the power switching sequence which ultimately controls the motors phase currents.

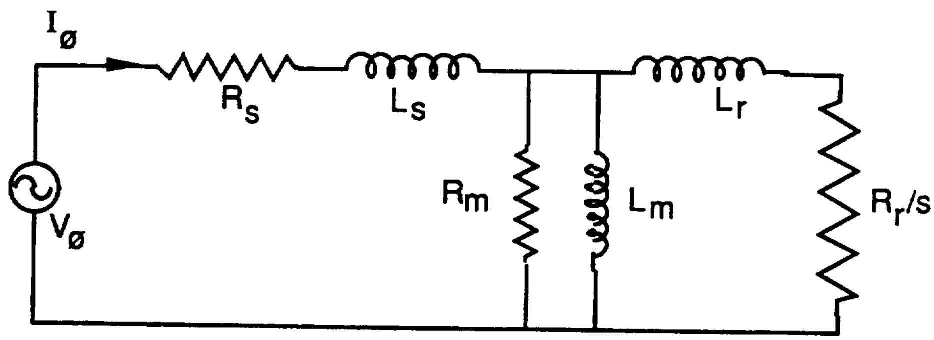


Figure 1-1: Induction Machine Equivalent Circuit For Field Orientation Operation

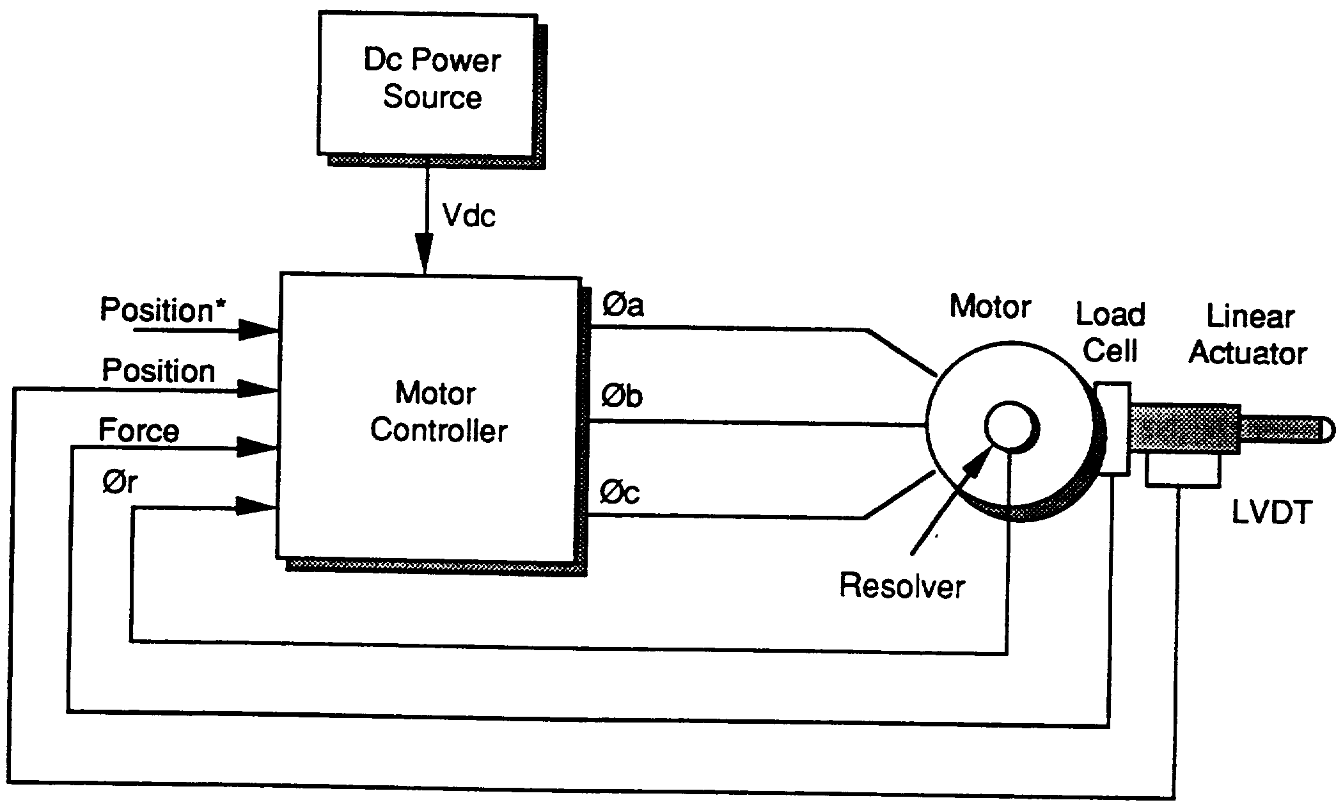


Figure 1-2: Motor Controller Block Diagram

1.2 MOTOR

The motor being tested is the 70 Hp induction machine developed by Sundstrand for NASA contract number NAS3-25799, task order 1 and EMA ADP 2402.

1.3 DYNAMOMETER TEST STAND

Motor testing under load shall be performed on the dynamometer test stand procured under the EMA ADP 2402. The motor shall be coupled to the dynamometer through a 4:1 gear box which reduces the rotational rate of the shaft to a maximum of 3500 RPM.

2.0 TEST PLAN DESCRIPTION

2.1 OBJECTIVE

This test plan was developed to provide a method of testing the DC link resonant motor controller and the motor/actuator system. The objective of the testing is to determine system capabilities including the motor operating parameters, motor performance, motor efficiency, controller efficiency, system efficiency, system frequency and phase response, optimum operating point information, and maximum output power.

2.2 MEASUREMENTS

The testing requires measurement of several parameters including currents, voltages, power, motor speed, torque, temperature and actuator position. The following paragraphs indicate proposed measurement methods for all quantities of interest as well as proposed equipment.

2.2.1 VOLTAGE, CURRENT, AND POWER

Input voltage is measured with a digital voltmeter and input current is measured with a digital voltmeter on the output of a coaxial current shunt. The measurement points for motor current, voltage, and power determination are shown in Figure 2-1. The Yokogawa 2533 Digital Power Meter is capable of measuring the voltage, current and power on the complex pulse density modulated waveforms that are present in this system. The Yokogawa 2533 Digital Power Meter contains circuitry to analyze the voltage and current waveforms and calculate the apparent and real powers.

2.2.2 TORQUE

Torque shall be measured using the in-line torque transducer on the dynamometer. The torque transducer's signal is processed by a signal conditioner which generates a DC voltage proportional to the torque output of the torque transducer. This voltage is interpreted by the dynamometer's computer terminal and displayed on the terminal monitor.

2.2.3 SPEED

When the dynamometer is in use, the shaft speed of the motor may be calculated from the dynamometer speed (displayed on the terminal monitor) and the gear box ratio. The actual motor speed is displayed on the motor controller's computer monitor.

2.2.4 TEMPERATURE

There are two temperature measurement points within the system. One is part of the heat exchanger system and indicates the temperature of the coolant in the cold plate. The final temperature point is a thermocouple embedded within the stator. This temperature is monitored using a temperature meter.

2.2.5 ACTUATOR POSITION

The actuator position is measured by the LVDT (Linear Variable Displacement Transducer) mounted in the actuator's housing. The signal from this device is processed by the Controllers computer software and is available as an output to the strip chart recorder.

2.3 TESTS

The testing is comprised of two major test areas: static load testing and open loop actuator testing.

2.3.1 STATIC LOAD TESTING

The dynamometer is to be used during these tests. Two static load tests are to be carried out. They are the motor characteristic curves and steady-state power loss/efficiency tests. The test set-up for the static load testing is illustrated in figure 2-1.

2.3.1.1 MOTOR CHARACTERISTIC CURVES

The purpose of these tests is to determine the torque and associated efficiencies for both the motor and the system over the operating speed range of the motor for various constant stator frequencies and currents. To establish a set stator current, $i^e_{ds}{}^*$ and $i^e_{qs}{}^*$ are set to specific values and therefore the normal operating mode of calculating $i^e_{qs}{}^*$ is bypassed. In order to maintain a constant stator frequency, it is necessary to use the dynamometer to drive the induction motor to a set speed and adjust the rotor slip until the stator frequency is the desired value.

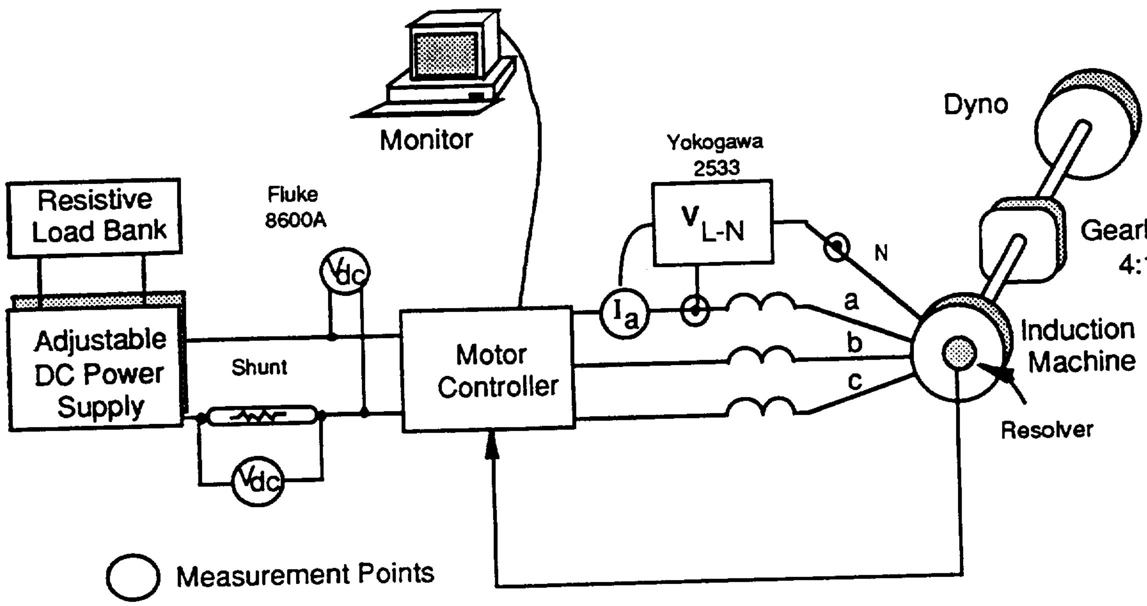


Figure 2-1: The Static Load Test Set-up

2.3.1.2 STEADY-STATE POWER LOSS/EFFICIENCY DETERMINATION

The purpose of the steady state power loss measurements is primarily to establish the operating efficiencies for a given speed/torque requirement. Due to the characteristics of the controller and the dynamometer, the only static loading capability of the test system is to operate the motor at a commanded speed against a torque supplied by the dynamometer. For the purpose of this test, the commanded rate can be anywhere within the range of 0, stall, to about 14000 RPM under a load of up to 23.5 ft-lbs. The top speed is limited by the dynamometer's maximum speed.

The $i^e_{ds}{}^*$ shall be varied to command from 25% of rated flux to 100% of rated flux. By measuring the power into the controller, power into the motor, and mechanical power out of the motor, the power loss and total system efficiency can be determined.

2.3.2 MOTOR DYNAMIC NO LOAD TESTING

Dynamic no load testing is performed without the dynamometer attached and only motor's rotor inertia acting to oppose the motor movement. The test set-up is shown in Figure 2-1. A strip chart recorder is used to record the data. For this test the step response of the motor shall be measured. From the step response, the no load frequency response may be mathematically calculated.

There are two individual step response tests to be carried out. The first is a step from zero speed to 7500 RPM. The second is a step from 7500 RPM in one direction to 7500 the opposite direction. This second test will demonstrate the ability of the system to operate in a regenerative mode since it will enter a regenerative power phase as it dynamically brakes the inertial load.

2.3.3 ACTUATOR NO LOAD TESTING

This series of two tests measures the frequency response, phase response and step response of the entire system, with the actuator operating in a no-load condition. For the purpose of these tests the motor is attached to the actuator and the actuator is mounted on a table, with a coupling that allows free movement of the actuator end fitting.

3.0 TEST PLAN PROCEDURES

3.1 STATIC LOAD TEST PROCEDURES

3.1.1 MOTOR CHARACTERISTIC CURVES TEST PROCEDURE

1. Power up motor controller.

2. Initialize controller.

3. Power up the DC power supply and adjust the output voltage to 300 VDC.

4. Power up dynamometer in speed mode.

5. Command dynamometer speed to test value. Set phase voltage to frequency ratio to 120Vrms L-N / 750Hz. Keep this ratio constant for all data points in this test.

6. Adjust slip frequency until stator frequency is at desired test value. **NOTE:** Under no circumstance is the output dyno torque to exceed 1200 in-lb. This will result in the truncation of some of the motor curves.

7. Record stator current and frequency, dynamometer shaft speed, dynamometer torque, calculated motor torque and shaft speed through gear box, power into the controller, Vl-n, Ia, power, and power factor into motor.

8. Reduce dynamometer speed for next point on curve.

9. Repeat steps 6 thru 8 until sufficient points are generated to establish a speed-torque curve.

10. Repeat 6 thru 9 for each of the frequencies in the table.

11. Calculate and plot .vs. motor shaft speed the system efficiency, motor efficiency, and motor torque value.

Test	V/f ratio	Desired Stator Freq (Hz)
1	120/750	50
2	"	150
3	"	250 *
4	"	350 *
5	"	450 *
6	"	550 *
7	"	650 *
8	"	700 *

* May result in truncated motor curves due to torque limits.

3.1.2 STEADY-STATE POWER LOSS/EFFICIENCY TEST PROCEDURE

1. Power up the DC power supply and adjust the output voltage to 300 VDC.
   Set $i^e_{ds}{}^*$ for 25% flux.

2. Set dynamometer to test point torque values, as given in the table.

3. Command test point motor shaft speed and allow system to reach steady state condition.

4. Record $i^e_{ds}{}^*$, commanded motor shaft speed, actual dynamometer shaft speed, actual dynamometer torque, calculated motor torque through gear box, power into the controller, $V_{l\text{-}n}$, I_a, power, and power factor into motor.

5. Command next test point speed value at same load. Go to 2.

6. Repeat steps 2 thru 5 until all tests have been completed.

Test	Rated Flux	Dyno Torque Load (in-lb)	Rotor Speed (RPM)
1	25%	75	3000
2	25%		6000
3	25%		9000
4	25%		12000
5	25%		14000
6	25%	150	3000
7	25%		6000
8	25%		9000
9	25%		12000
10	25%		14000
11	50%	150	3000
12	50%		6000
13	50%		9000
14	50%		12000
15	50%		14000
16	50%	300	3000
17	50%		6000
18	50%		9000
19	50%		12000
20	50%		14000
21	100%	300	3000
22	100%		6000
23	100%		9000
24	100%		12000
25	100%		14000
26	100%	600	3000
27	100%		6000
28	100%		9000
29	100%		12000
30	100%		14000
31	100%	1200	3000
32	100%		6000
33	100%		9000
34	100%		12000
35	100%		14000

3.2 MOTOR DYNAMIC NO LOAD TEST PROCEDURE

1. Power up motor controller.

2. Initialize controller.

3. Power up the DC power supply and adjust the output voltage to 300 VDC.

4 Command a motor speed of 7500 RPM and allow to reach steady-state

condition.

5. Command a motor speed of 7500 RPM in the opposite direction and allow to reach steady-state condition. Record the step response of the motor.

6. Power down the DC power source.

7. Power down or reset motor controller.

8. Plot and evaluate the step response and estimate frequency response from the data.

3.3 ACTUATOR FREQUENCY RESPONSE TEST

1. Power up motor controller.

2. Initialize controller for rated flux.

3 Apply the specified SINUSOIDAL command (see table) for a ten cycle minimum.

4. Plot the position vs. command on an X-Y plot.

5. Record the position and command signals on a strip chart recorder.

5. Repeat for all test points.

Test	Frequency (Hz)	Amplitude (In) Peak-Peak
1	0.05	1,2,5.0
2	0.25	0.1,0.25,0.5
3	0.5	0.1,0.25,0.5
4	1.0	0.1,0.25,0.5
5	2.0	0.1,0.25,0.5
6	3.0	0.1,0.25,0.5
7	4.0	0.1,0.25,0.5
8	5.0	0.1,0.25,0.5
9	6.0	0.1,0.25,0.5
10	8.0	0.1,0.25,0.5

3.4 ACTUATOR STEP RESPONSE TEST

1. Power up motor controller.

2. Initialize controller to rated flux.

3 Apply the specified STEP command (see table) for a five cycle minimum.

4. Record the position and command signals on a strip chart recorder.

5. Repeat for all test points.

Test	Frequency (Hz)	Amplitude (In) Peak-Peak
1	0.3	0.5
2	0.3	1.0
3	0.3	2.0
4	0.3	4.0
5	0.3	6.0
6	0.3	8.0
7	0.3	10.0
8	0.3	11.0

APPENDIX E

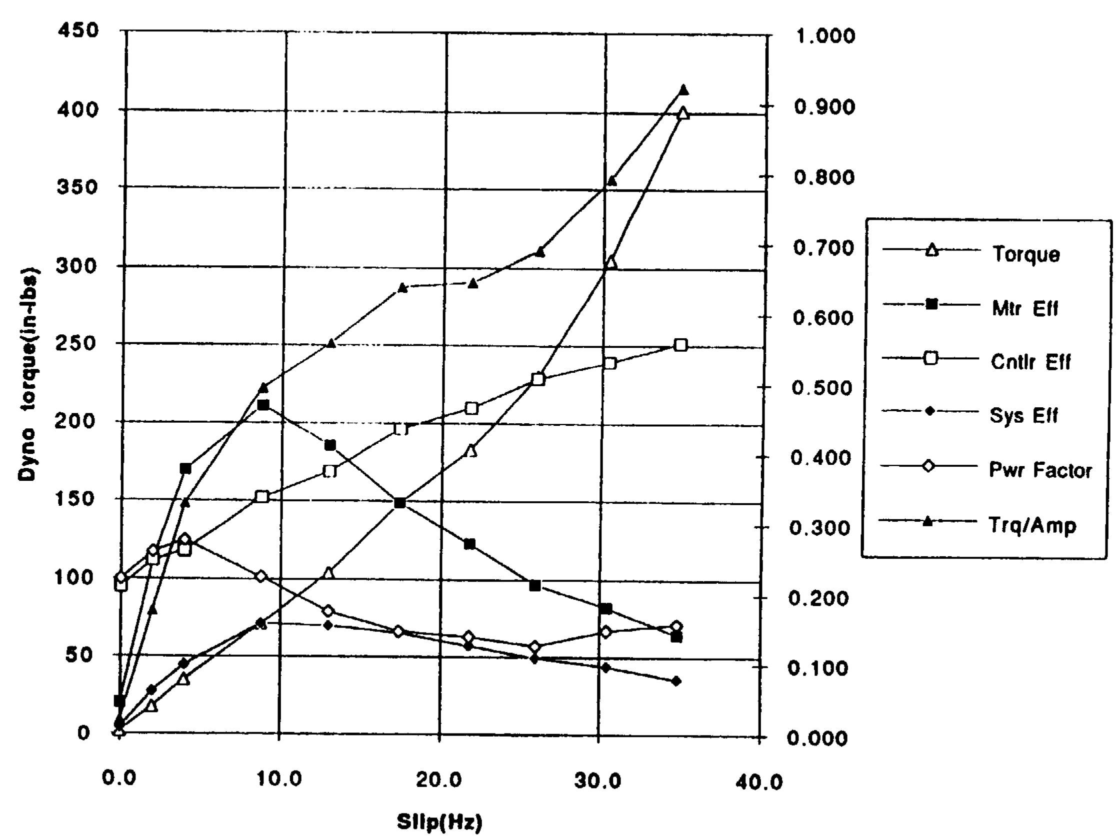
MOTOR AND UNLOADED ACTUATOR TEST DATA

Section 1 – Motor Curves Test Data

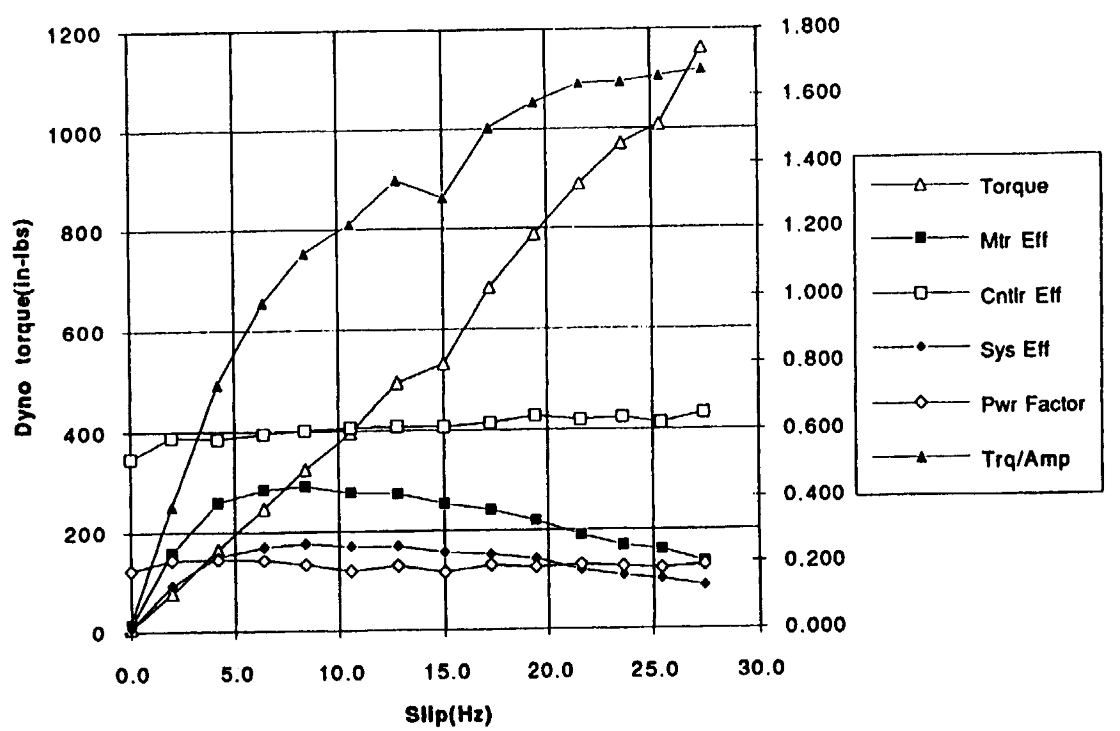
The tables containing the measured data have column headings defined below:

Heading	Definition
Stator Frequency	Motor fundamental stator frequency in Hz.
Slip Frequency	The difference between the stator frequency and the rotor frequency times the pole pairs(3).
Vdc	Input dc voltage.
Idc	Input dc current in amps.
Ids	Commanded flux current (Ids=85A is full rated flux).
Motor Current (A/phase)	The measured stator current amps per phase.
Horsepower	Output power measured with torque transducer and resolver on the dynamometer.
Dyno Torque in-lbs	The dyno torque output at the torque transducer. The motor torque is one-fourth due to the speed reducer.
Dyno Speed	Speed measured be the resolver on the dyno motor. The test motor speed is four times to speed reducer.
Motor Voltage L-N	The Line-to-Neutral motor voltage.
Motor Power (per Ø)	The real power measured in watts in one phase of the motor.
Power Factor	The power factor of the power into the motor.
Motor Temp	Motor Temp in deg F as measured by a thermocouple in the motor stator.
Motor Eff.	The efficiency of the motor. Calculated by dividing the output power as measured on the dyno by the power into the motor.
Controller Eff.	The efficiency of the controller. Calculated be dividing the input power into the motor by the input power into the controller (from 0 to 1.00).
Overall Eff.	End to end system efficiency . Calculated be dividing the output power as measured on the dyno by the input power into the controller (from 0 to 1.00).
Torque/Amp	The ratio of motor output torque divided by the current into the motor per phase.

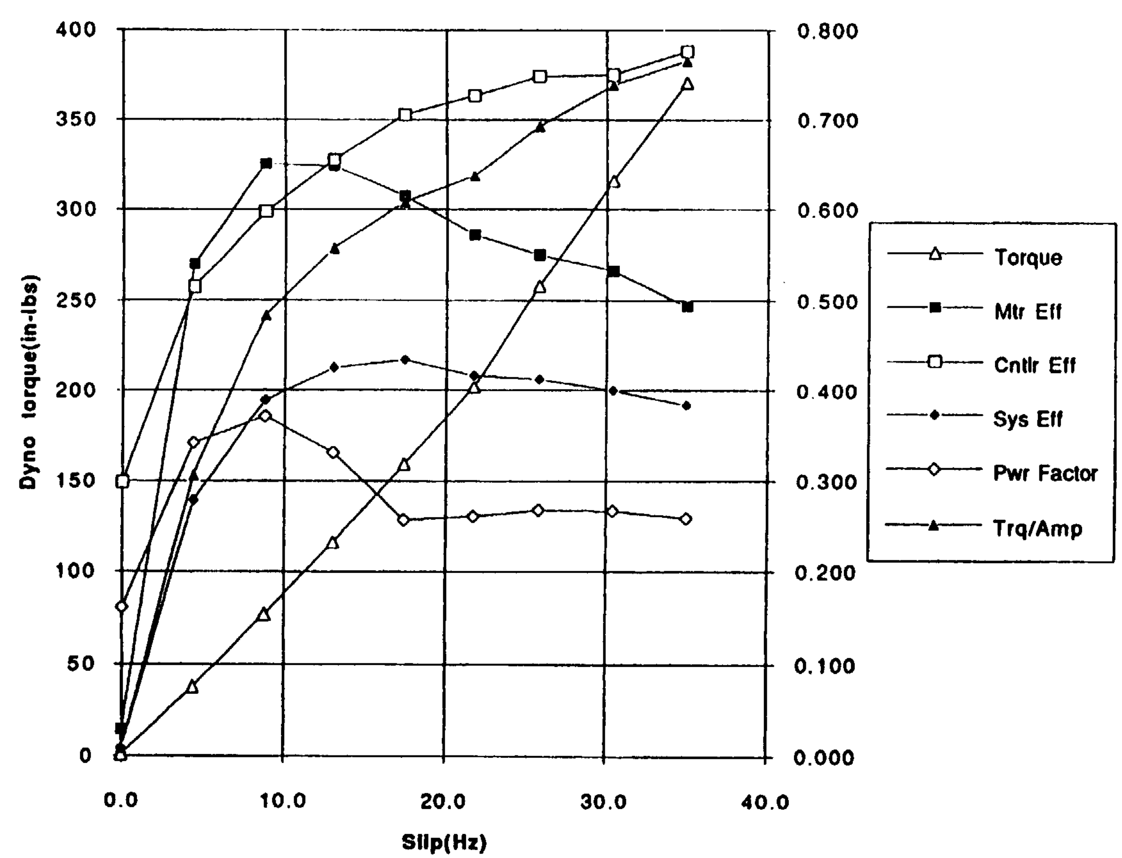
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
50Hz/42A																
50	0.0	301.1	2.6	42	25.1	0.01	2	250	10.0	55	0.222	96	0.045	0.211	0.010	0.02
50	2.0	301.2	2.8	42	25.4	0.07	18	240	10.5	70	0.261	105	0.249	0.249	0.062	0.18
50	4.0	301.2	3.0	42	26.5	0.12	35	230	10.7	79	0.277	114	0.378	0.262	0.099	0.33
50	8.8	301.2	3.6	42	35.9	0.23	71	206	15.2	122	0.224	124	0.469	0.338	0.158	0.49
50	13.0	301.2	4.8	42	46.5	0.30	104	185	22.2	181	0.176	134	0.412	0.376	0.155	0.56
50	17.4	301.2	6.0	42	58.2	0.35	149	163	30.8	263	0.147	143	0.331	0.437	0.144	0.64
50	21.8	301.2	7.8	42	70.7	0.40	183	141	37.2	365	0.140	152	0.273	0.466	0.127	0.65
50	26.0	301.2	10.0	42	83.1	0.44	230	120	44.0	510	0.127	158	0.215	0.508	0.109	0.69
50	30.4	301.1	12.0	42	96.0	0.47	305	98	45.9	641	0.148	167	0.182	0.532	0.097	0.79
50	34.8	301.0	15.0	42	108.5	0.48	401	76	49.2	842	0.158	179	0.142	0.559	0.079	0.92



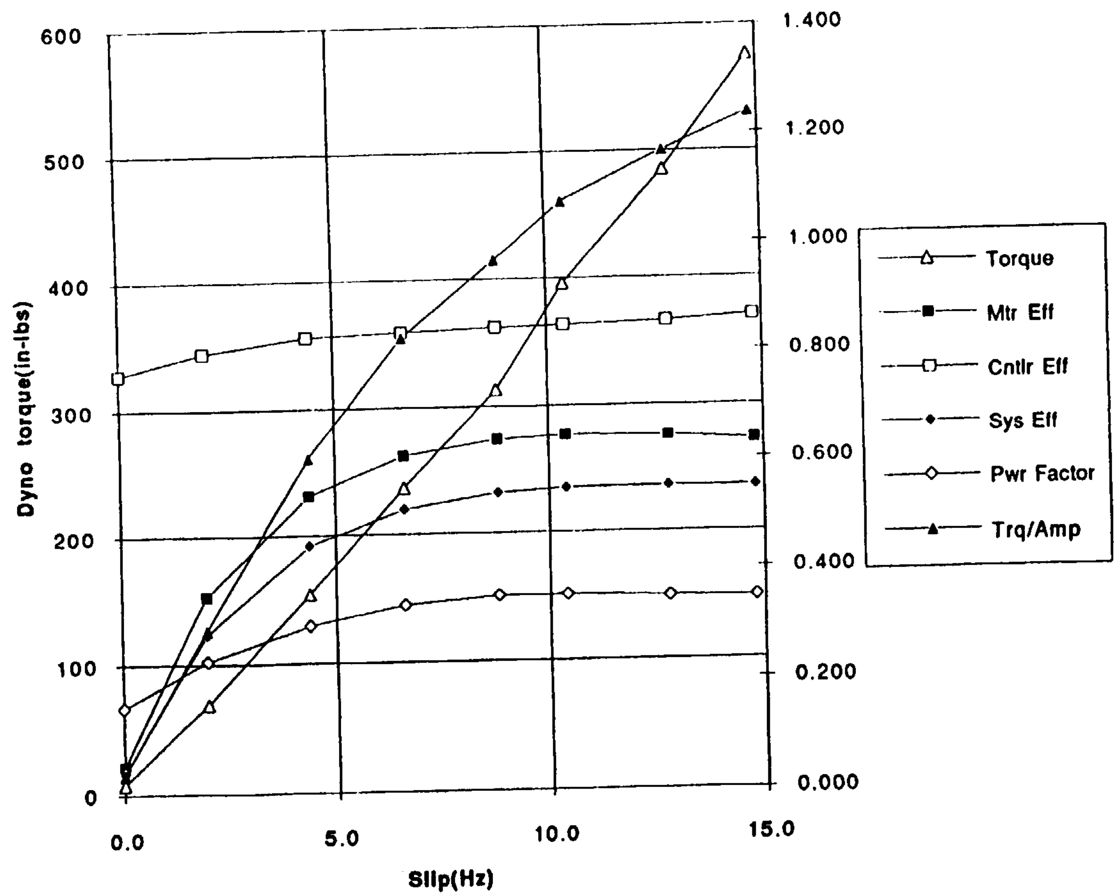
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
50Hz/85A																
50	0.0	301.0	4.6	85	49.9	0.02	6	250	26.0	240	0.183	96	0.021	0.520	0.011	0.03
50	2.0	301.0	5.2	85	50.9	0.29	77	240	27.8	305	0.214	105	0.236	0.585	0.138	0.38
50	4.2	301.0	6.6	85	55.3	0.60	164	229	32.5	384	0.215	114	0.389	0.580	0.225	0.74
50	6.4	301.0	8.2	85	62.7	0.84	247	218	36.7	489	0.213	124	0.427	0.594	0.254	0.98
50	8.4	301.0	10.0	85	71.6	1.06	324	208	42.6	604	0.198	134	0.436	0.602	0.263	1.13
50	10.6	300.8	12.0	85	81.6	1.23	397	197	49.6	735	0.179	143	0.416	0.611	0.254	1.22
50	12.8	300.9	14.2	85	91.9	1.45	496	186	49.7	874	0.193	152	0.413	0.614	0.253	1.35
50	15.0	300.7	15.6	85	102.7	1.47	532	175	52.7	956	0.174	158	0.382	0.611	0.234	1.30
50	17.2	300.8	19.6	85	113.8	1.79	685	164	55.5	1225	0.194	167	0.363	0.623	0.226	1.50
50	19.4	300.7	22.0	85	124.9	1.87	789	153	60.2	1418	0.187	190	0.328	0.643	0.211	1.58
50	21.6	300.5	26.8	85	135.9	1.92	890	142	63.8	1690	0.193	190	0.283	0.630	0.178	1.64
50	23.6	300.5	31.2	85	147.9	2.02	971	132	71.6	1993	0.188	195	0.252	0.638	0.161	1.64
50	25.4	300.5	32.8	85	151.7	1.97	1008	123	75.1	2040	0.183	195	0.240	0.621	0.149	1.66
50	27.4	299.8	40.0	85	173.2	2.09	1163	113	78.1	2600	0.192	195	0.200	0.650	0.130	1.68



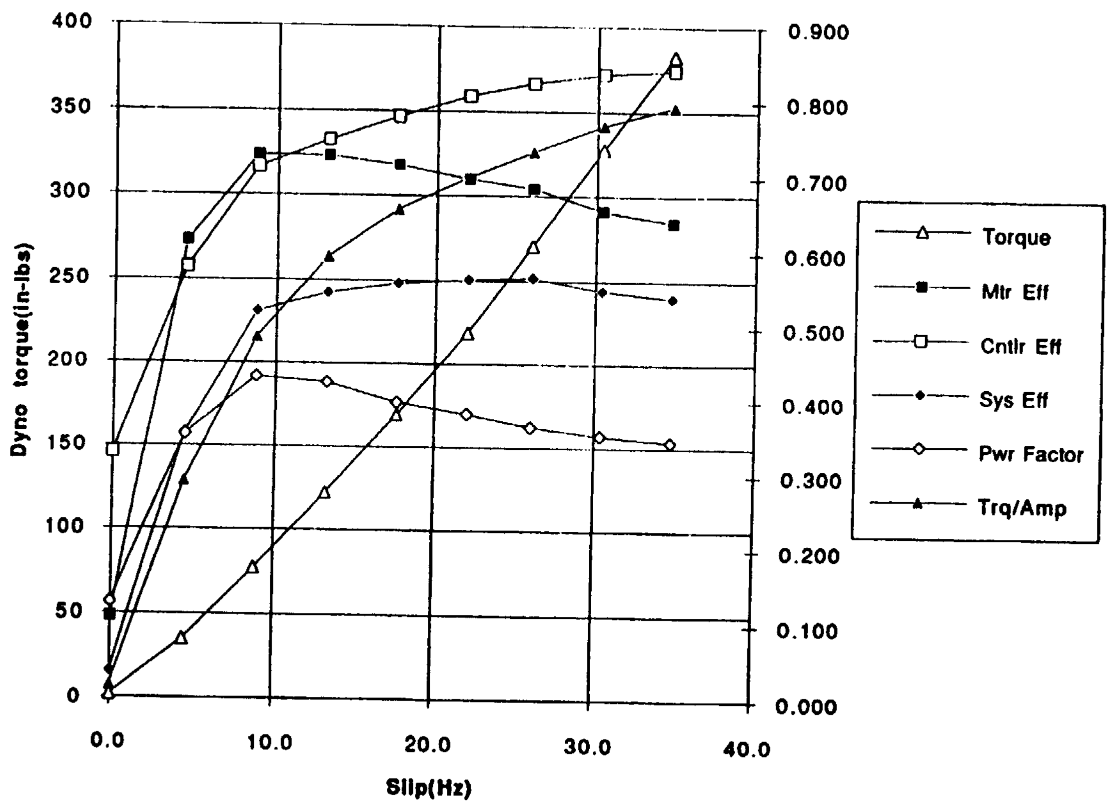
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
150Hz/42A																
150	0.0	301.1	2.8	42	27.8	0.01	1	750	19.0	84	0.161	190	0.030	0.299	0.009	0.01
150	4.4	301.1	4.0	42	31.0	0.45	38	728	19.6	207	0.342	191	0.541	0.516	0.279	0.31
150	8.8	301.2	5.6	42	39.8	0.88	77	706	22.8	336	0.371	191	0.651	0.598	0.389	0.48
150	13.0	301.2	7.4	42	51.9	1.27	116	685	28.4	487	0.331	190	0.648	0.655	0.425	0.56
150	17.4	301.0	9.6	42	65.3	1.68	159	663	36.1	680	0.257	191	0.614	0.706	0.434	0.61
150	21.8	301.0	12.2	42	79.2	2.05	202	641	43.0	890	0.261	191	0.573	0.727	0.416	0.64
150	25.8	301.0	15.2	42	93.0	2.53	258	621	45.5	1142	0.268	190	0.551	0.749	0.413	0.69
150	30.4	300.9	18.6	42	106.9	3.00	316	598	50.0	1400	0.267	191	0.533	0.750	0.400	0.74
150	35.0	300.8	22.0	42	121.1	3.40	371	575	54.0	1714	0.259	190	0.493	0.777	0.383	0.77



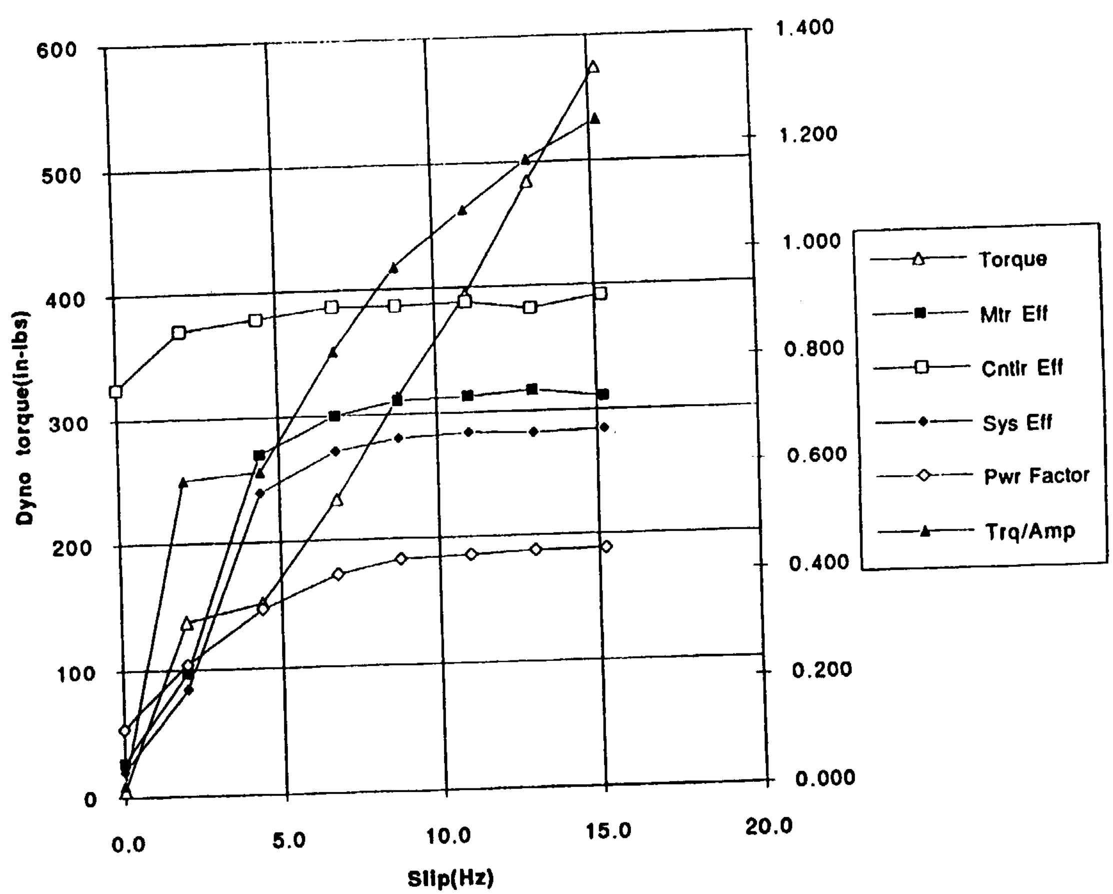
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
150Hz/85A																
150	0.0	301.2	4.6	85	57.2	0.07	8	750	39.9	353	0.155	191	0.049	0.764	0.038	0.03
150	2.0	301.0	7.0	85	58.5	0.81	69	740	40.5	565	0.239	192	0.356	0.804	0.287	0.29
150	4.4	301.0	9.8	85	63.3	1.77	154	728	42.8	818	0.302	190	0.538	0.832	0.448	0.61
150	6.6	300.9	13.0	85	71.2	2.68	236	717	45.8	1093	0.336	191	0.610	0.838	0.511	0.83
150	8.8	300.9	16.0	85	80.8	3.48	313	706	48.2	1357	0.351	190	0.638	0.846	0.539	0.97
150	10.4	300.9	19.8	85	92.0	4.37	396	698	52.2	1685	0.352	190	0.645	0.848	0.547	1.08
150	12.8	300.7	24.0	85	103.8	5.31	485	686	56.8	2055	0.348	191	0.643	0.854	0.549	1.17
150	14.8	300.7	28.0	85	116.3	6.19	576	676	60.2	2426	0.347	190	0.634	0.864	0.548	1.24



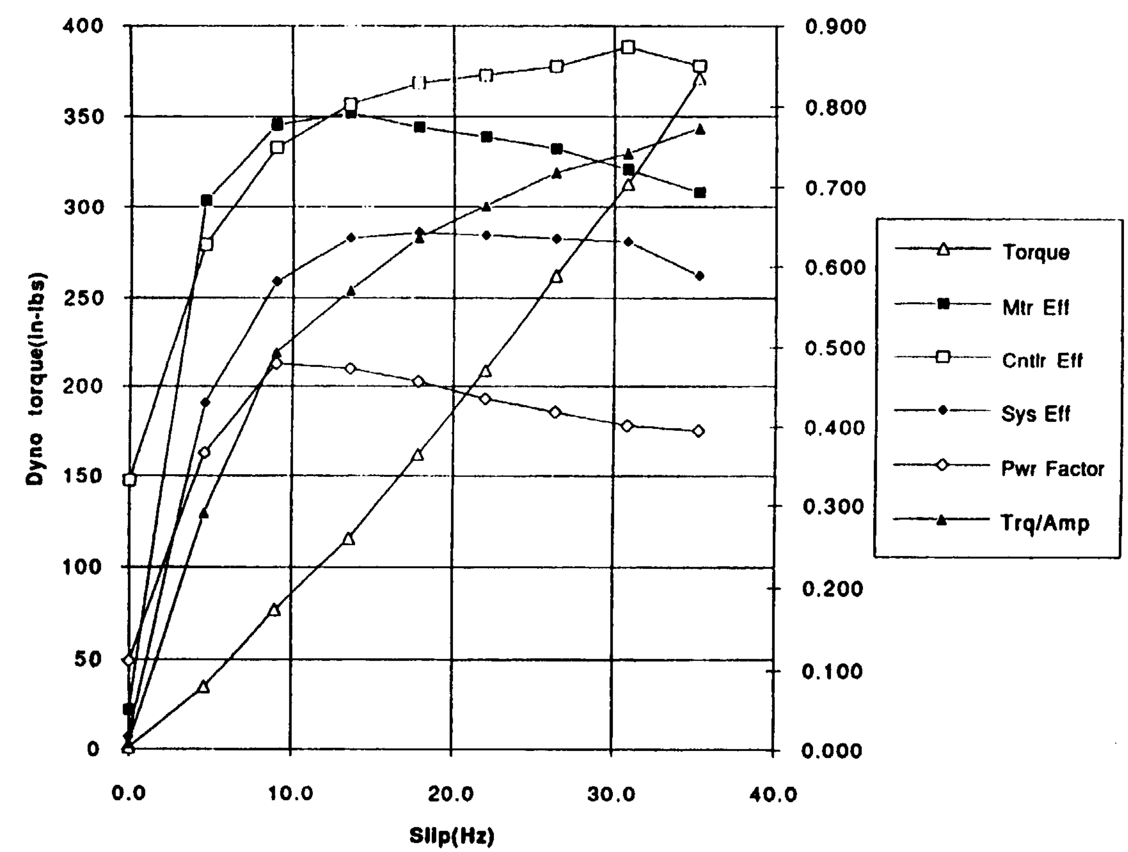
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
250Hz/42A																
250	0.0	301.0	2.8	42	27.9	0.04	2	1250	26.0	92	0.127	185	0.108	0.327	0.035	0.02
250	4.4	301.0	4.8	42	30.2	0.69	35	1228	26.2	279	0.354	186	0.615	0.579	0.356	0.29
250	8.8	300.9	7.2	42	39.6	1.51	77	1206	30.3	515	0.432	187	0.729	0.713	0.520	0.49
250	13.2	301.0	10.4	42	51.3	2.29	122	1184	36.1	782	0.425	188	0.728	0.749	0.546	0.59
250	17.6	301.0	13.8	42	64.3	3.11	169	1162	42.1	1080	0.398	188	0.716	0.780	0.559	0.66
250	22.0	300.8	17.4	42	78.2	3.96	219	1140	47.1	1410	0.382	191	0.698	0.808	0.564	0.70
250	26.0	300.7	21.2	42	92.2	4.84	271	1120	52.0	1754	0.365	191	0.686	0.825	0.566	0.73
250	30.4	300.6	25.8	42	106.5	5.71	328	1098	57.0	2166	0.354	192	0.656	0.838	0.549	0.77
250	34.8	300.5	30.2	42	120.6	6.57	383	1076	61.4	2549	0.346	194	0.641	0.843	0.540	0.79



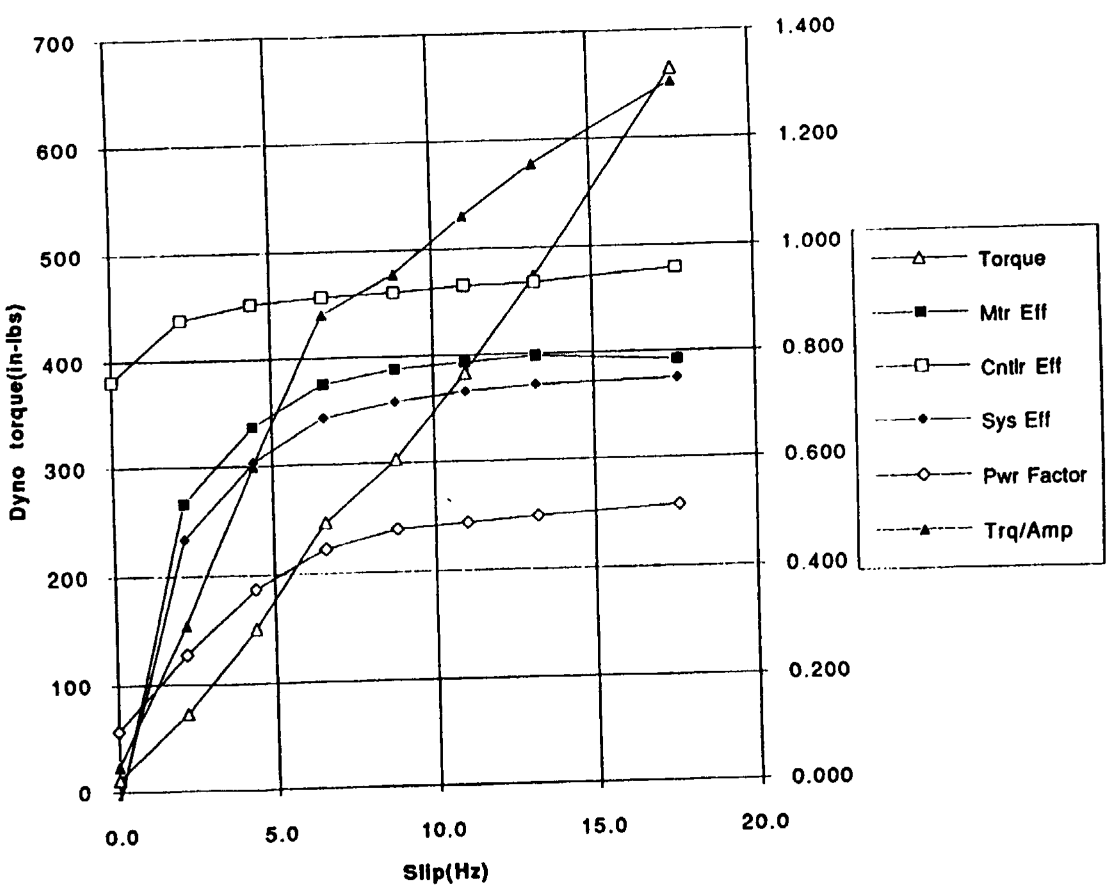
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
250Hz/85A																
250	0.0	300.9	5.2	85	58.2	0.10	5	1250	53.9	395	0.126	184	0.063	0.757	0.048	0.02
250	2.0	301.0	8.8	85	59.0	0.70	138	1240	53.3	764	0.243	190	0.228	0.865	0.197	0.58
250	4.4	300.8	13.2	85	63.5	2.97	152	1228	53.7	1170	0.344	190	0.631	0.884	0.558	0.60
250	6.8	300.7	17.6	85	70.7	4.49	232	1216	55.8	1595	0.404	188	0.700	0.904	0.633	0.82
250	8.8	300.7	22.6	85	80.2	5.97	313	1206	59.5	2046	0.429	190	0.726	0.903	0.655	0.98
250	11.0	300.6	28.0	85	91.2	7.48	394	1195	64.2	2546	0.434	190	0.731	0.907	0.663	1.08
250	13.0	300.4	34.2	85	103.3	9.09	484	1185	67.8	3058	0.440	191	0.739	0.893	0.660	1.17
250	15.2	300.2	40.0	85	115.5	10.70	574	1174	71.3	3665	0.441	192	0.726	0.916	0.665	1.24



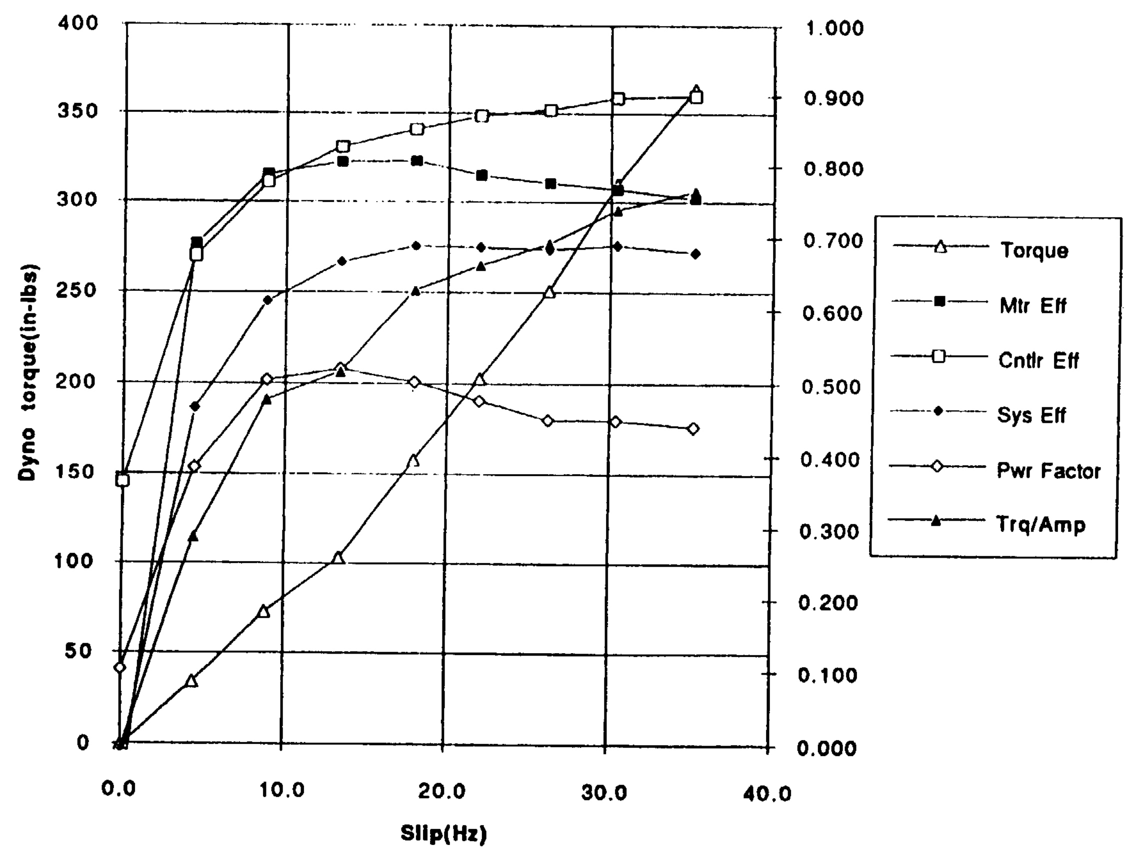
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
350Hz/42A																
350	0.0	301.0	3.0	42	27.8	0.02	1	1750	32.6	100	0.111	185	0.050	0.332	0.017	0.01
350	4.6	301.0	5.6	42	30.0	0.97	35	1727	32.2	353	0.367	186	0.683	0.628	0.429	0.29
350	9.0	301.0	8.8	42	39.0	2.07	77	1705	35.5	662	0.479	187	0.778	0.750	0.583	0.49
350	13.6	300.9	12.4	42	50.7	3.18	116	1682	41.3	999	0.473	188	0.792	0.803	0.636	0.57
350	17.8	300.8	16.6	42	63.6	4.30	162	1661	47.6	1380	0.456	189	0.775	0.829	0.642	0.64
350	22.0	300.8	21.2	42	77.2	5.47	209	1640	52.8	1782	0.435	189	0.763	0.838	0.640	0.68
350	26.4	300.6	26.4	42	91.1	6.76	262	1618	59.3	2247	0.418	193	0.748	0.849	0.635	0.72
350	30.8	300.4	31.2	42	105.3	7.93	313	1596	64.3	2730	0.401	195	0.722	0.874	0.631	0.74
350	35.2	300.3	39.0	42	119.8	9.26	371	1574	68.4	3320	0.395	199	0.694	0.850	0.590	0.77



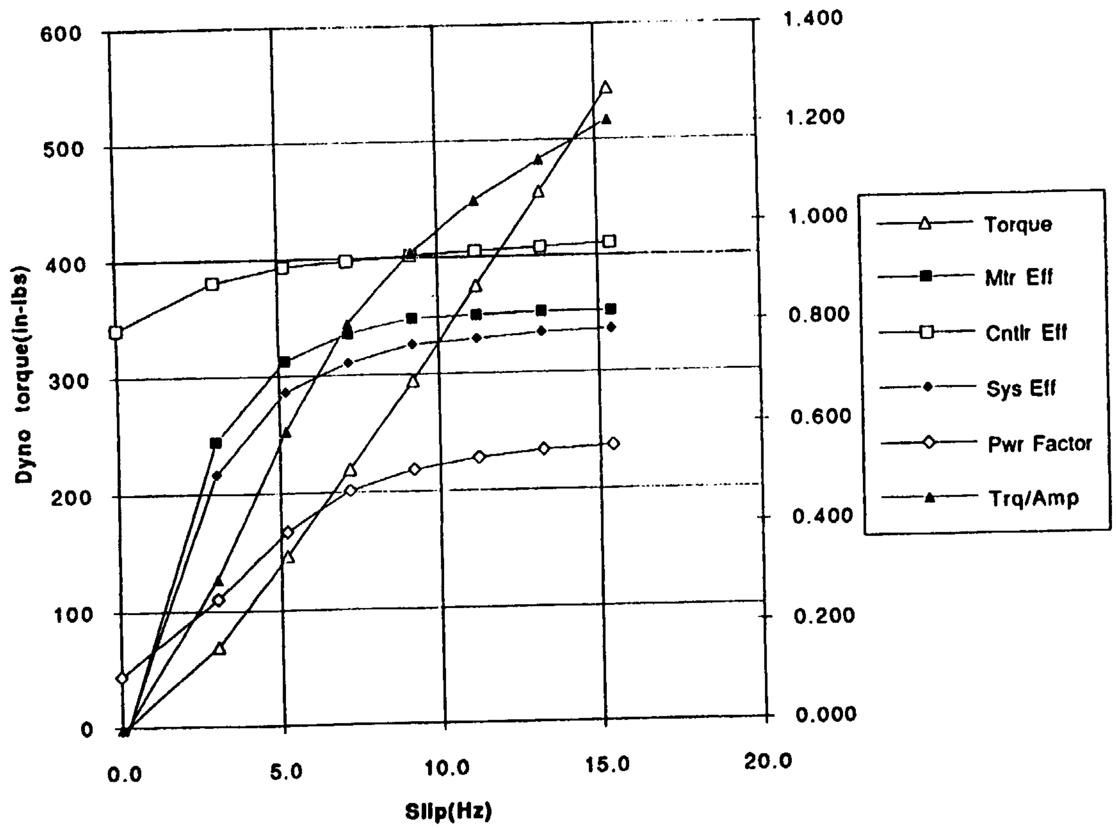
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
350Hz/85A																
350	0.0	300.8	5.4	85	58.2	-0.04	11	1750	63.4	412	0.112	188	-0.024	0.761	-0.018	0.05
350	2.2	300.7	10.6	85	58.4	1.99	72	1739	62.4	930	0.255	189	0.532	0.875	0.466	0.31
350	4.4	300.7	16.4	85	62.5	4.01	150	1728	63.3	1484	0.374	190	0.672	0.903	0.607	0.60
350	6.6	300.5	22.2	85	69.8	6.14	246	1717	65.8	2034	0.443	190	0.751	0.915	0.687	0.88
350	8.8	300.2	28.6	85	79.4	8.22	303	1706	69.4	2634	0.477	191	0.776	0.920	0.714	0.95
350	11.0	300.3	35.0	85	90.2	10.30	383	1695	74.0	3258	0.486	191	0.786	0.930	0.731	1.06
350	13.2	300.1	42.4	85	102.1	12.66	472	1684	77.9	3960	0.497	194	0.795	0.934	0.742	1.16
350	17.6	299.7	58.4	85	127.2	17.59	665	1662	84.1	5580	0.513	198	0.784	0.956	0.750	1.31



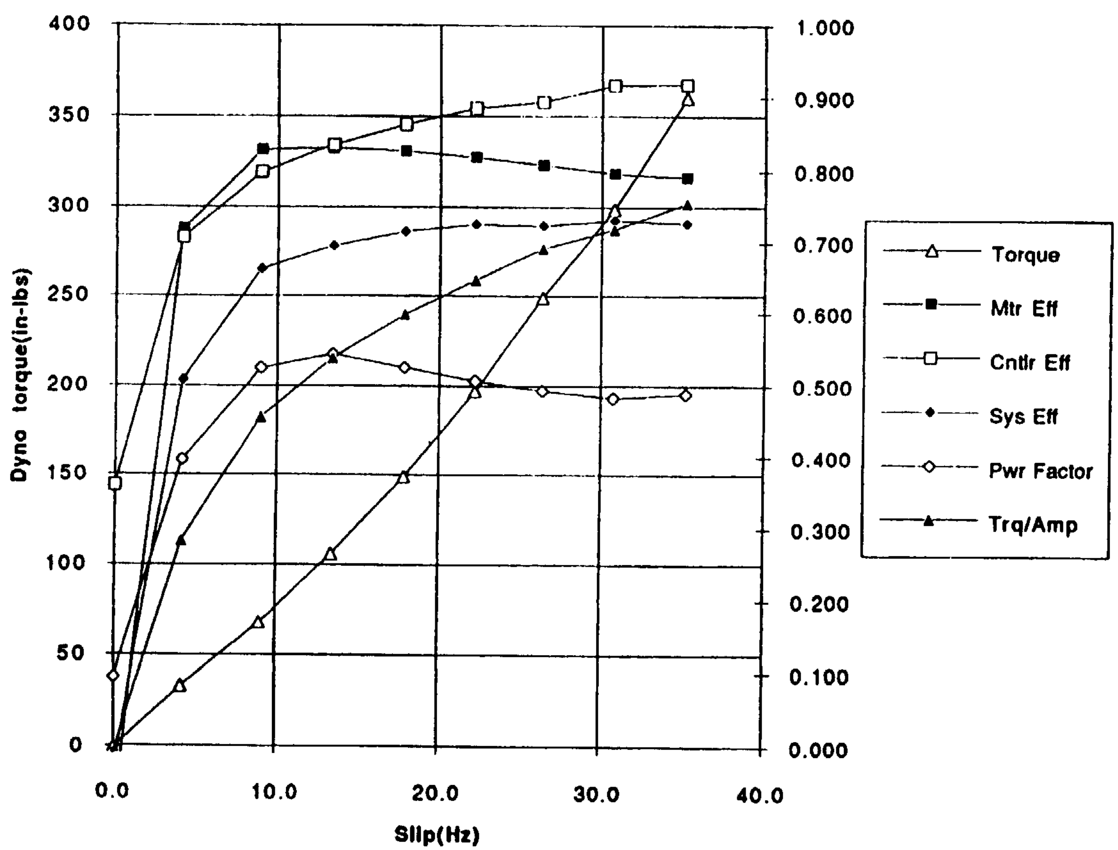
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
450Hz/42A																
450	0.0	300.0	3.0	42	27.8	-0.04	-1	2250	38.7	109	0.102	186	-0.091	0.363	-0.033	-0.01
450	4.4	300.1	6.4	42	29.6	1.20	34	2228	37.9	432	0.384	189	0.691	0.675	0.466	0.29
450	8.8	299.9	10.4	42	38.2	2.56	73	2206	41.6	808	0.505	191	0.788	0.777	0.612	0.48
450	13.4	299.9	14.6	42	49.8	3.91	103	2183	46.7	1207	0.520	198	0.806	0.827	0.666	0.52
450	18.0	299.9	19.6	42	62.9	5.42	158	2160	53.0	1669	0.502	190	0.808	0.852	0.688	0.63
450	22.0	299.9	25.0	42	76.7	6.90	203	2140	59.6	2179	0.476	192	0.787	0.872	0.687	0.66
450	26.2	299.7	30.8	42	90.7	8.45	251	2119	66.4	2707	0.450	192	0.776	0.880	0.683	0.69
450	30.4	299.4	37.4	42	104.9	10.34	310	2098	71.0	3350	0.449	198	0.768	0.898	0.689	0.74
450	35.2	299.1	44.0	42	119.0	11.99	364	2074	74.3	3950	0.441	202	0.755	0.900	0.680	0.76



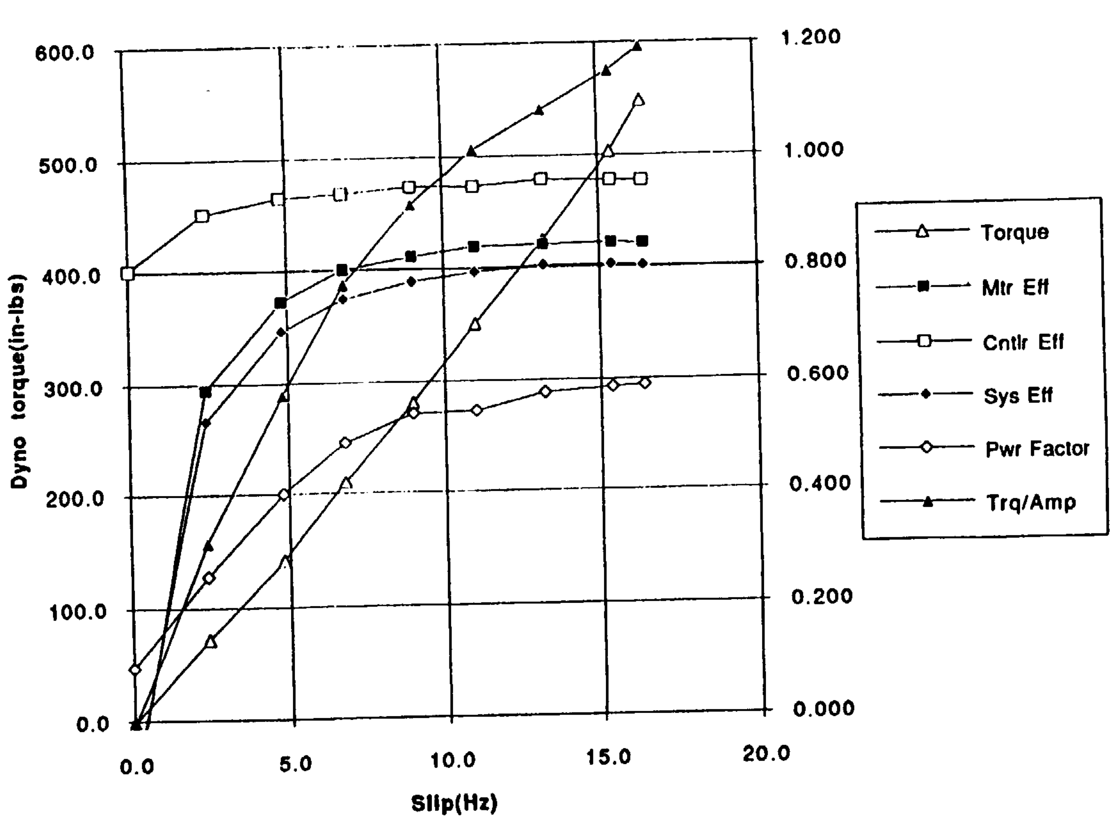
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (In-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
450Hz/85A																
450	0.0	300.7	5.6	85	58.0	-0.08	-4	2250	74.6	446	0.102	192	-0.045	0.795	-0.035	-0.02
450	3.0	300.6	12.2	85	58.0	2.49	69	2235	73.0	1083	0.256	190	0.572	0.886	0.507	0.30
450	5.2	300.1	19.2	85	61.8	5.16	146	2224	73.1	1760	0.390	188	0.729	0.916	0.668	0.59
450	7.2	300.2	26.4	85	68.6	7.70	220	2214	75.5	2447	0.471	191	0.782	0.926	0.725	0.80
450	9.2	300.0	33.6	85	78.0	10.25	294	2204	78.6	3146	0.512	192	0.810	0.936	0.759	0.94
450	11.2	300.0	42.0	85	89.3	12.99	374	2194	83.0	3965	0.533	192	0.815	0.944	0.769	1.05
450	13.2	300.0	50.4	85	100.9	15.80	455	2184	86.6	4790	0.547	195	0.820	0.950	0.780	1.13
450	15.4	299.6	59.6	85	112.8	18.78	544	2173	90.5	5695	0.554	198	0.820	0.957	0.785	1.21



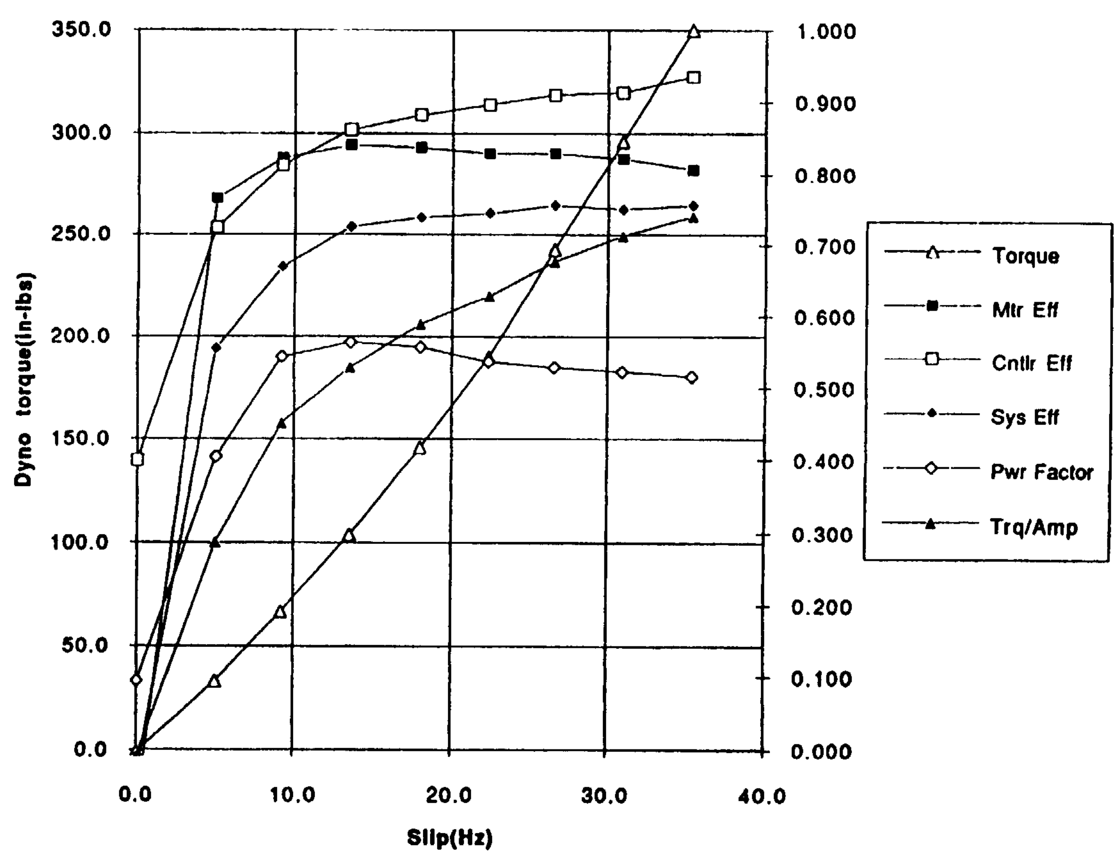
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (In-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
550Hz/42A																
550	0.0	300.0	3.2	42	27.3	-0.05	-1	2750	45.0	115	0.095	181	-0.108	0.359	-0.039	-0.01
550	4.2	300.0	7.0	42	29.1	1.43	33	2729	43.3	495	0.396	183	0.718	0.707	0.508	0.28
550	9.0	299.9	11.2	42	37.3	2.98	68	2705	45.7	894	0.524	183	0.829	0.798	0.662	0.46
550	13.4	299.9	16.4	42	49.2	4.58	106	2683	51.2	1370	0.544	182	0.831	0.836	0.695	0.54
550	17.8	299.8	22.0	42	62.2	6.32	149	2661	58.0	1899	0.525	188	0.828	0.864	0.715	0.60
550	22.2	299.6	28.6	42	76.1	8.33	197	2639	65.4	2530	0.507	192	0.819	0.886	0.725	0.65
550	26.4	299.5	35.6	42	90.0	10.34	249	2618	71.6	3179	0.493	199	0.809	0.894	0.723	0.69
550	30.8	299.2	42.2	42	104.0	12.37	299	2596	76.2	3860	0.483	196	0.797	0.917	0.731	0.72
550	35.2	299.1	50.6	42	119.1	14.75	360	2574	79.4	4630	0.489	197	0.792	0.918	0.727	0.76



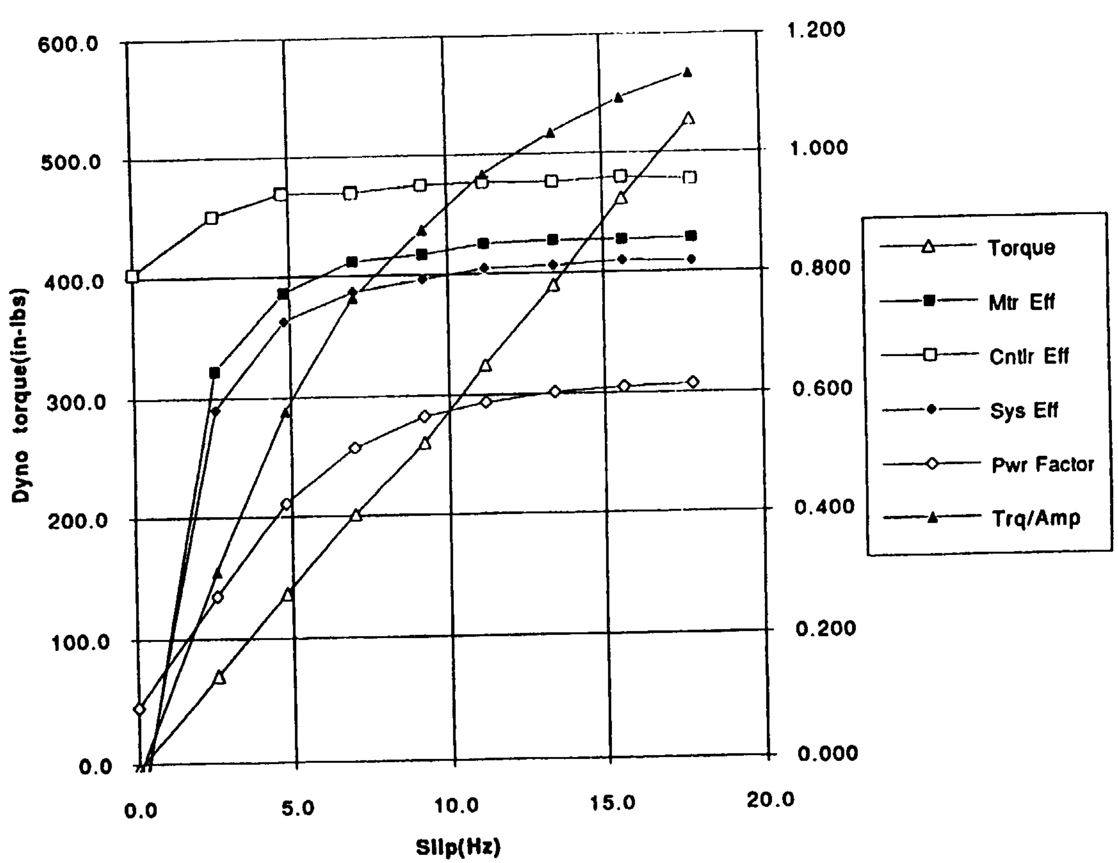
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
550Hz/85A																
550	0.0	300.7	5.8	85	57.8	-0.22	-2.0	2750	85.5	467	0.095	187	-0.117	0.803	-0.094	-0.01
550	2.4	300.6	13.6	85	57.5	2.92	72.0	2738	83.9	1230	0.255	191	0.590	0.903	0.533	0.31
550	4.8	300.5	21.8	85	60.9	6.10	141.0	2726	83.2	2030	0.400	190	0.747	0.930	0.695	0.58
550	6.8	300.3	30.0	85	67.7	9.06	210.0	2716	84.4	2812	0.491	190	0.801	0.936	0.750	0.78
550	9.0	299.8	38.4	85	76.8	12.02	281.0	2705	87.3	3635	0.542	191	0.822	0.947	0.779	0.91
550	11.0	300.0	47.2	85	87.0	15.06	352.0	2695	91.0	4465	0.546	192	0.839	0.946	0.793	1.01
550	13.2	299.8	56.0	85	98.0	18.10	424.0	2684	94.1	5357	0.577	191	0.840	0.957	0.804	1.08
550	15.4	299.4	66.0	85	109.4	21.32	503.0	2673	97.9	6290	0.586	196	0.843	0.955	0.805	1.15
550	16.4	299.0	72.0	85	115.0	23.17	548.0	2668	100.0	6847	0.589	205	0.841	0.954	0.803	1.19



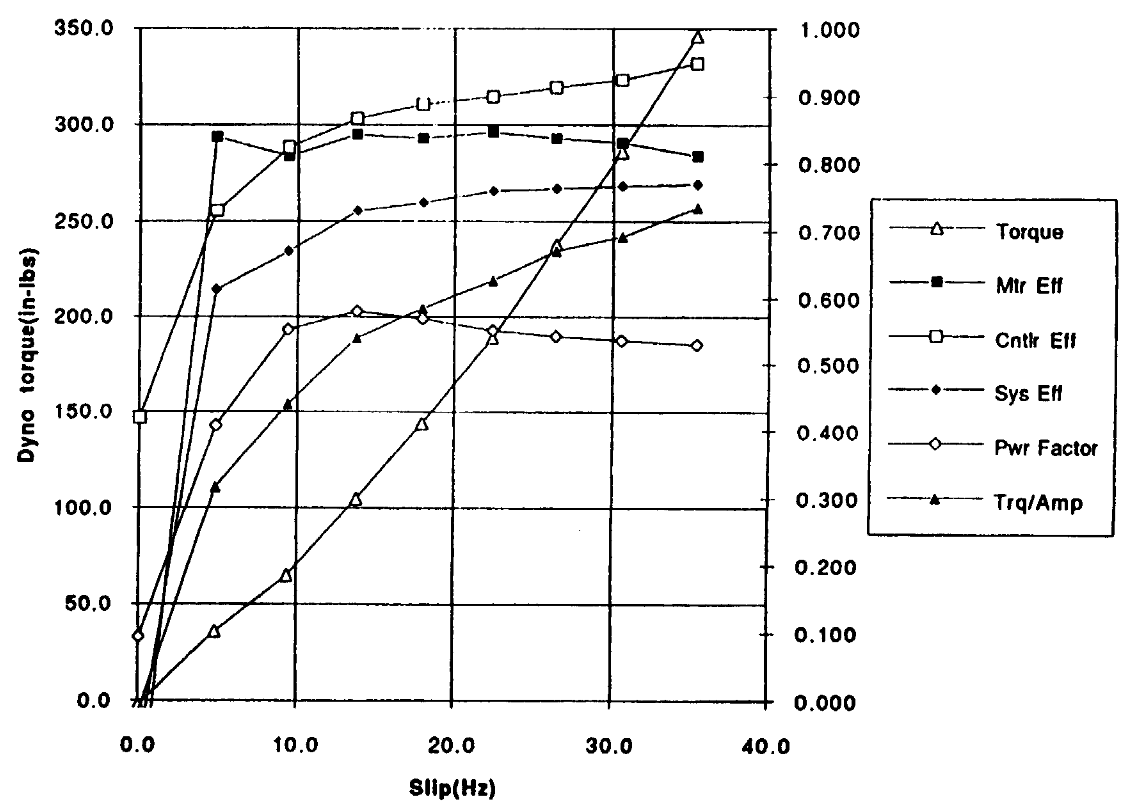
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
650Hz/42A																
650	0.0	300.7	3.4	42	27.3	-0.05	-1.0	3250	51.3	136	0.095	180	-0.091	0.399	-0.036	-0.01
650	5.0	300.7	7.6	42	28.7	1.70	33.0	3225	47.8	552	0.404	176	0.766	0.725	0.555	0.29
650	9.2	300.7	12.6	42	37.1	3.40	67.0	3204	51.0	1027	0.543	186	0.823	0.813	0.669	0.45
650	13.6	300.5	18.0	42	49.2	5.26	104.0	3182	56.1	1555	0.563	175	0.841	0.862	0.725	0.53
650	18.0	300.3	24.6	42	61.9	7.32	146.0	3160	63.0	2172	0.556	187	0.838	0.882	0.739	0.59
650	22.4	300.2	31.6	42	75.5	9.47	190.0	3138	70.0	2836	0.536	185	0.830	0.897	0.745	0.63
650	26.6	300.0	39.6	42	89.7	12.03	243.0	3117	75.7	3605	0.529	191	0.830	0.910	0.755	0.68
650	31.0	299.9	48.0	42	103.8	14.49	296.0	3095	90.9	4383	0.523	194	0.822	0.913	0.751	0.71
650	35.4	299.6	56.2	42	118.2	17.05	350.0	3073	85.2	5250	0.516	197	0.808	0.935	0.755	0.74



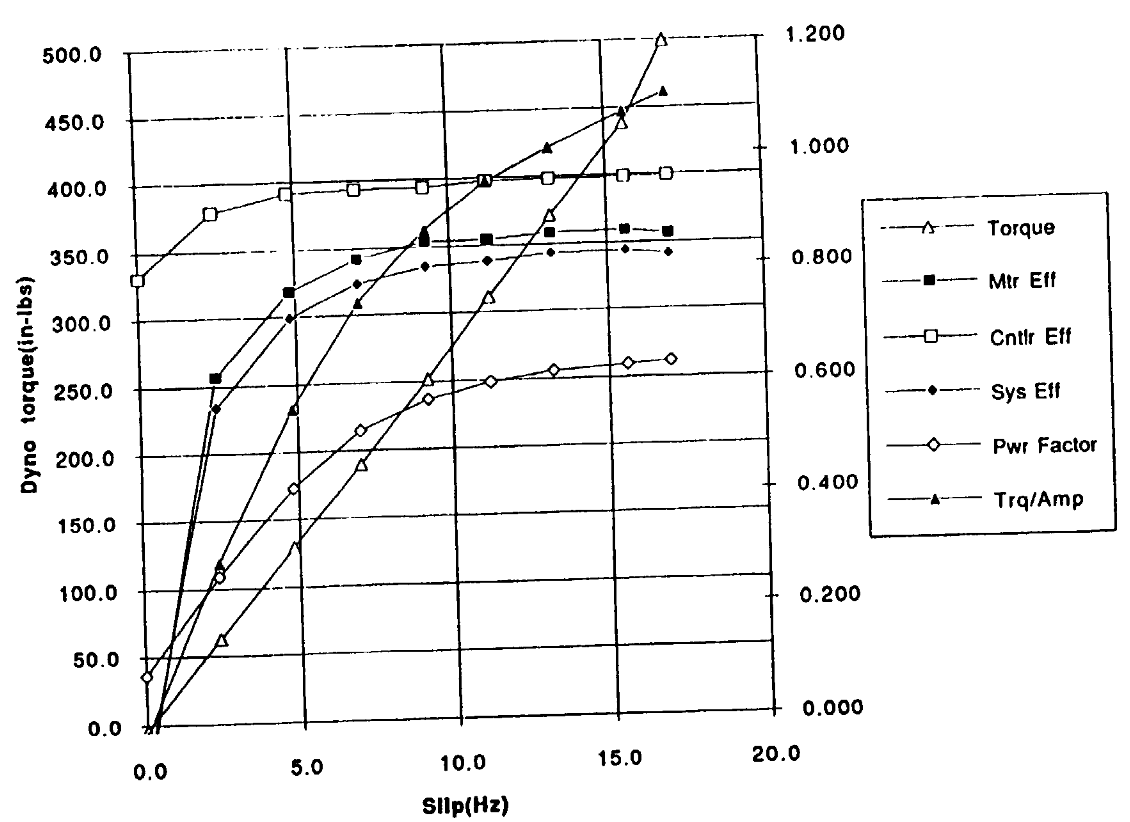
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
650Hz/85A																
650	0.0	300.5	6.0	85	57.1	-0.20	-4.0	3250	94.0	485	0.090	189	-0.103	0.807	-0.083	-0.02
650	2.6	300.4	15.4	85	56.4	3.60	70.0	3237	91.4	1390	0.269	189	0.644	0.901	0.581	0.31
650	4.8	300.1	24.0	85	59.3	7.01	137.0	3226	89.7	2255	0.423	185	0.773	0.939	0.726	0.58
650	7.0	299.9	33.0	85	65.8	10.26	201.0	3215	91.1	3098	0.515	190	0.824	0.939	0.773	0.76
650	9.2	299.8	41.6	85	74.5	13.24	261.0	3204	94.0	3950	0.565	190	0.834	0.950	0.792	0.88
650	11.2	299.6	50.8	85	84.0	16.52	325.0	3194	97.6	4835	0.588	191	0.850	0.953	0.810	0.97
650	13.4	299.2	60.4	85	94.1	19.70	390.0	3183	100.7	5735	0.603	192	0.854	0.952	0.813	1.04
650	15.6	299.2	70.6	85	105.6	23.21	462.0	3172	104.6	6755	0.610	200	0.854	0.959	0.820	1.09
650	17.8	298.5	81.0	85	116.4	26.50	528.0	3161	107.1	7695	0.614	197	0.856	0.955	0.818	1.13

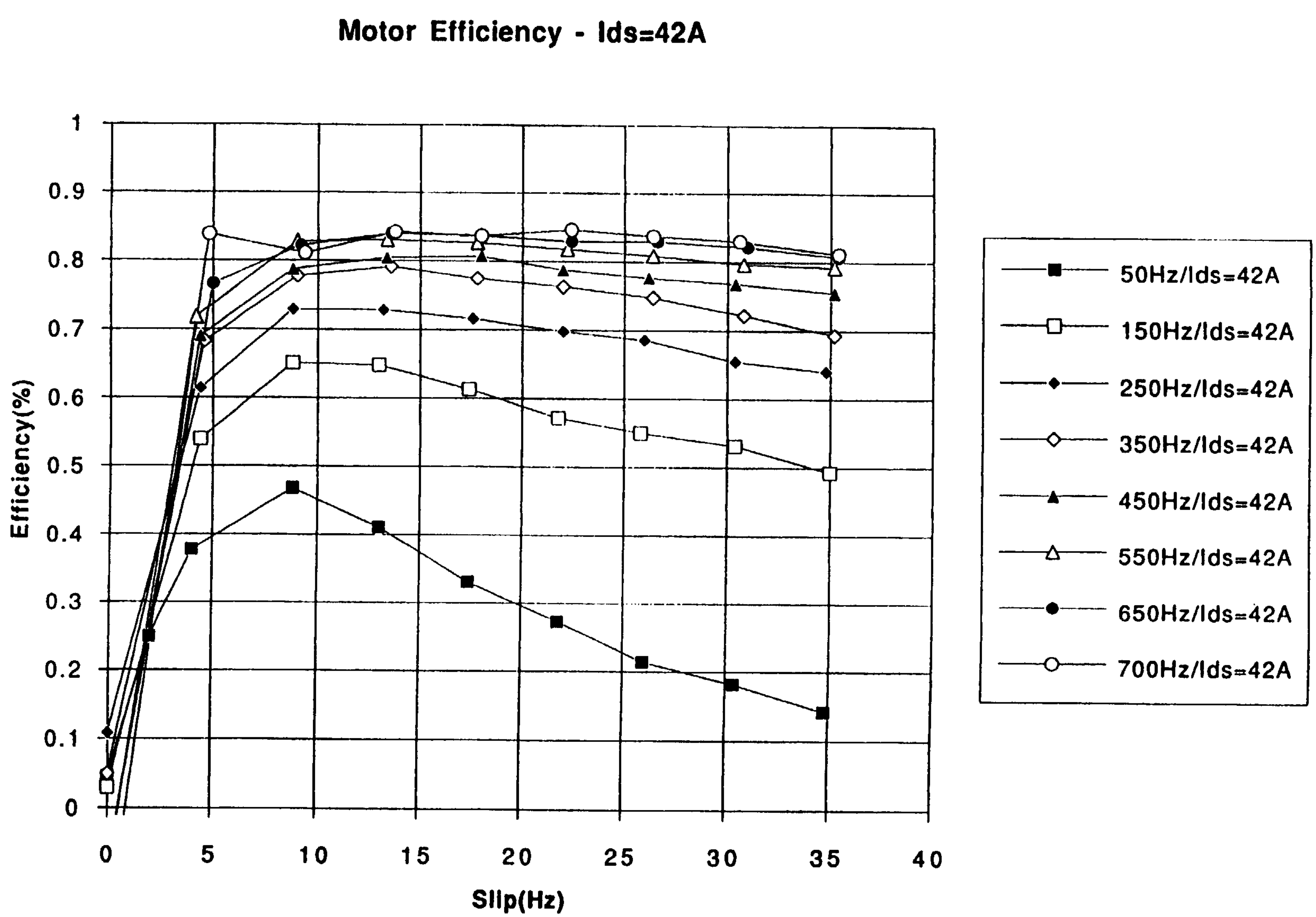


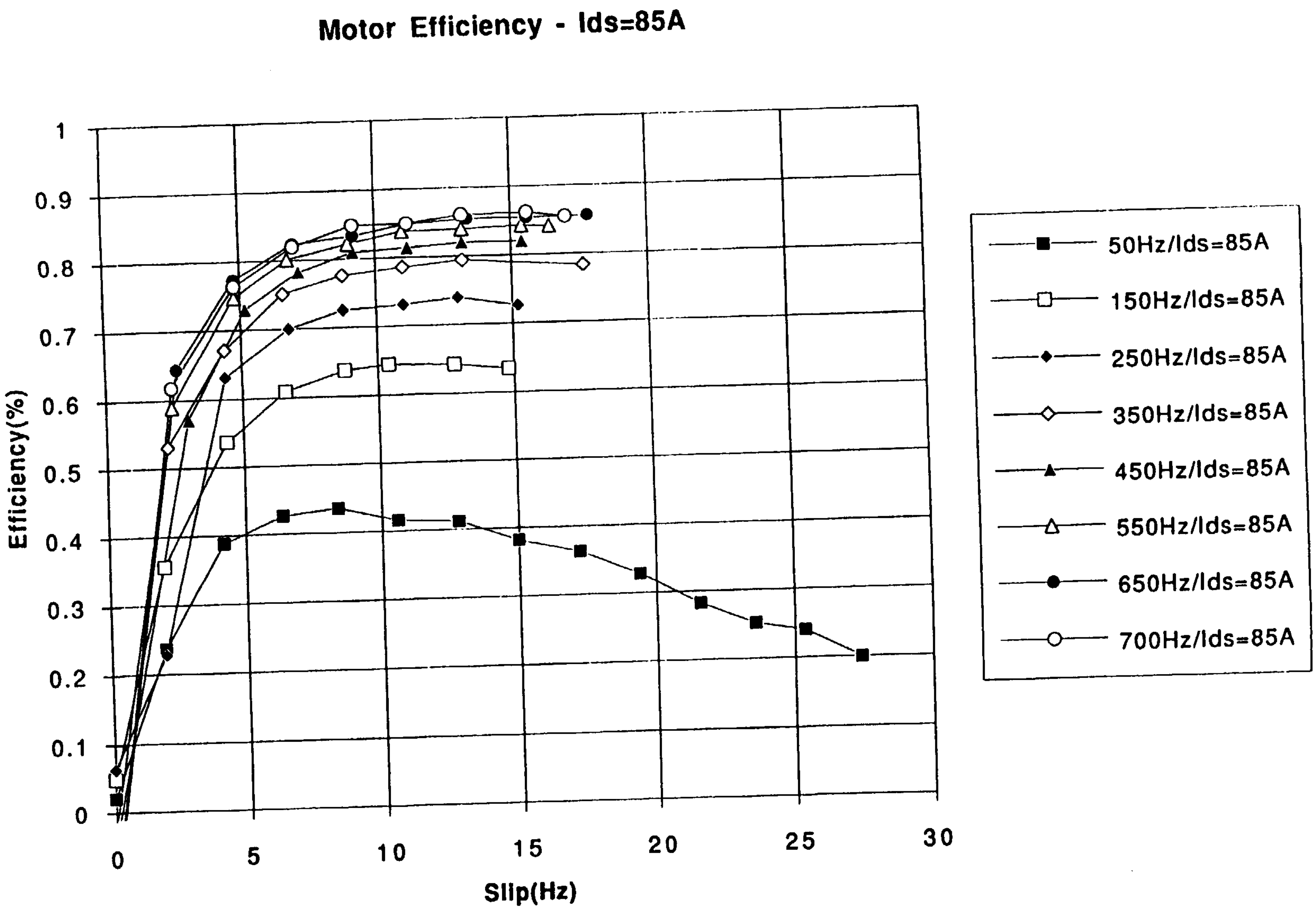
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
700Hz/42A																
700	0.0	301.1	3.4	42	27.8	-0.11	-2.0	3500	54.7	143	0.095	190	-0.191	0.419	-0.080	-0.02
700	4.8	301.2	8.0	42	28.4	1.98	36.0	3476	50.6	587	0.408	187	0.839	0.731	0.613	0.32
700	9.4	300.9	13.2	42	36.9	3.56	65.0	3453	53.5	1091	0.553	188	0.811	0.824	0.669	0.44
700	13.8	300.8	19.4	42	48.6	5.71	105.0	3431	59.4	1685	0.581	188	0.843	0.866	0.730	0.54
700	18.0	300.8	26.0	42	61.5	7.79	144.0	3410	65.9	2313	0.569	191	0.837	0.887	0.743	0.59
700	22.4	300.7	33.0	42	75.3	10.12	189.0	3388	71.6	2973	0.552	189	0.846	0.899	0.761	0.63
700	26.4	300.3	41.6	42	88.9	12.80	238.0	3368	78.2	3800	0.543	192	0.838	0.913	0.764	0.67
700	30.6	300.4	49.6	42	103.4	15.34	286.0	3347	82.9	4590	0.536	193	0.831	0.924	0.768	0.69
700	35.4	300.1	58.6	42	117.6	18.16	346.0	3323	88.3	5560	0.530	200	0.812	0.948	0.770	0.74

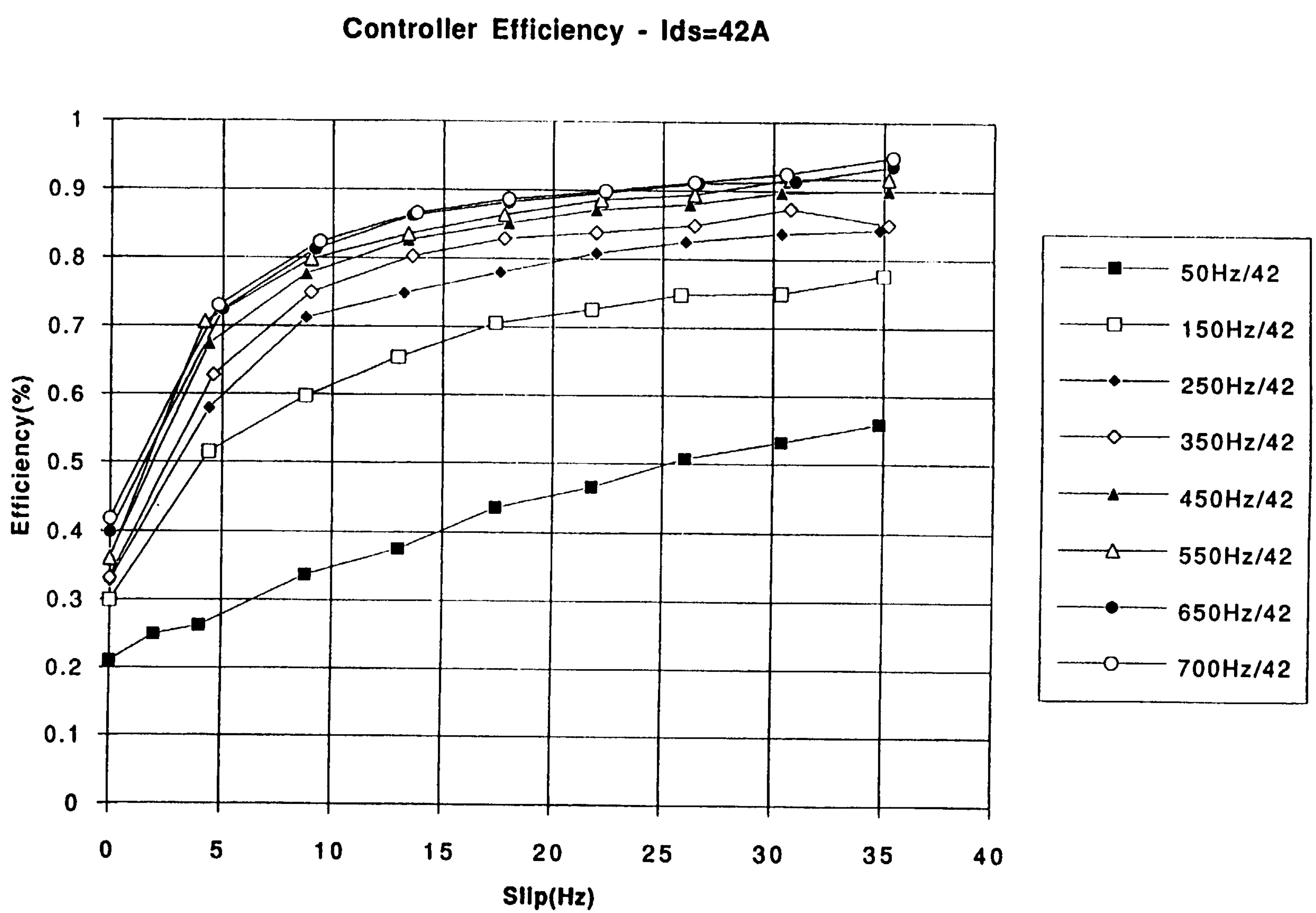


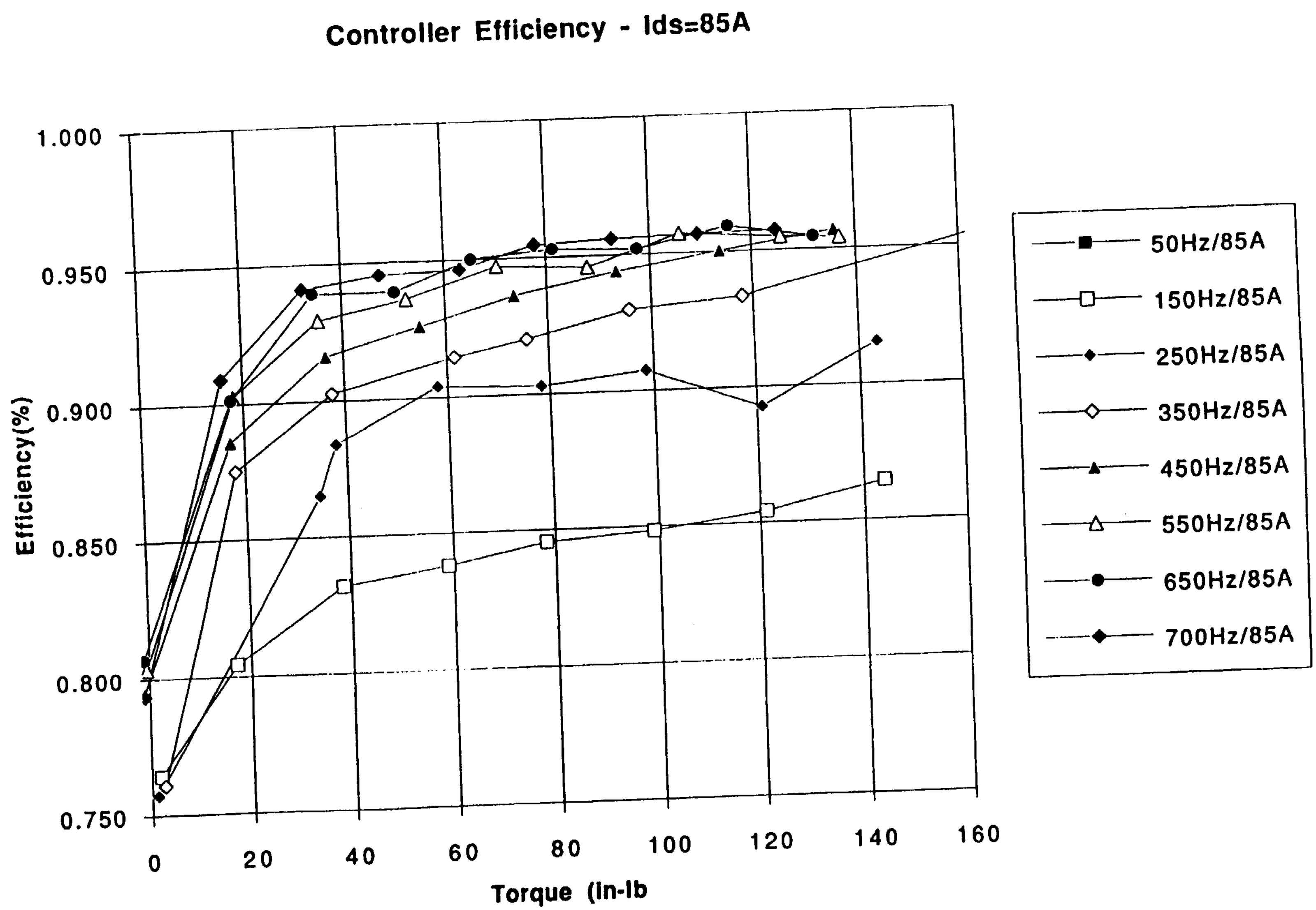
Stator Freq (Hz)	Slip Frequency (Hz)	Vdc (Volts)	Idc (Amps)	Ids	Motor Current (Amps)	Horse-power	Dyno Torque (in-lbs)	Dyno Speed (rpm)	Motor Voltage (L-N)	Motor Power (per Ø)	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff	Torque /Amp
700Hz/85A																
700	0.0	301.3	6.2	85	56.0	-0.20	-4.0	3500	100.8	494	0.088	198	-0.101	0.793	-0.080	-0.02
700	2.4	301.1	15.4	85	55.4	3.49	63.0	3488	97.5	1405	0.261	190	0.618	0.909	0.561	0.28
700	4.8	300.7	24.6	85	58.0	7.12	129.0	3476	95.9	2320	0.416	199	0.763	0.941	0.718	0.56
700	7.0	300.7	33.6	85	64.1	10.50	190.0	3465	96.3	3184	0.515	199	0.820	0.945	0.775	0.74
700	9.2	300.6	42.8	85	72.3	13.86	252.0	3454	98.7	4059	0.569	203	0.849	0.946	0.804	0.87
700	11.2	300.3	52.0	85	81.5	16.99	311.0	3444	102.2	4970	0.597	205	0.850	0.955	0.812	0.95
700	13.2	300.0	61.4	85	91.7	20.32	371.0	3434	104.4	5871	0.614	198	0.861	0.956	0.823	1.01
700	15.6	300.0	72.0	85	102.0	23.90	438.0	3422	108.9	6890	0.623	208	0.863	0.957	0.825	1.07
700	17.0	299.5	82.2	85	112.7	27.04	499.0	3415	111.3	7858	0.628	210	0.856	0.958	0.819	1.11



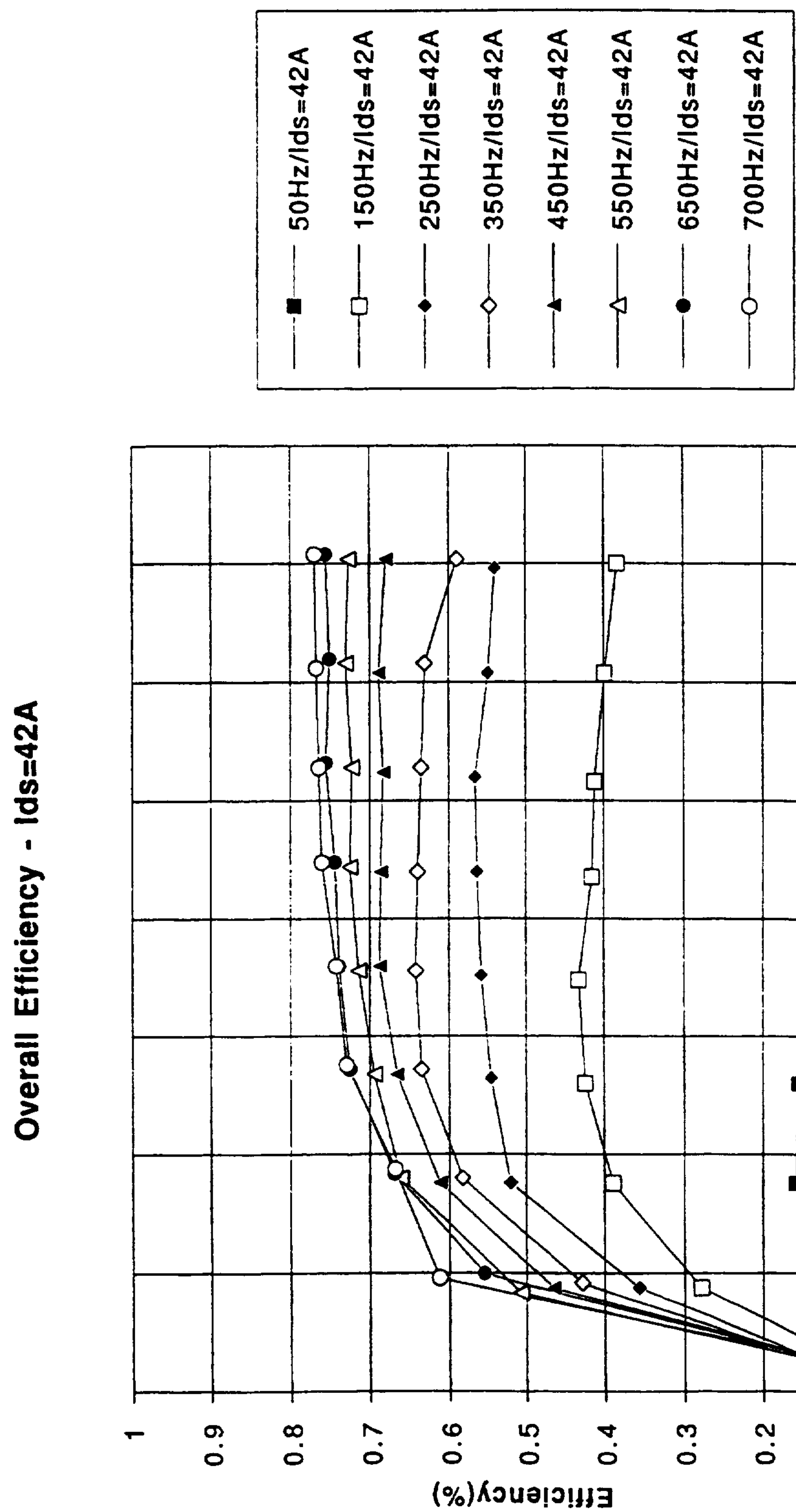

Motor Efficiency - Ids=42A
Efficiency(%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Slip(Hz)
0
5
10
15
20
25
30
35
40
50Hz/Ids=42A
150Hz/Ids=42A
250Hz/Ids=42A
350Hz/Ids=42A
450Hz/Ids=42A
550Hz/Ids=42A
650Hz/Ids=42A
700Hz/Ids=42A


Motor Efficiency - Ids=85A
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Efficiency(%)
0
5
10
15
20
25
30
Slip(Hz)
50Hz/Ids=85A
150Hz/Ids=85A
250Hz/Ids=85A
350Hz/Ids=85A
450Hz/Ids=85A
550Hz/Ids=85A
650Hz/Ids=85A
700Hz/Ids=85A


Controller Efficiency - Ids=42A
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Efficiency(%)
0
5
10
15
20
25
30
35
40
Slip(Hz)
50Hz/42
150Hz/42
250Hz/42
350Hz/42
450Hz/42
550Hz/42
650Hz/42
700Hz/42

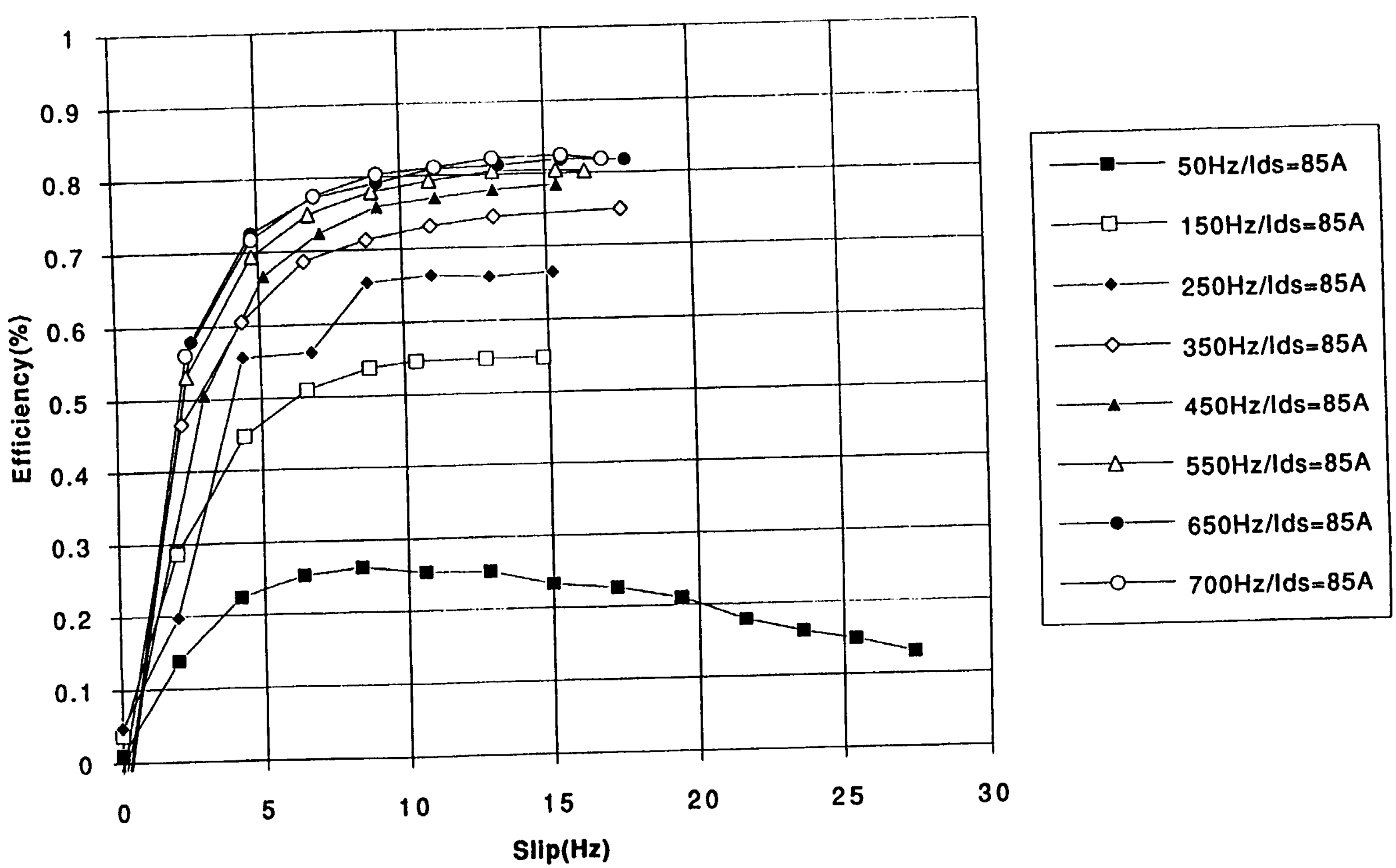


Controller Efficiency - Ids=85A
Efficiency(%)
1.000
0.950
0.900
0.850
0.800
0.750
0
20
40
60
80
100
120
140
160
Torque (in-lb
50Hz/85A
150Hz/85A
250Hz/85A
350Hz/85A
450Hz/85A
550Hz/85A
650Hz/85A
700Hz/85A



Overall Efficiency - Ids=42A
Efficiency(%)
Slip(Hz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
25
30
35
40
50Hz/Ids=42A
150Hz/Ids=42A
250Hz/Ids=42A
350Hz/Ids=42A
450Hz/Ids=42A
550Hz/Ids=42A
650Hz/Ids=42A
700Hz/Ids=42A

Overall Efficiency - Ids=85A



SECTION 2 – SYSTEM TEST DATA

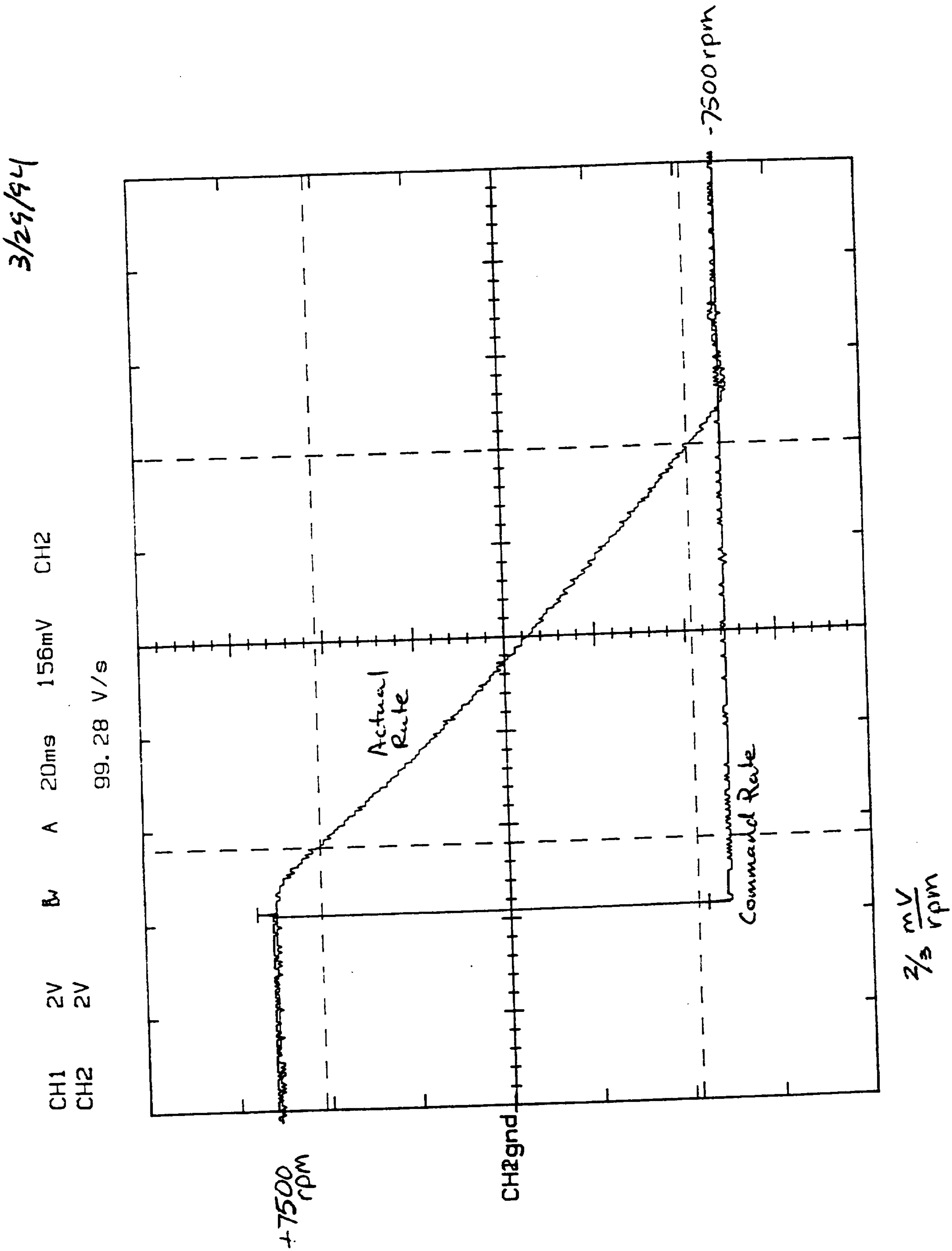
The tables containing the measured data have column headings defined below:

Heading	Definition
Stator Frequency	Motor fundamental stator frequency in Hz.
Vdc	Input dc voltage.
Idc	Input dc current in amps.
Ids	Commanded flux current (Ids=85A is full rated flux).
Motor Current (A/phase)	The measured stator current amps per phase.
Horsepower	Output power measured with torque transducer and resolver on the dynamometer.
Dyno Torque in-lbs	The dyno torque output at the torque transducer. The motor torque is one-fourth due to the speed reducer.
Dyno Speed	Speed measured be the resolver on the dyno motor. The test motor speed is four times to speed reducer.
Motor Voltage L-N	The Line-to-Neutral motor voltage.
Motor Power (per Ø)	The real power measured in watts in one phase of the motor.
Power Factor	The power factor of the power into the motor.
Motor Temp	Motor Temp in deg F as measured by a thermocouple in the motor stator.
Motor Eff.	The efficiency of the motor. Calculated by dividing the output power as measured on the dyno by the power into the motor.
Controller Eff.	The efficiency of the controller. Calculated be dividing the input power into the motor by the input power into the controller (from 0 to 1.00).
Overall Eff.	End to end system efficiency . Calculated be dividing the output power as measured on the dyno by the input power into the controller (from 0 to 1.00).

Stator Freq	Vdc	Idc	Ids	Motor Current	HP	Dyno Torque	Dyno Speed	Motor Voltage L-N	Motor Power /Phase	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff
Ids=21A														
	301.6	5.6	21	44.7	0.72	61	750	22.9	308	0.301	185	58.1	54.7	31.8
	301.6	9.2	21	68.7	1.20	101	750	36.2	595	0.240	185	50.2	64.3	32.3
	301.4	14.8	21	98.9	1.77	150	750	49.2	1043	0.220	185	42.2	70.1	29.6
	301.7	6.6	21	39.4	1.21	51	1500	26.6	412	0.392	180	73.0	62.1	45.3
	301.5	12.2	21	68.7	2.44	103	1500	42.5	905	0.311	179	67.0	73.8	49.5
	301.4	18.6	21	93.1	3.53	149	1500	52.6	1452	0.303	196	60.5	77.7	47.0
	301.5	10.0	21	47.2	2.20	62	2250	36.1	722	0.419	180	75.8	71.8	54.4
	301.3	17.0	21	74.7	3.87	109	2250	50.5	1363	0.363	188	70.6	79.8	56.4
	301.2	23.2	21	93.9	5.11	144	2250	58.8	1893	0.344	197	67.1	81.3	54.6
	301.4	12.2	21	49.3	2.88	62	2946	42.1	948	0.455	184	75.5	77.3	58.4
	301.3	19.6	21	73.7	4.74	102	2945	54.9	1625	0.401	186	72.5	82.6	59.9
	301.0	78.8	21	99.2	6.83	147	2944	67.5	2444	0.368	196	69.5	30.9	21.5
	301.3	12.0	21	44.3	2.98	54	3496	42.5	914	0.492	188	81.1	75.8	61.5
	301.2	22.6	21	75.0	5.74	104	3497	60.1	1913	0.426	193	74.6	84.3	62.9
	301.0	33.0	21	99.3	8.11	147	3497	71.7	2832	0.406	205	71.2	85.5	60.9
Ids=42A														
	301.6	6.8	42	44.9	1.18	100	749	26.7	460	0.384	192	63.8	67.3	42.9
	301.6	12.6	42	70.9	2.37	201	749	41.6	948	0.322	194	62.2	74.8	46.5
	301.4	19.6	42	99.0	3.57	302	749	50.1	1523	0.312	196	58.3	77.3	45.1
	301.6	10.0	42	45.0	2.36	100	1498	37.0	772	0.463	193	76.0	76.8	58.4
	301.4	18.6	42	72.5	4.65	197	1498	49.7	1548	0.431	193	74.7	82.8	61.9
	301.1	29.6	42	103.0	7.07	300	1494	61.9	2514	0.397	199	69.9	84.6	59.2
	301.4	13.6	42	46.4	3.58	104	2245	46.5	1124	0.519	197	79.2	82.3	65.2
	301.1	25.6	42	75.9	7.01	198	2245	61.0	2245	0.485	194	77.6	87.4	67.8
	300.8	38.4	42	105.9	10.85	307	2241	72.1	3444	0.467	195	78.3	89.4	70.1
	301.2	17.2	42	47.6	4.82	102	2996	55.8	1477	0.555	197	81.1	85.5	69.4
	301.0	32.4	42	77.4	9.49	201	2994	70.5	2900	0.531	195	81.4	89.2	72.6
	300.6	47.8	42	104.8	13.91	295	2989	80.3	4325	0.519	205	80.0	90.3	72.2
	301.2	20.4	42	50.1	6.01	109	3497	62.0	1800	0.579	191	83.0	87.9	73.0
	300.4	37.6	42	79.6	11.35	206	3495	76.4	3420	0.564	201	82.5	90.8	75.0
	300.4	52.8	42	105.4	15.96	290	3490	85.7	4876	0.544	200	81.4	92.2	75.1

Stator Freq	Vdc	Idc	Ids	Motor Current	HP	Dyno Torque	Dyno Speed	Motor Voltage L-N	Motor Power /Phase	Power Factor	Motor Temp	Motor Eff	Controller Eff	Overall Eff
Ids=85A														
	301.5	11.8	85	66.8	2.30	195	748	45.5	1012	0.333	196	56.5	85.3	48.2
	301.5	18.8	85	84.6	4.18	354	748	51.7	1628	0.374	194	63.8	86.2	55.0
	301.3	25.8	85	103.1	5.86	497	748	58.2	2267	0.378	200	64.3	87.5	56.2
	301.2	18.2	85	67.2	4.68	198	1498	60.9	1655	0.404	195	70.3	90.6	63.7
	301.0	29.4	85	85.1	8.23	348	1499	68.7	2720	0.465	198	75.2	92.2	69.4
	300.8	41.0	85	105.7	11.58	490	1498	75.3	3788	0.480	198	76.0	92.1	70.0
	300.9	25.2	85	67.7	7.33	207	2246	77.0	2369	0.455	200	76.9	93.7	72.1
	300.7	41.6	85	87.1	12.79	361	2247	84.0	3912	0.534	197	81.3	93.8	76.3
	300.1	56.8	85	107.7	17.56	497	2241	90.4	5391	0.556	200	81.0	94.9	76.9
	300.8	31.2	85	66.4	9.50	201	2996	90.2	2950	0.492	198	80.1	94.3	75.5
	300.5	52.0	85	87.6	16.54	350	2996	96.9	4950	0.583	199	83.1	95.0	79.0
	299.9	72.8	85	111.9	23.33	494	2995	102.8	6898	0.603	203	84.1	94.8	79.7
	300.6	36.0	85	66.5	11.35	206	3495	96.7	3430	0.534	194	82.3	95.1	78.2
	300.1	58.4	85	88.5	18.93	343	3499	103.3	5580	0.611	200	84.4	95.5	80.6
	299.6	83.0	85	115.4	27.72	504	3488	111.1	8040	0.627	202	85.7	97.0	83.2
	299.6	90.0	85	121.4	29.44	537	3476	113.2	8633	0.631	207	84.8	96.1	81.5

Section 3 – Motor Step Response

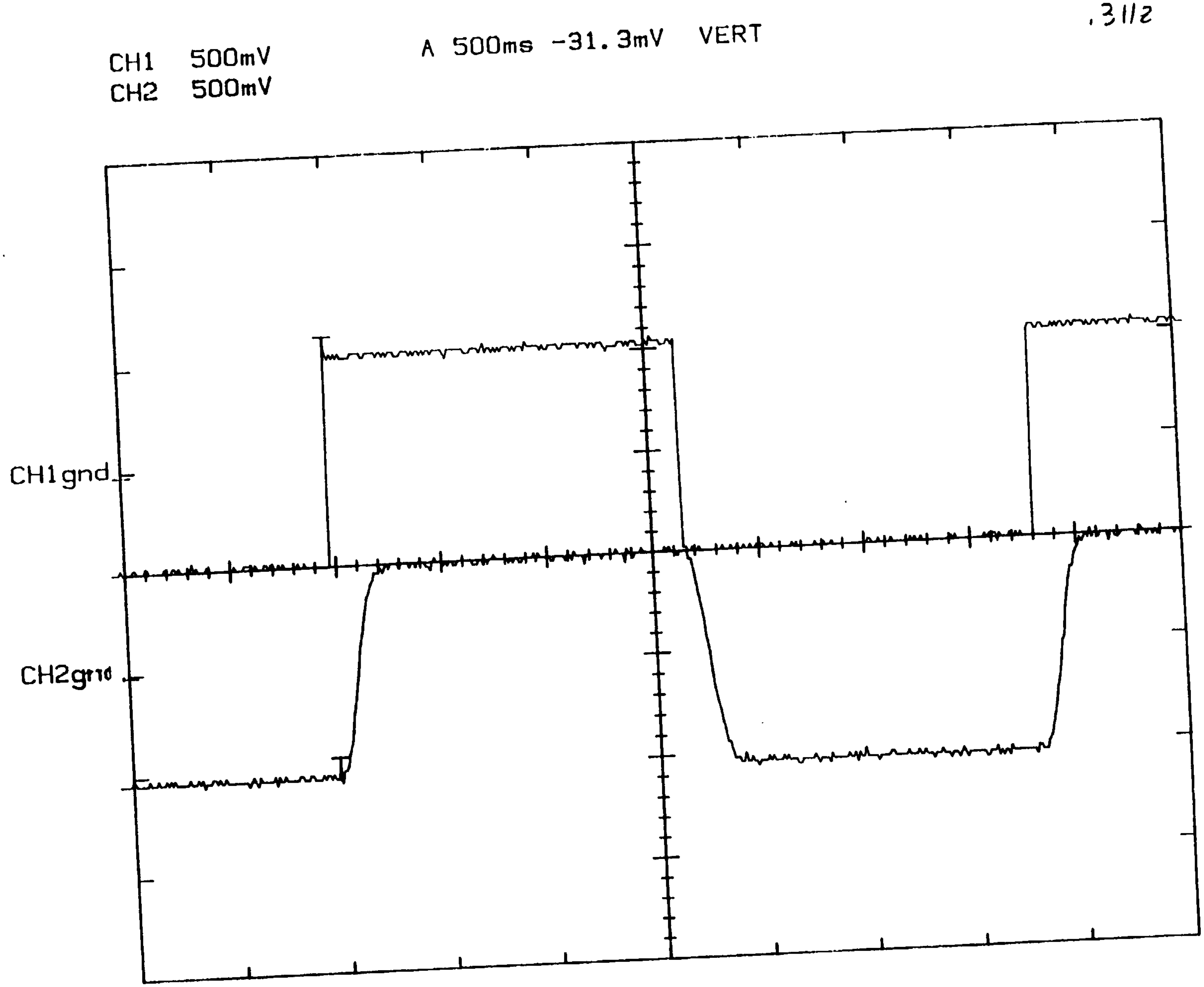

3/25/94
CH1 2V
CH2 2V
BW
A 20ms 156mV CH2
99.28 V/s
-7500 rpm
+7500 rpm
CH2gnd
Actual Rate
Command Rate
2/3 mV/rpm

SECTION 4 – ACTUATOR NO-LOAD STEP RESPONSE

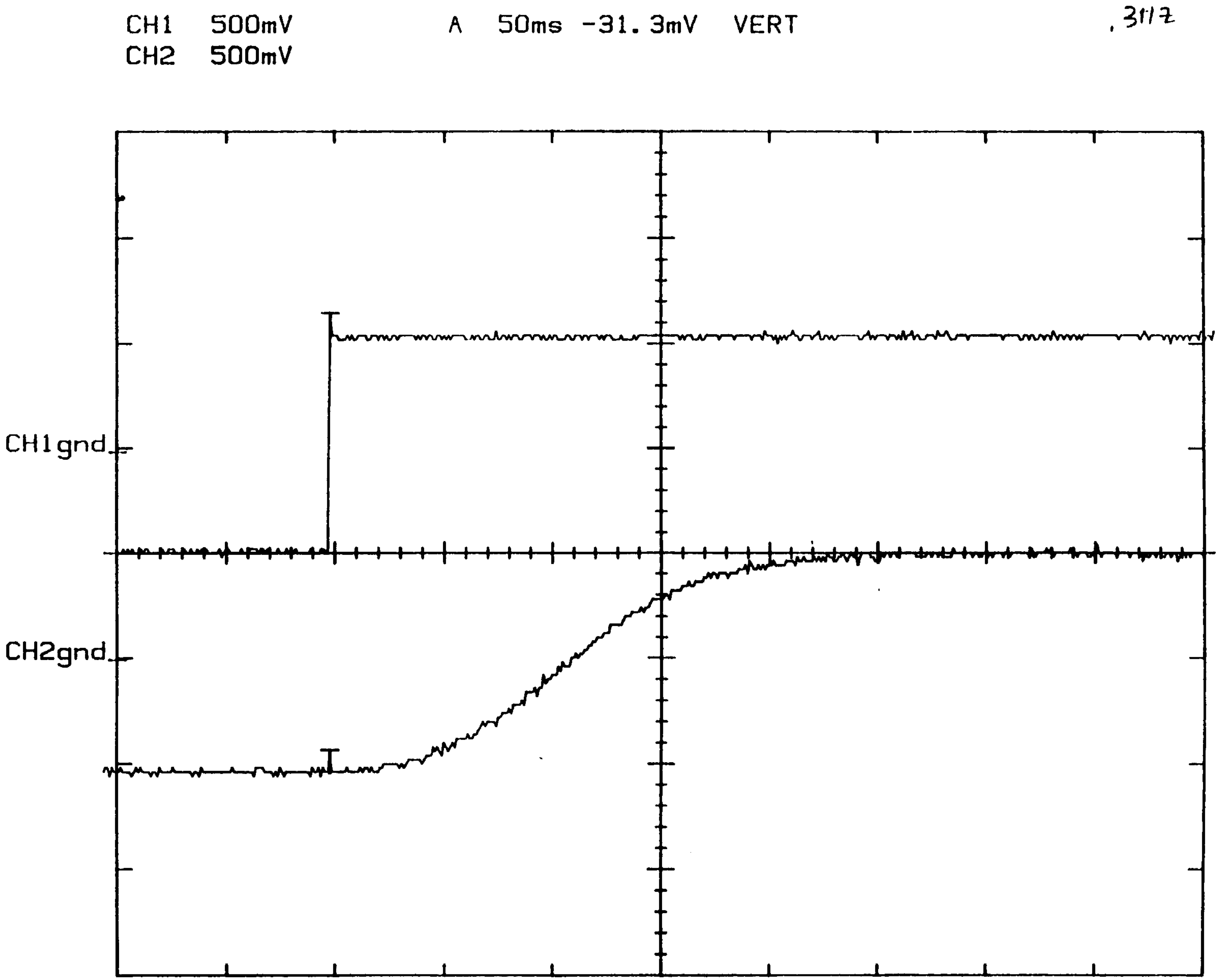
The no load test data was recorded under the following conditions:

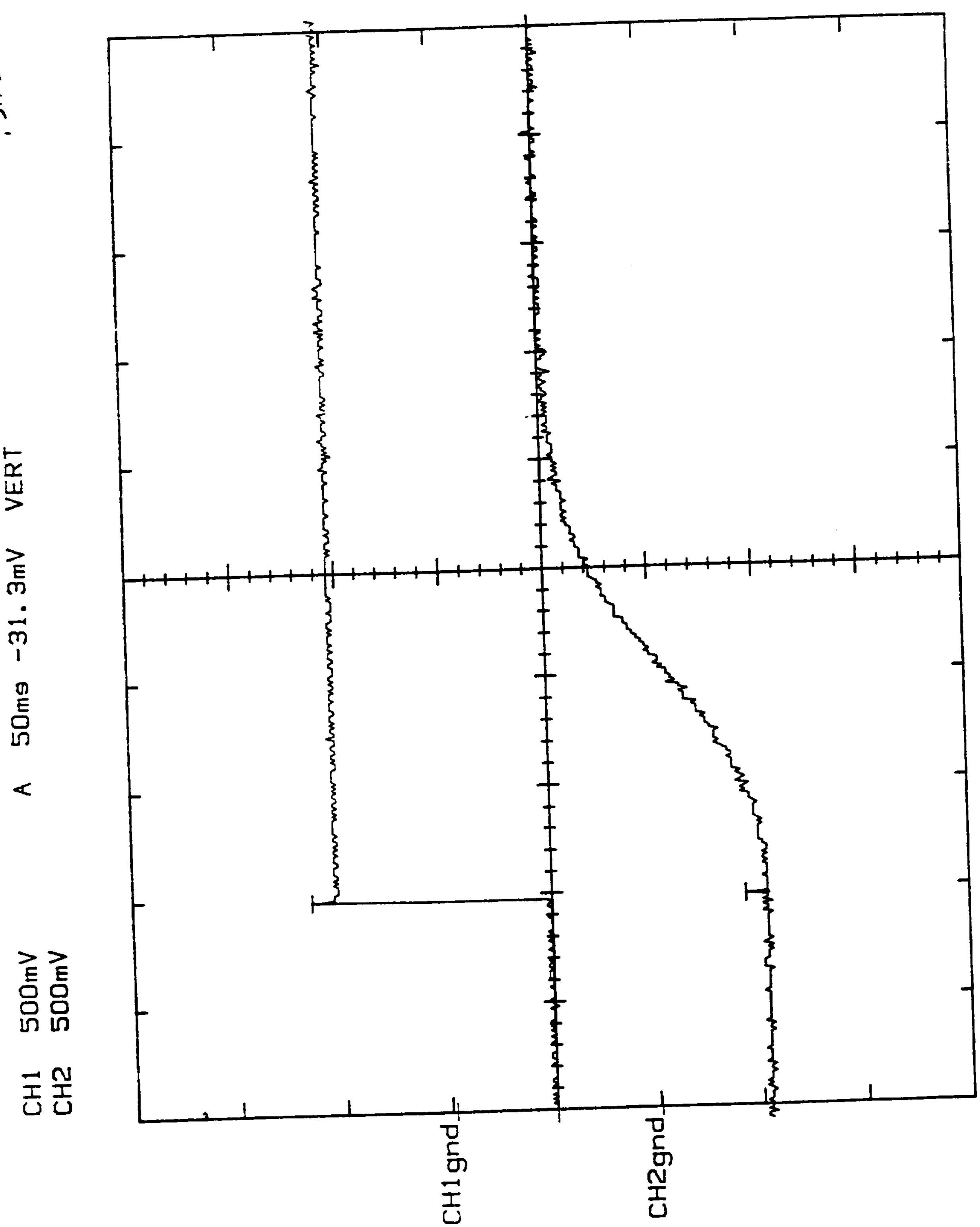
- Kp = 8.0, Ki = 0.1, and Kr = 35.0 unless otherwise noted.
- Command and Position scales are equal on the strip charts unless otherwise noted.

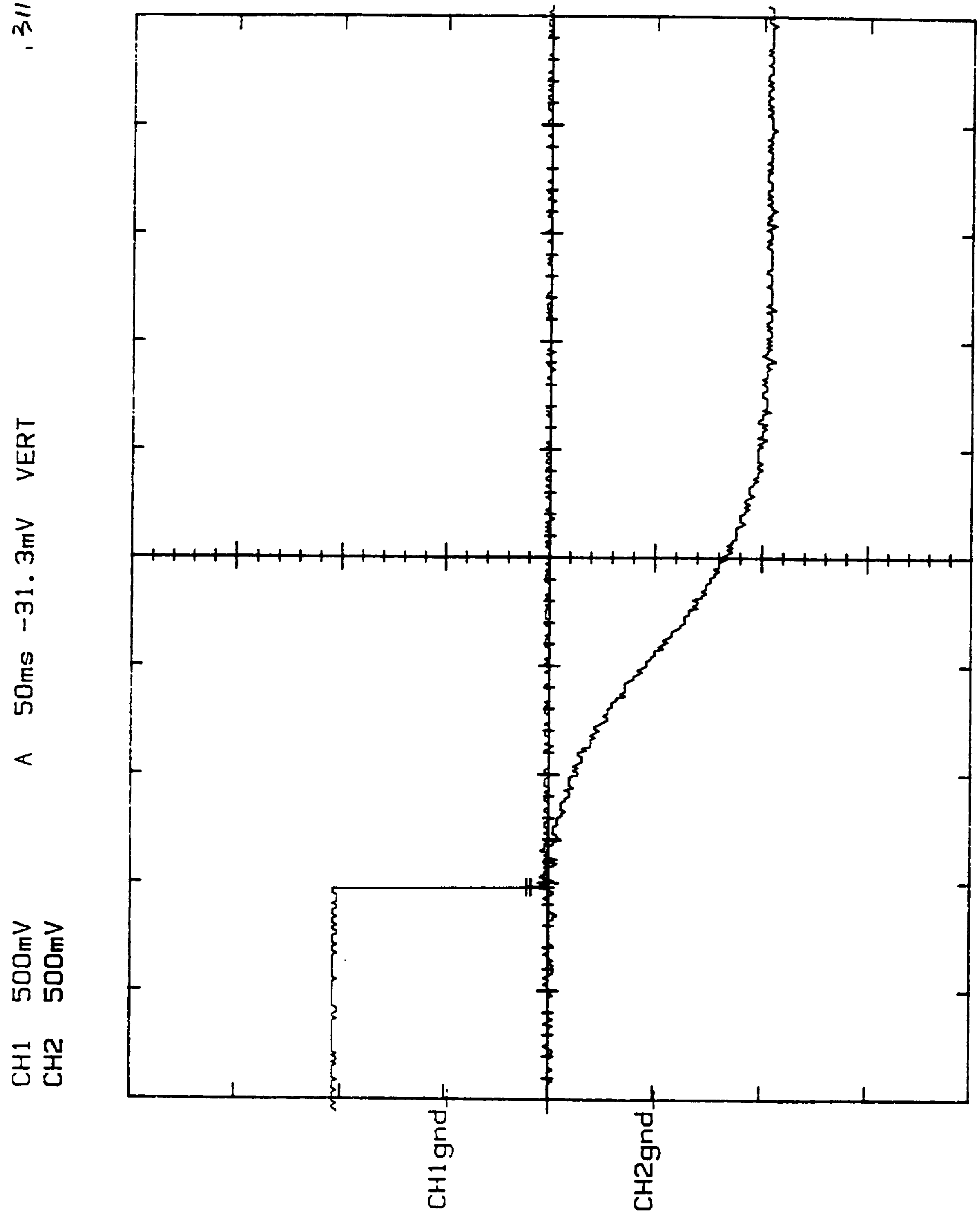
2U/in
.3112



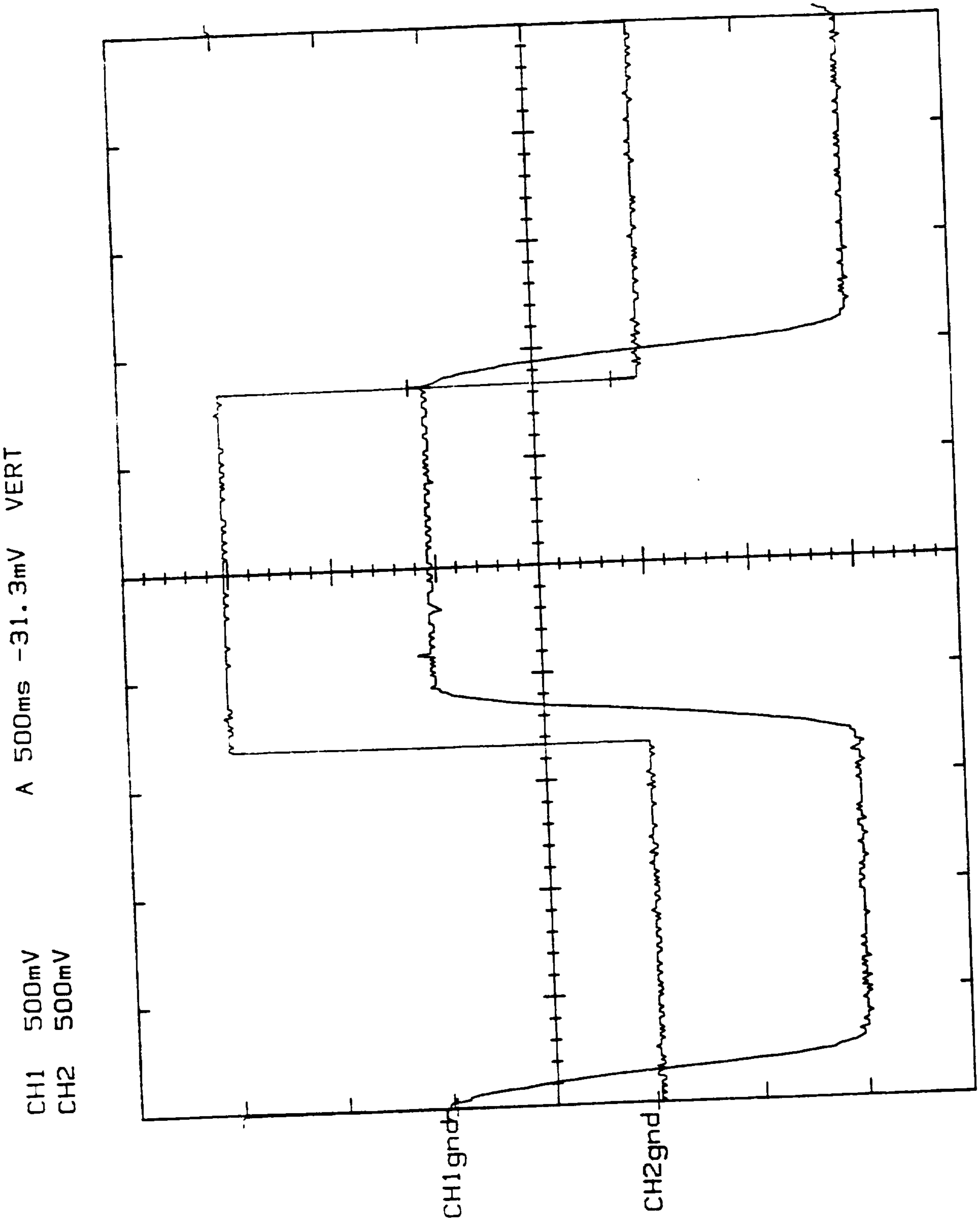
$J_{qc\,max} = 165$, $J_{ds} = 85$, $K_s = 34$, $K_p = 12$, $K_i = .001$, $K_r = 60$, $K_a = \emptyset$


CH1 500mV
CH2 500mV
A 50ms -31.3mV VERT
CH1gnd
CH2gnd

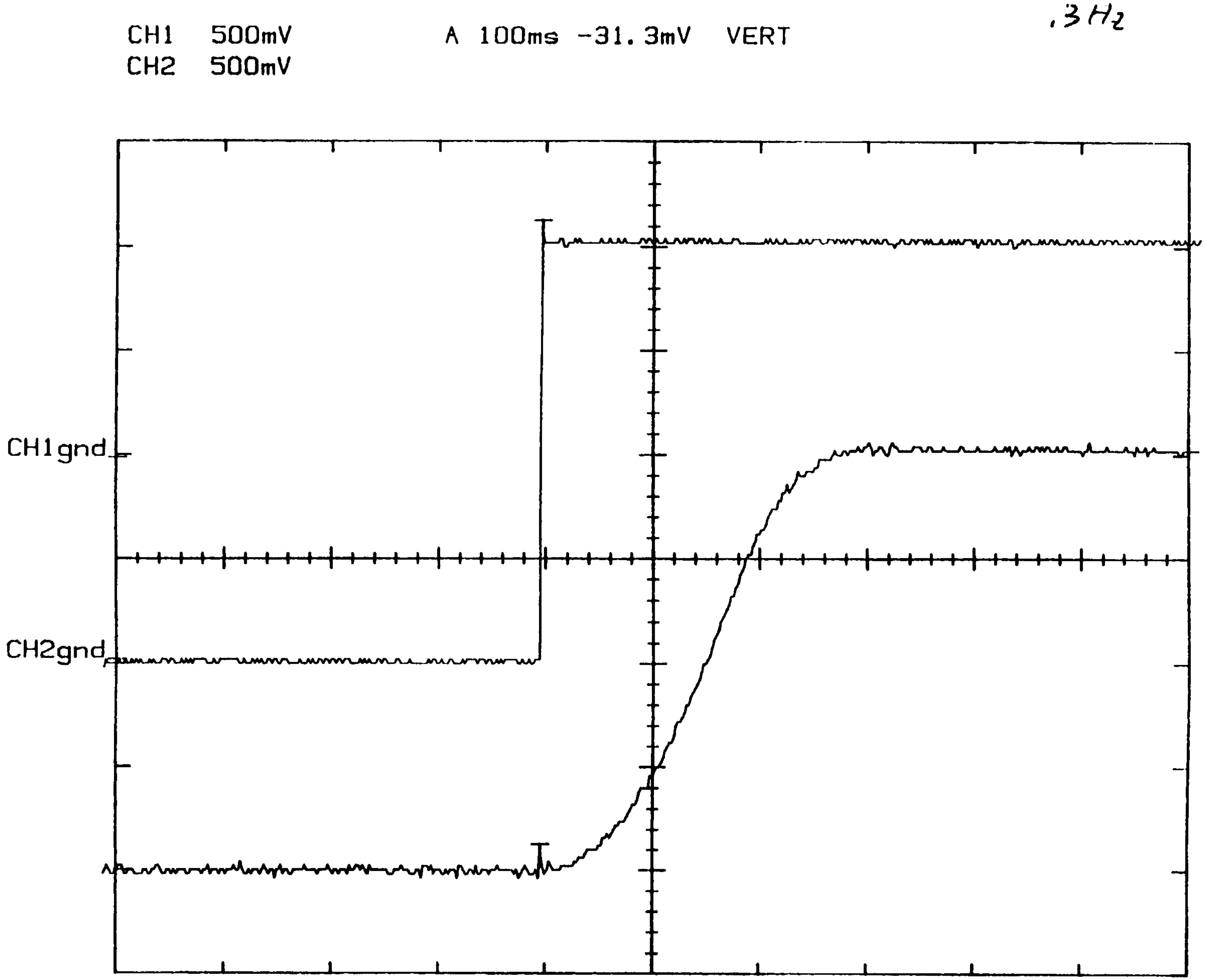

CH1 500mV
CH2 500mV
A 50ms -31.3mV VERT
CH1gnd
CH2gnd

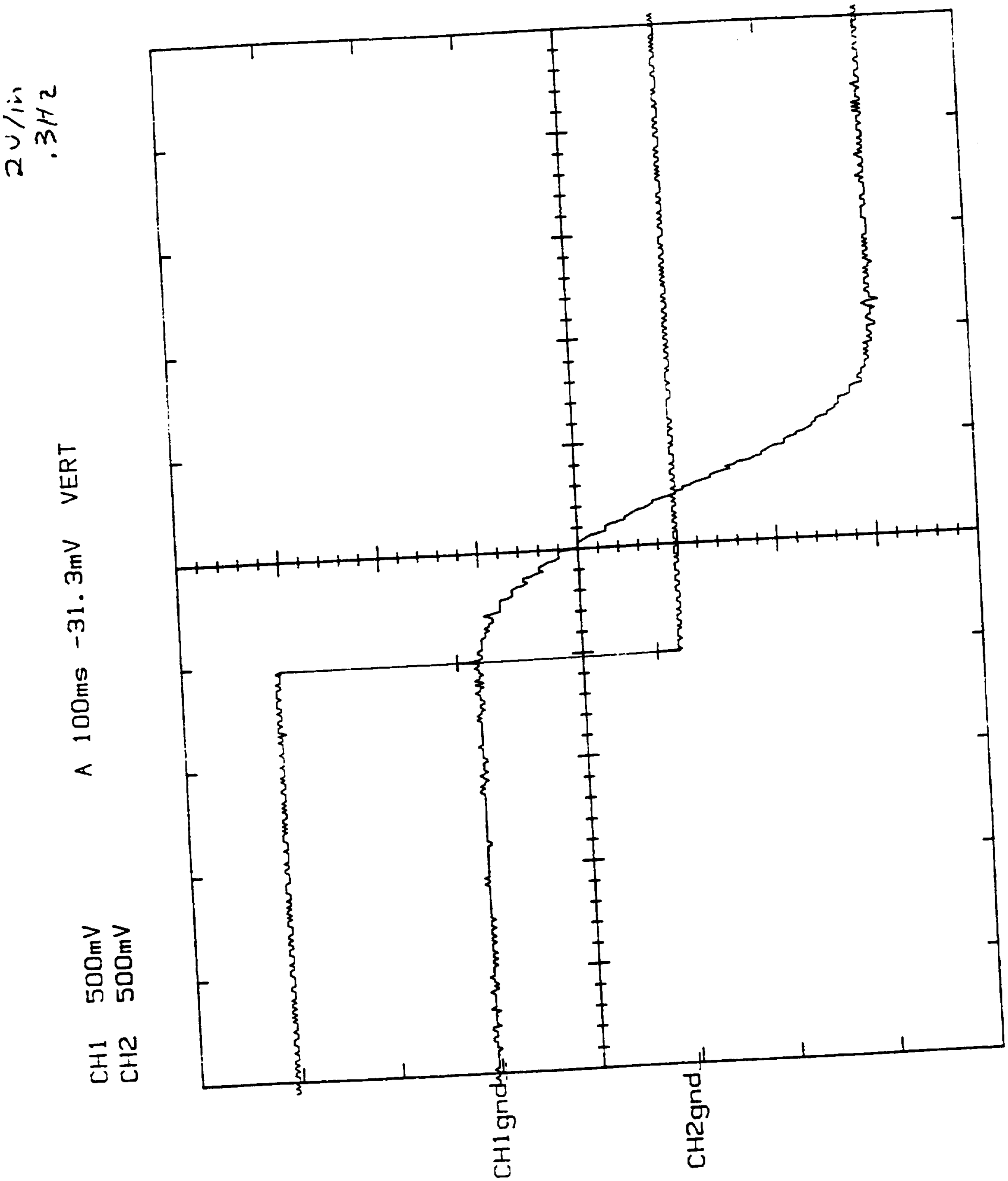

CH1 500mV
CH2 500mV
A 50ms -31.3mV VERT
CH1gnd
CH2gnd

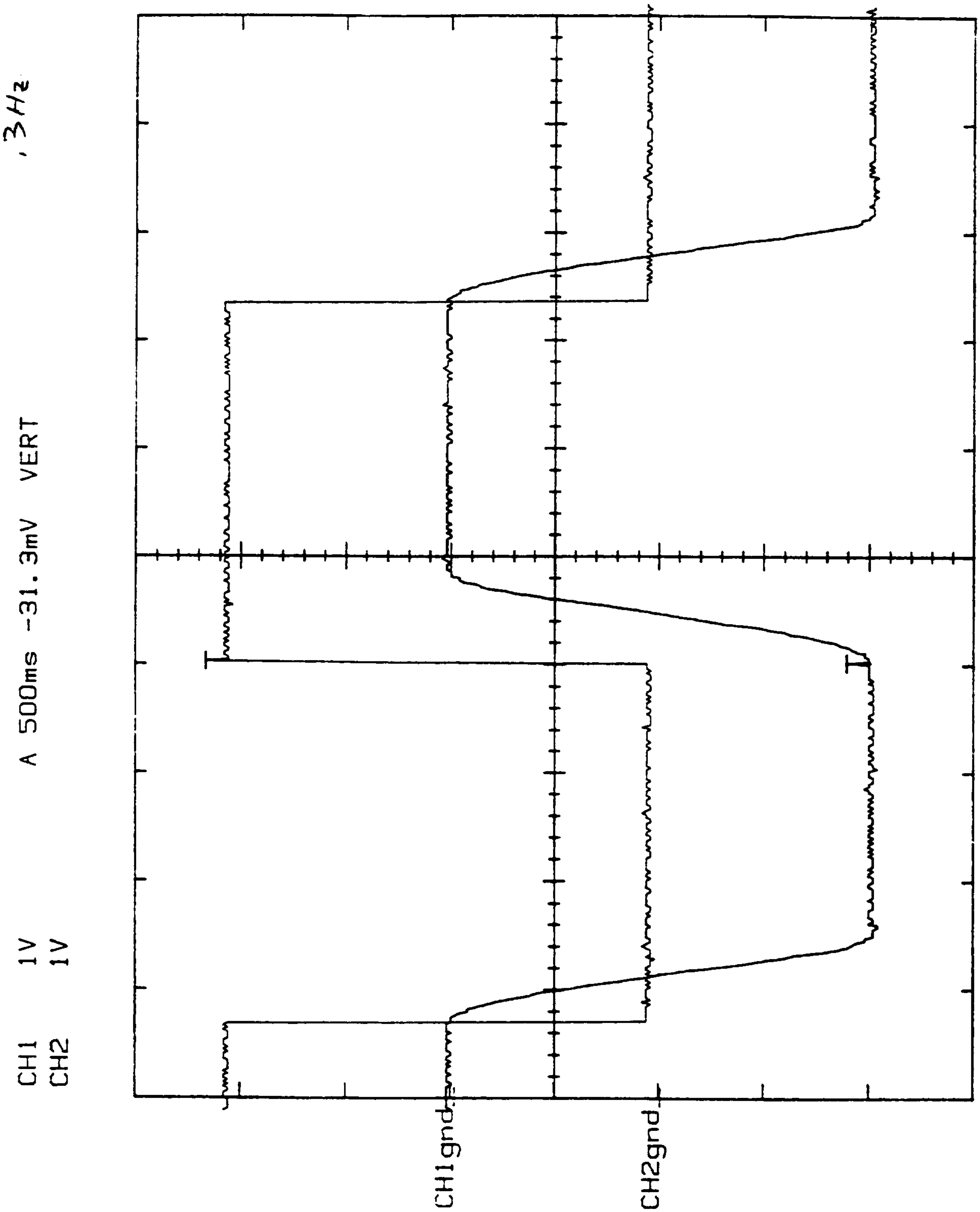
,3Hz



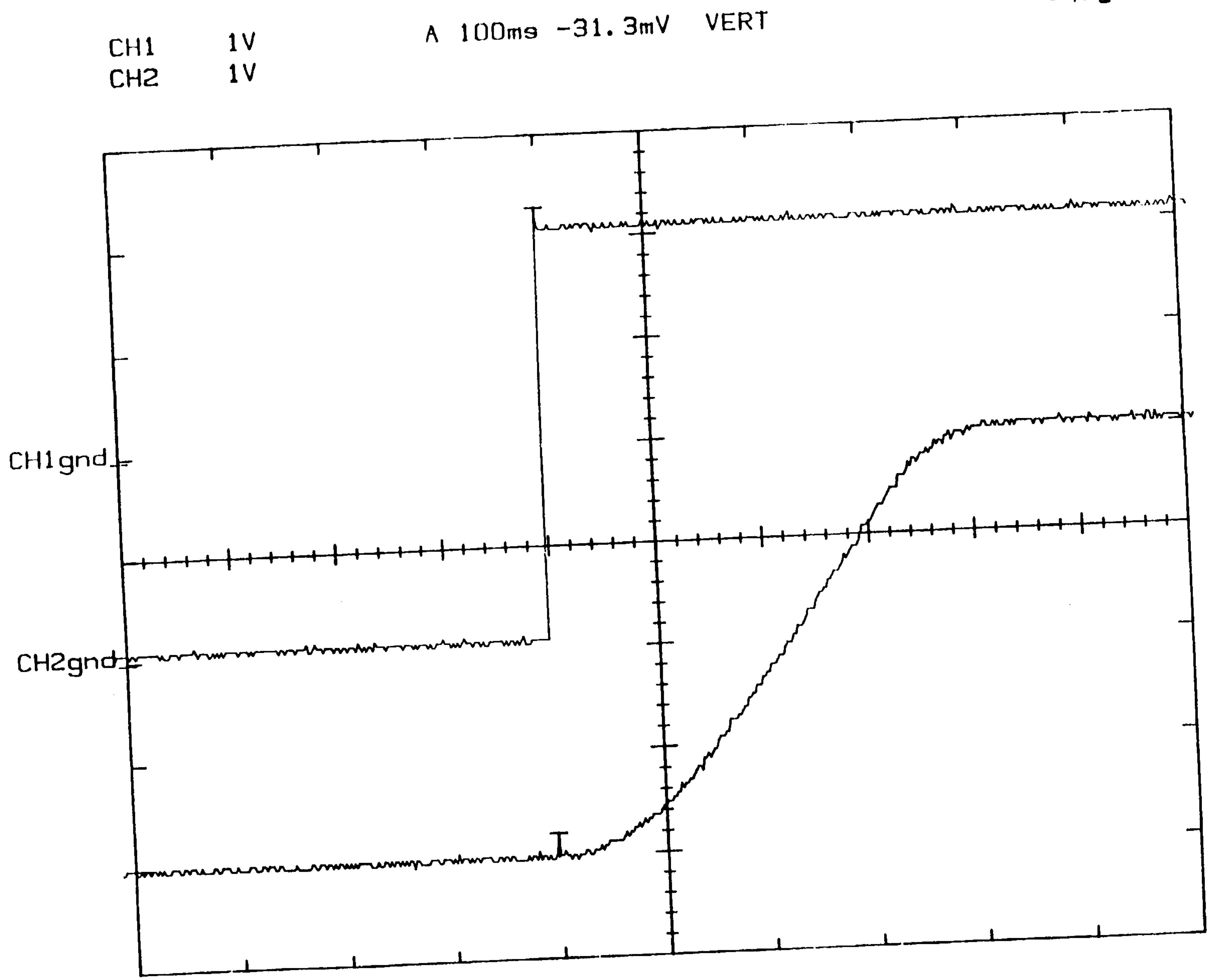
± .5 in
2 V/in
.3 Hz

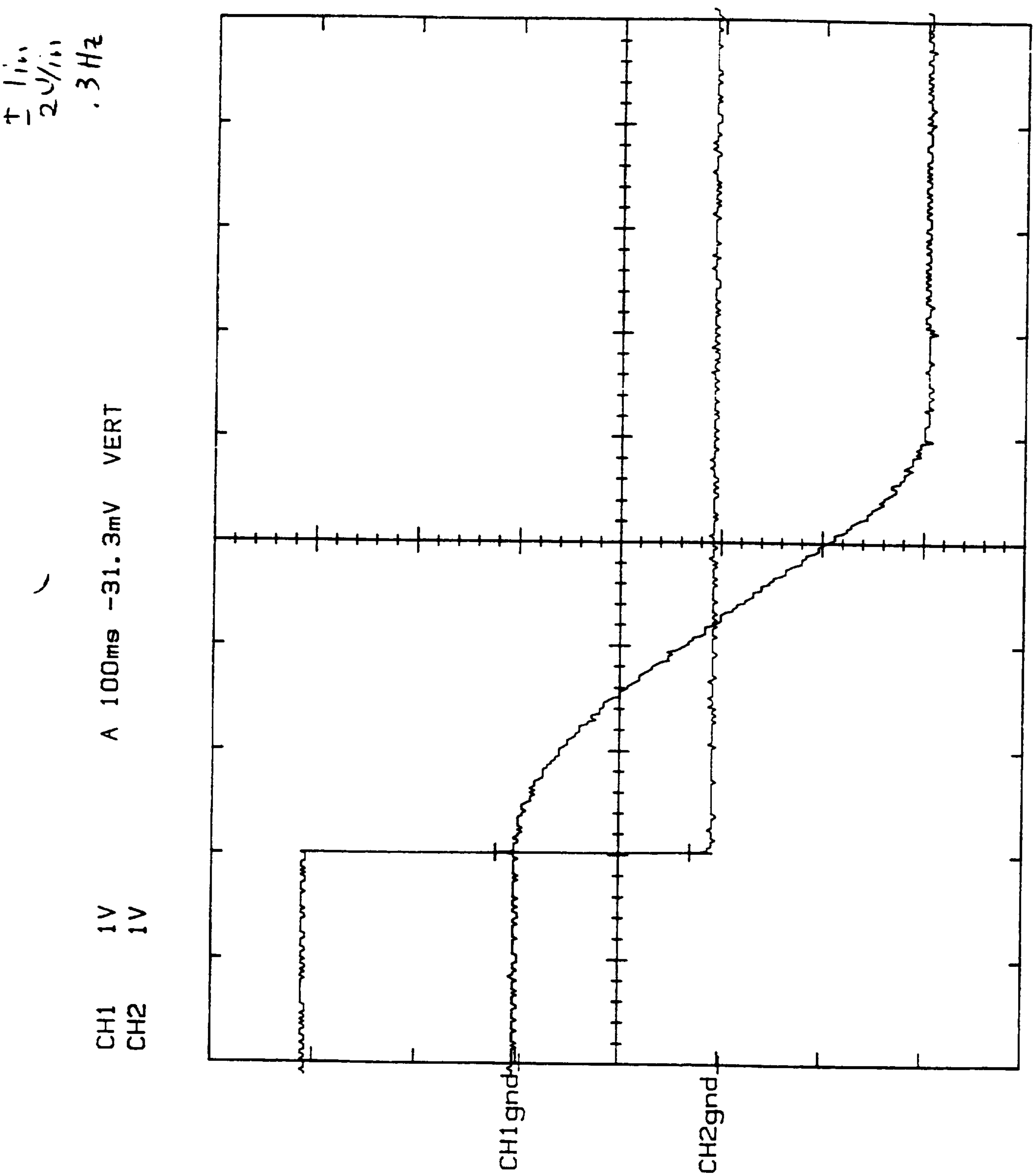


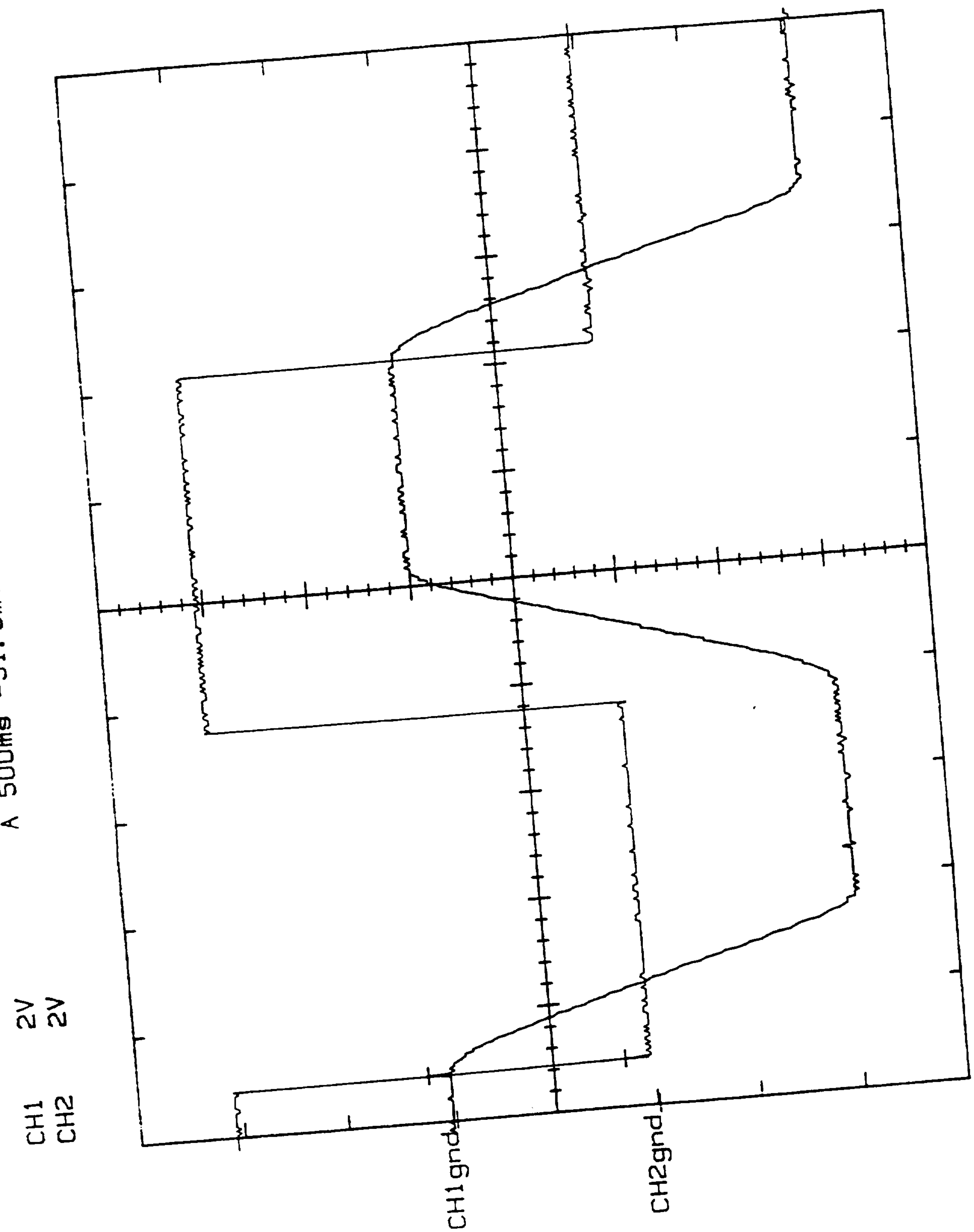

2V/in
.3Hz
A 100ms -31.3mV VERT
CH1 500mV
CH2 500mV
CH1gnd
CH2gnd

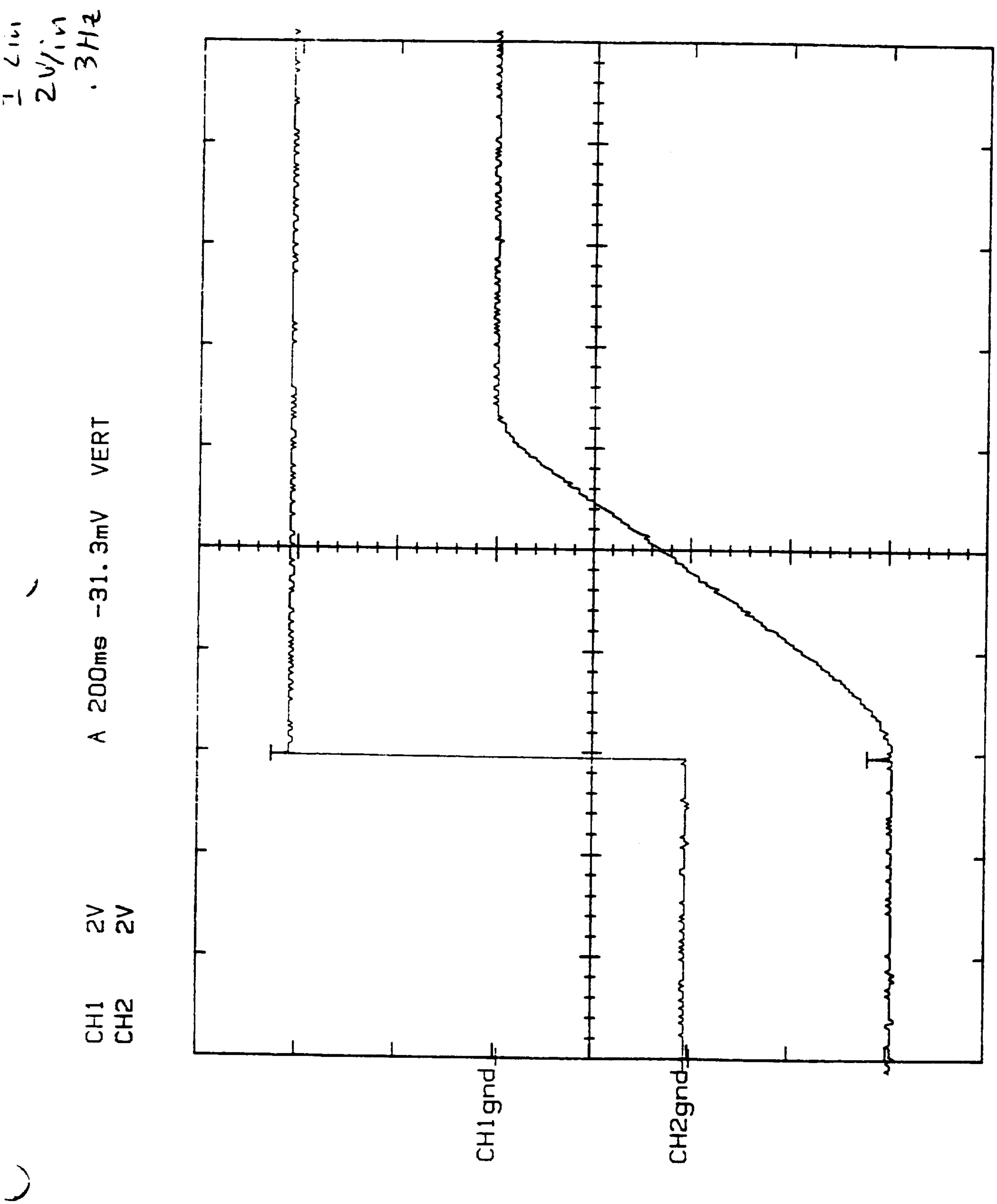

CH1 1V
CH2 1V
A 500ms -31.3mV VERT
CH1gnd
CH2gnd
2 V/in
.3 Hz

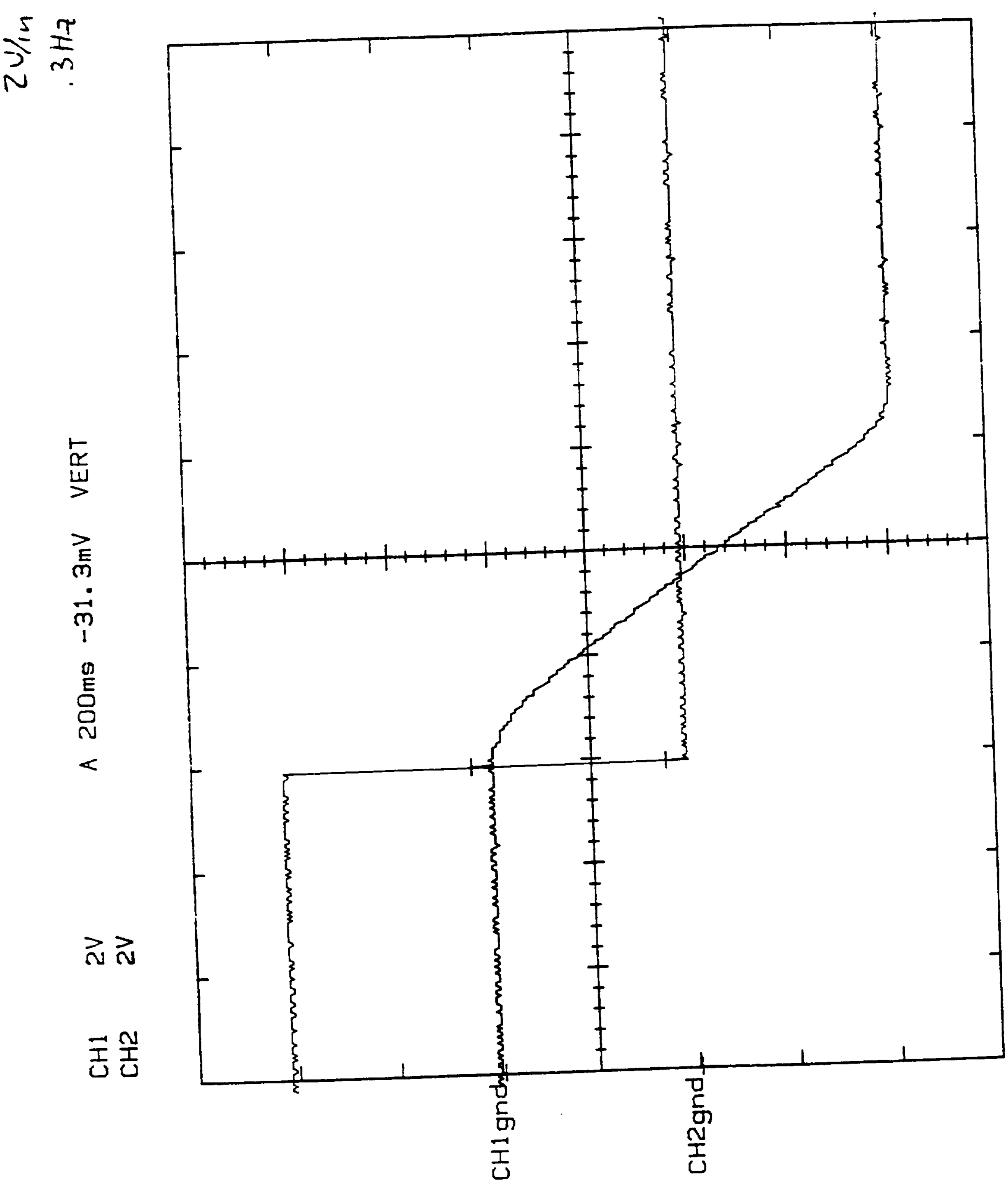
2V/in
.3Hz

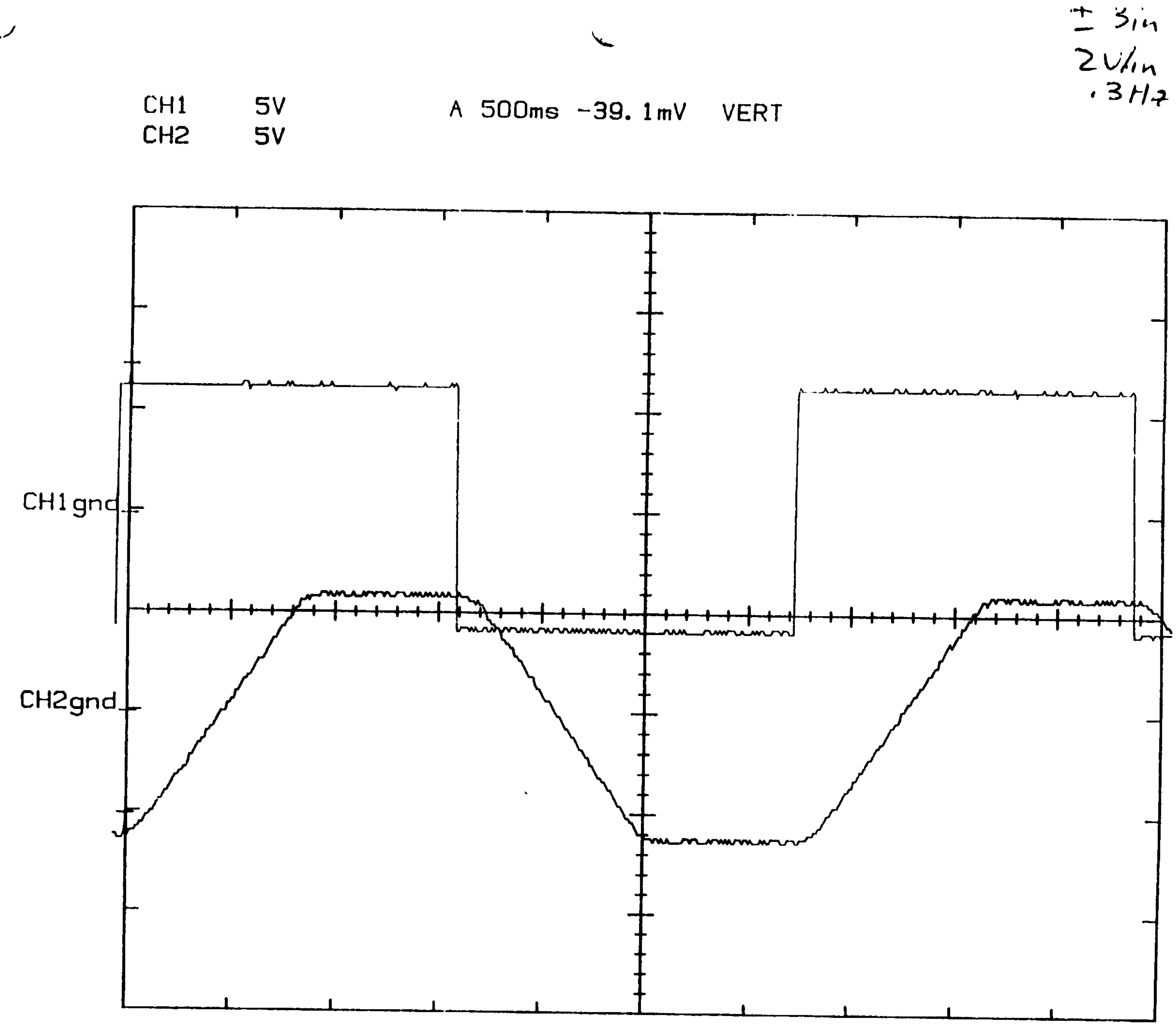



CH1 1V
CH2 1V
A 100ms -31.3mV VERT
CH1gnd
CH2gnd

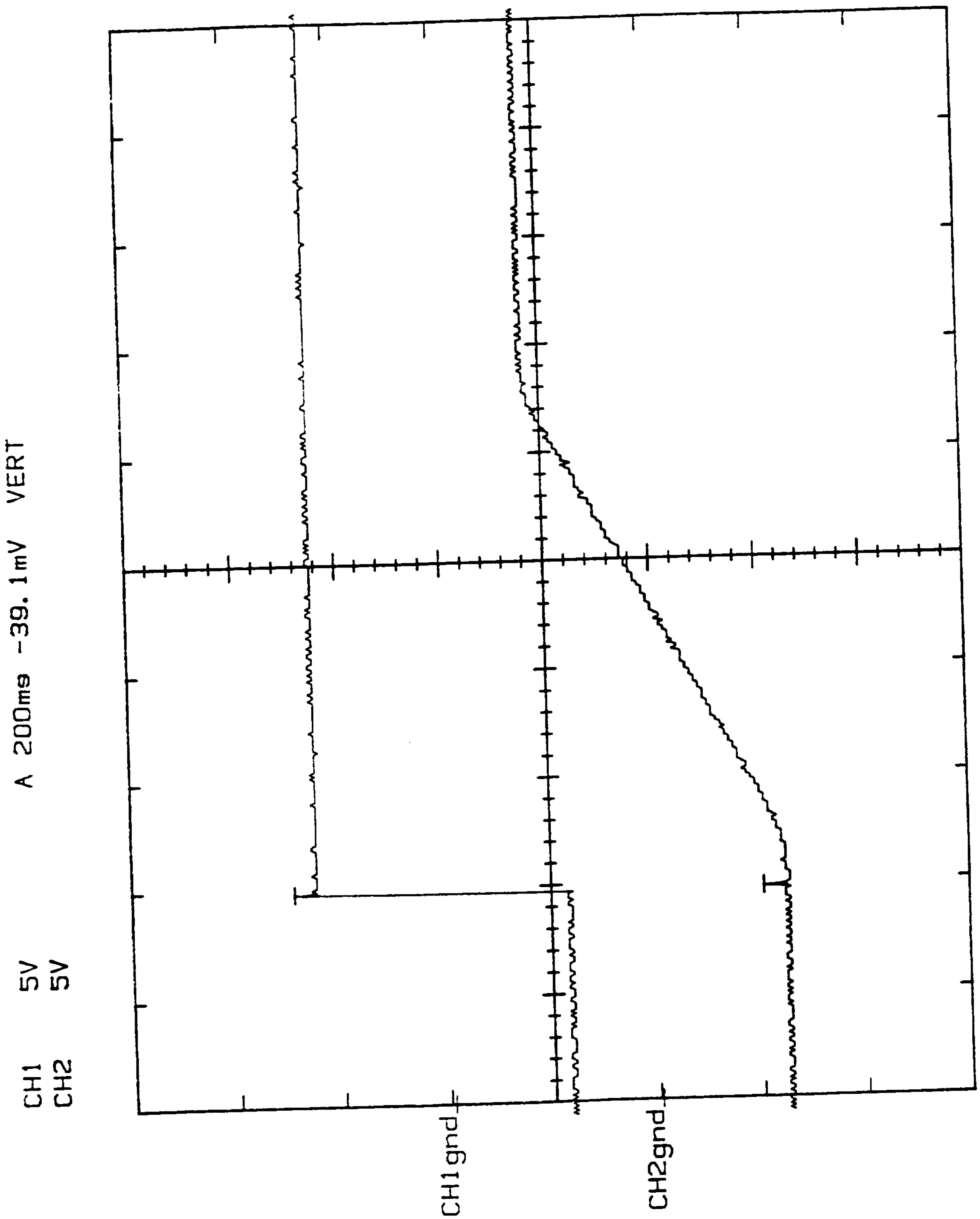

A 500ms -31.3mV VERT
CH1 2V
CH2 2V
CH1gnd
CH2gnd

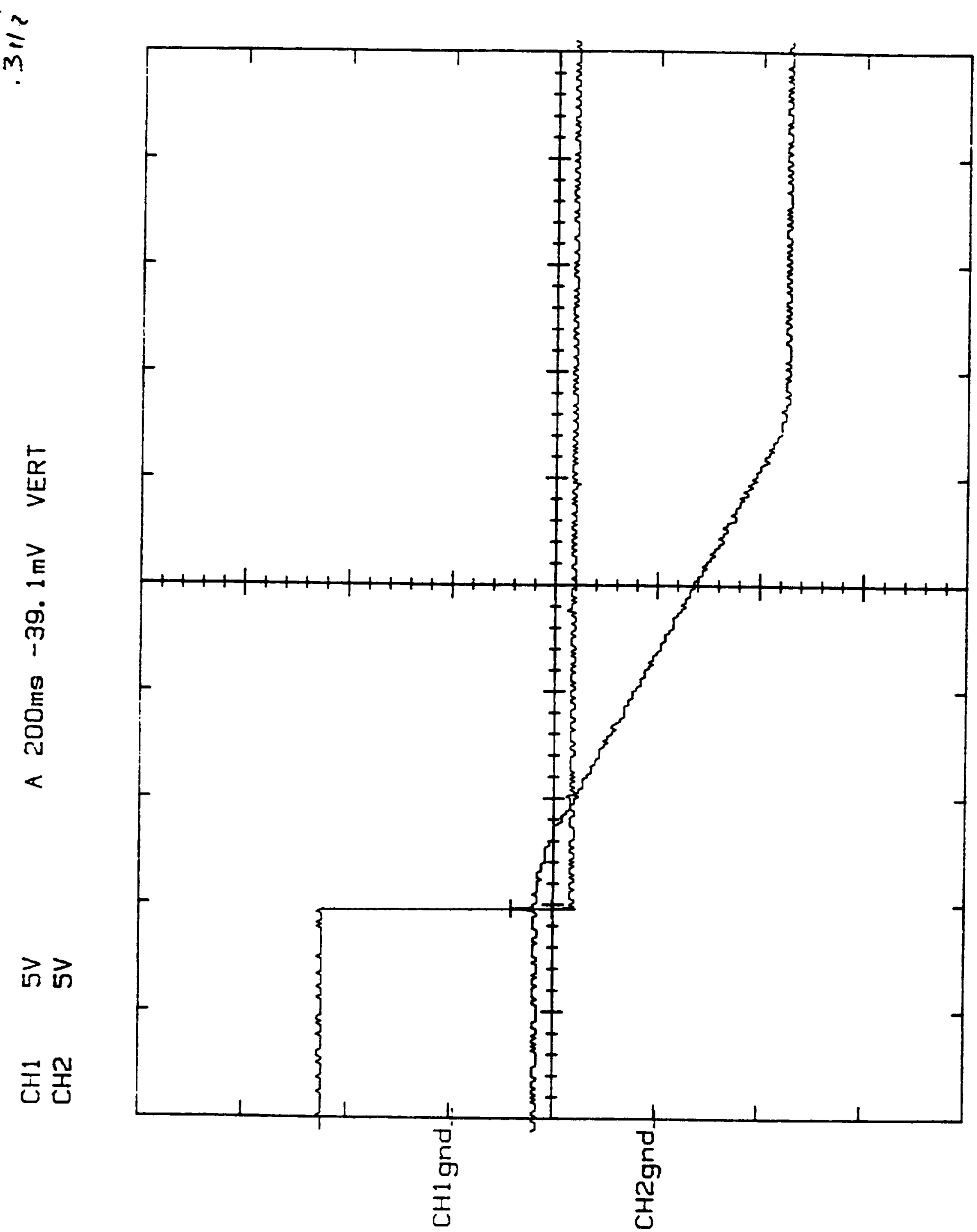

CH1 2V
CH2 2V
A 200ms -31.3mV VERT
CH1gnd
CH2gnd
2V/in
.3Hz

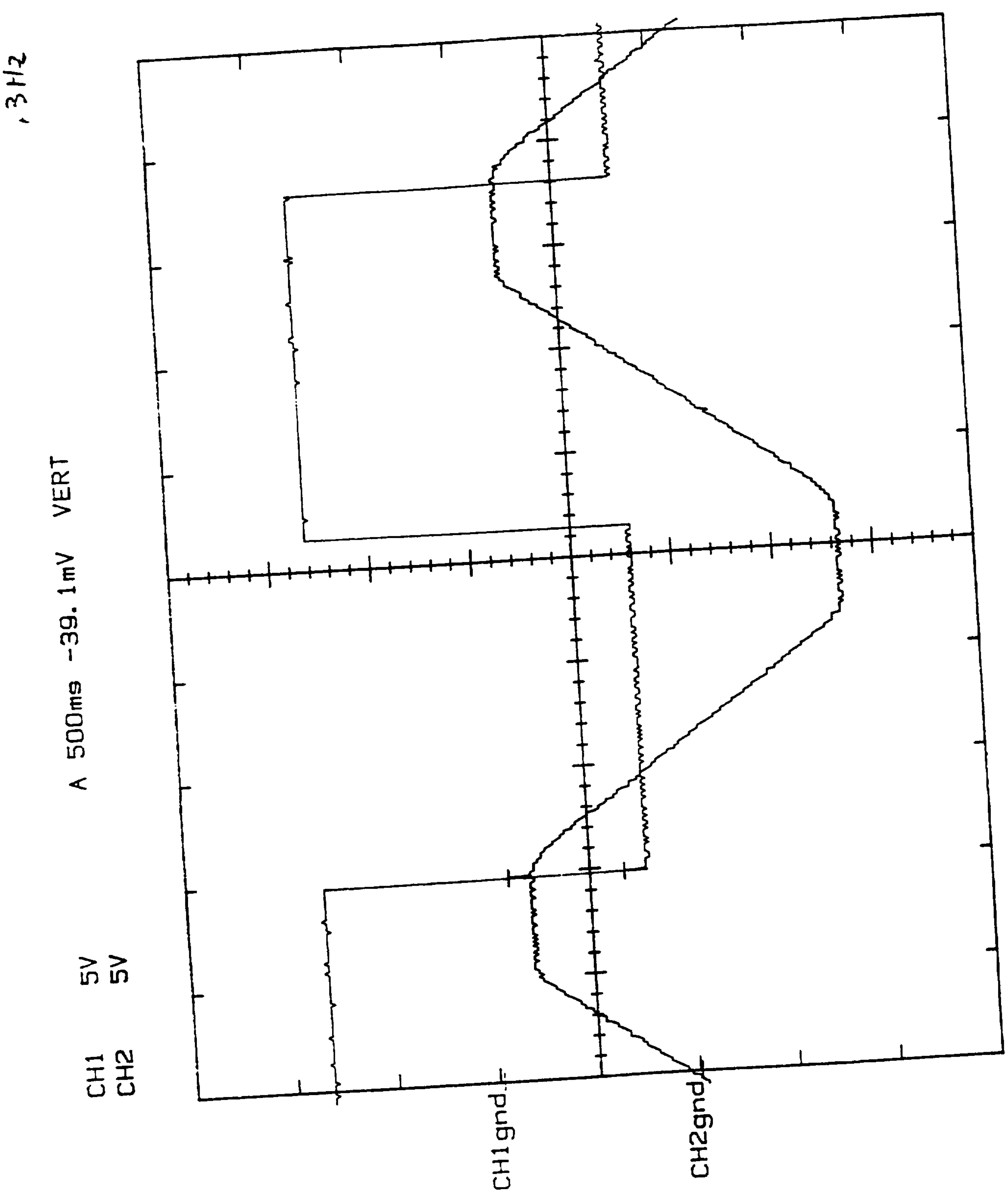

2V/in
.3Hz
CH1 2V
CH2 2V
A 200ms -31.3mV VERT
CH1gnd
CH2gnd

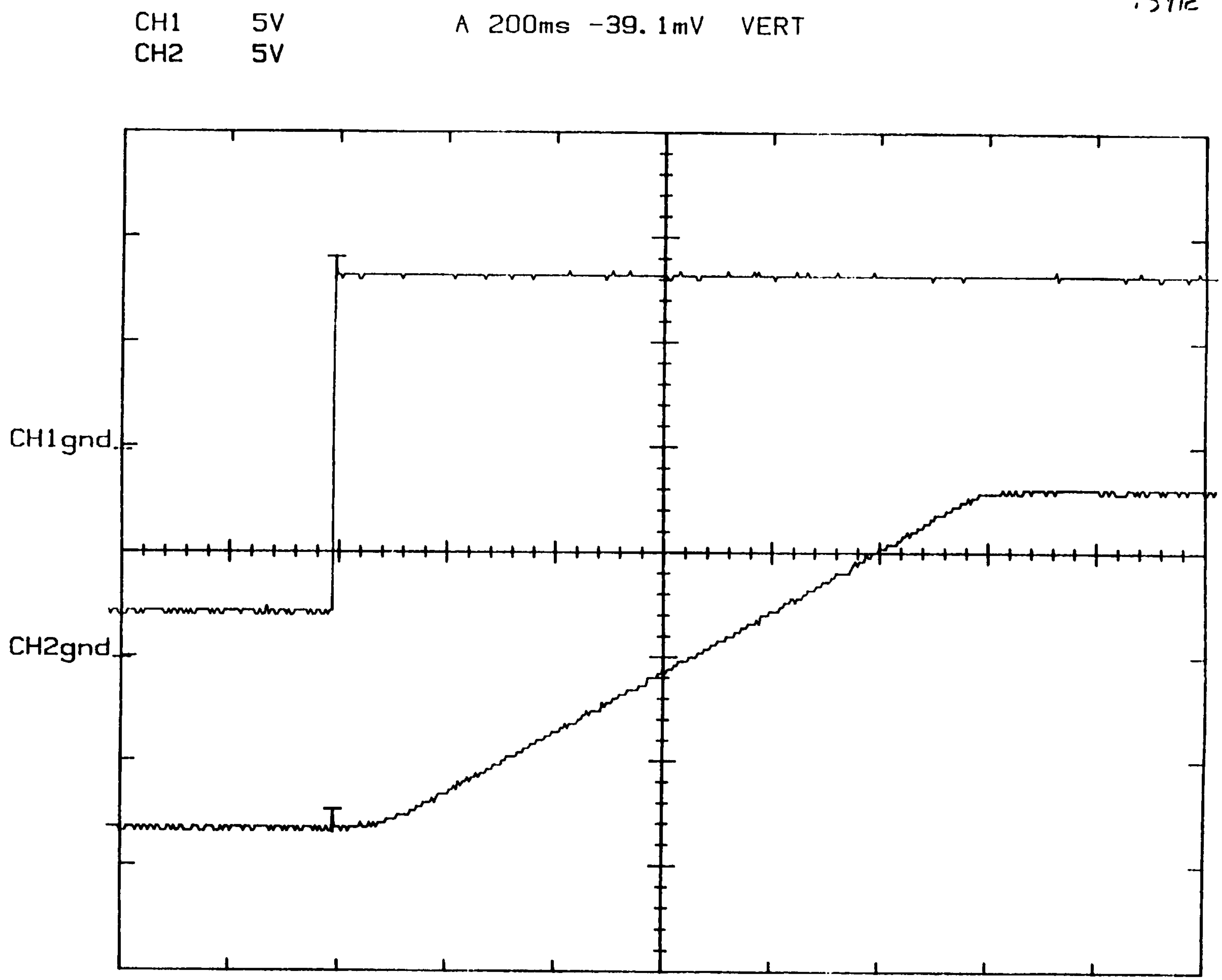


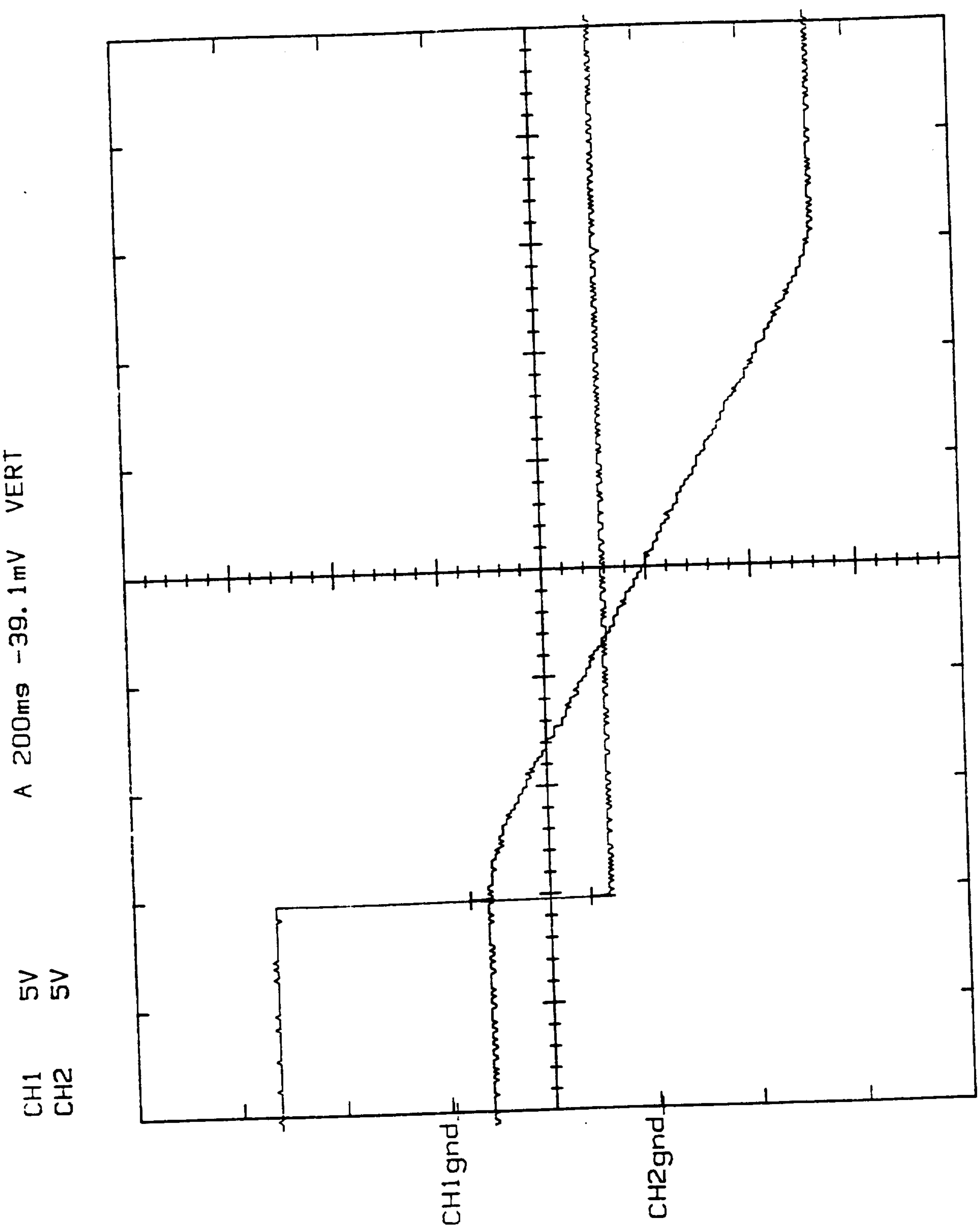
CH1 5V
CH2 5V
A 500ms -39.1mV VERT
± 3in
2V/in
.3Hz
CH1gnd
CH2gnd


CH1 5V
CH2 5V
A 200ms -39.1mV VERT
CH1gnd
CH2gnd
.3Hz

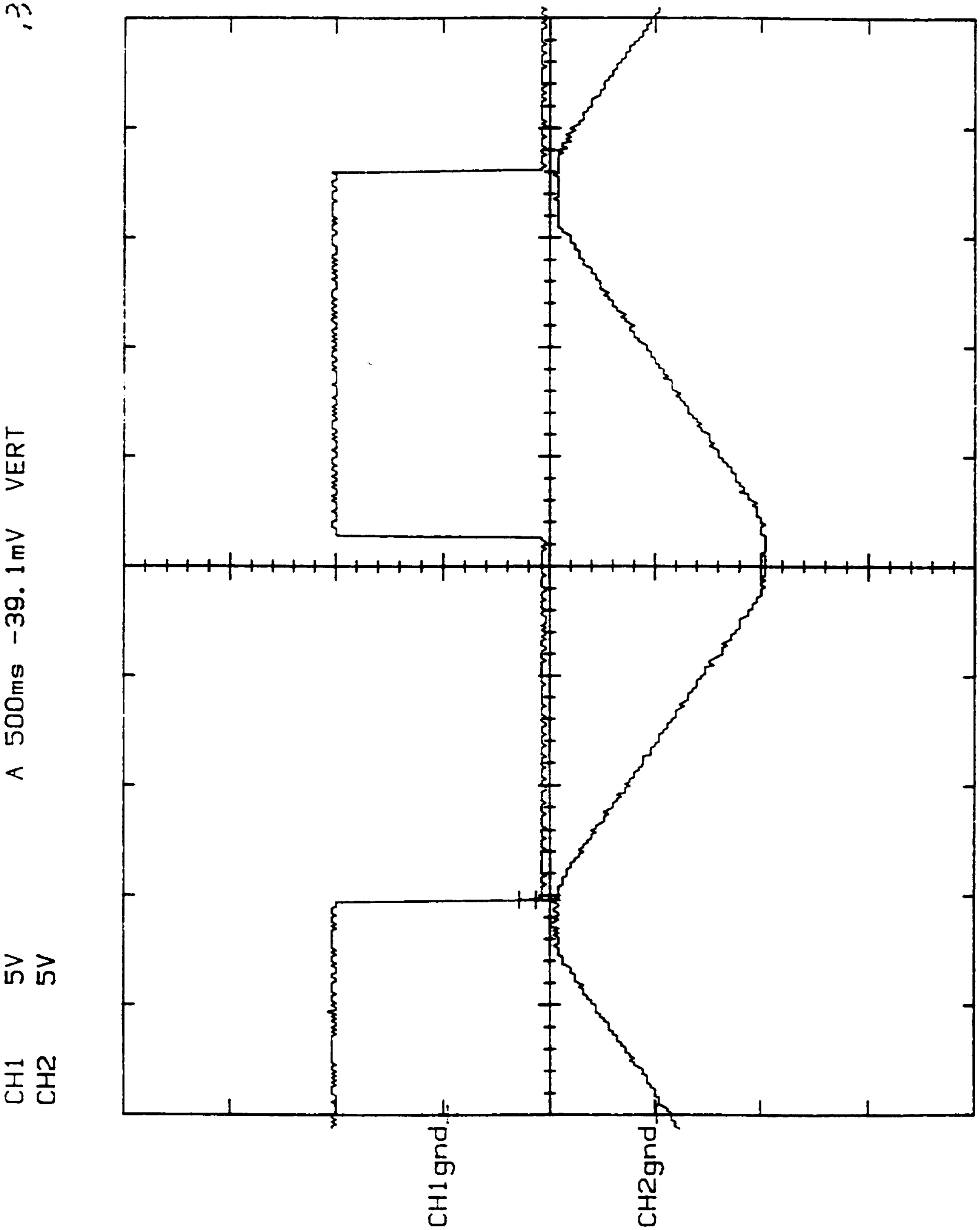

CH1 5V
CH2 5V
A 200ms -39. 1mV VERT
CH1gnd
CH2gnd

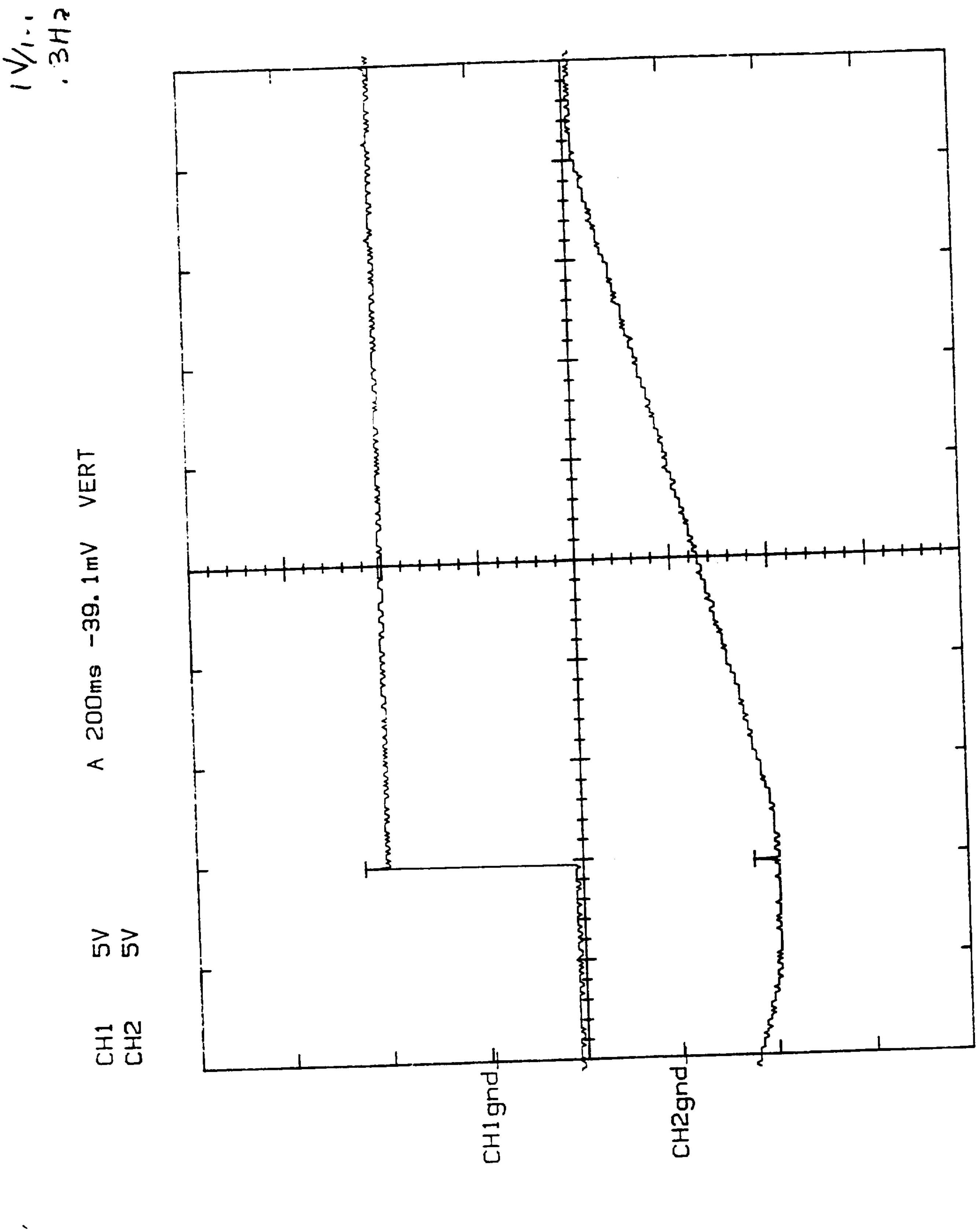

.3Hz
A 500ms -39.1mV VERT
CH1 5V
CH2 5V
CH1gnd
CH2gnd

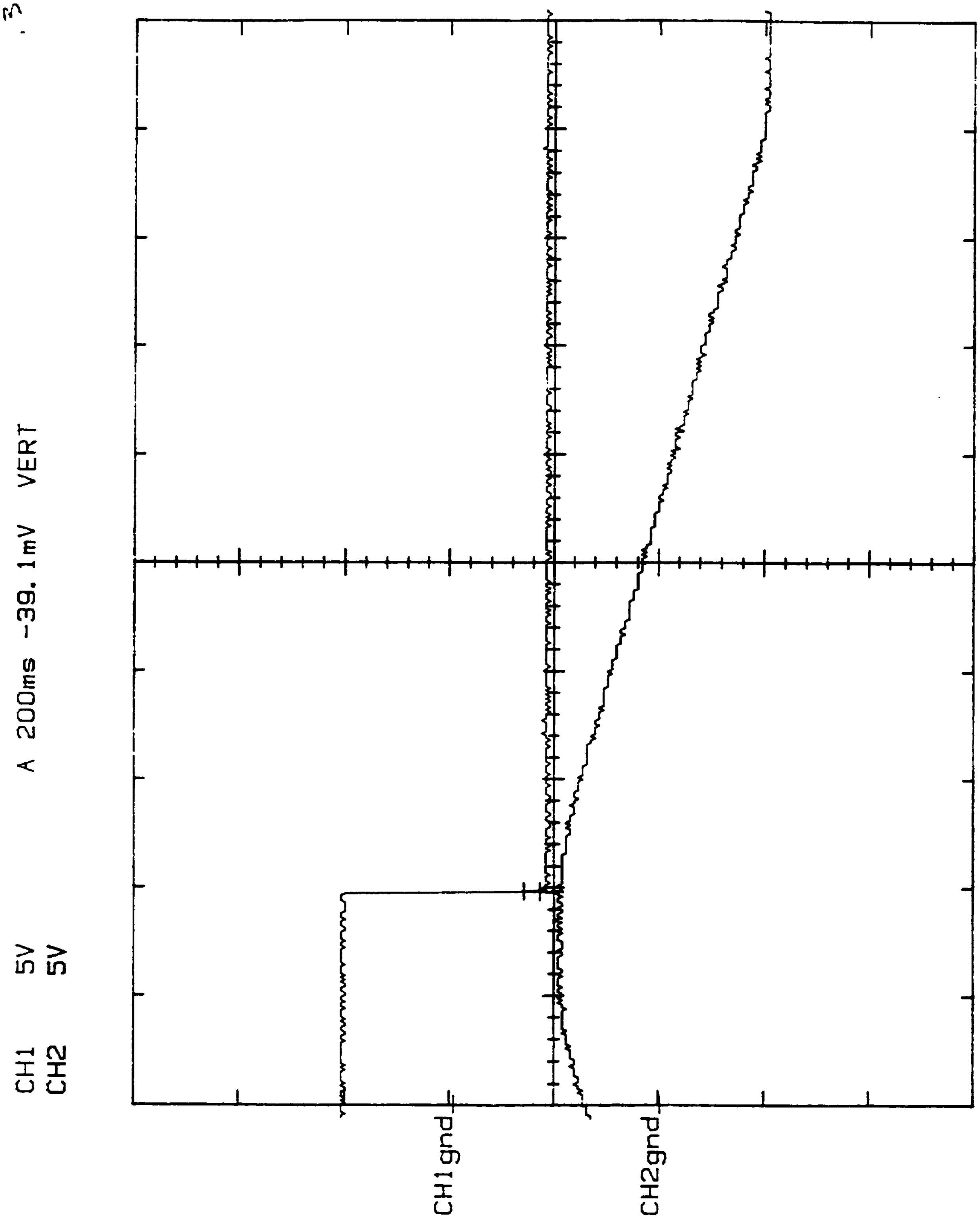

CH1 5V
CH2 5V
A 200ms -39.1mV VERT
CH1gnd
CH2gnd

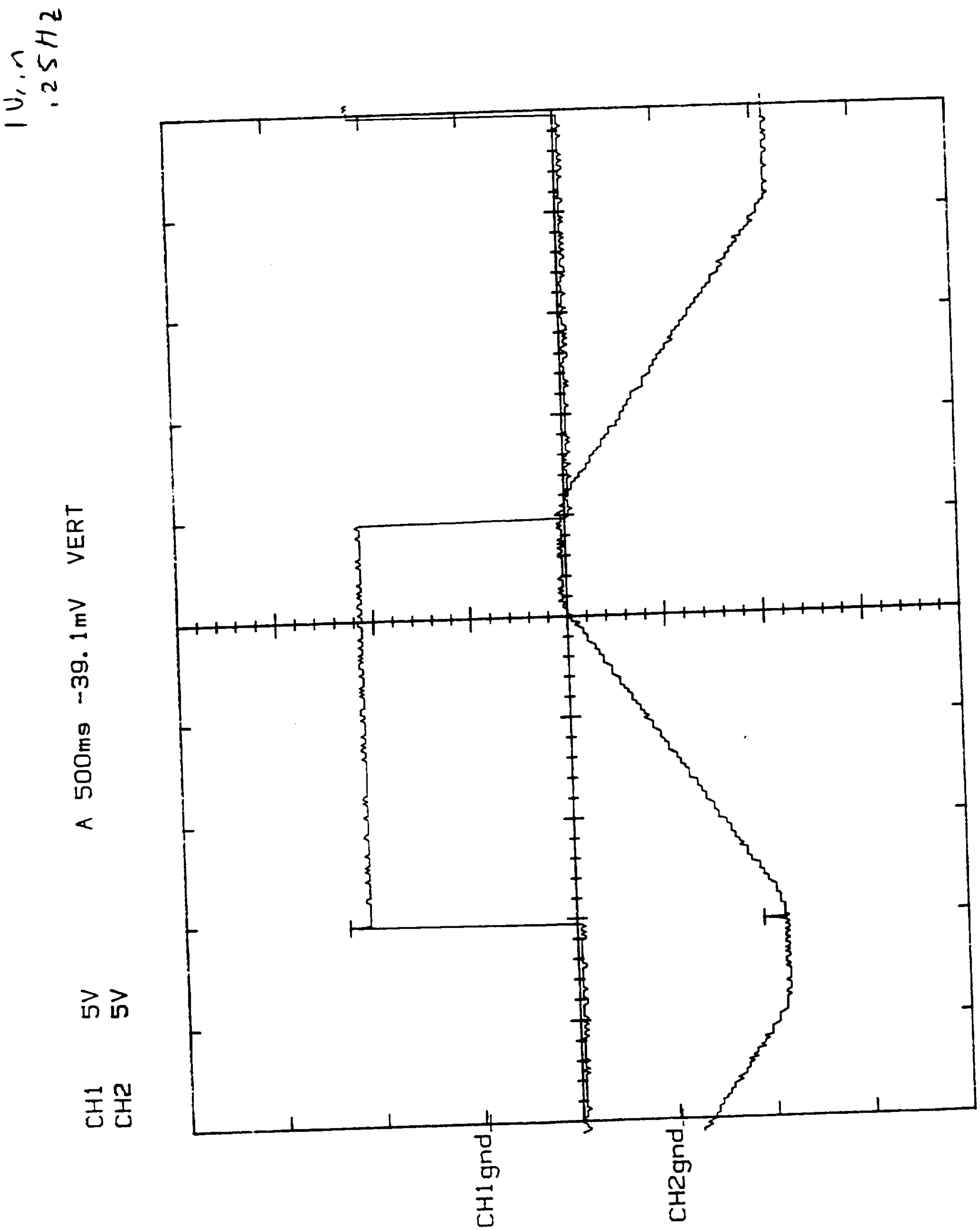

CH1 5V
CH2 5V
A 200ms -39.1mV VERT
CH1gnd
CH2gnd

± 5
1V/in
.3Hz




A 200ms -39.1mV VERT
CH1 5V
CH2 5V
CH1gnd
CH2gnd

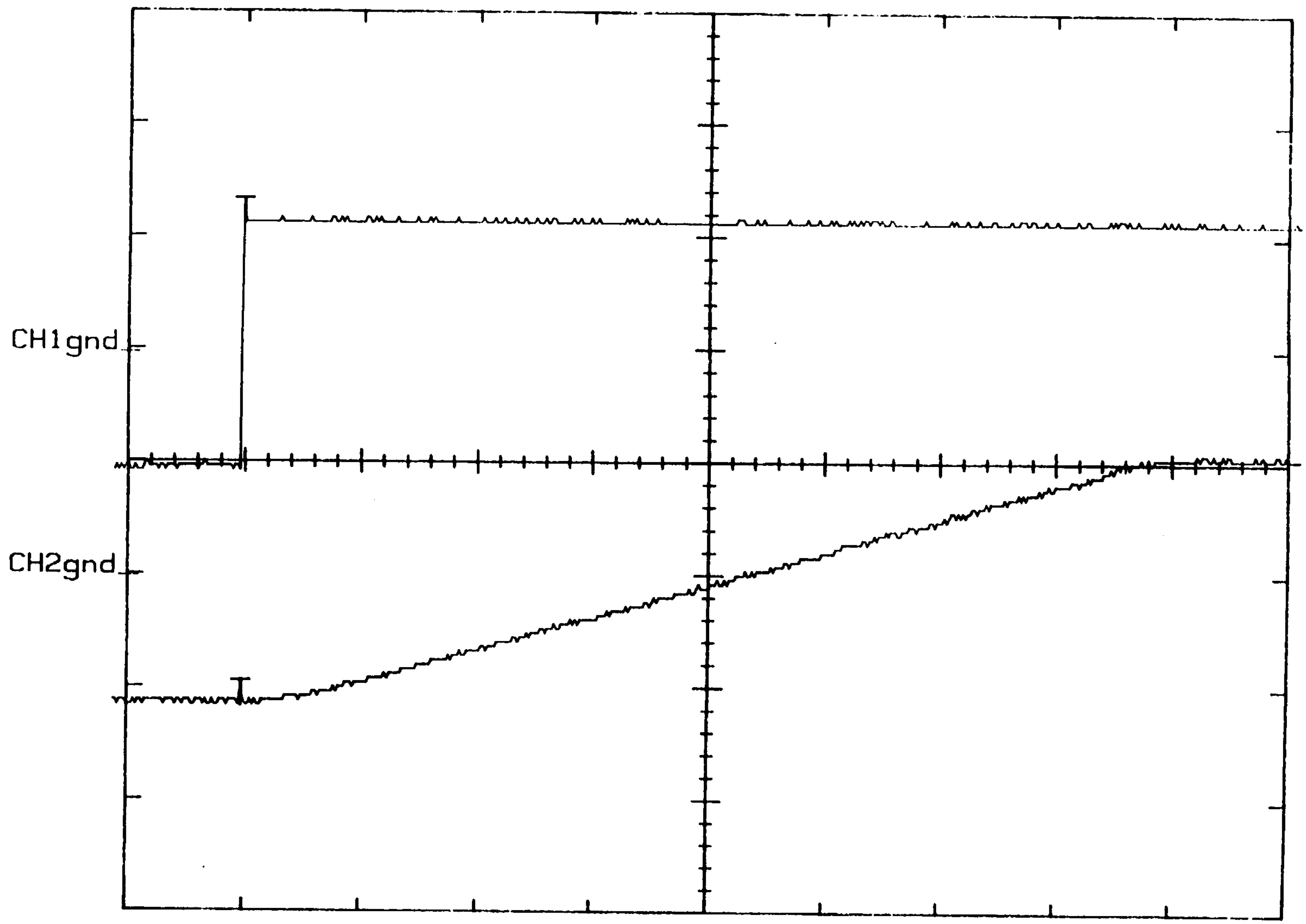

CH1 5V
CH2 5V
A 200ms -39.1mV VERT
CH1gnd
CH2gnd

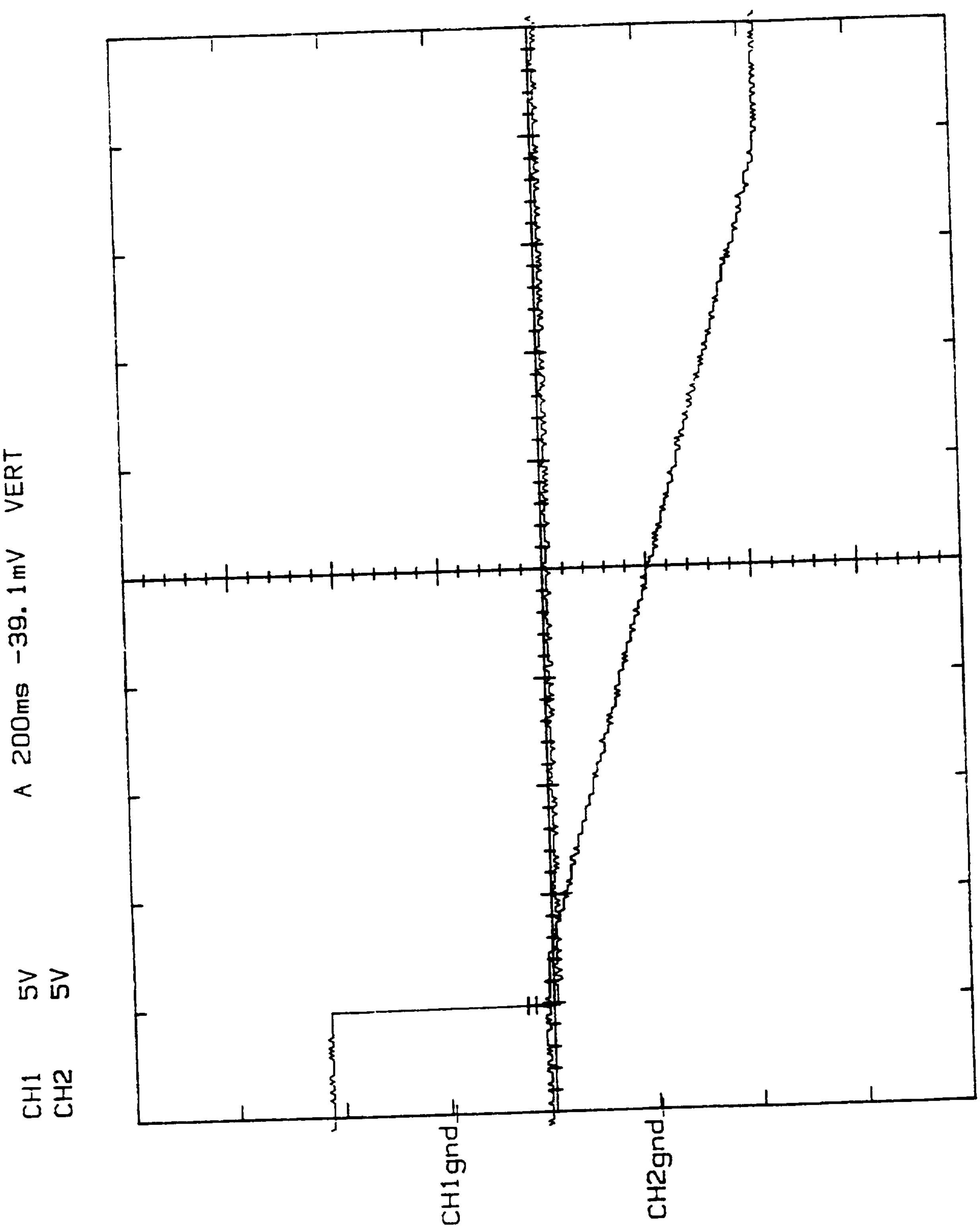

CH1 5V
CH2 5V
A 500ms -39.1mV VERT
CH1gnd
CH2gnd

± .5 in
1V/in
.25Hz

CH1 5V
CH2 5V

A 200ms -39.1mV VERT

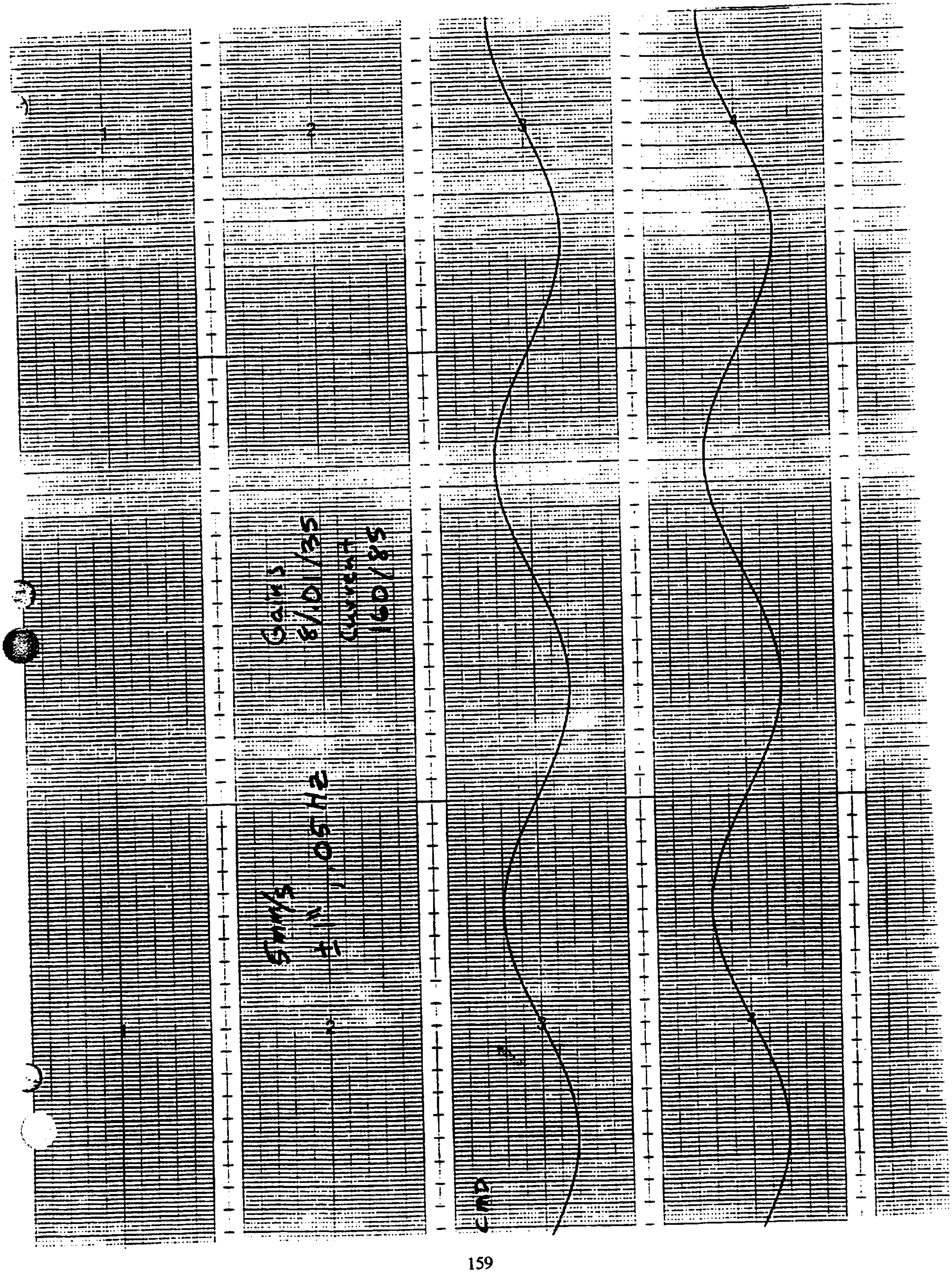


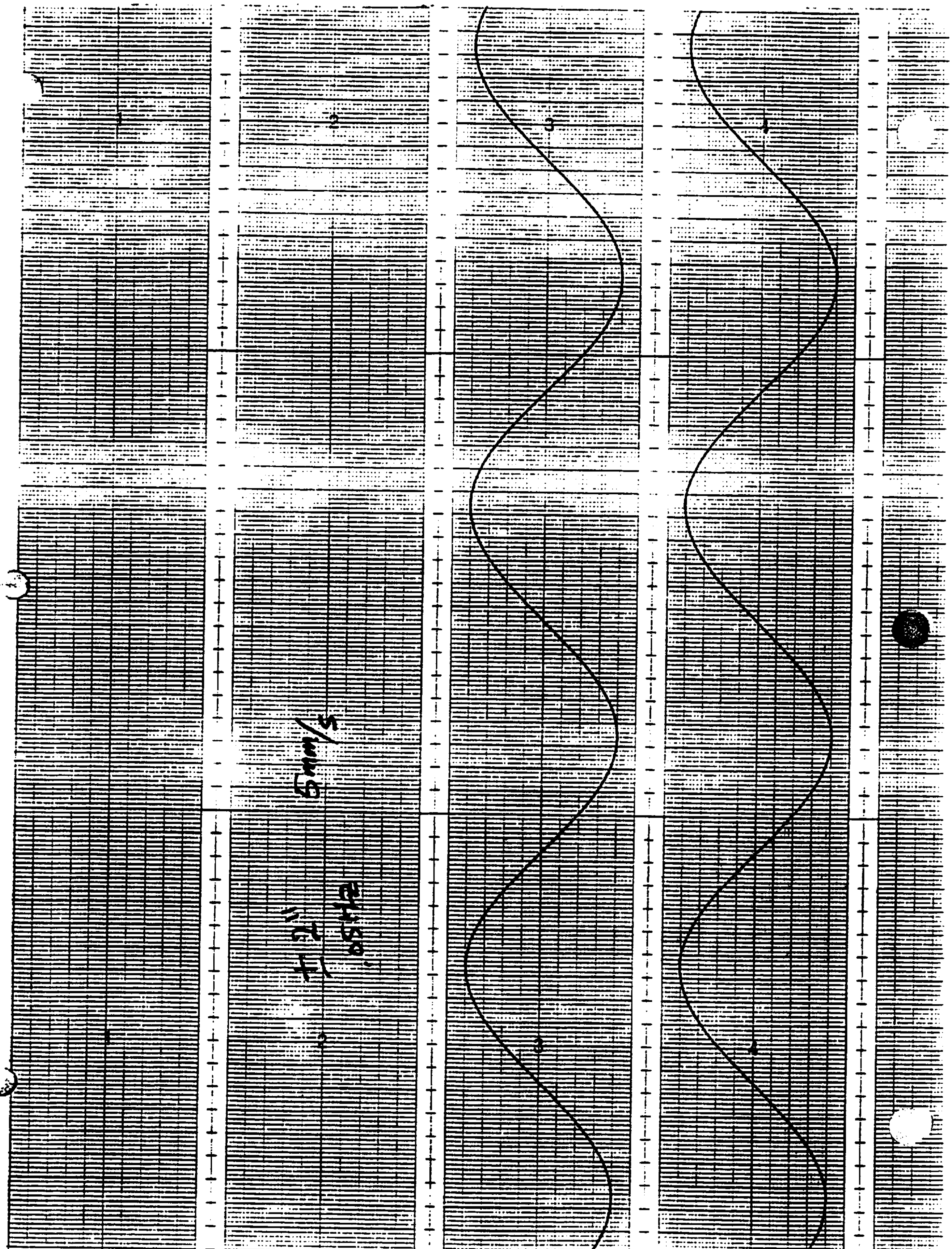

CH1 5V
CH2 5V
A 200ms -39.1mV VERT
CH1gnd
CH2gnd

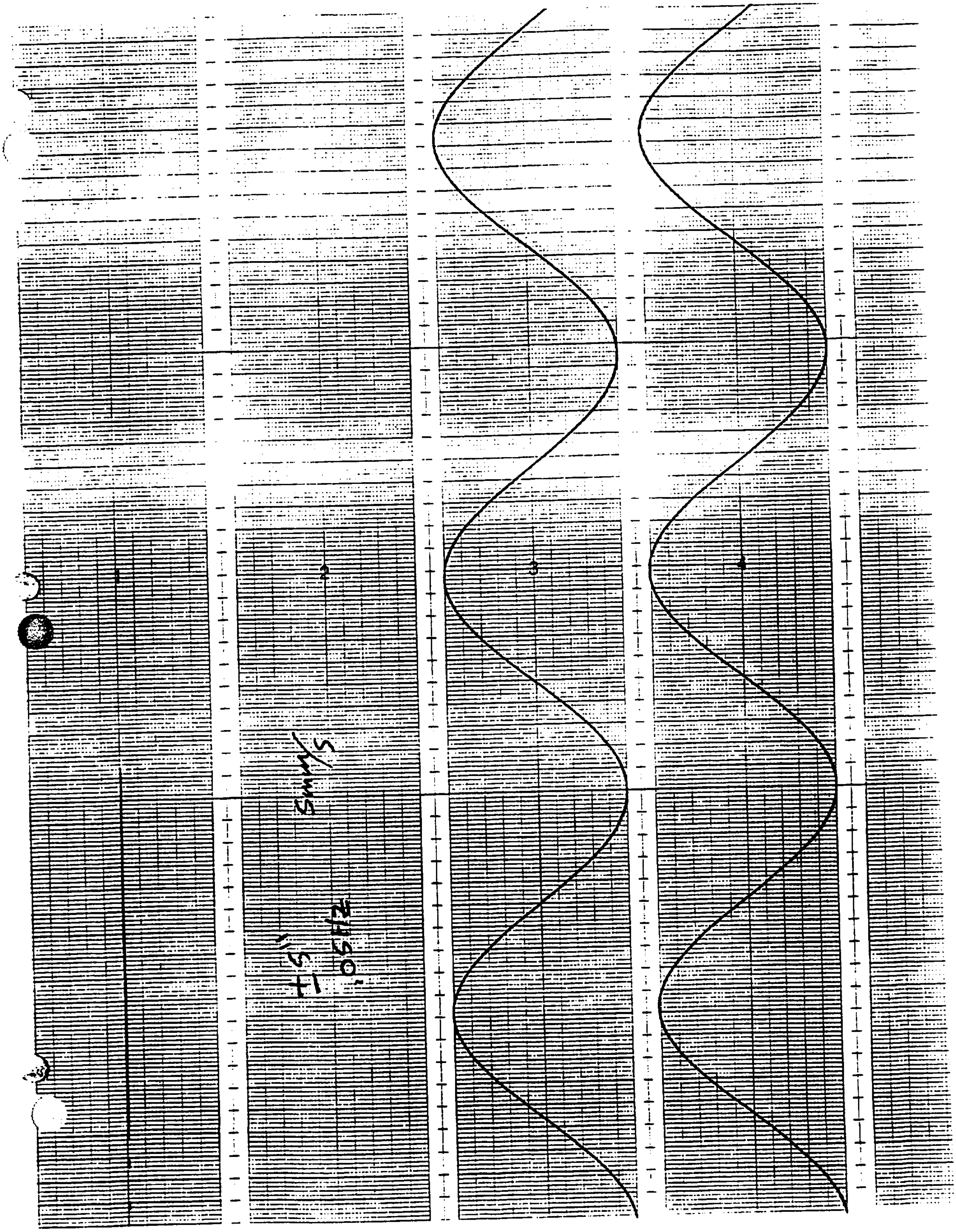
SECTION 5 – ACTUATOR NO-LOAD SINUSOIDAL RESPONSE

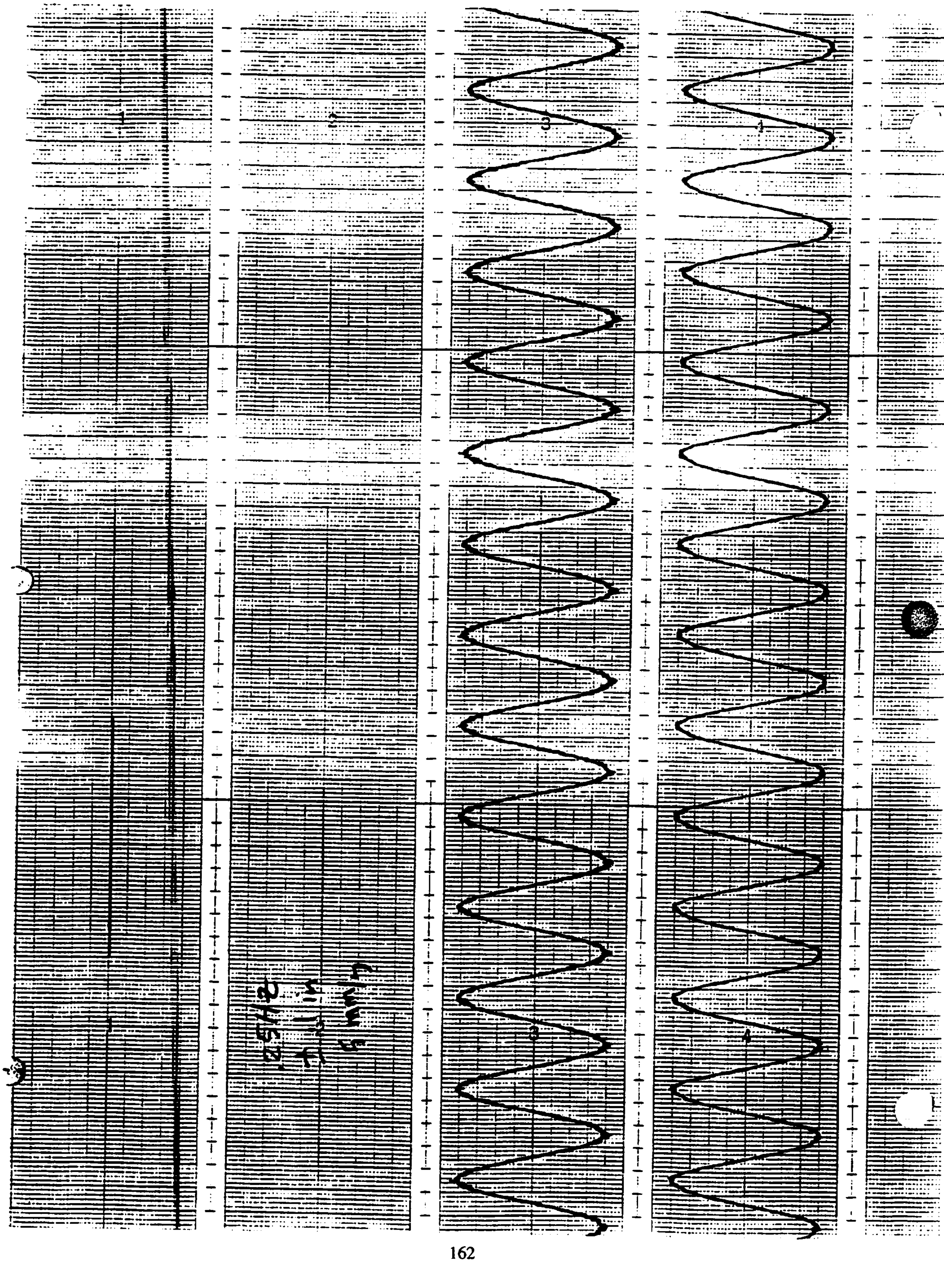
The no load test data was recorded under the following conditions:

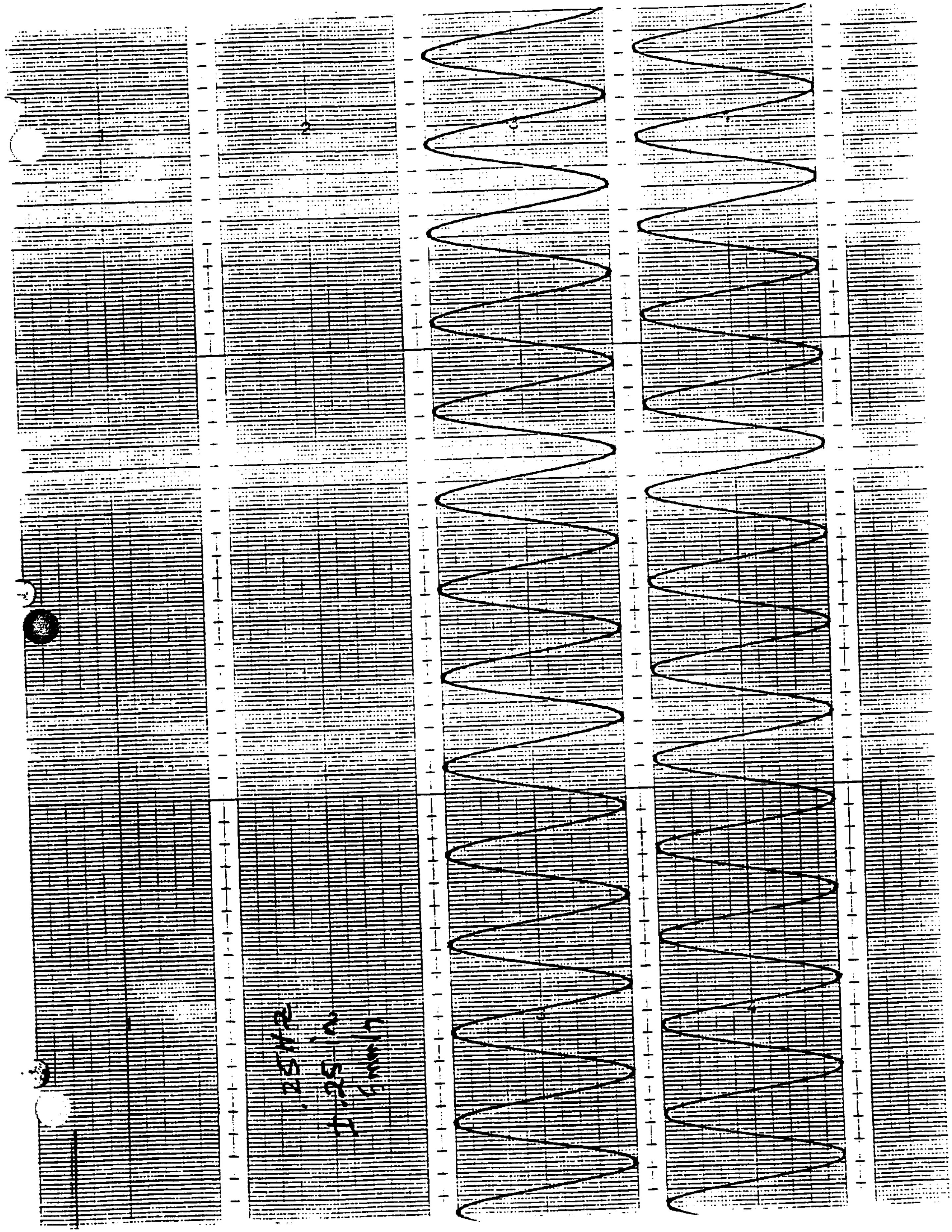
- Kp = 8.0, Ki = 0.1, and Kr = 35.0 unless otherwise noted.
- Command and Position scales are equal on the strip charts unless otherwise noted.

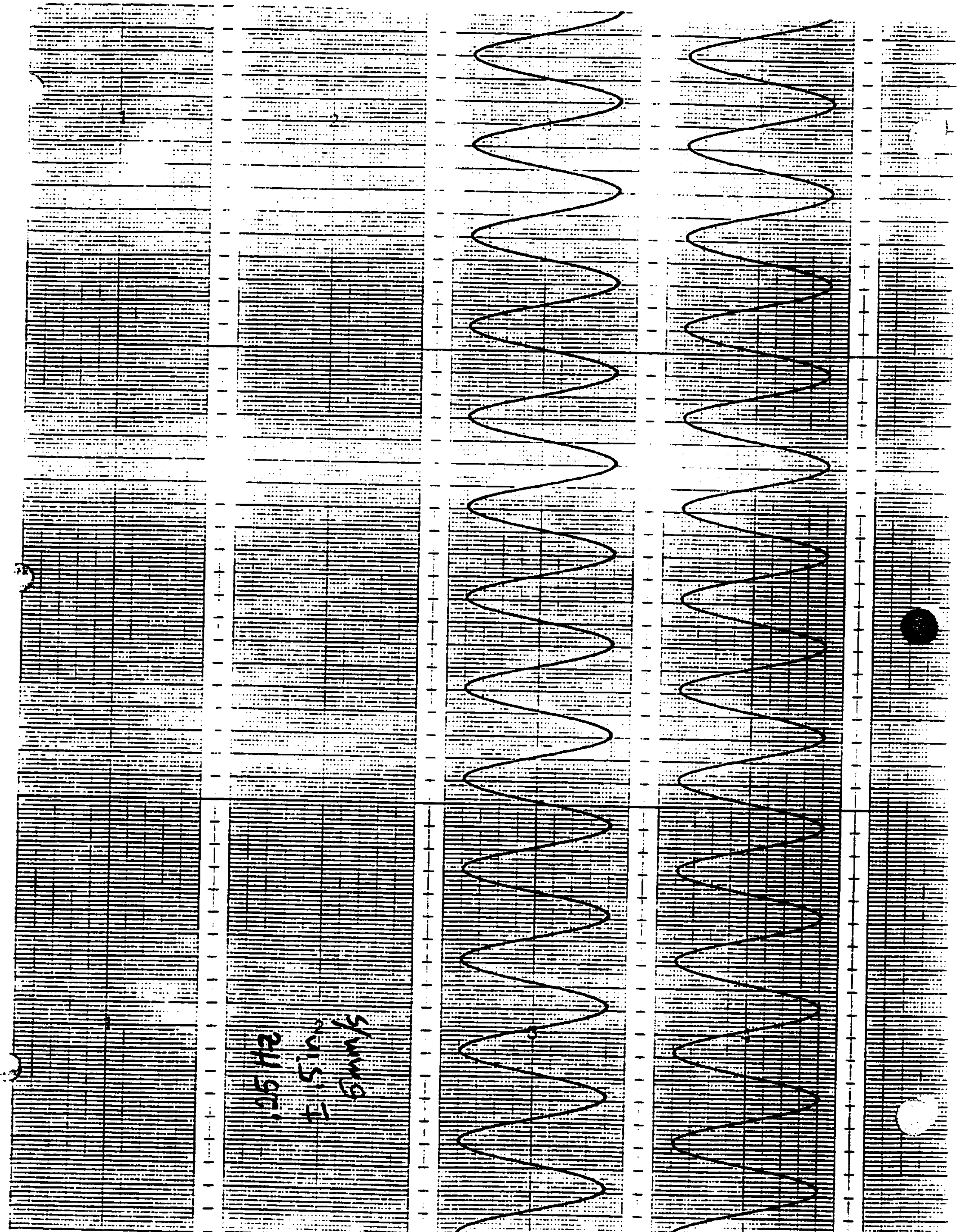

Gains
8/.01/35
Current
160/85
5mm/s
±1, .05 Hz
CMD

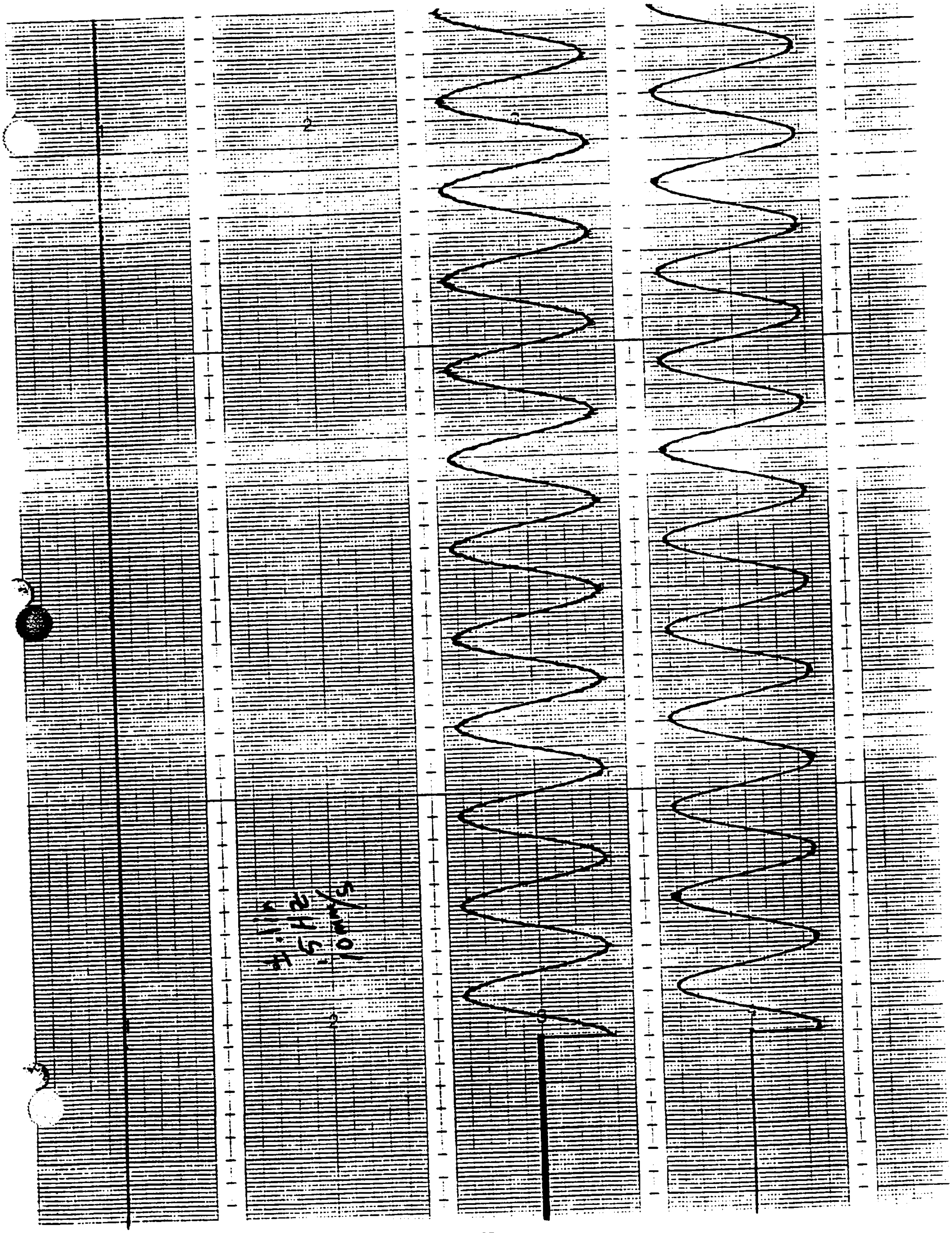

5mm/s

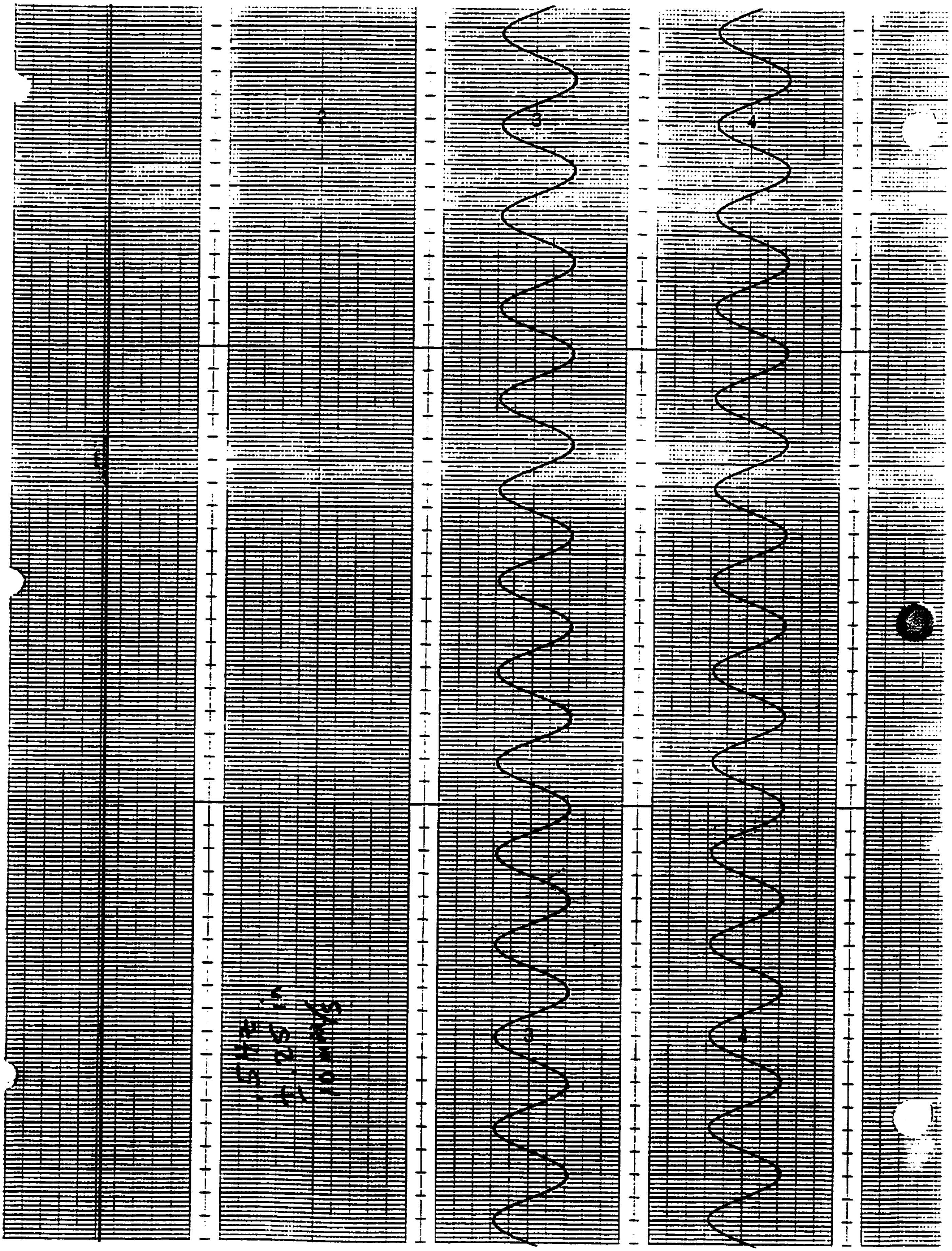


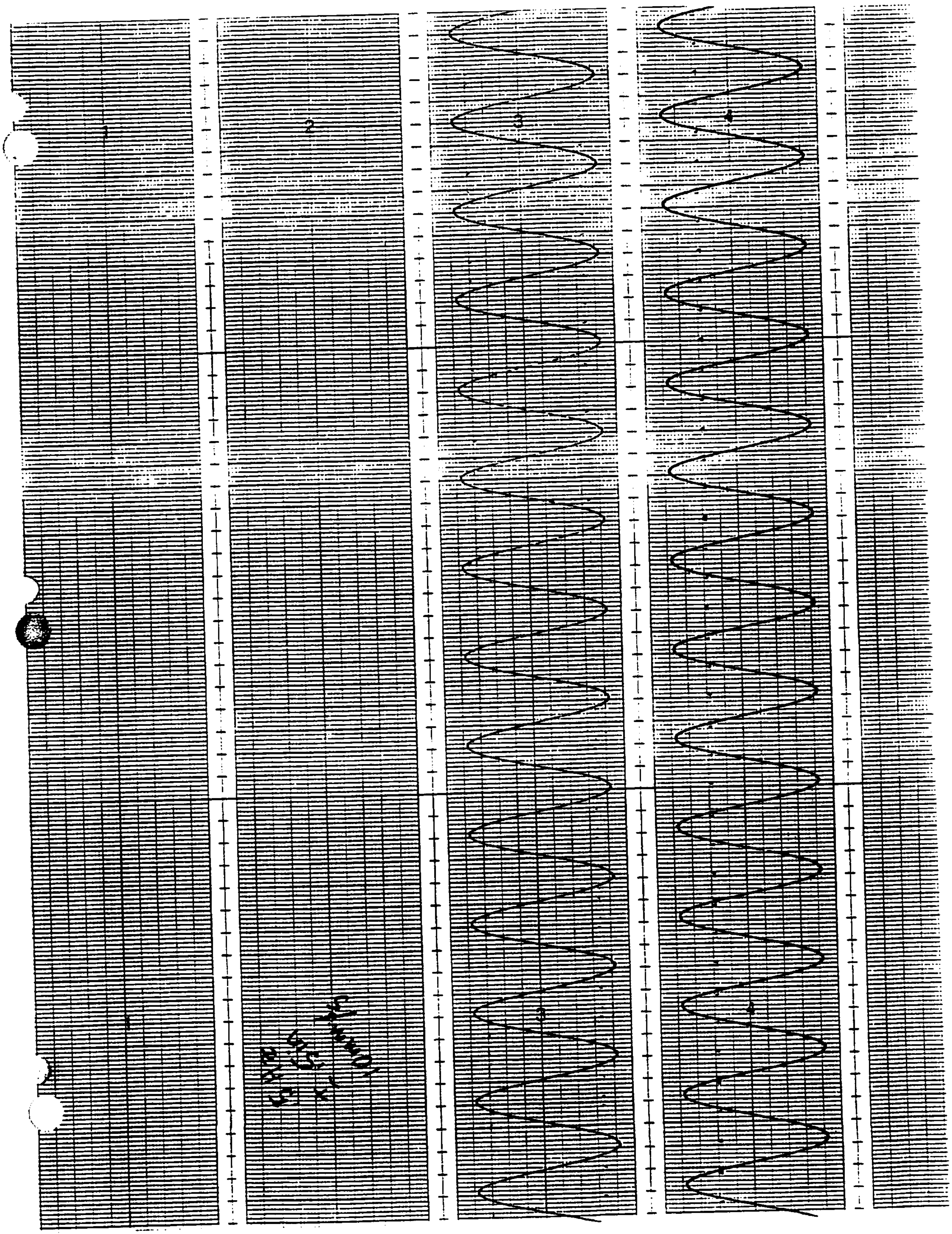


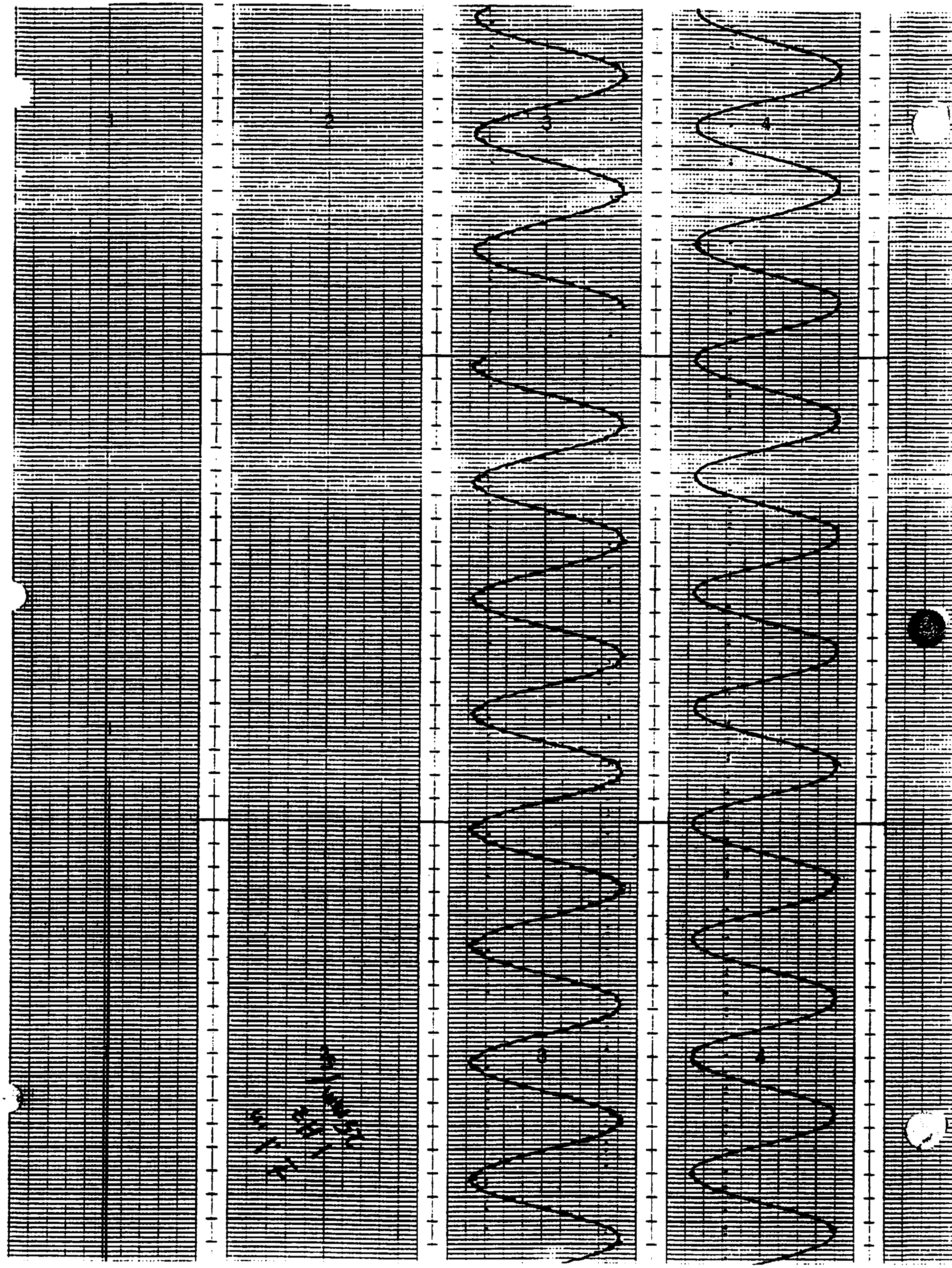


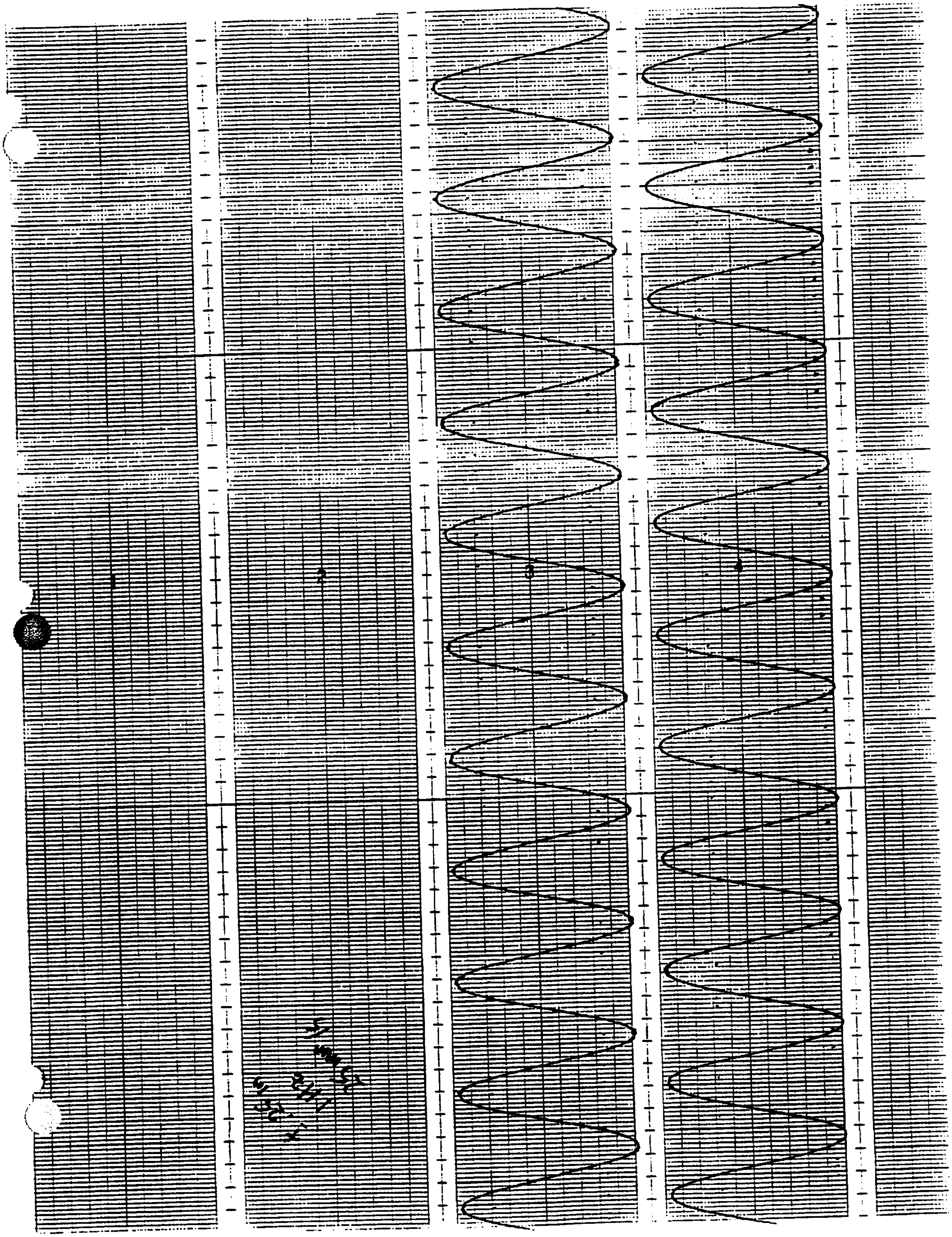


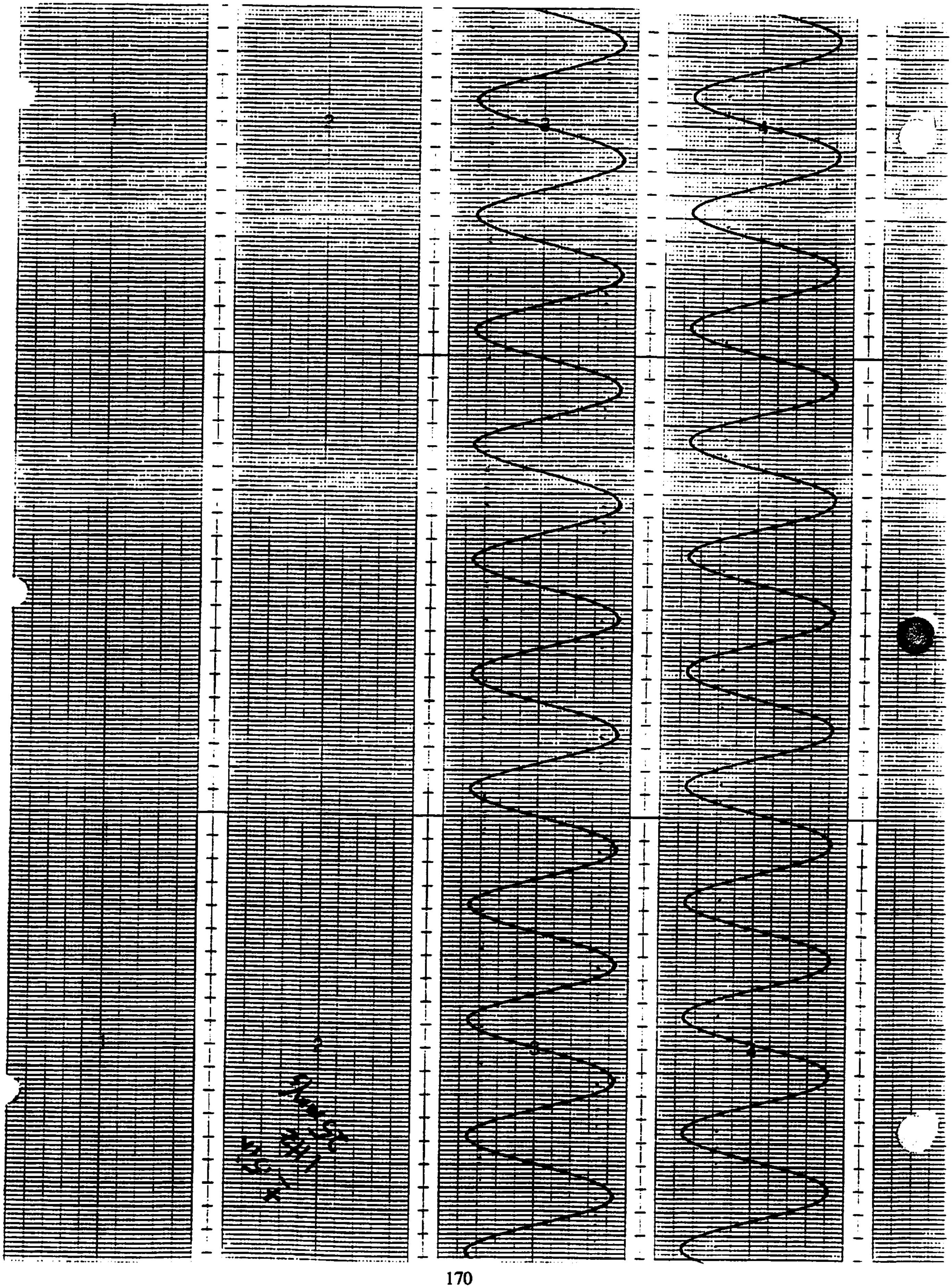


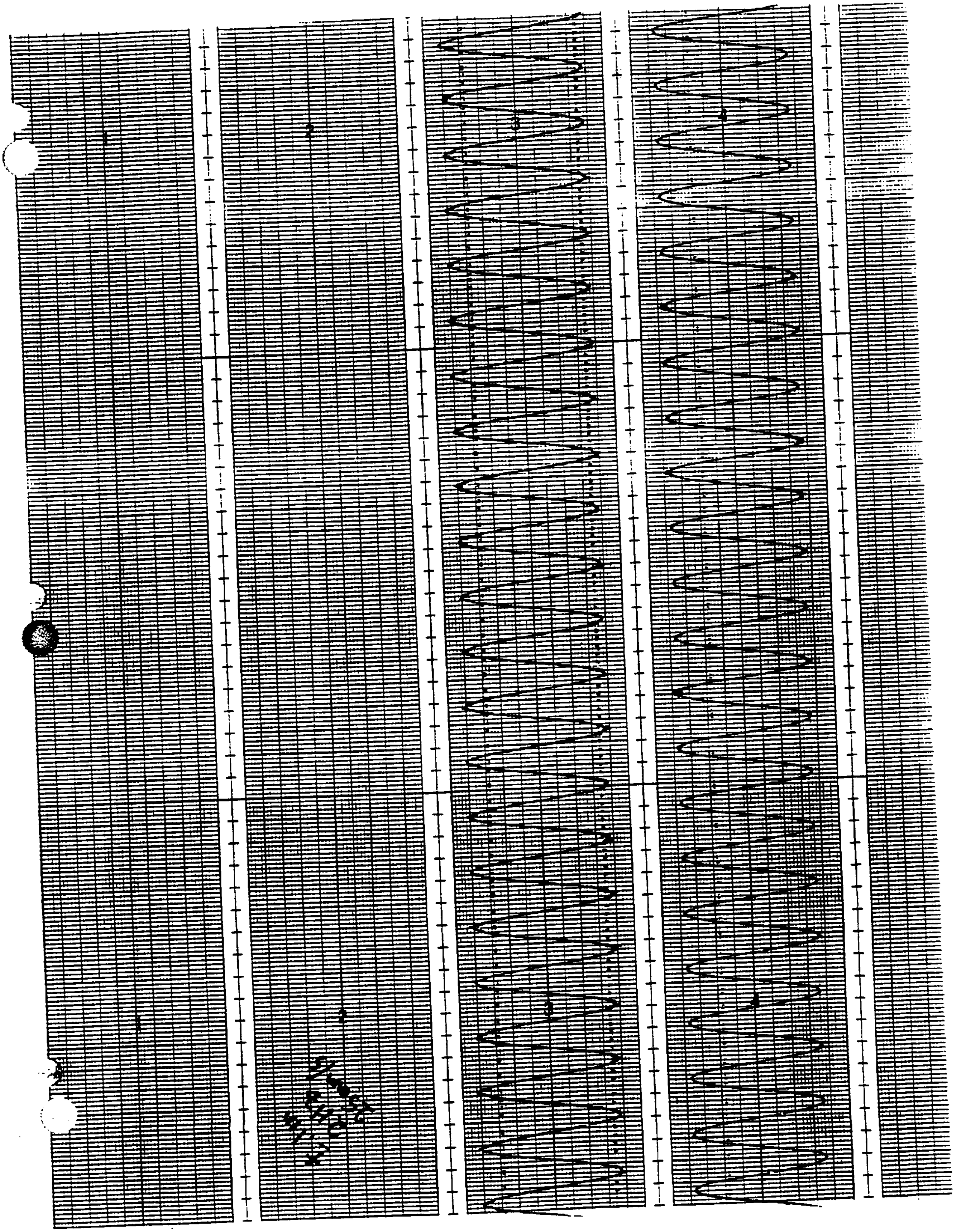


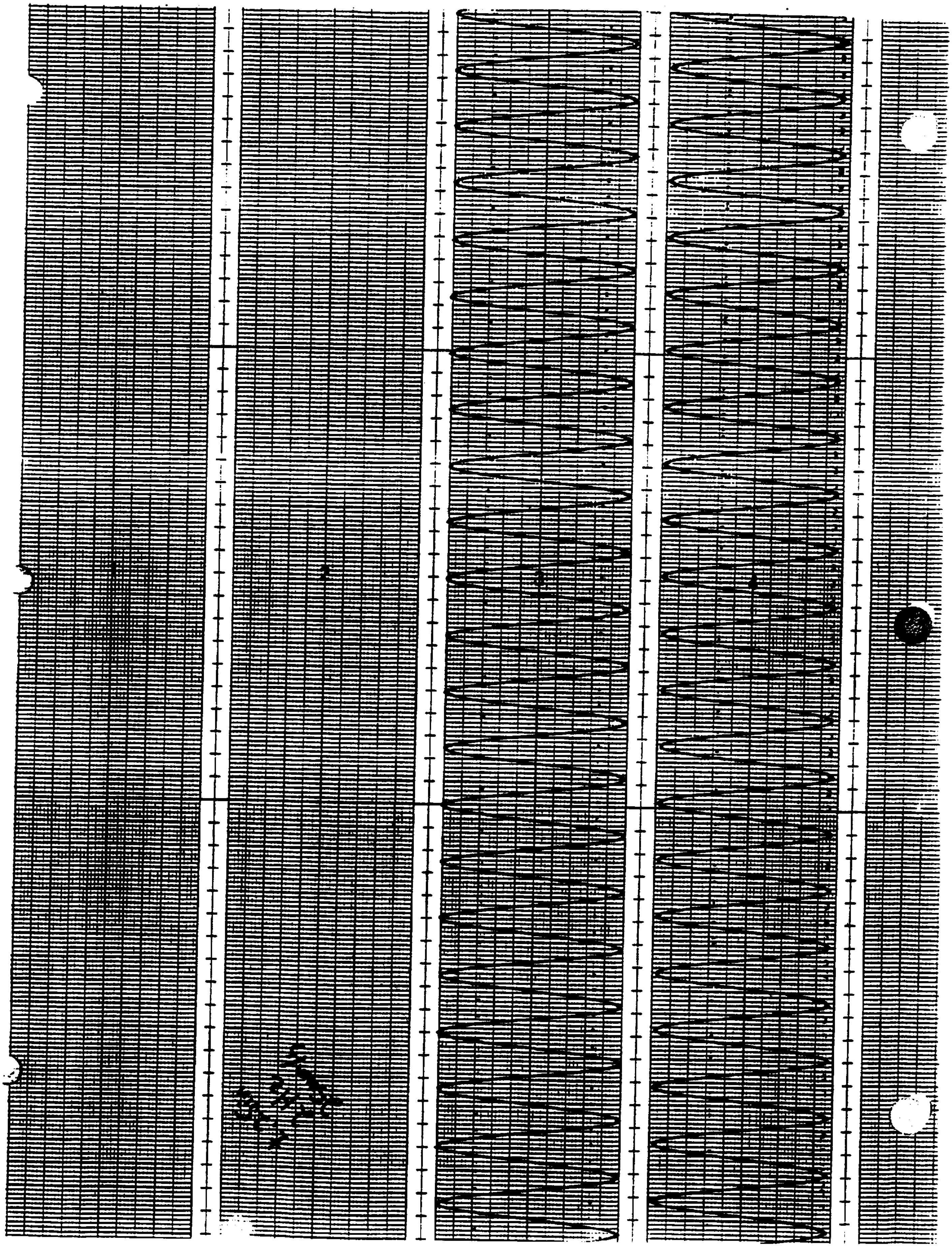


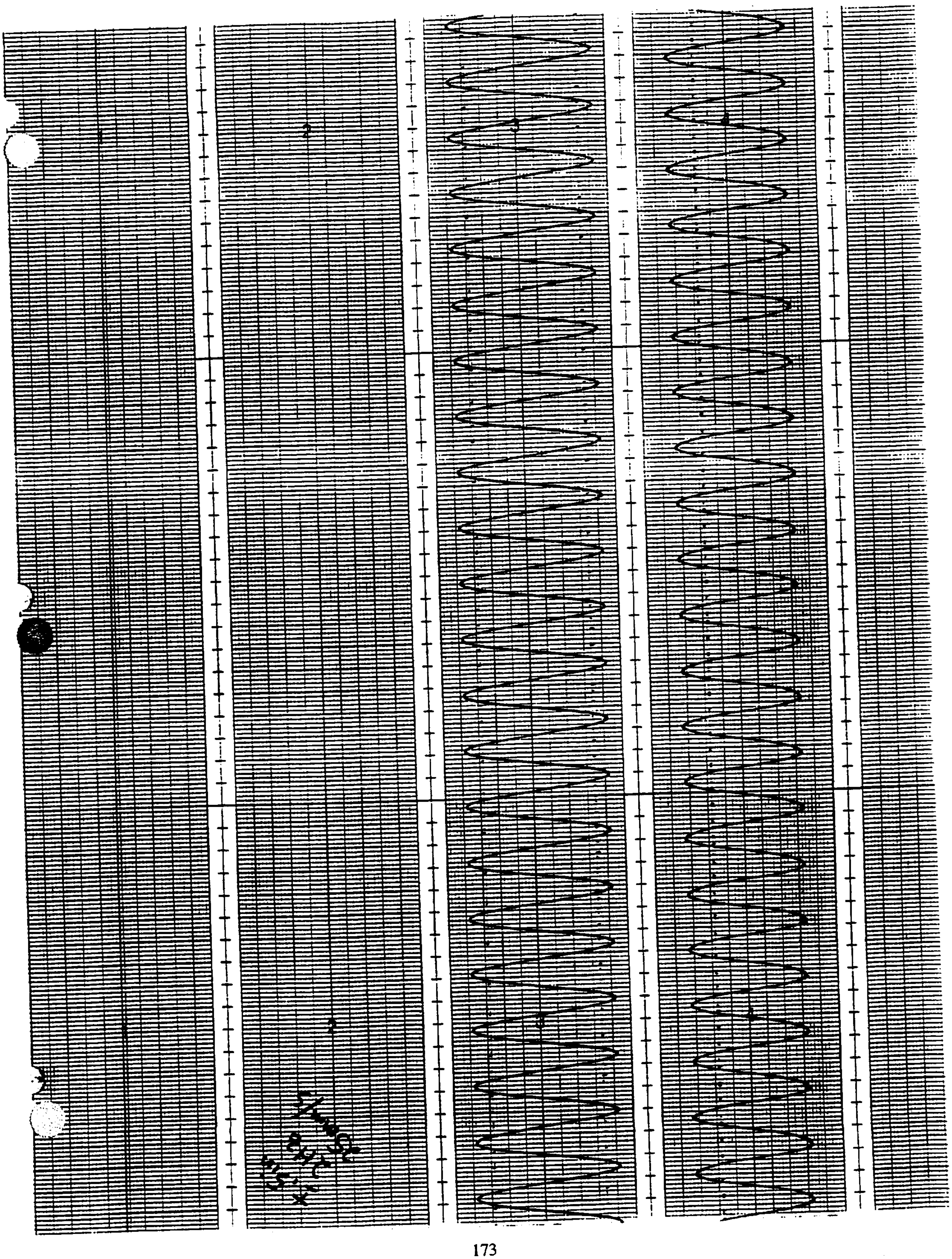


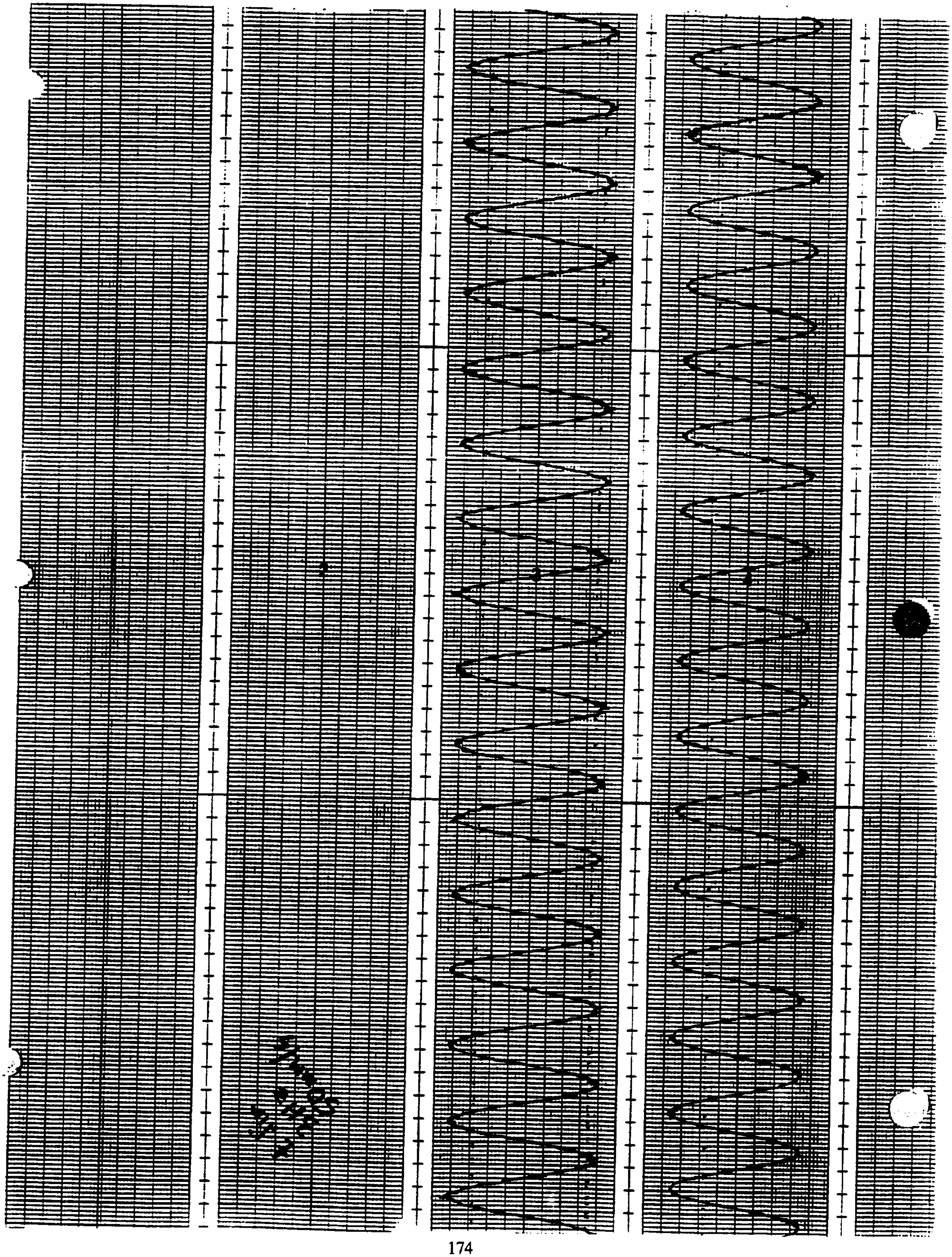


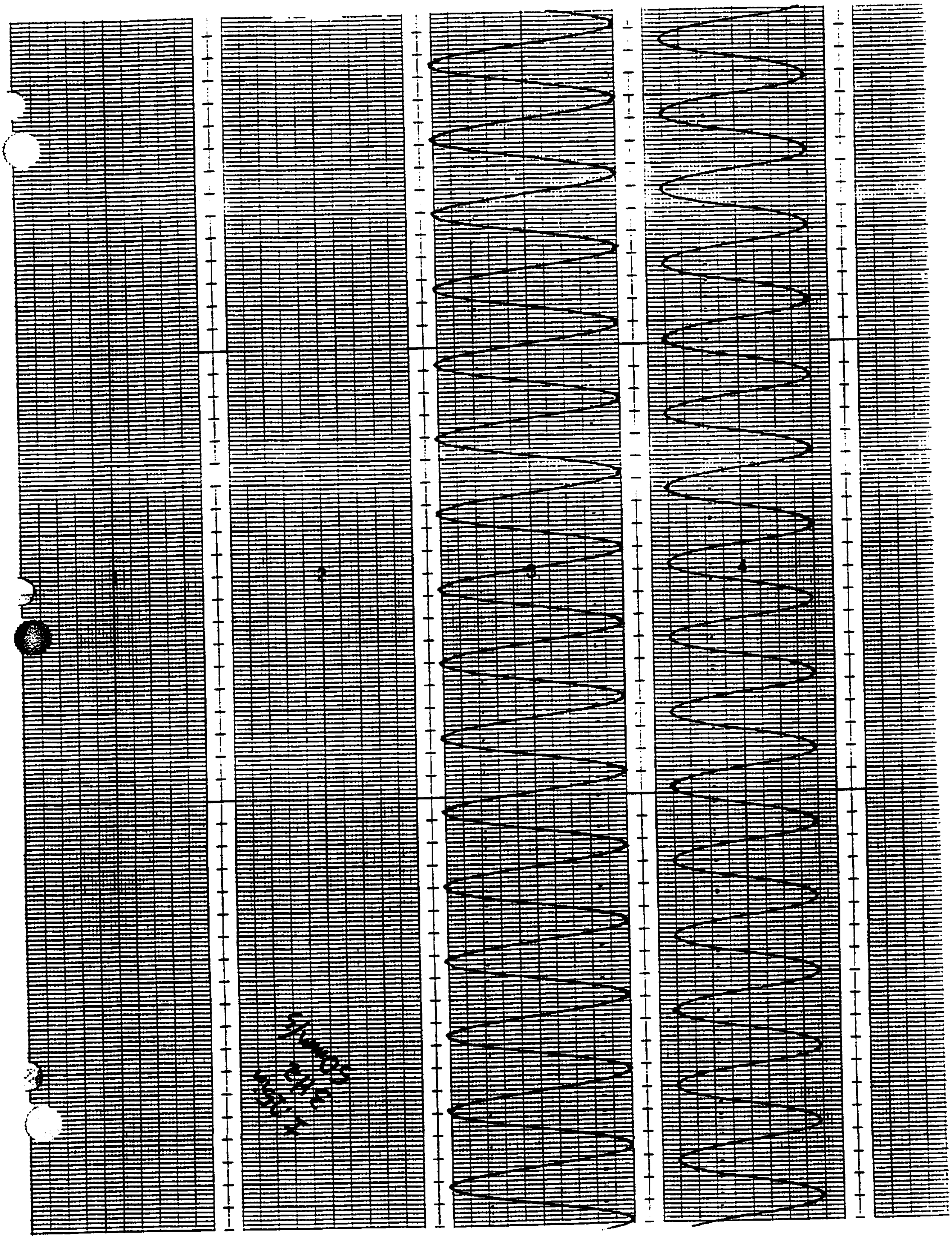


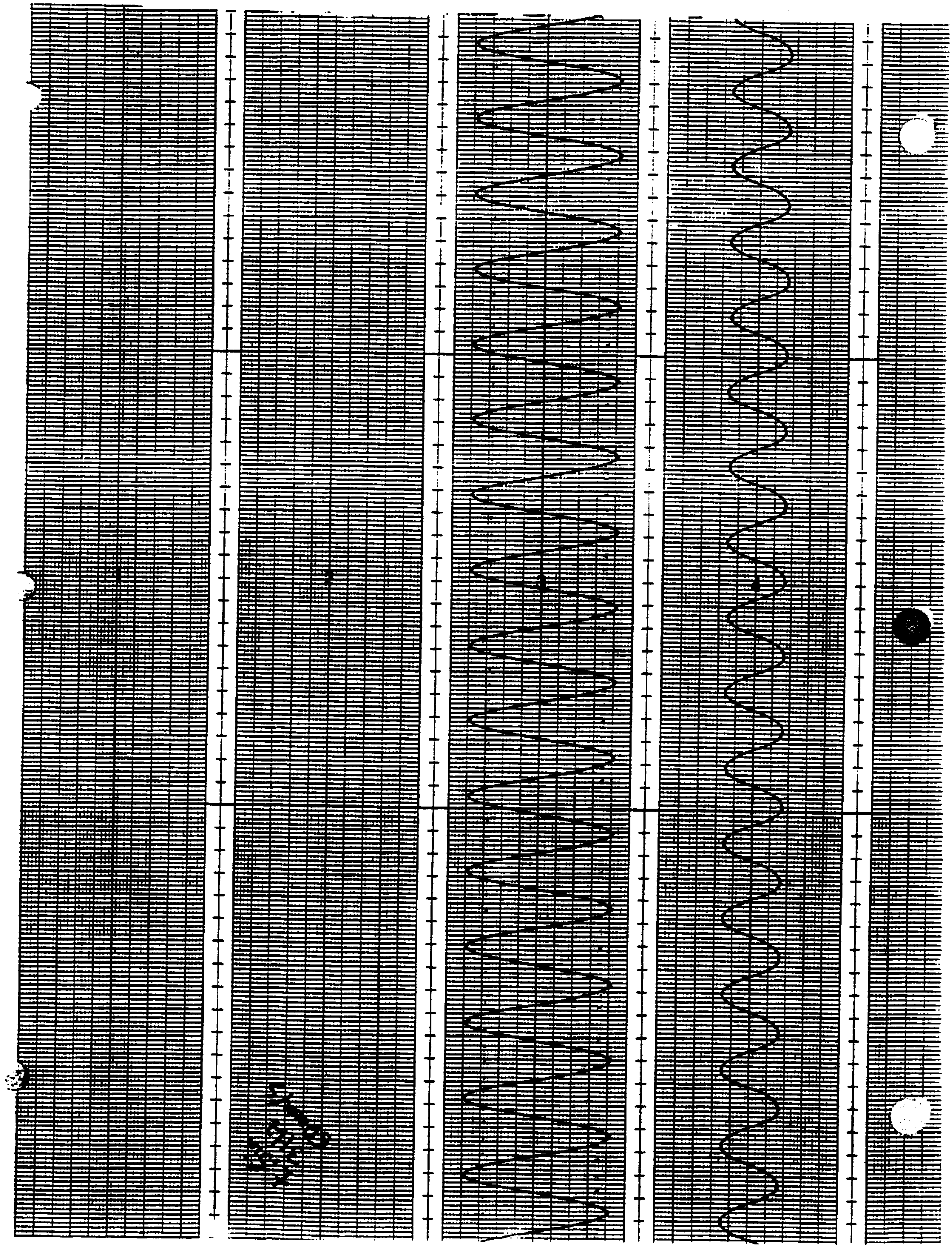


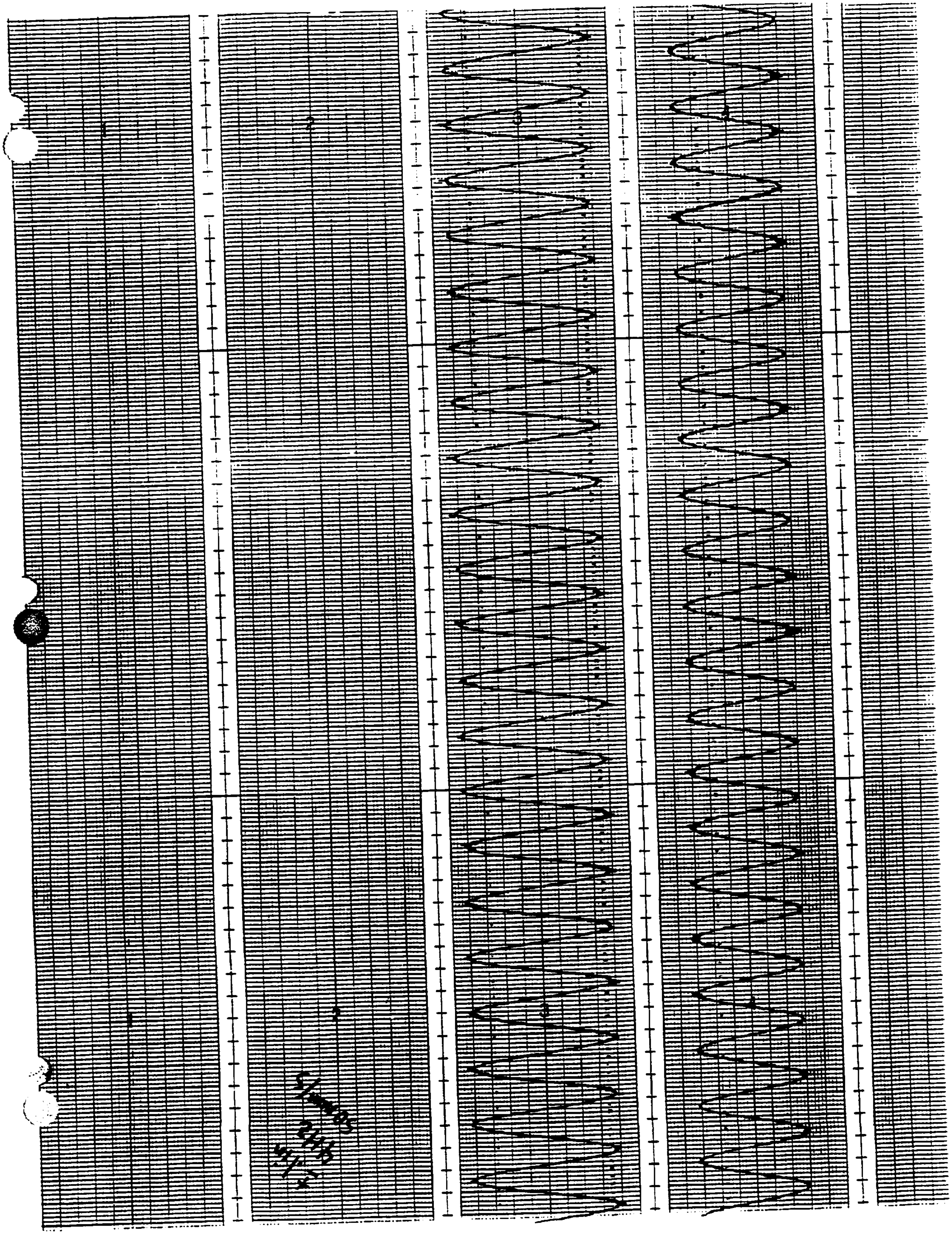


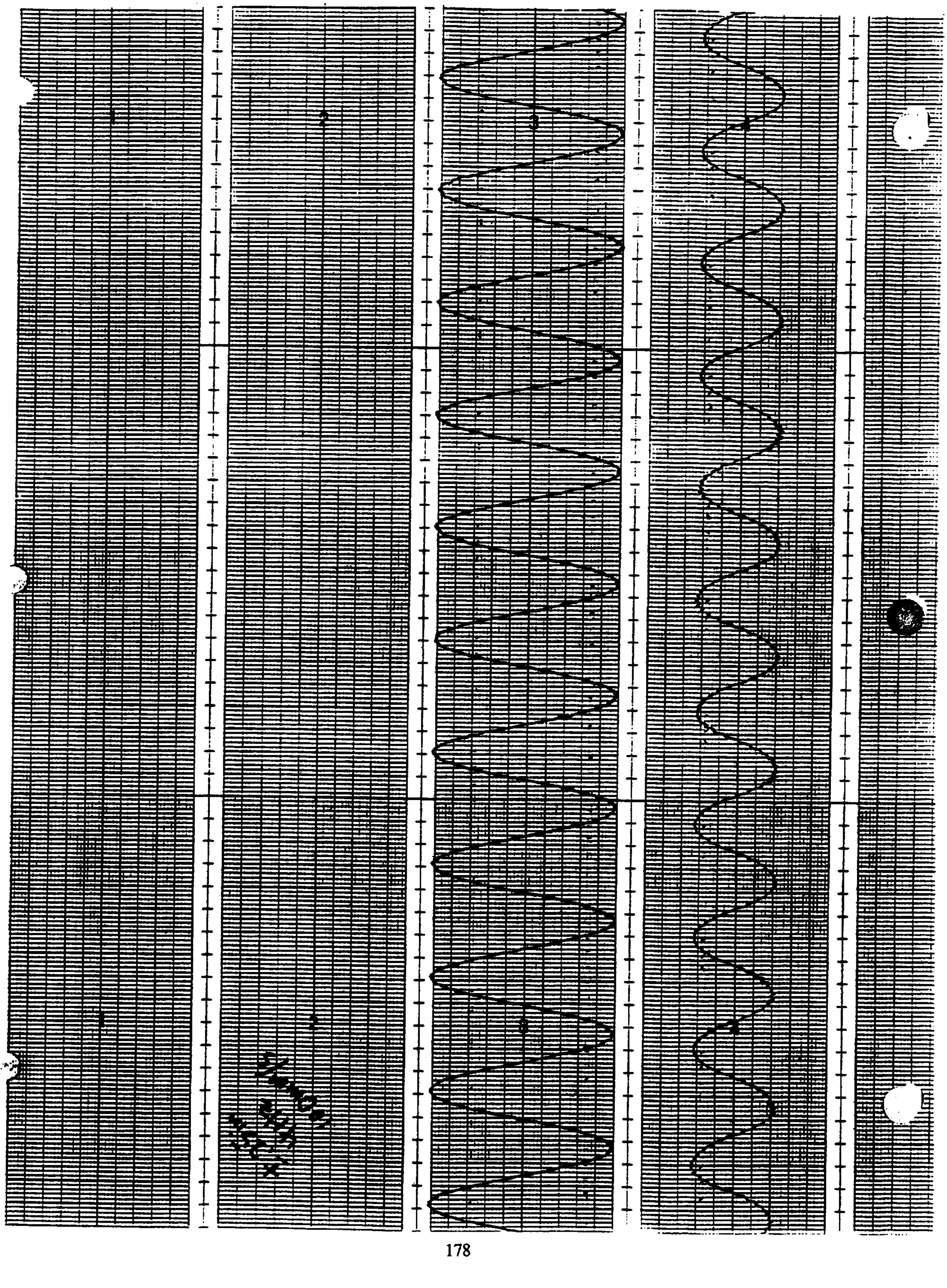


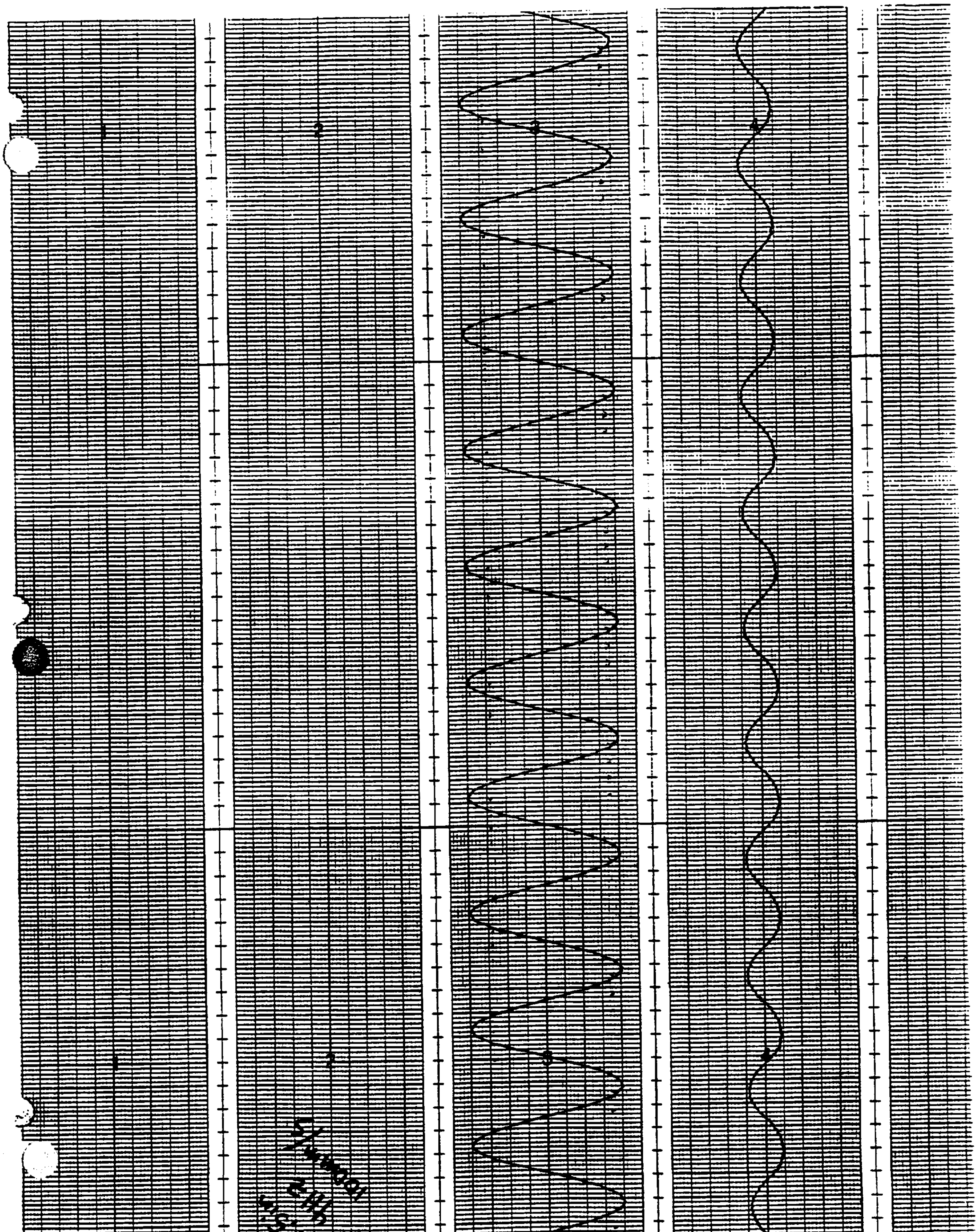


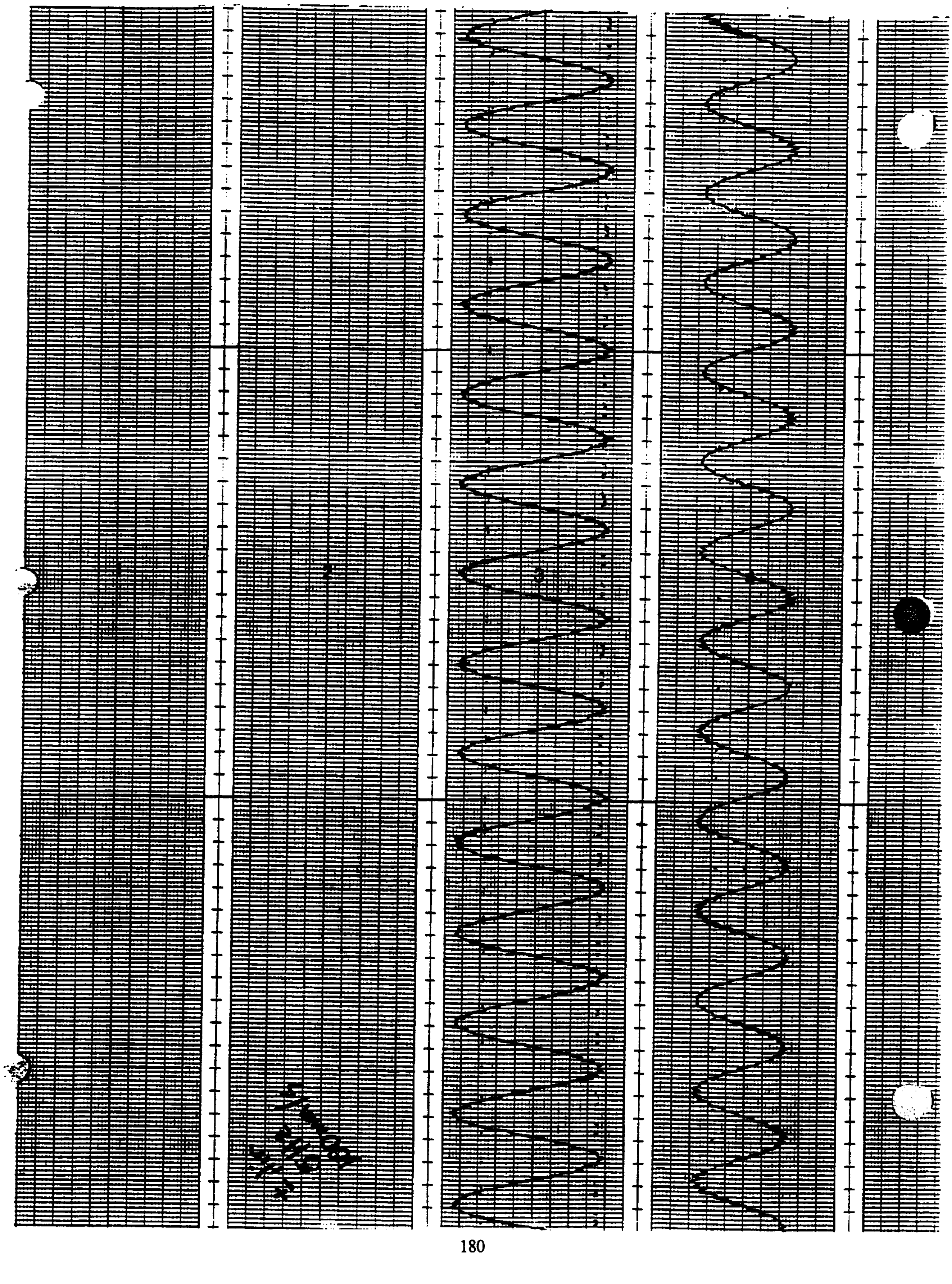


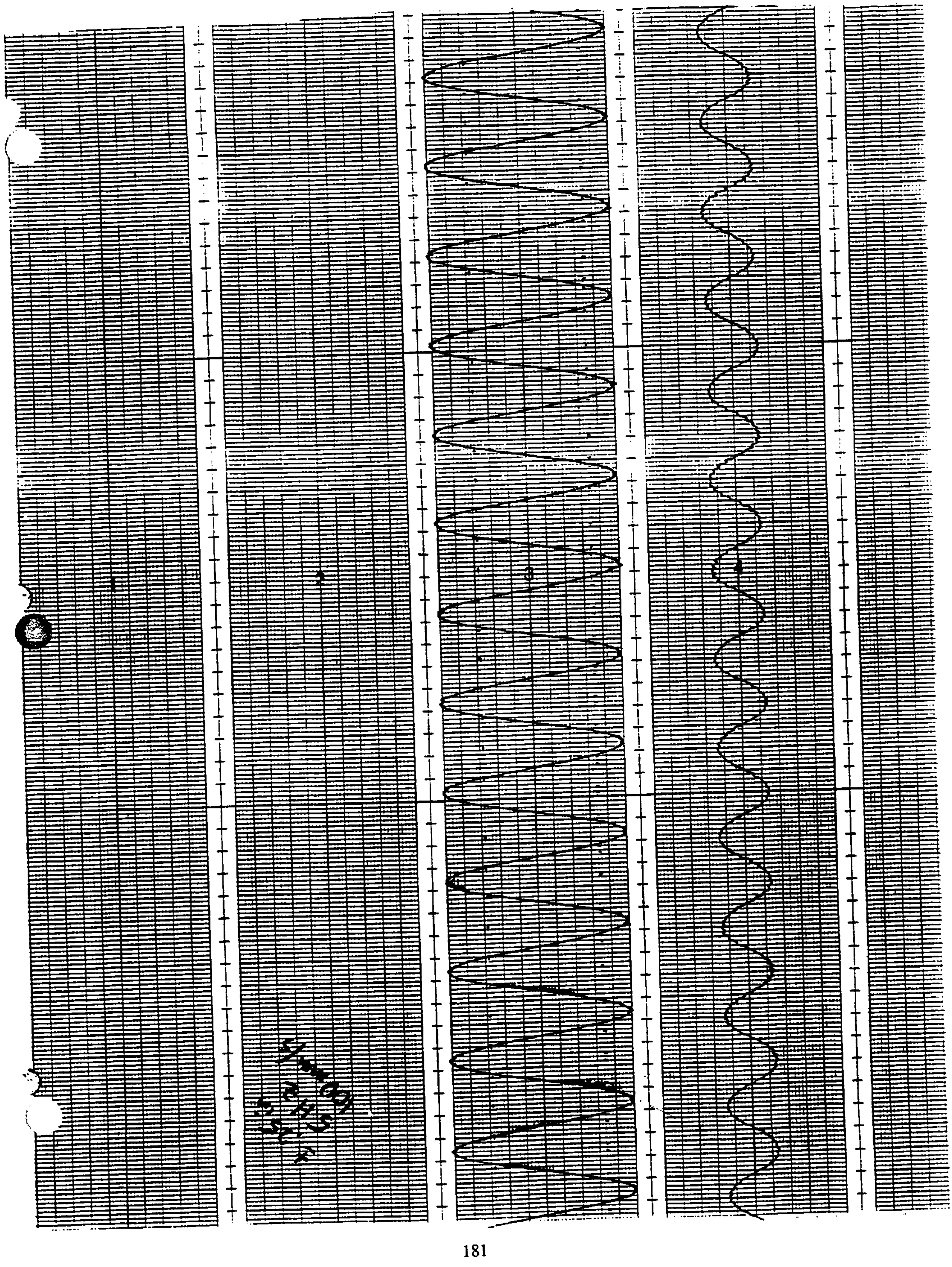


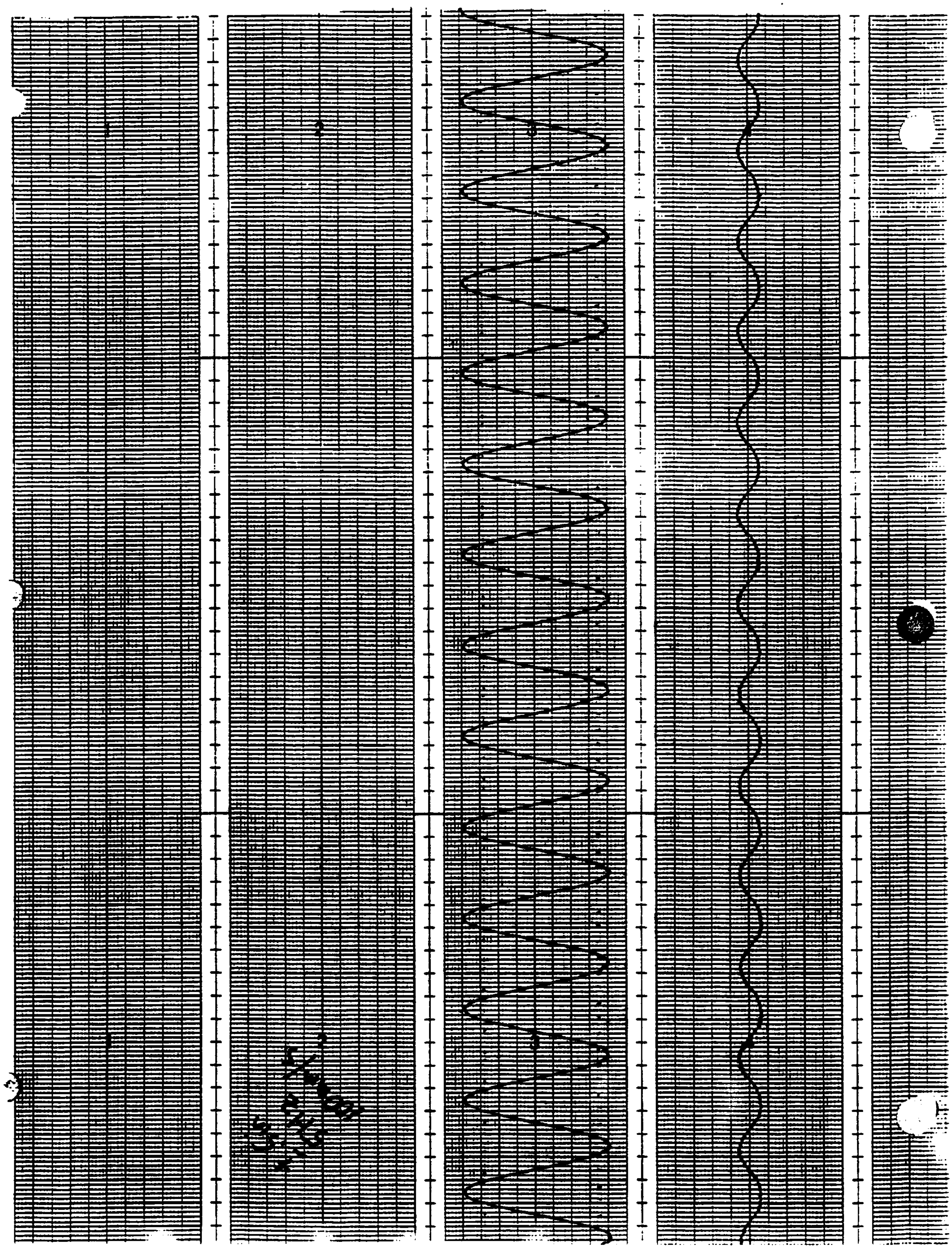


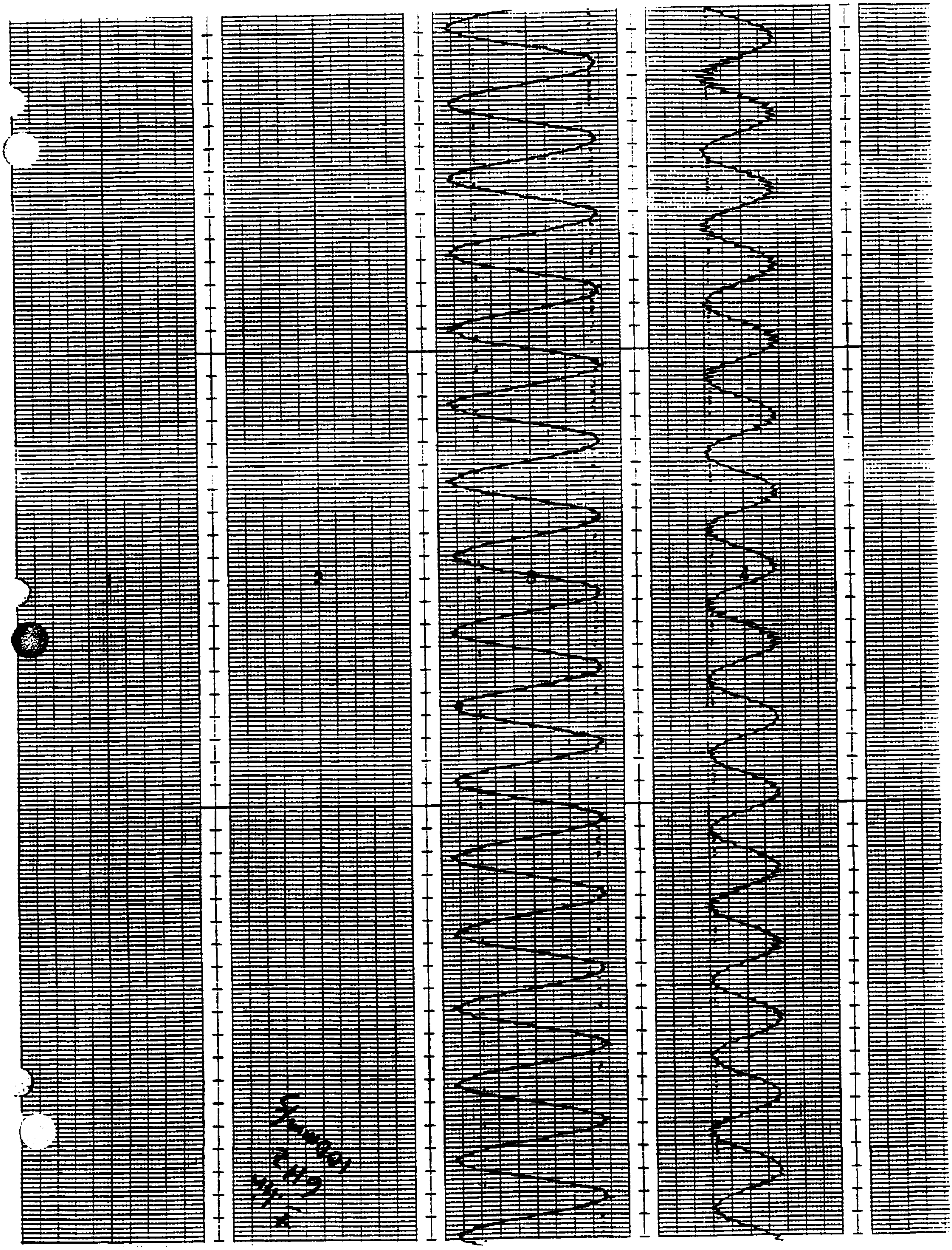


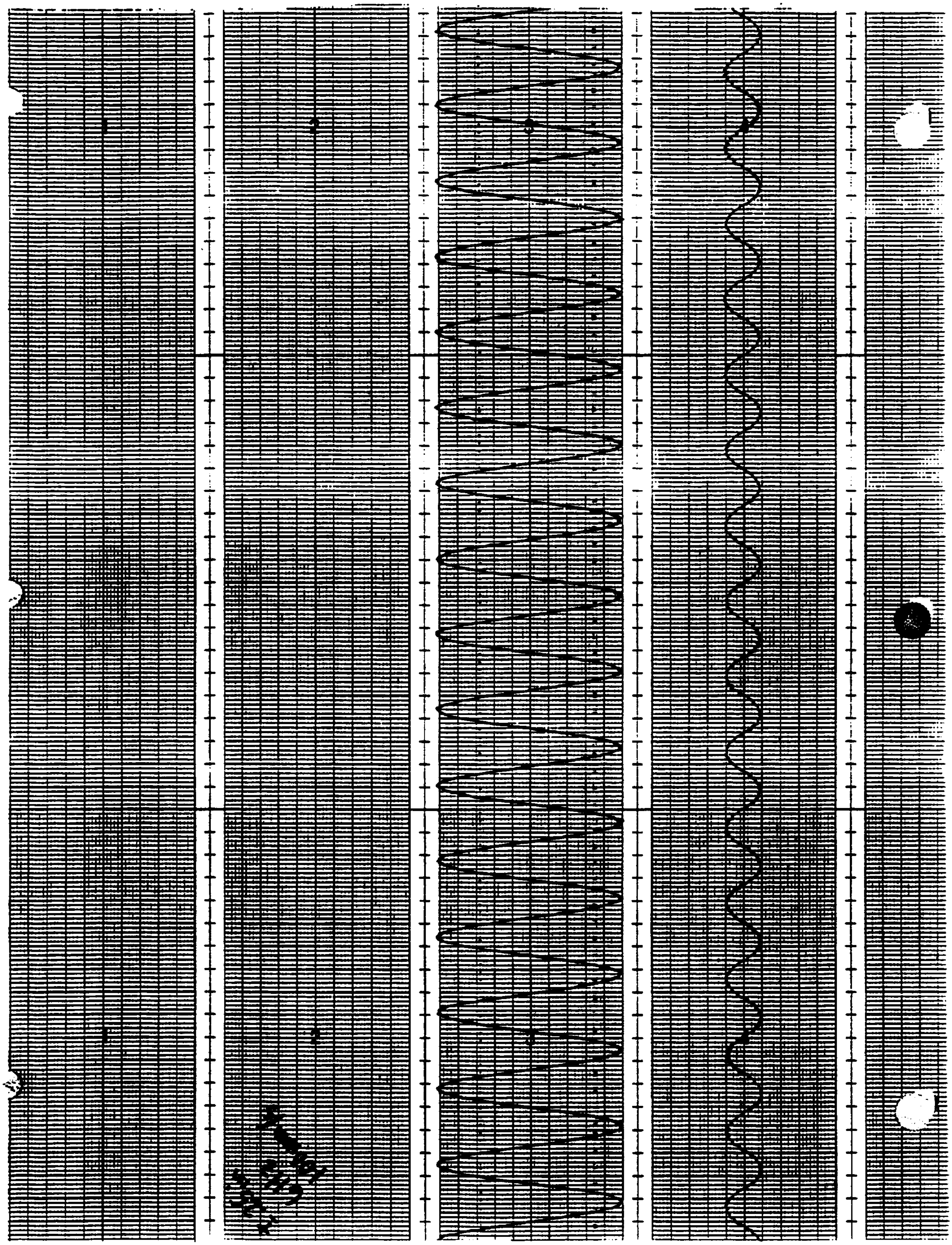


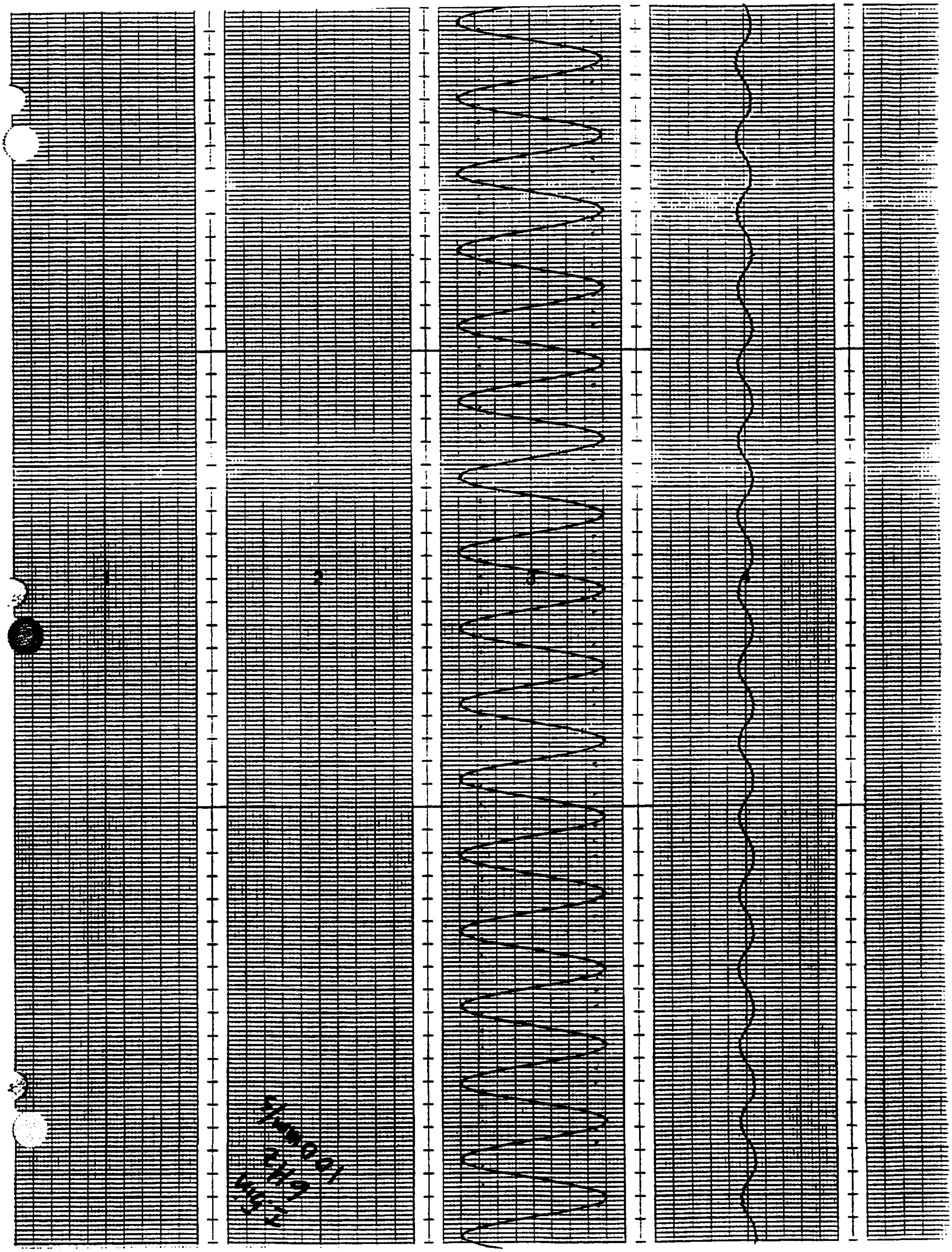


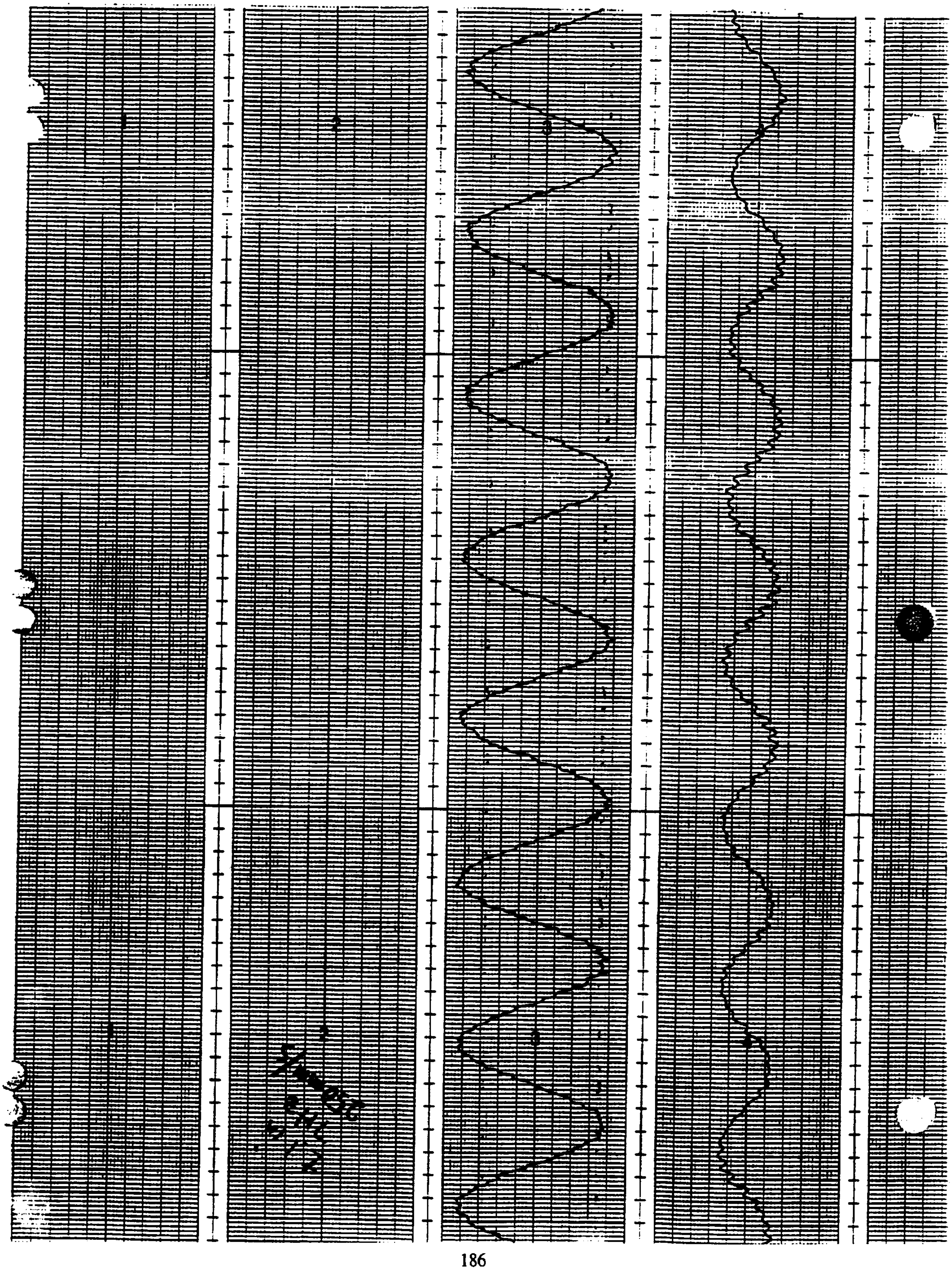


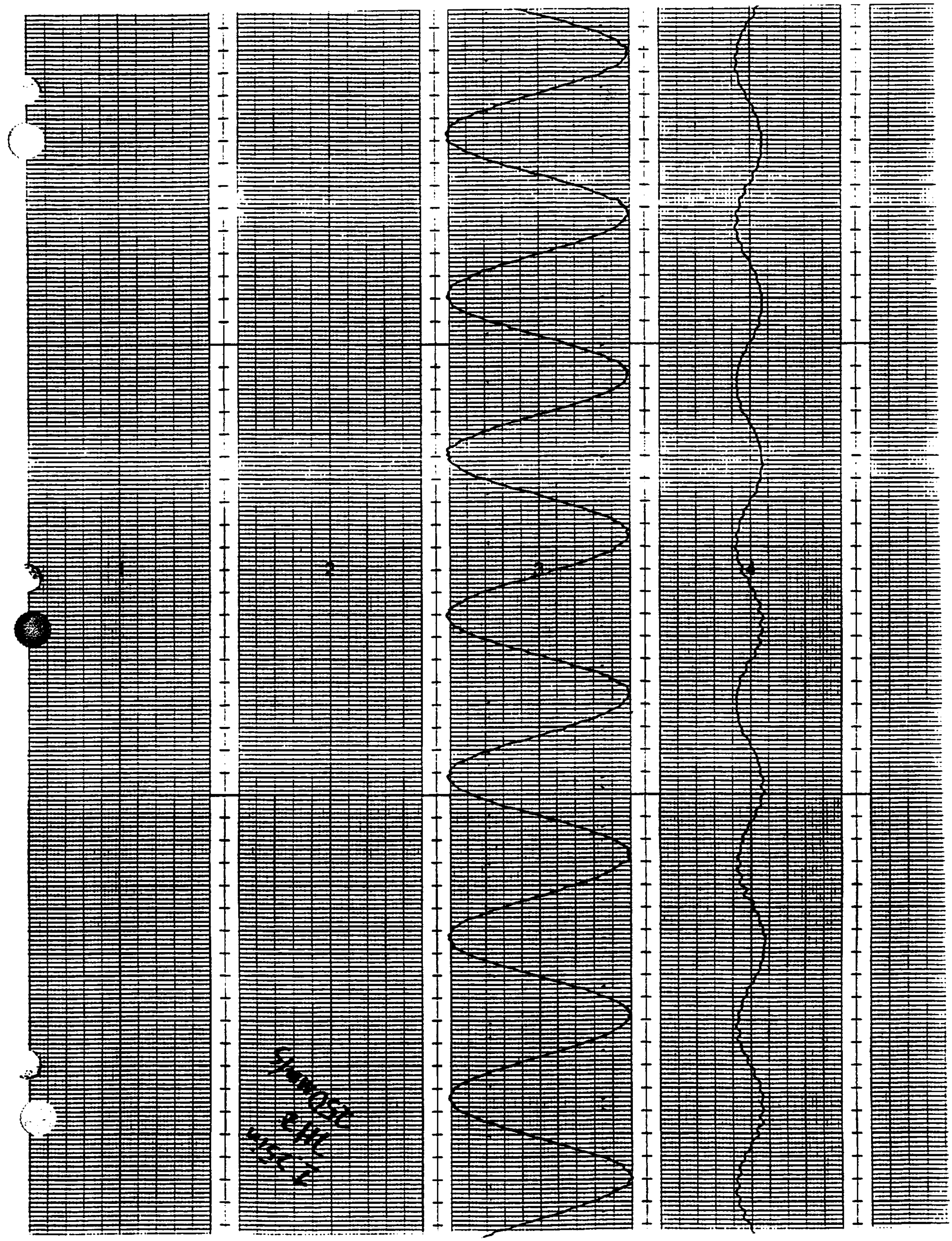


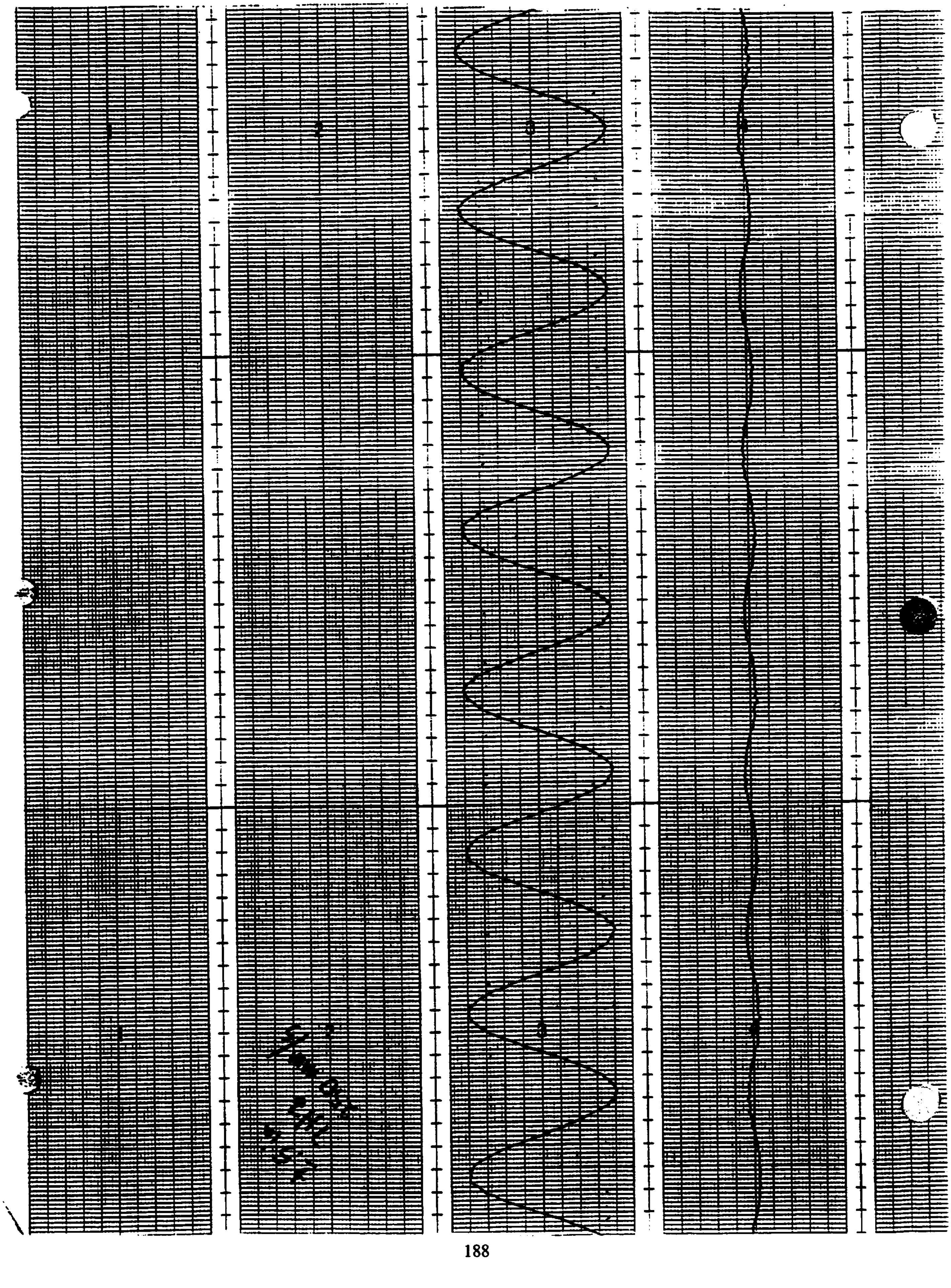








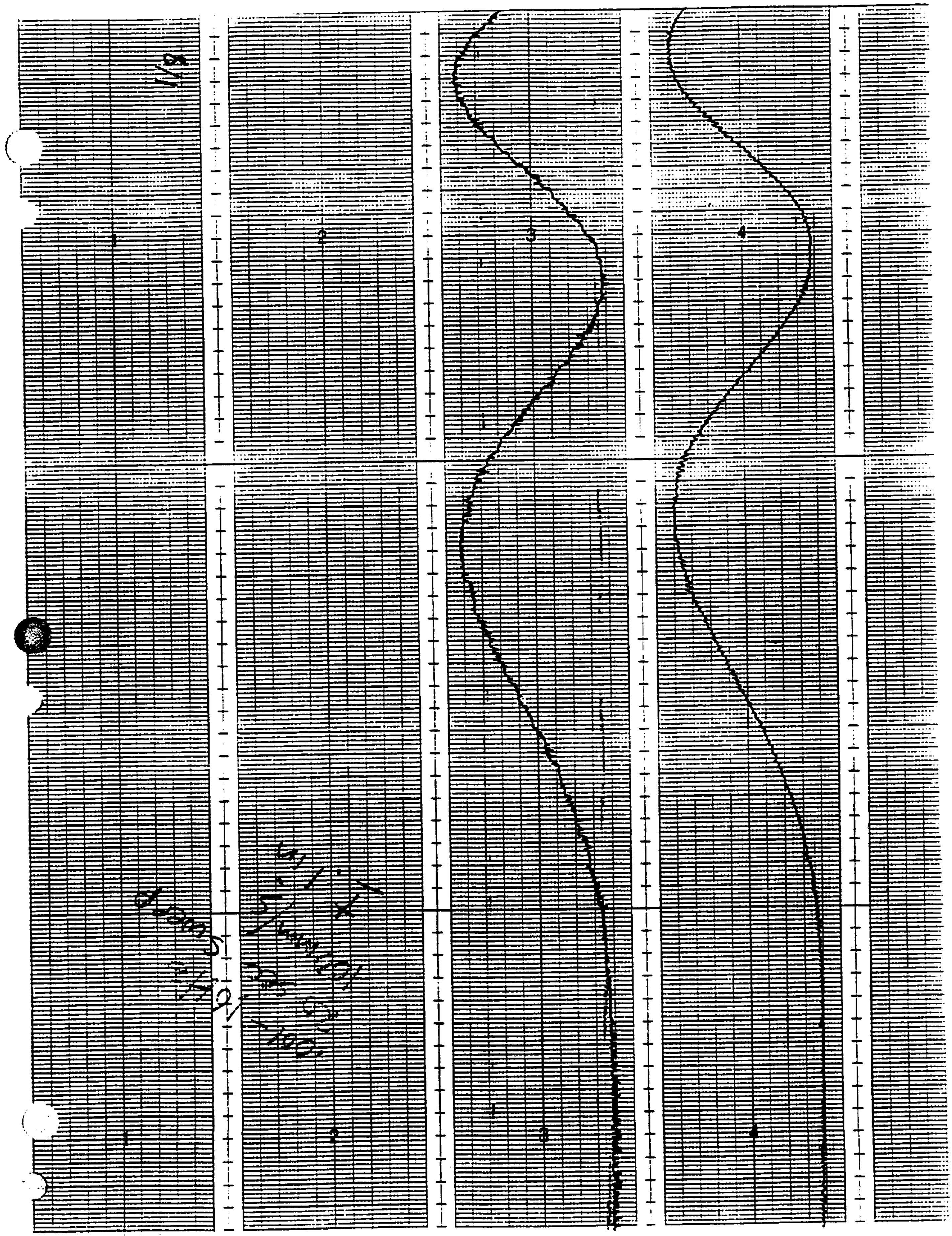


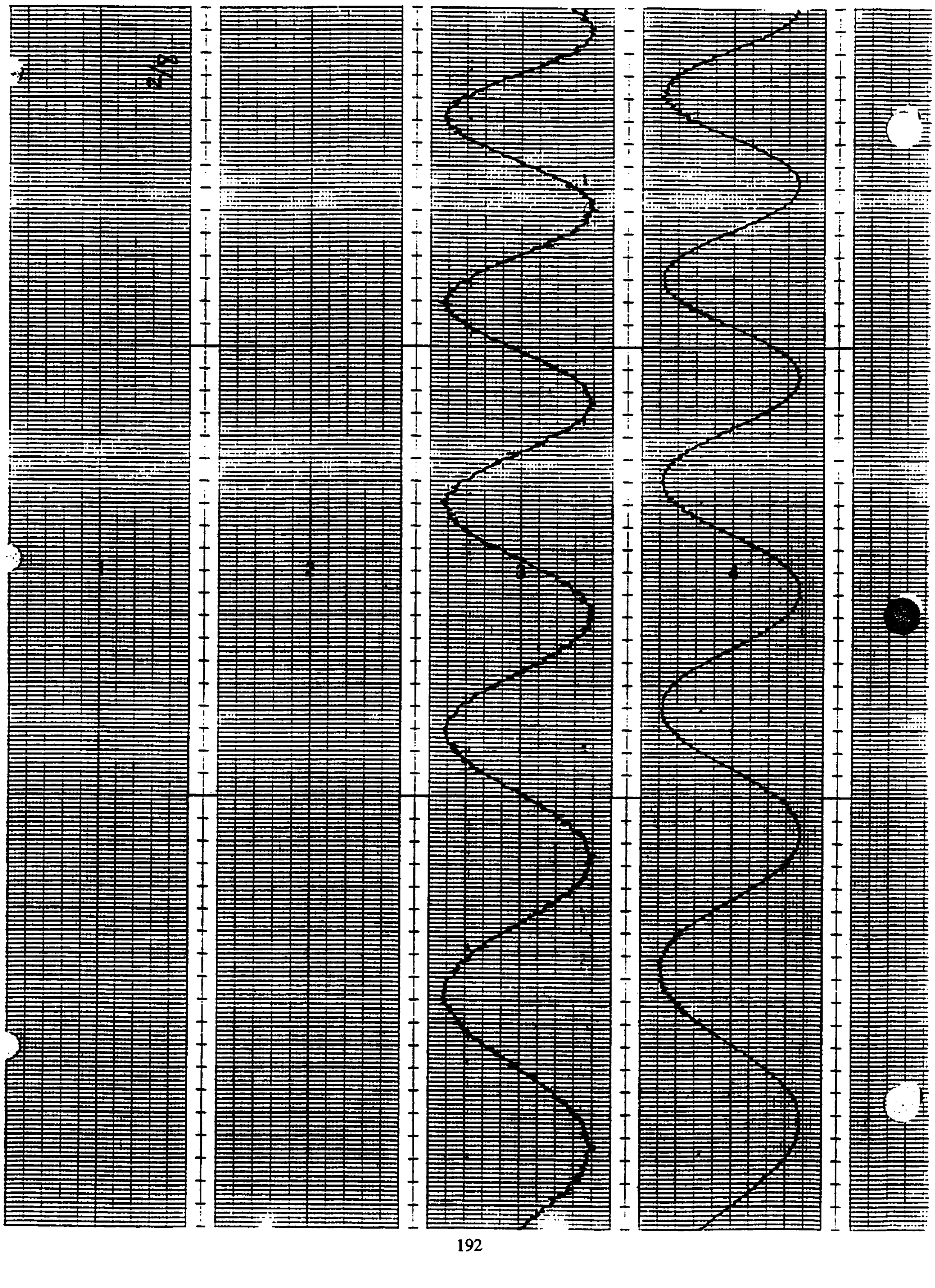


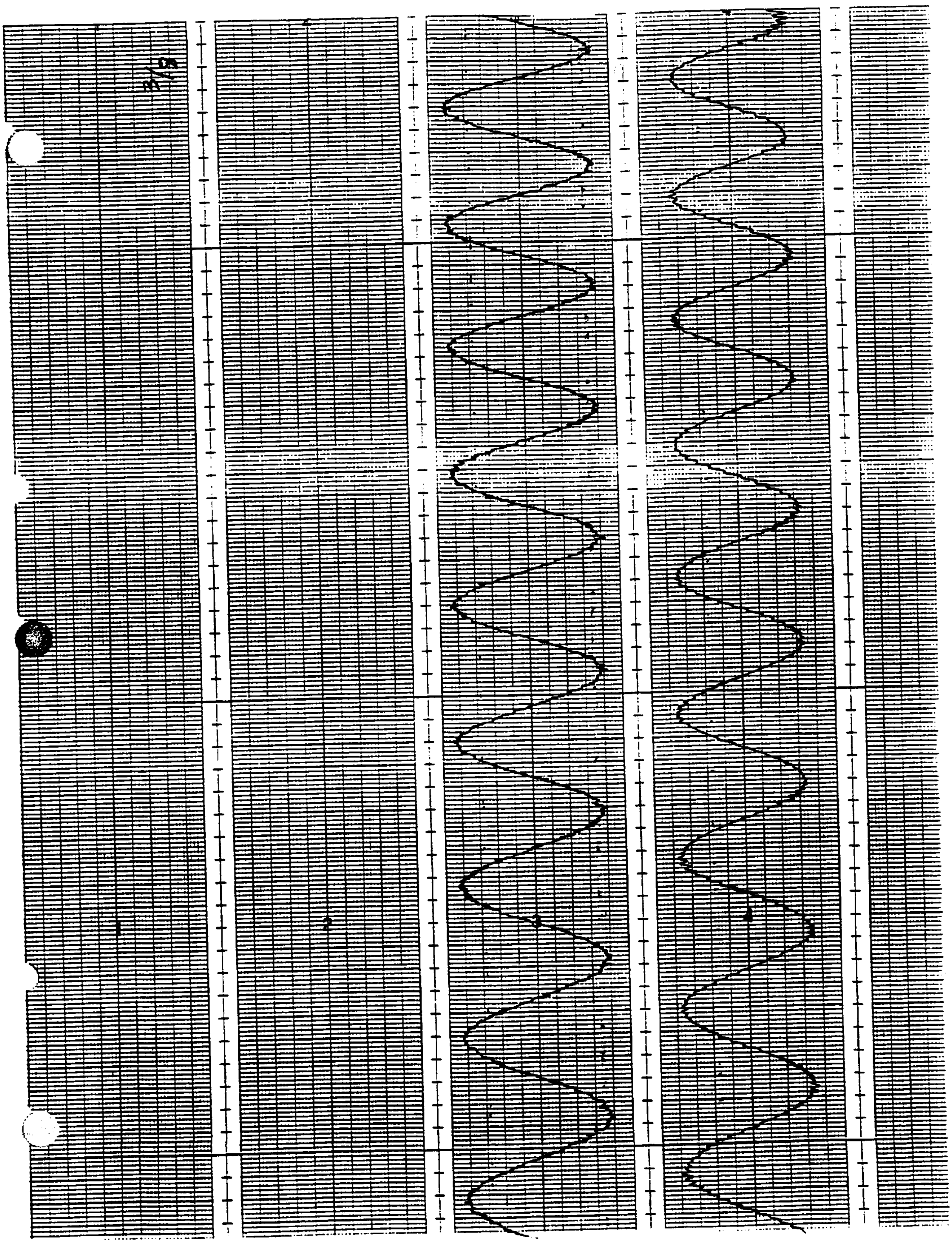
SECTION 6 – ACTUATOR NO-LOAD SINE SWEEP

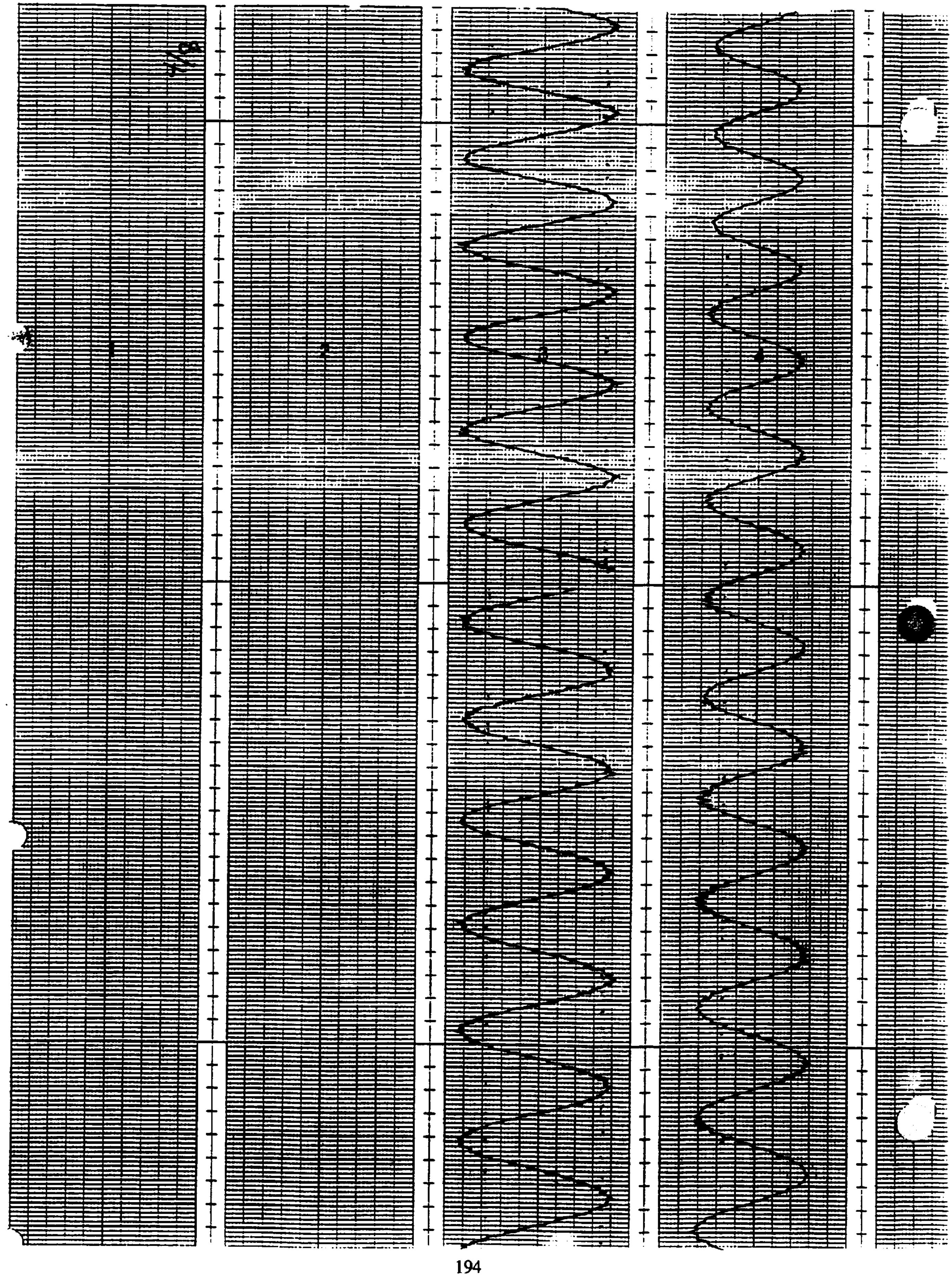
The no load test data was recorded under the following conditions:

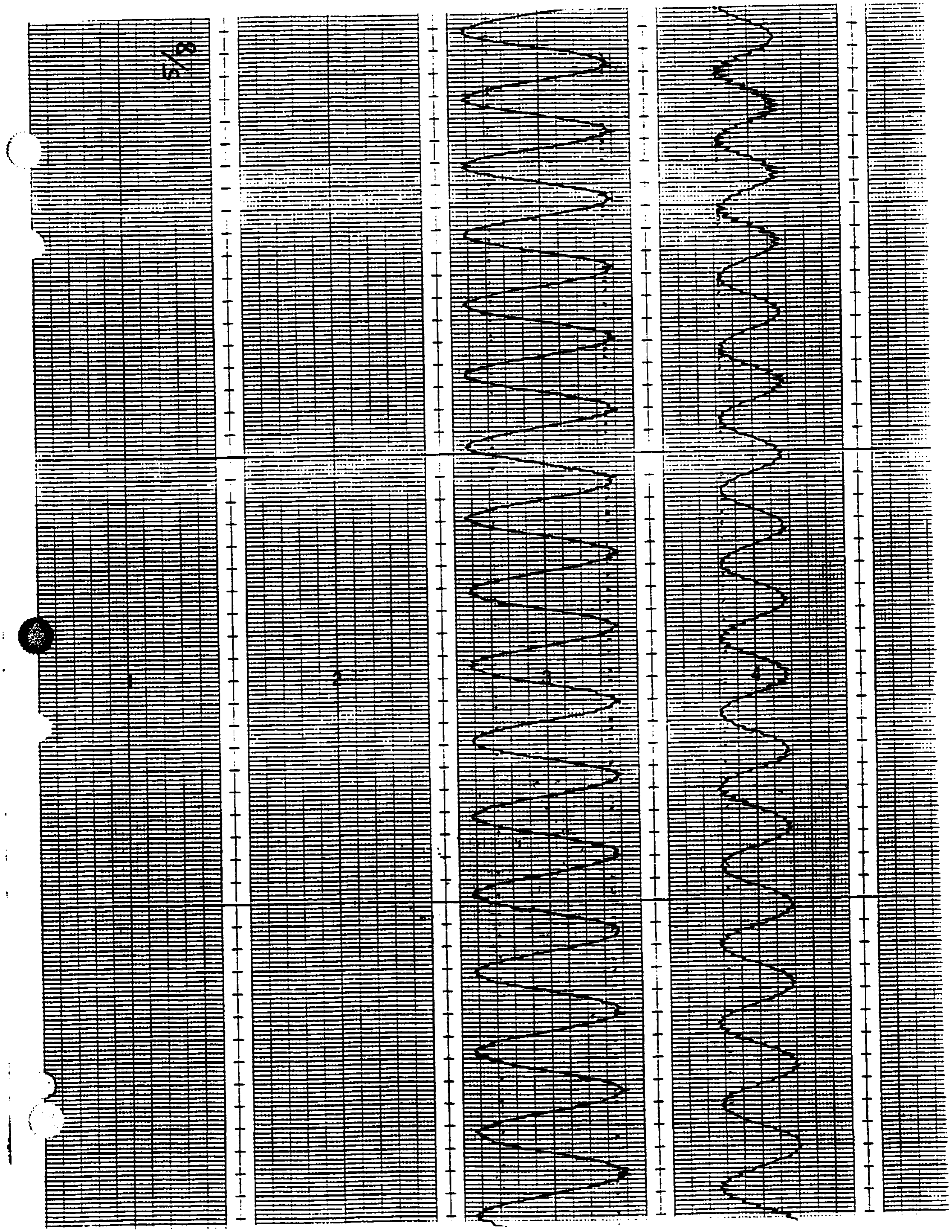
- Kp = 8.0, Ki = 0.1, and Kr = 35.0 unless otherwise noted.
- Command and Position scales are equal on the strip charts unless otherwise noted.

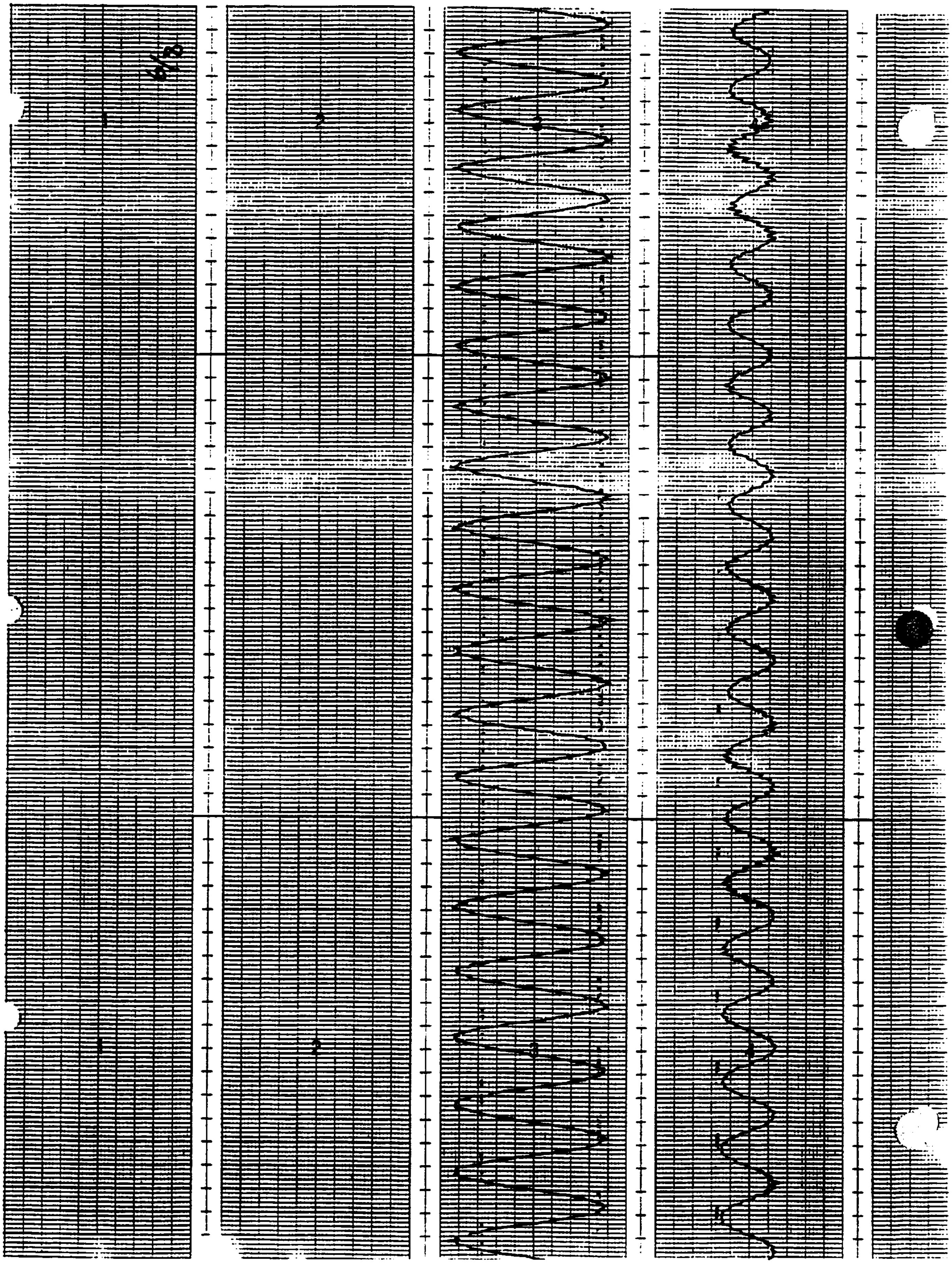


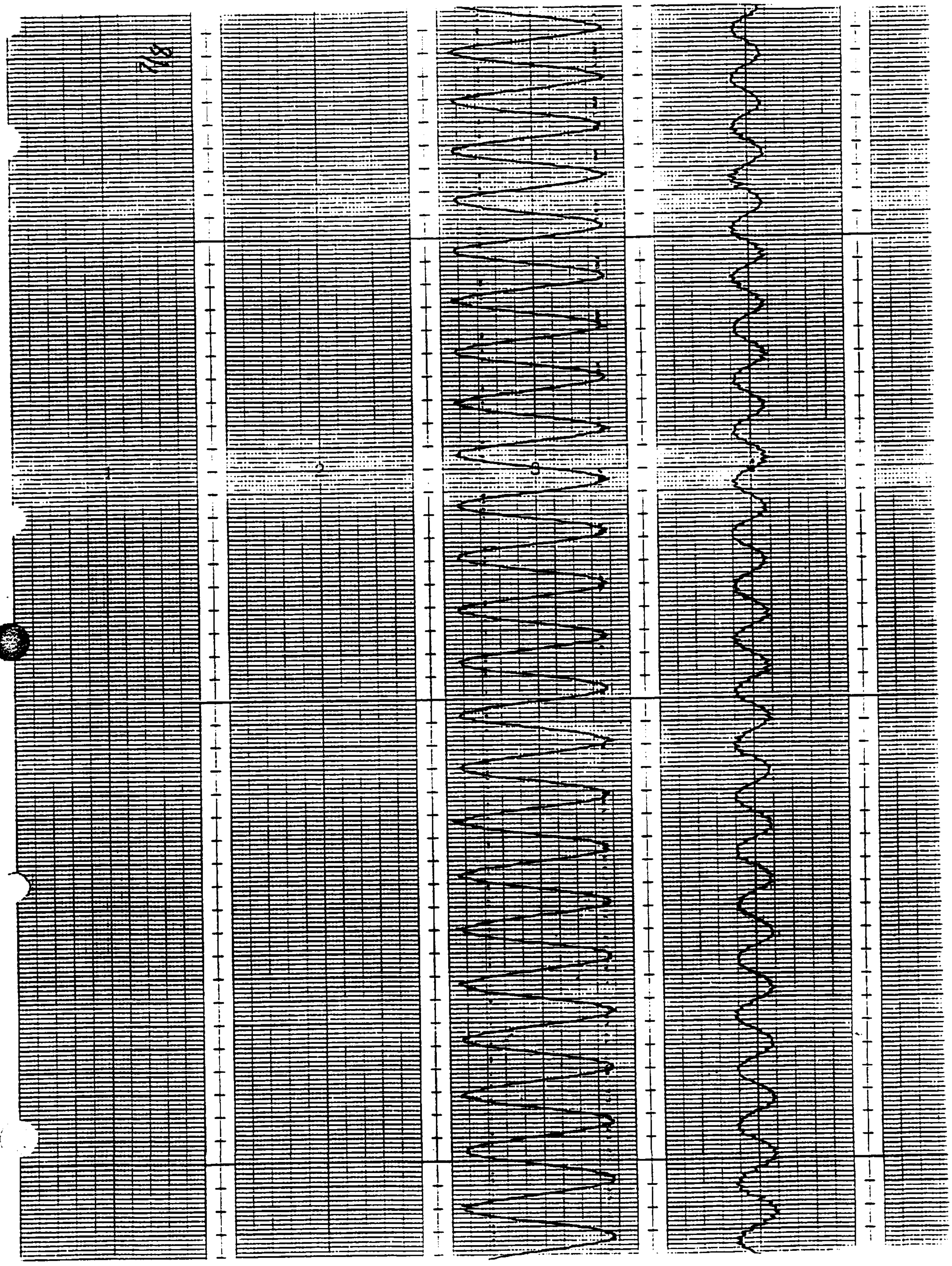


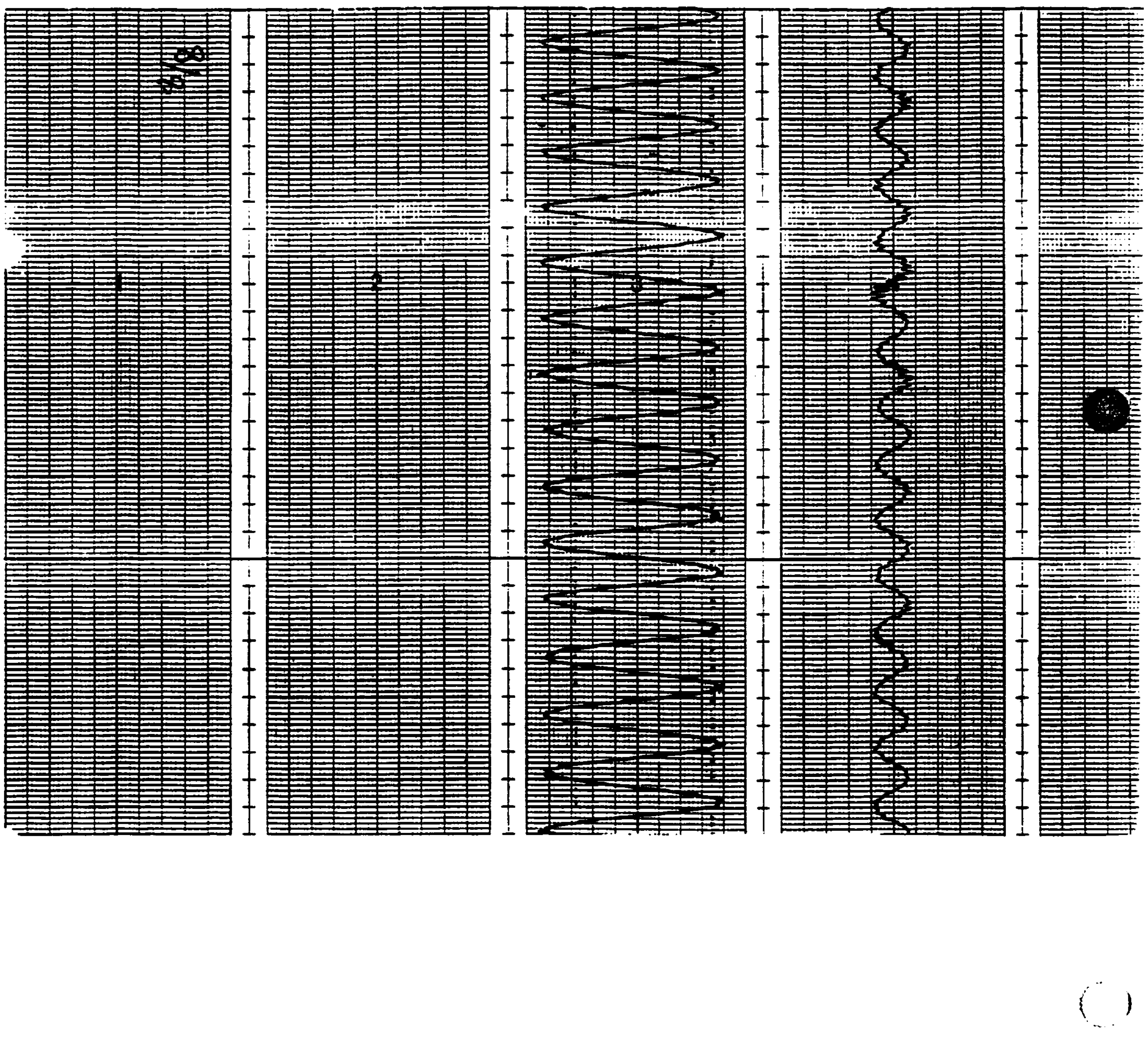


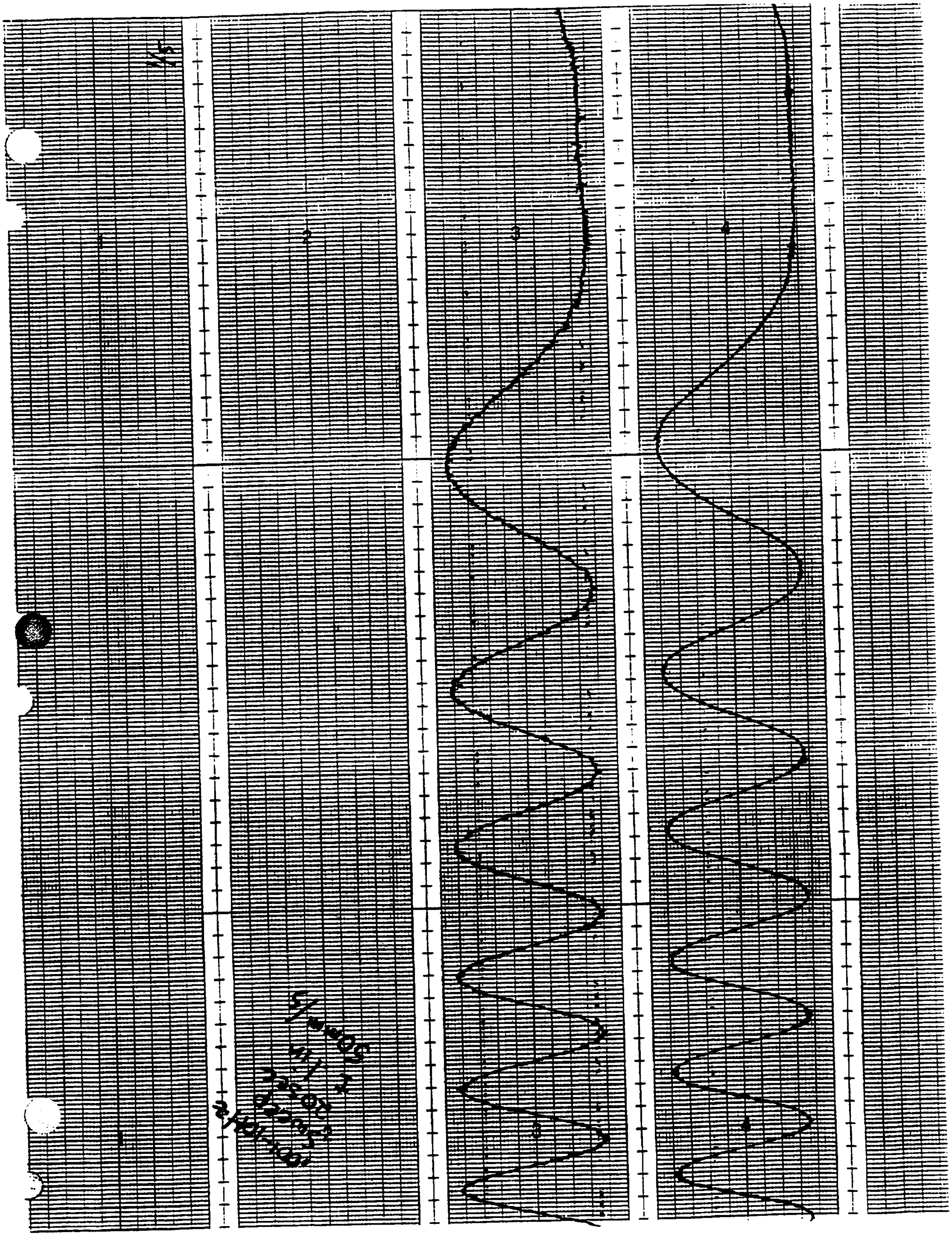


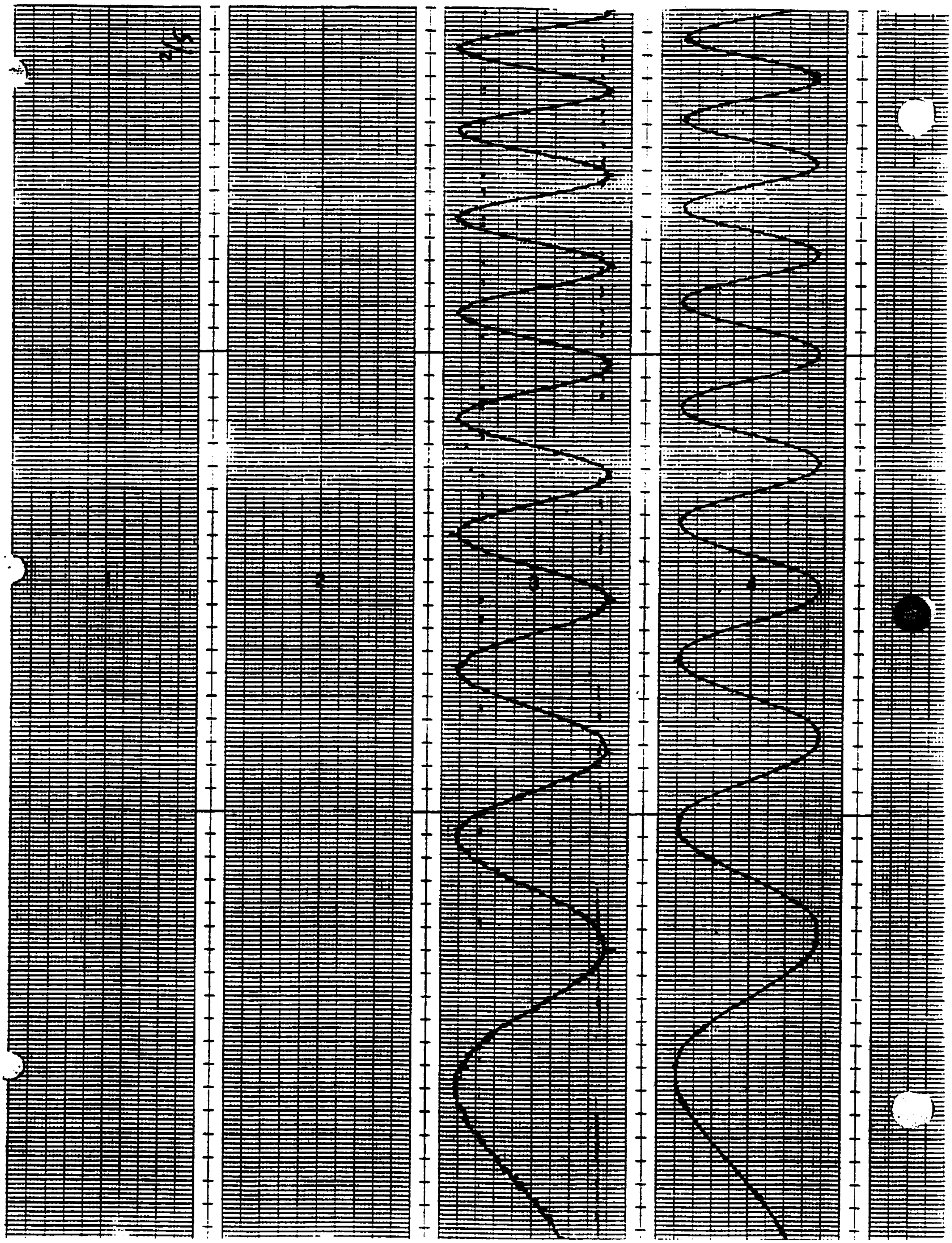


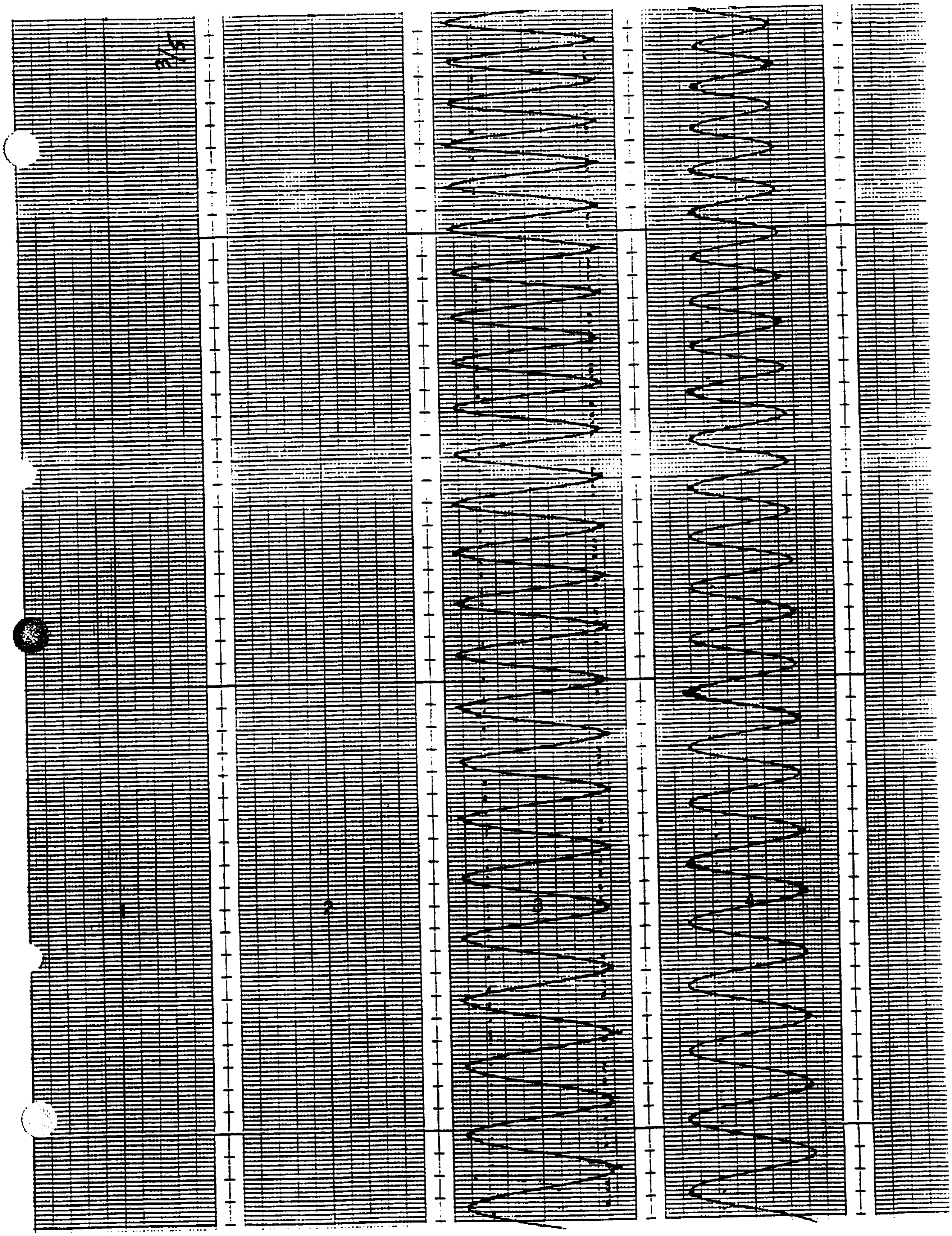


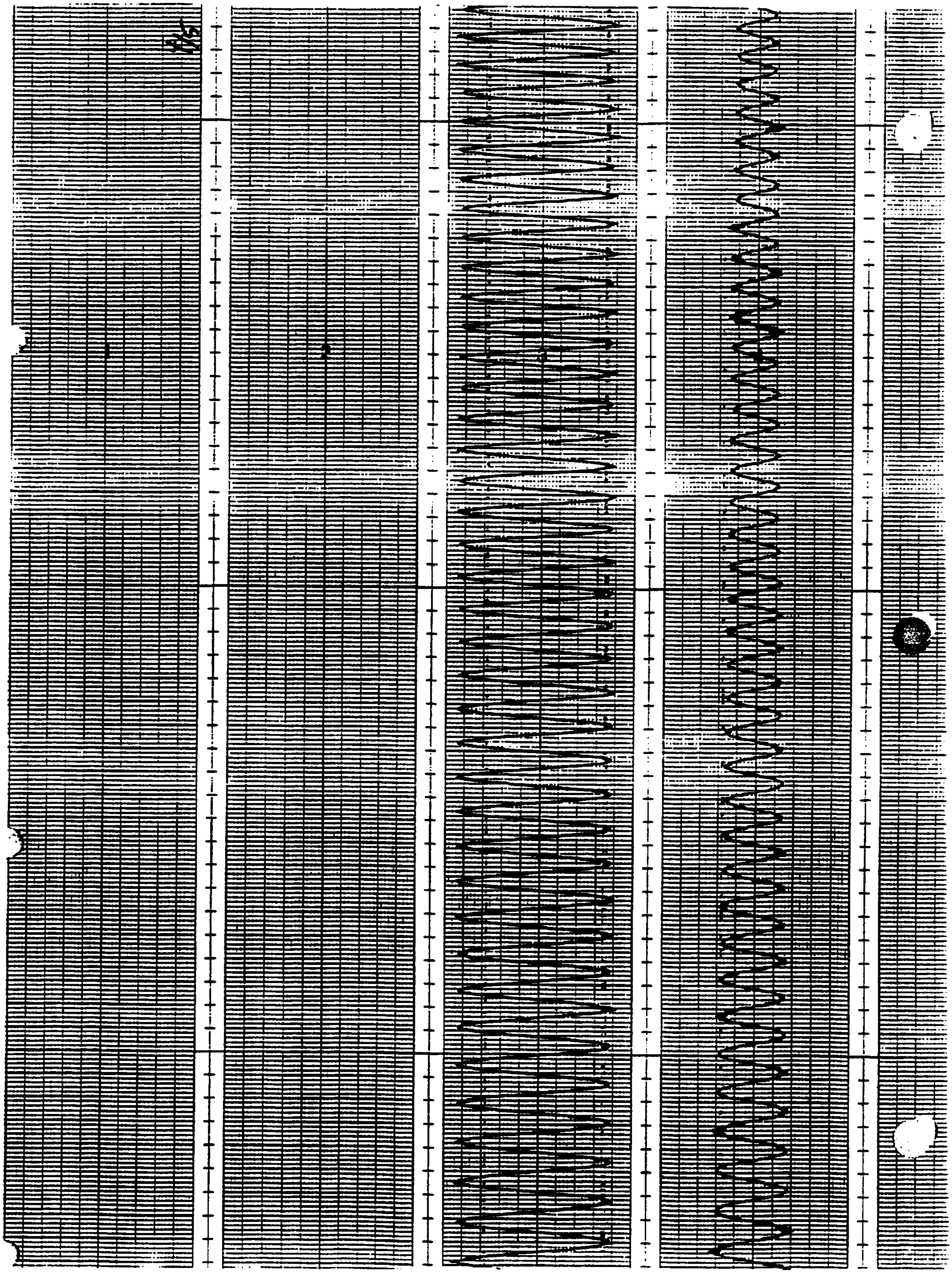


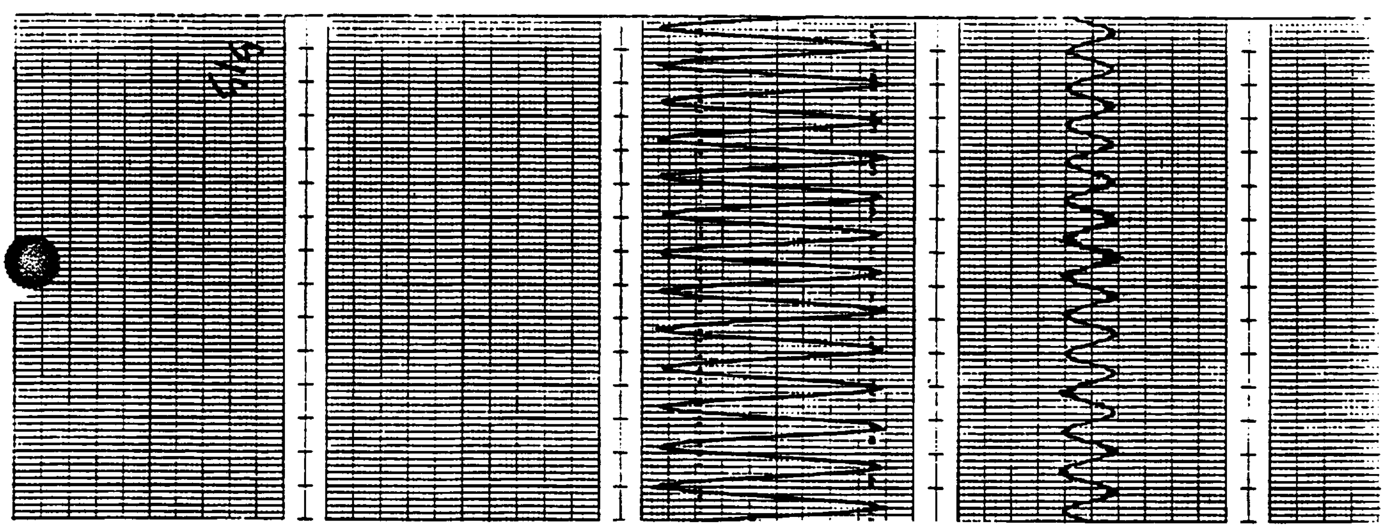


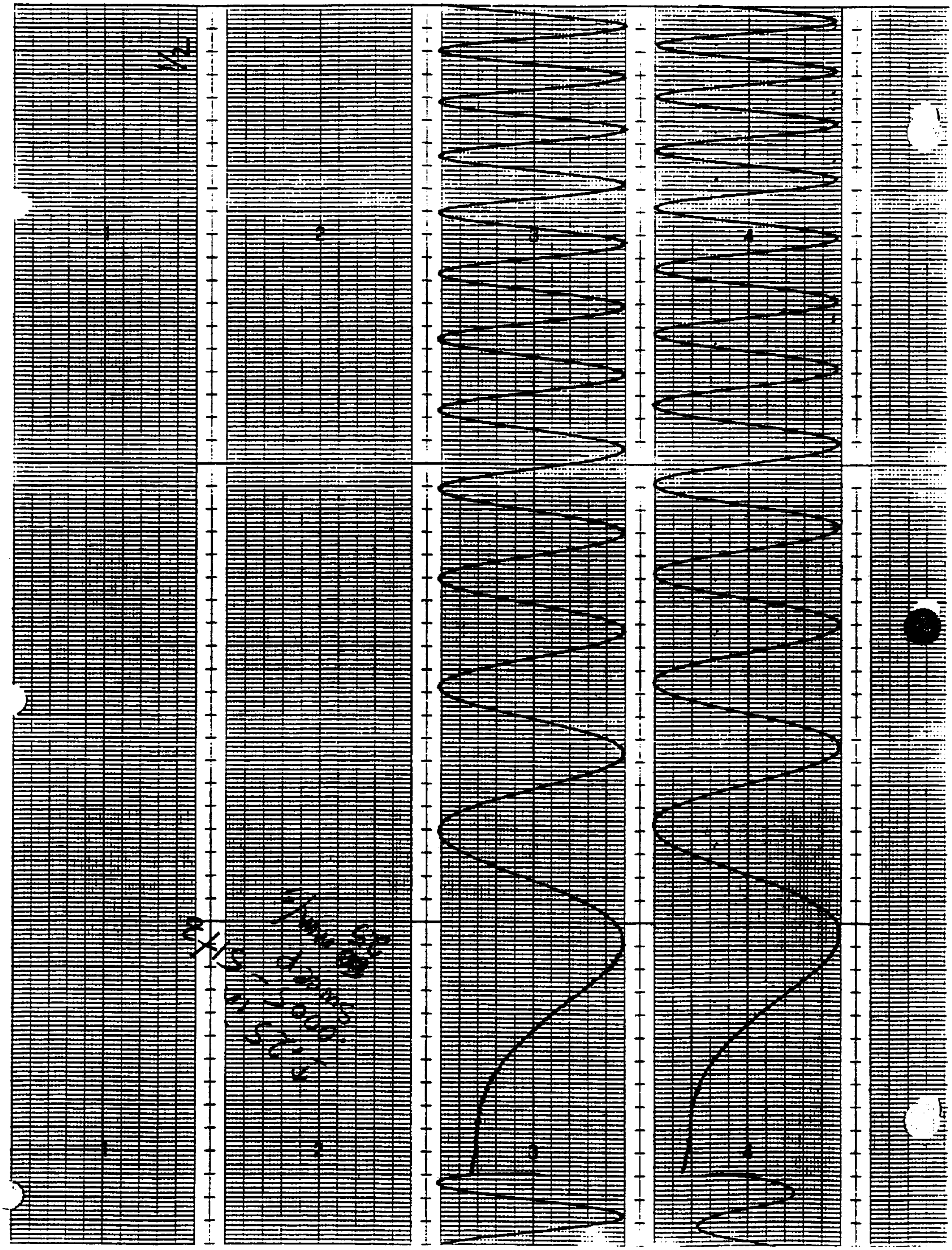


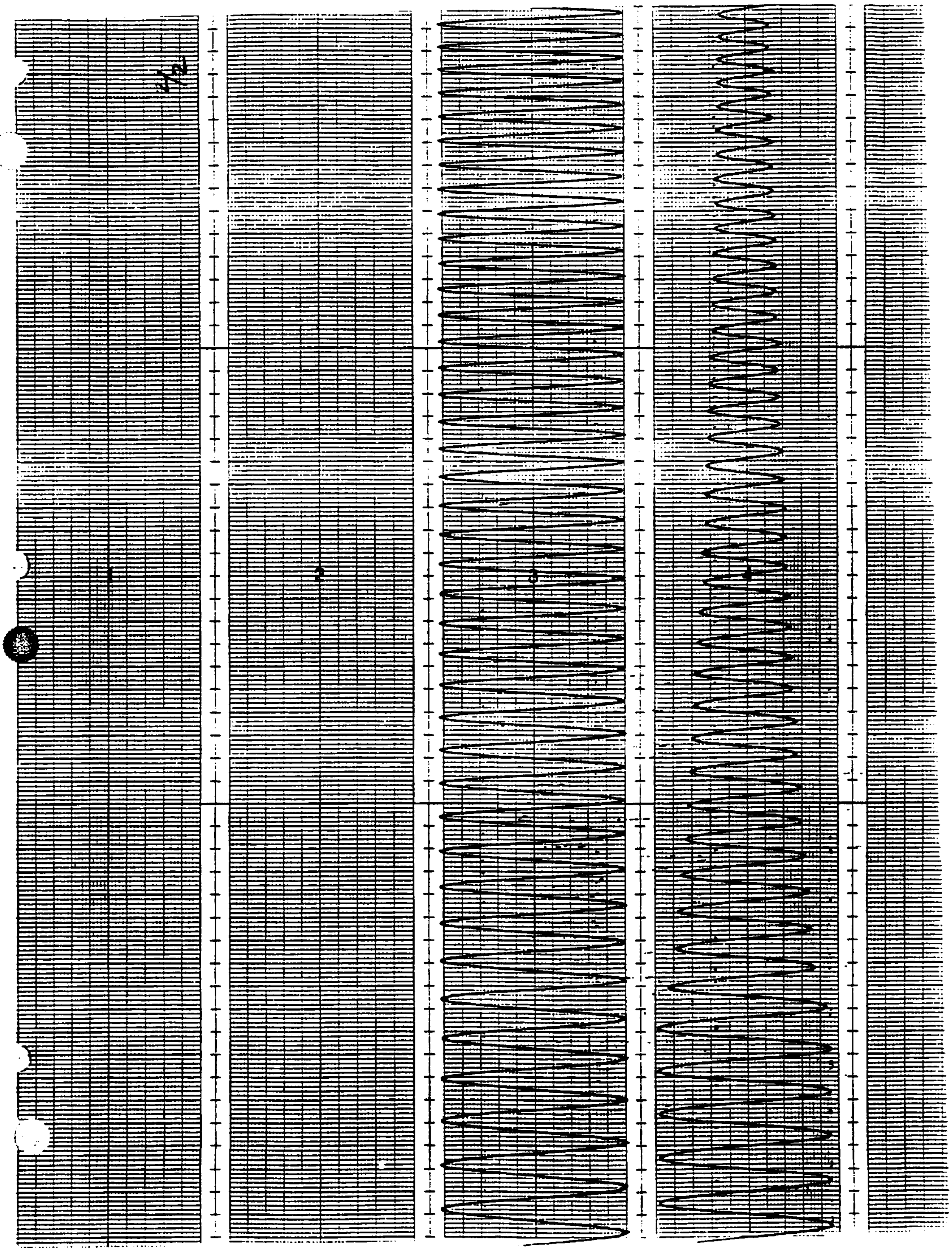


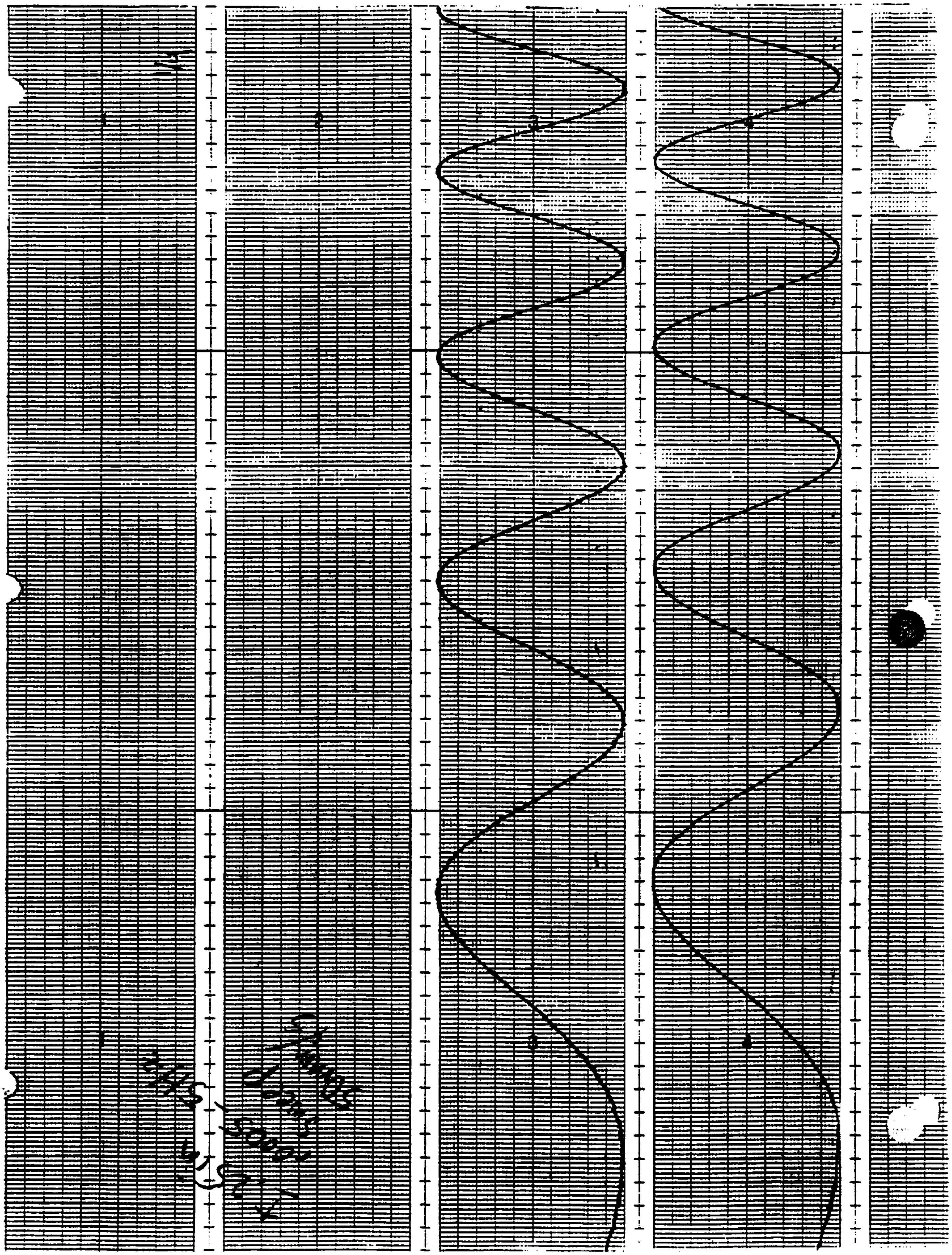


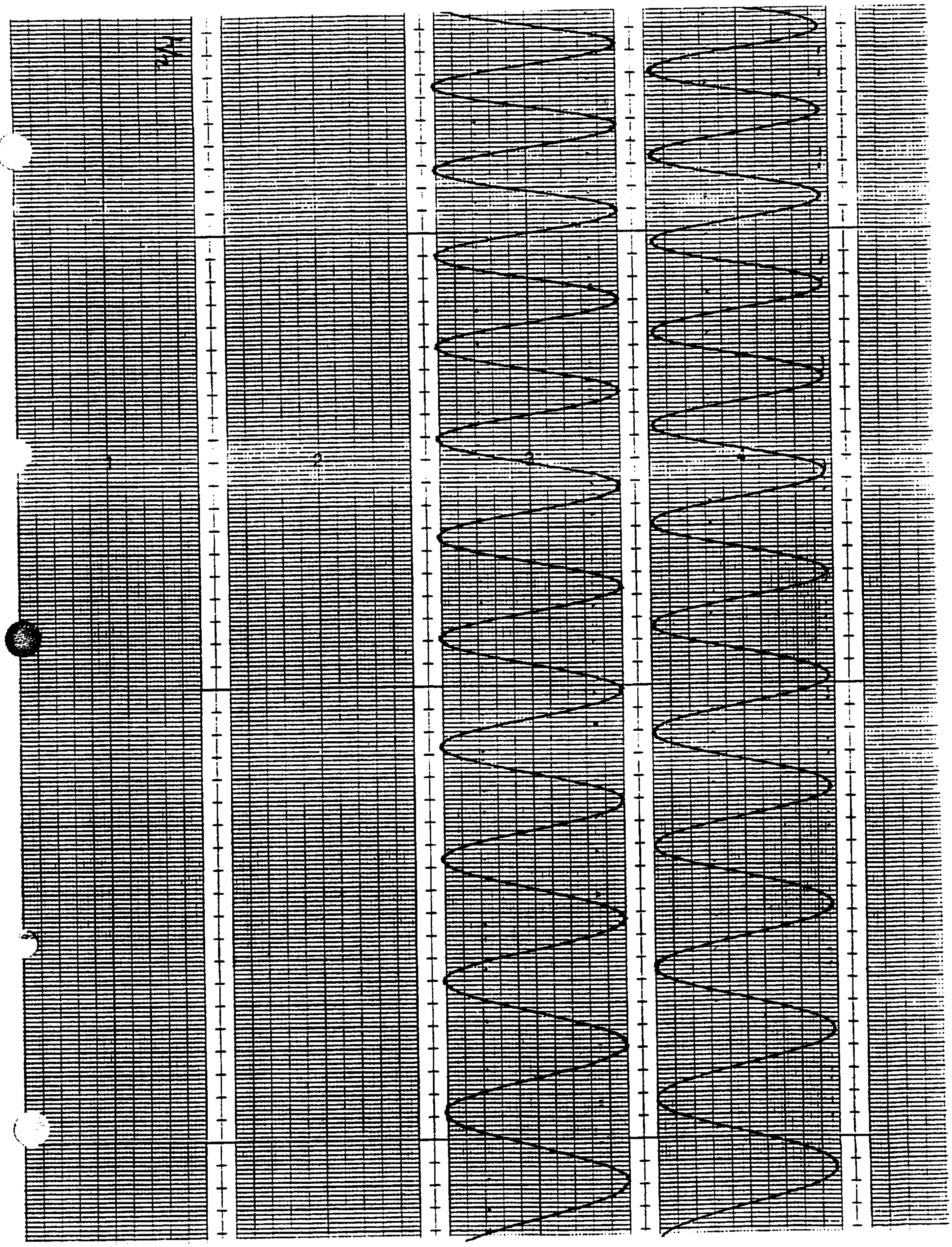


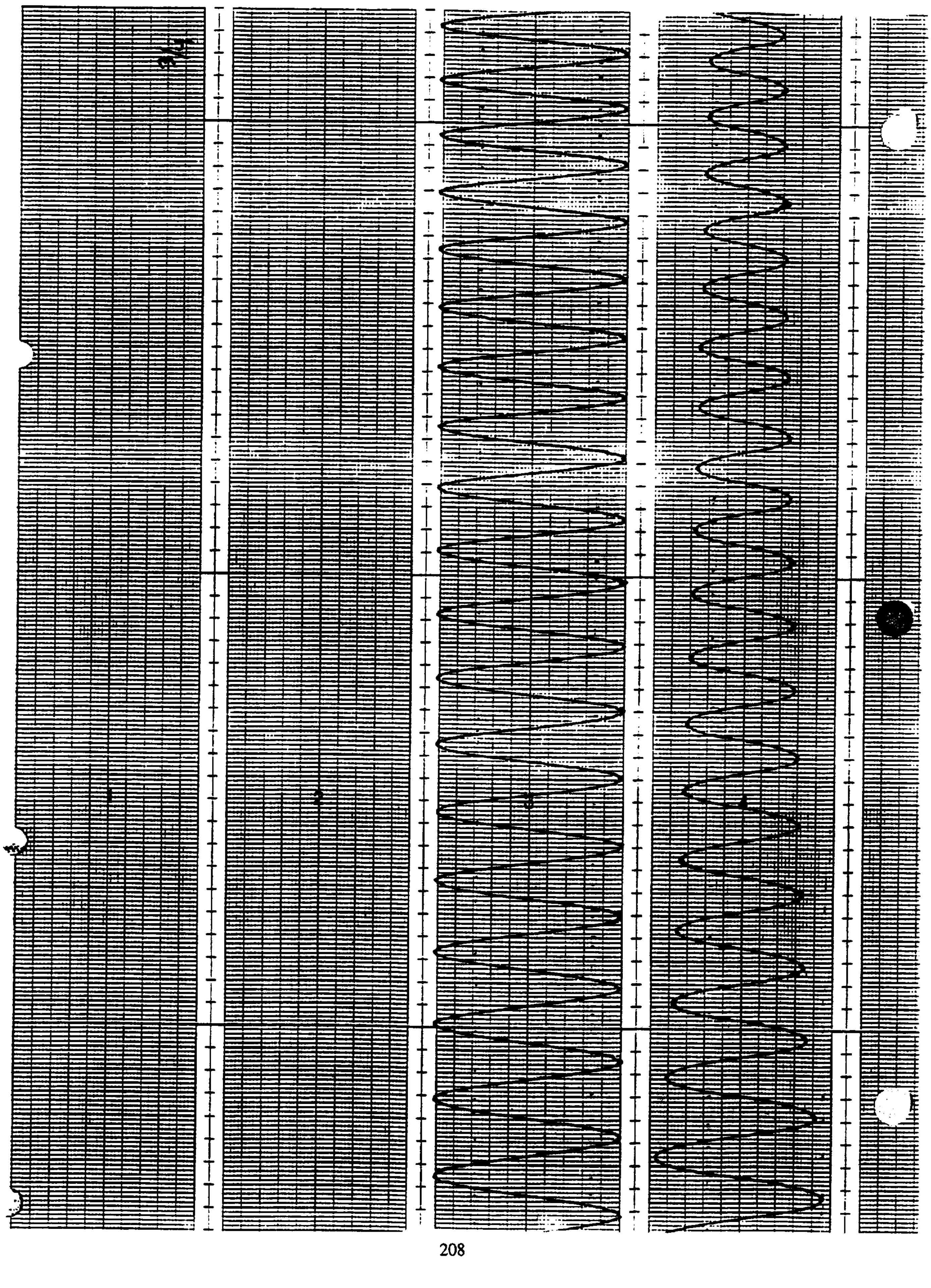


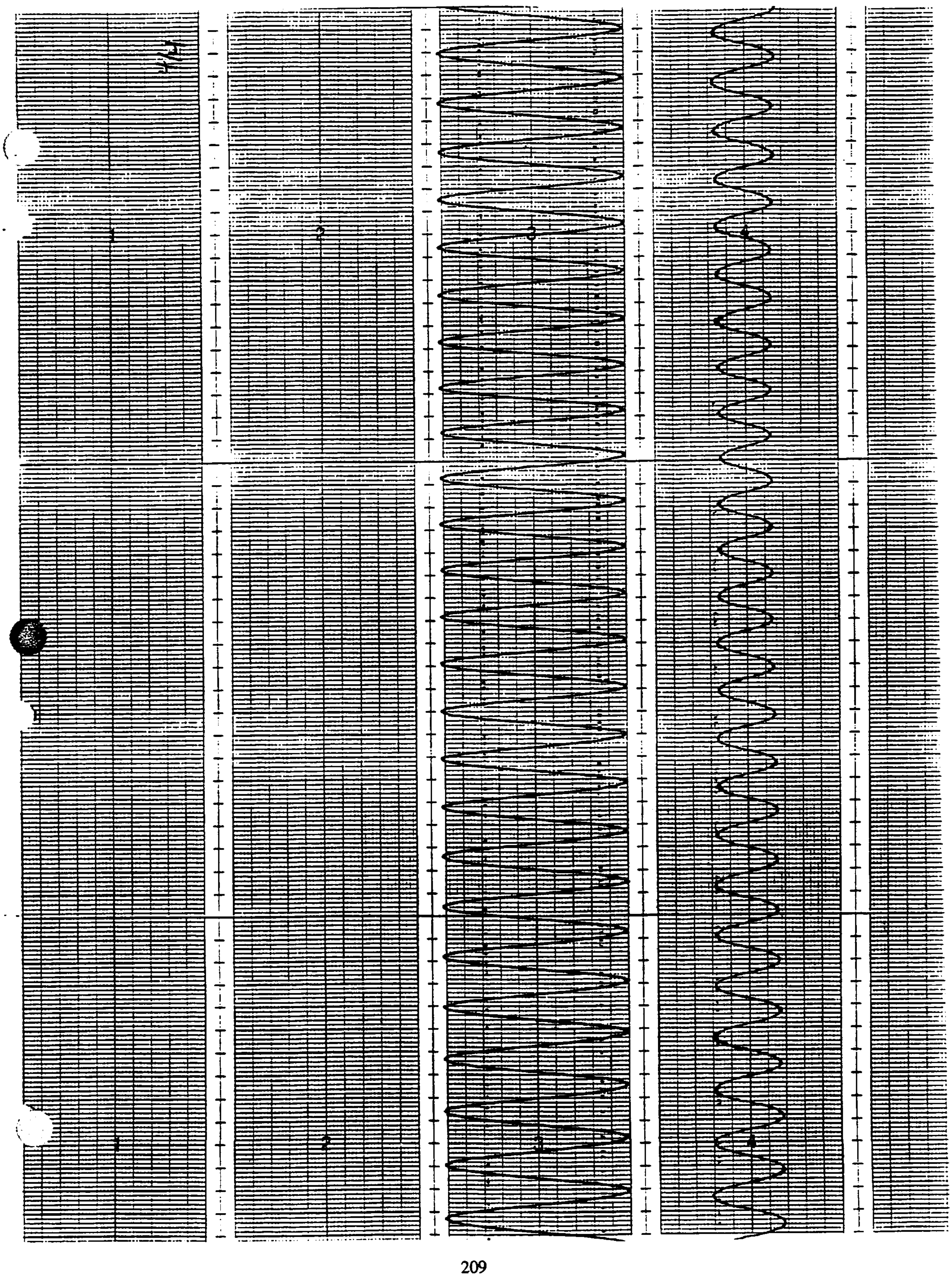


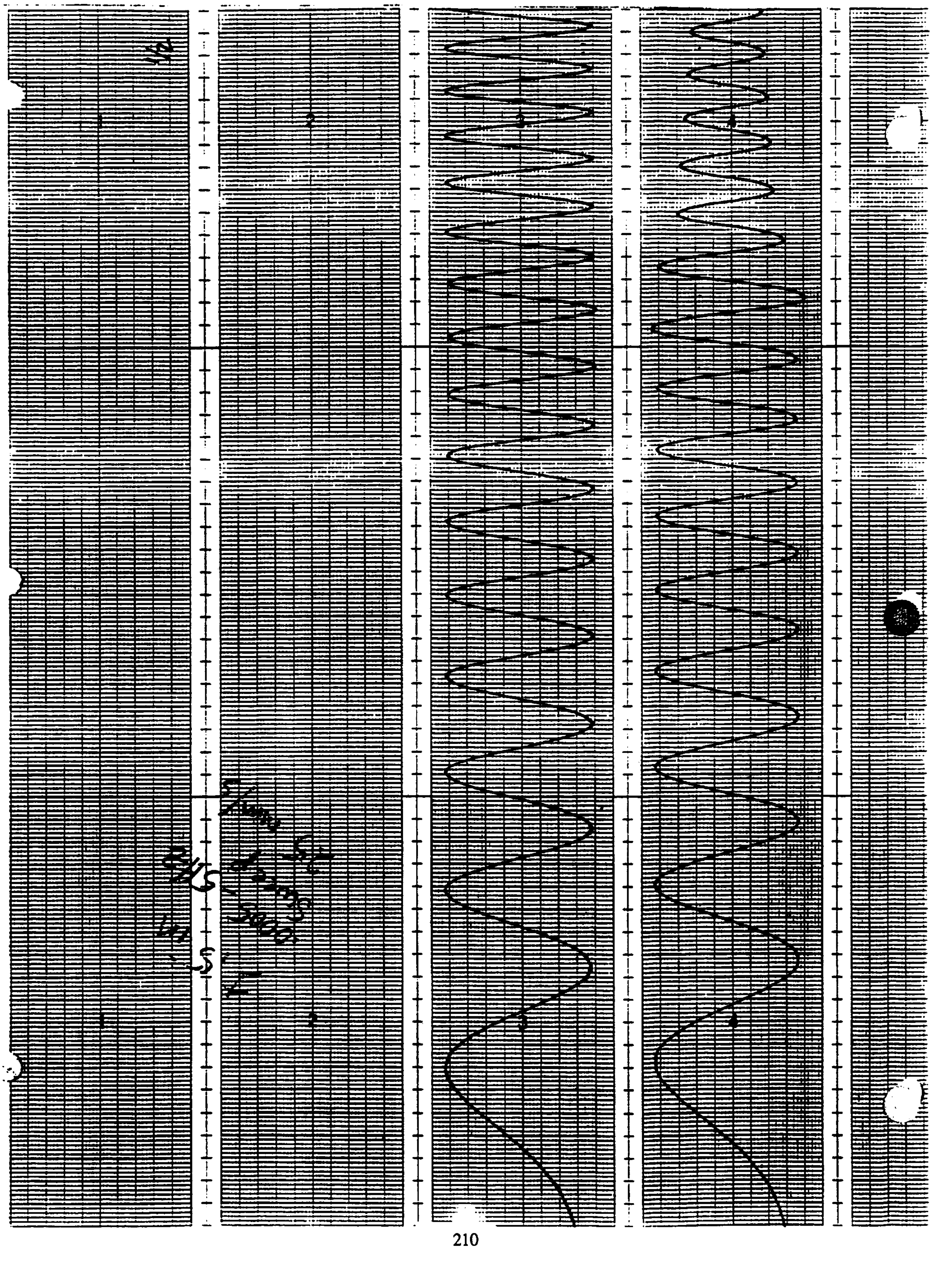


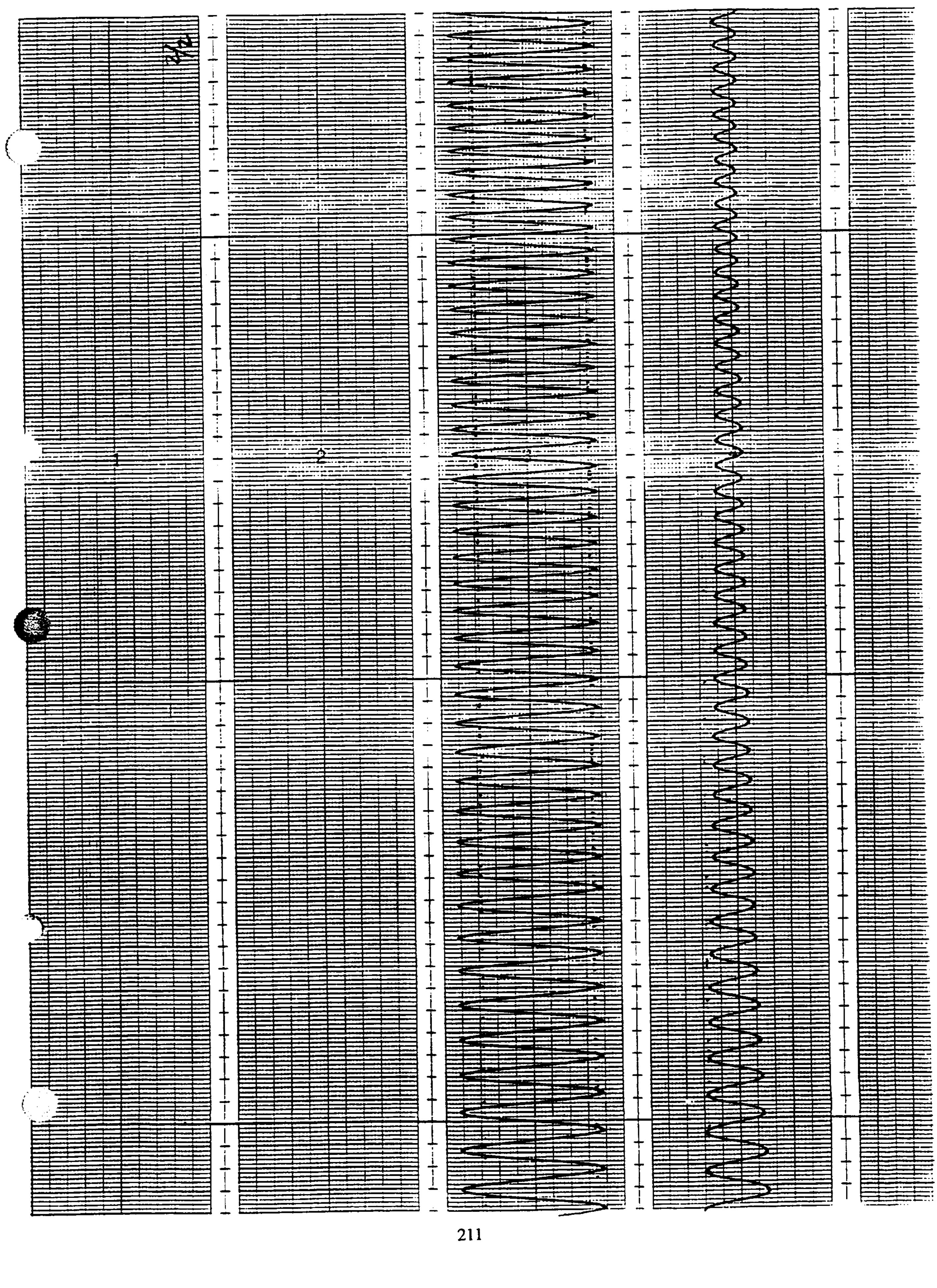












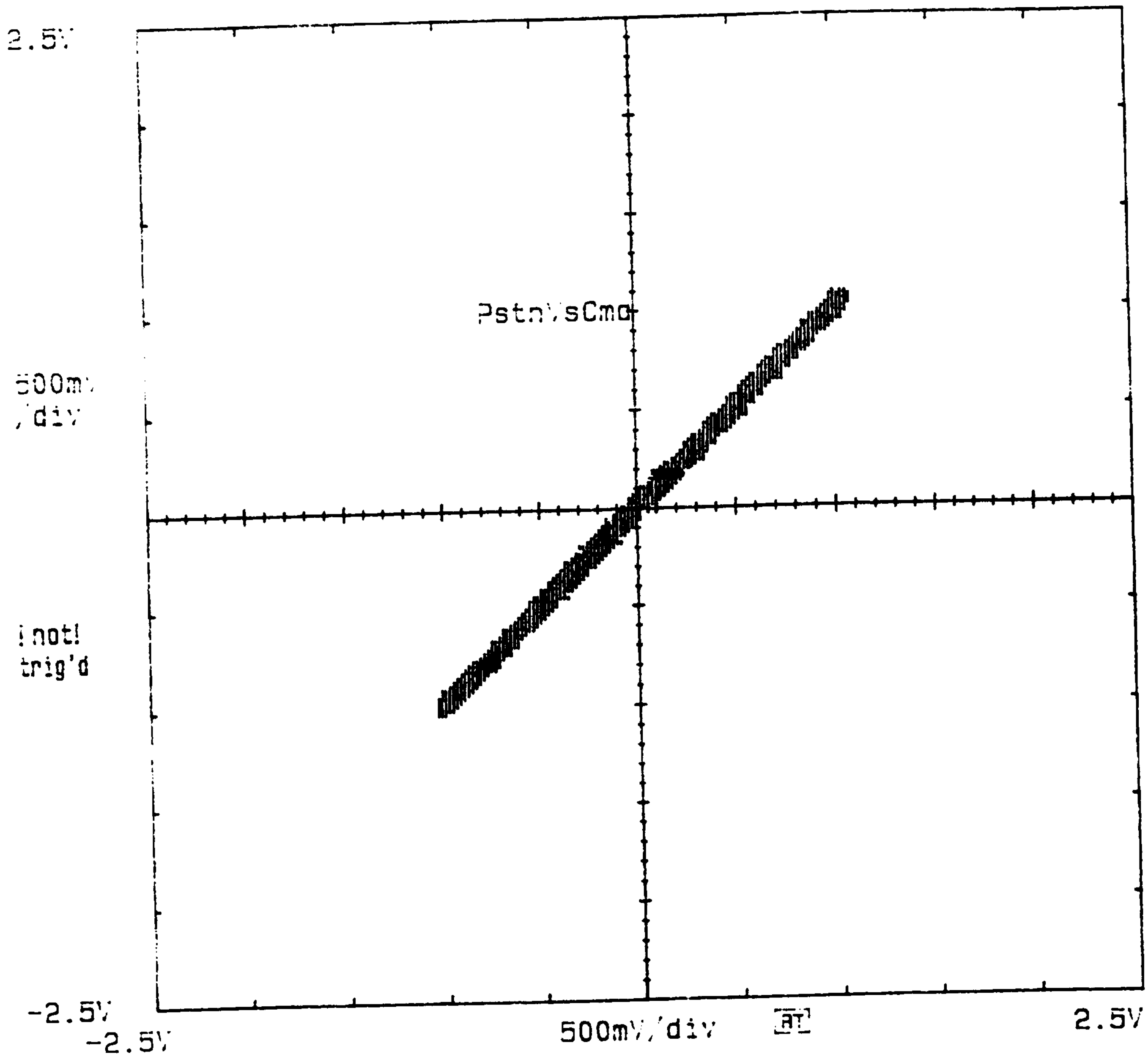
SECTION 7 – ACTUATOR NO-LOAD X-Y SINUSOIDAL PLOTS

The no load test data was recorded under the following conditions:

- Kp = 8.0, Ki = 0.1, and Kr = 35.0 unless otherwise noted.
- Command and Position scales are equal on the strip charts unless otherwise noted.

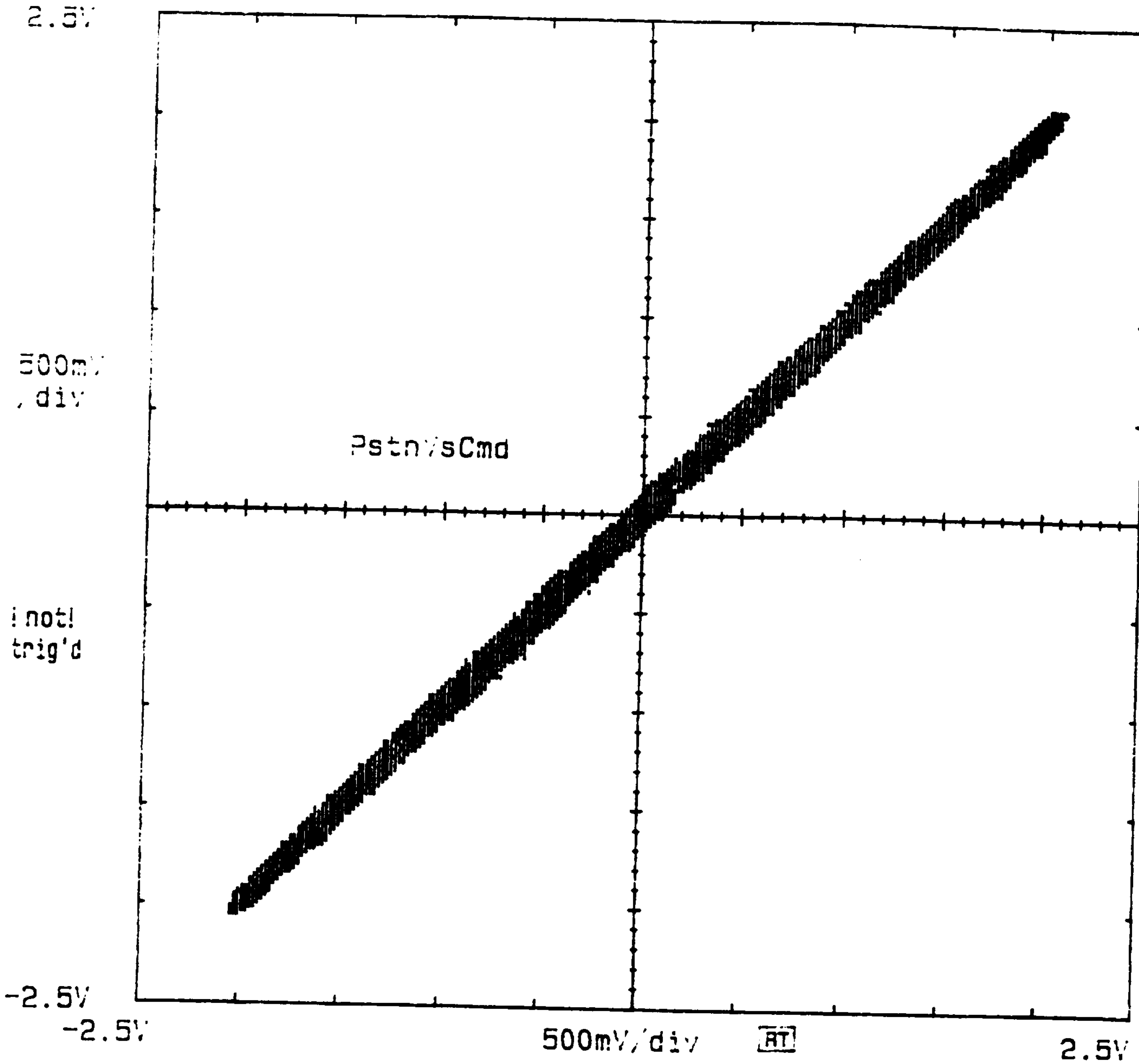
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 13:36:58

± 1" .05Hz
1 Volt/inch



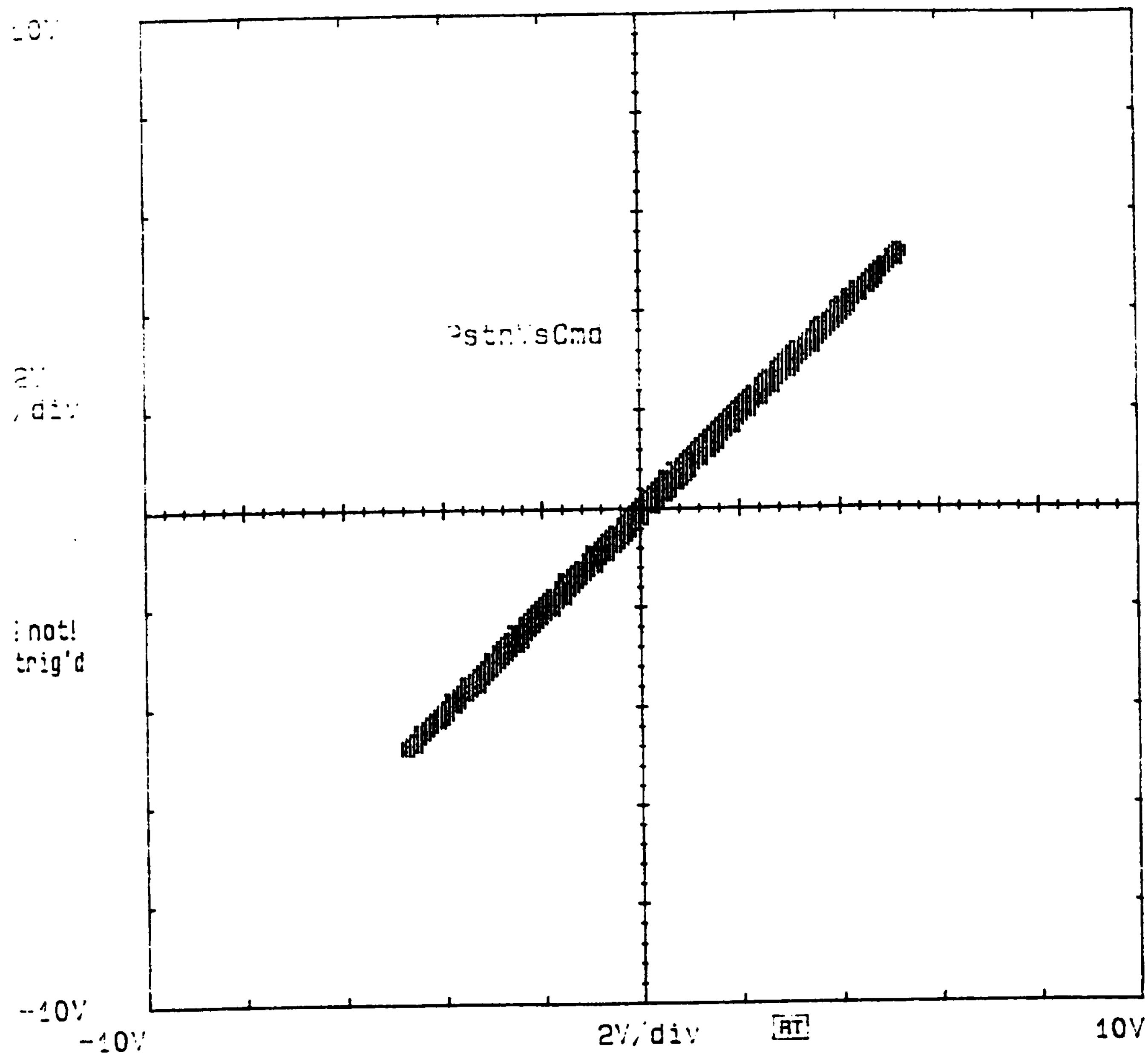
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 13:25:12

±2" .05 Hz
1 V/inch



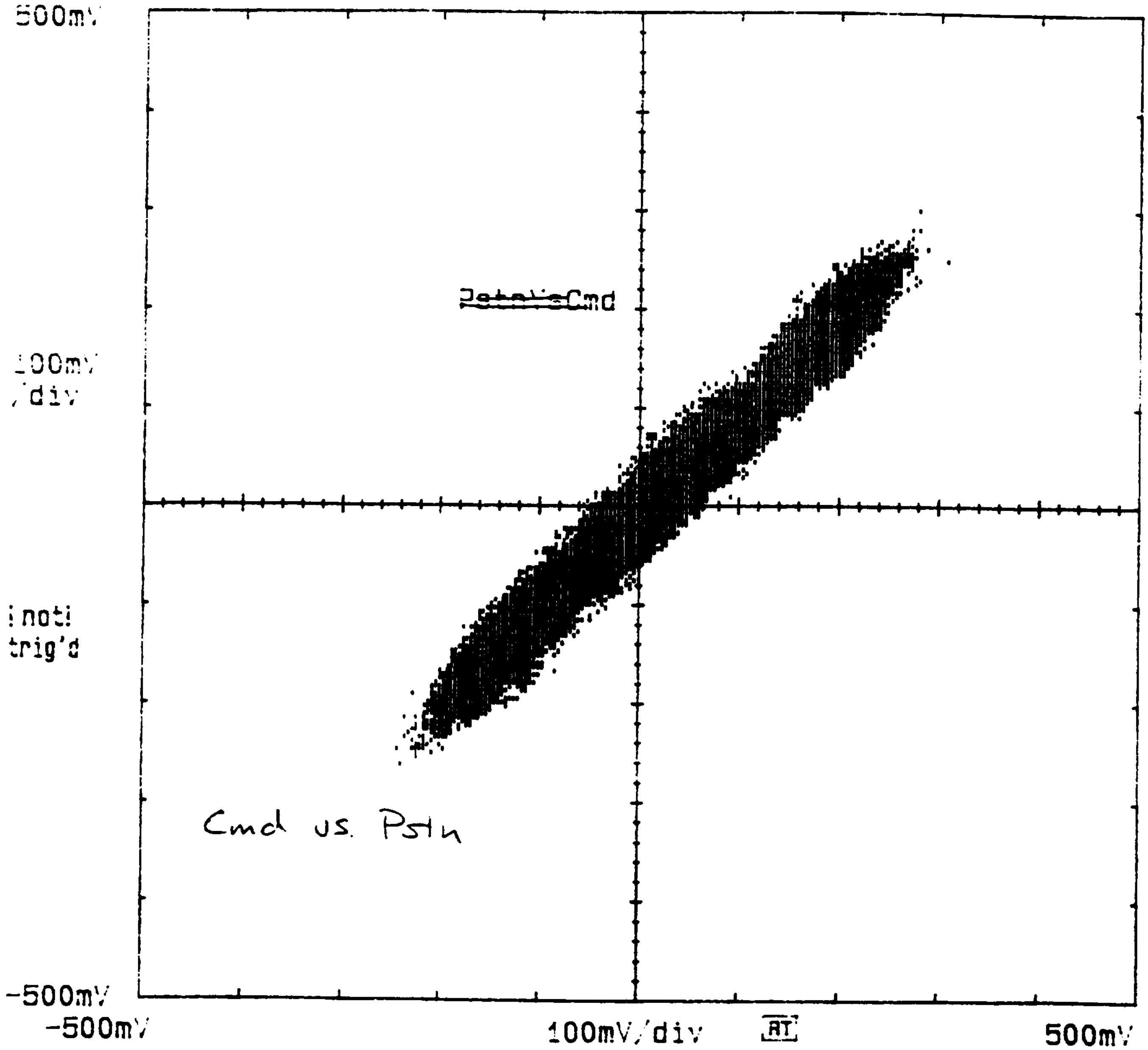
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 13:42:50

±5" .05Hz
1V/inch



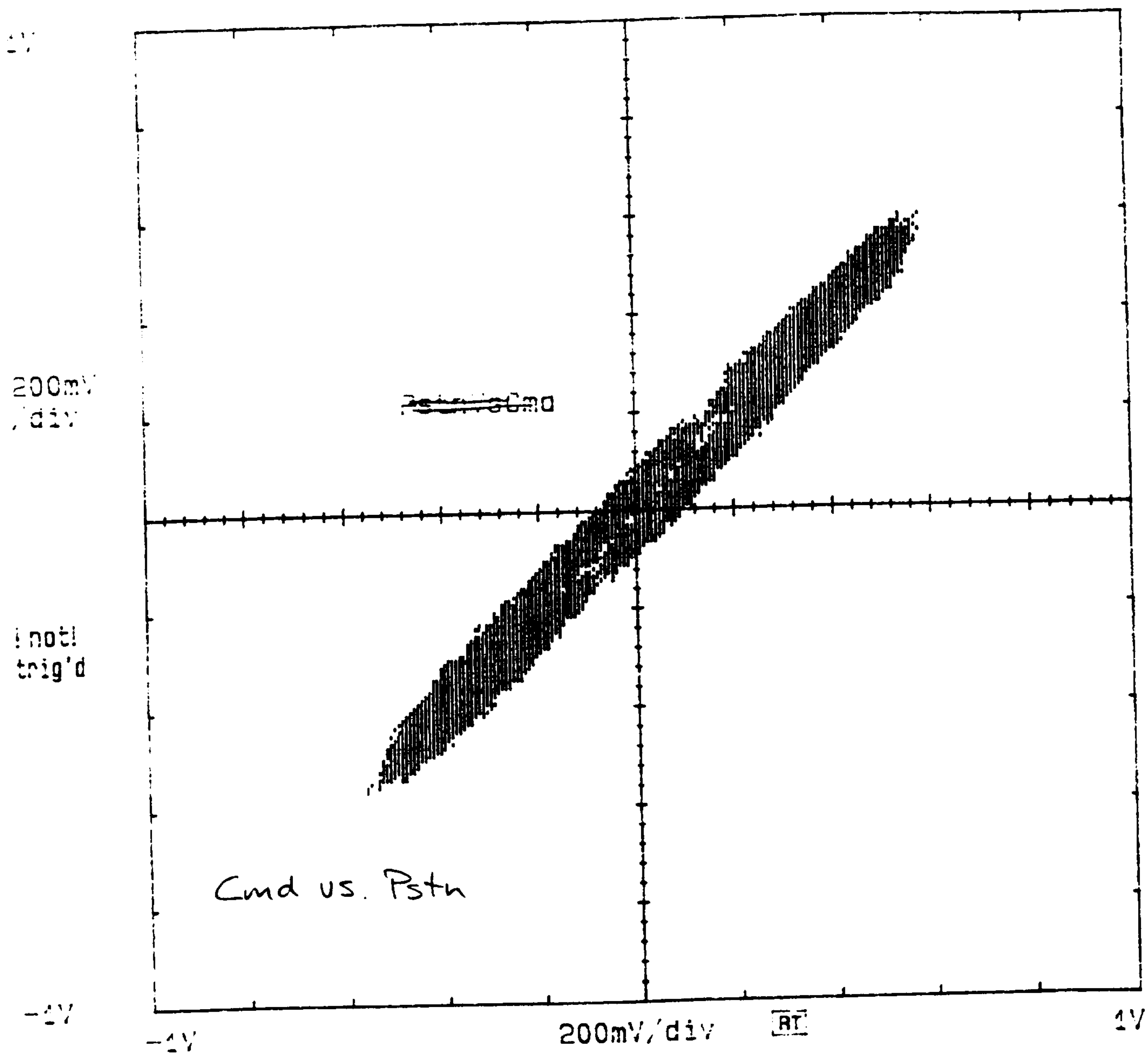
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 14:53:45

.25 Hz
± .1 in
2V/inch



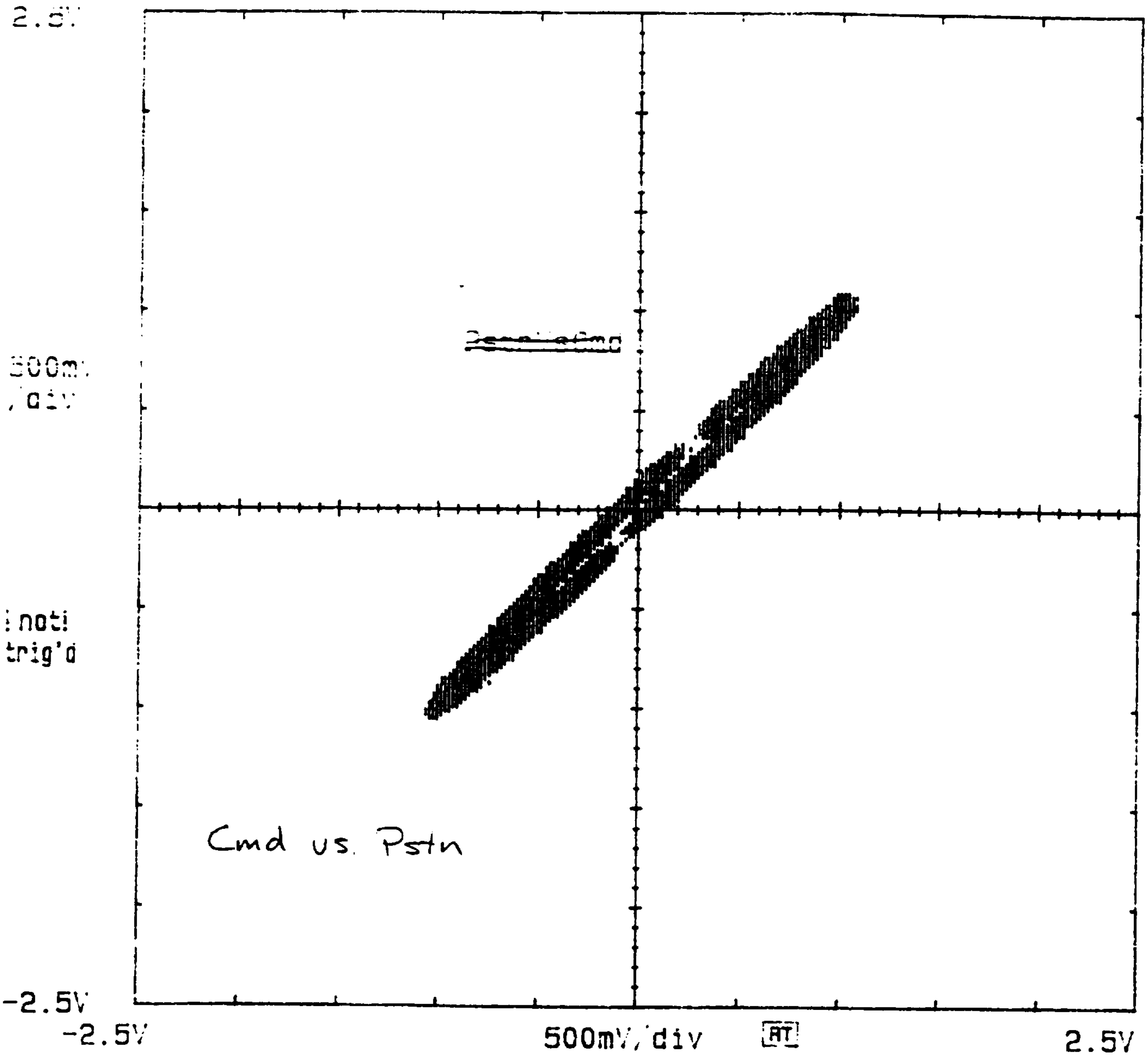
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 15:18:54

.25 Hz
I .25 in
2V/in



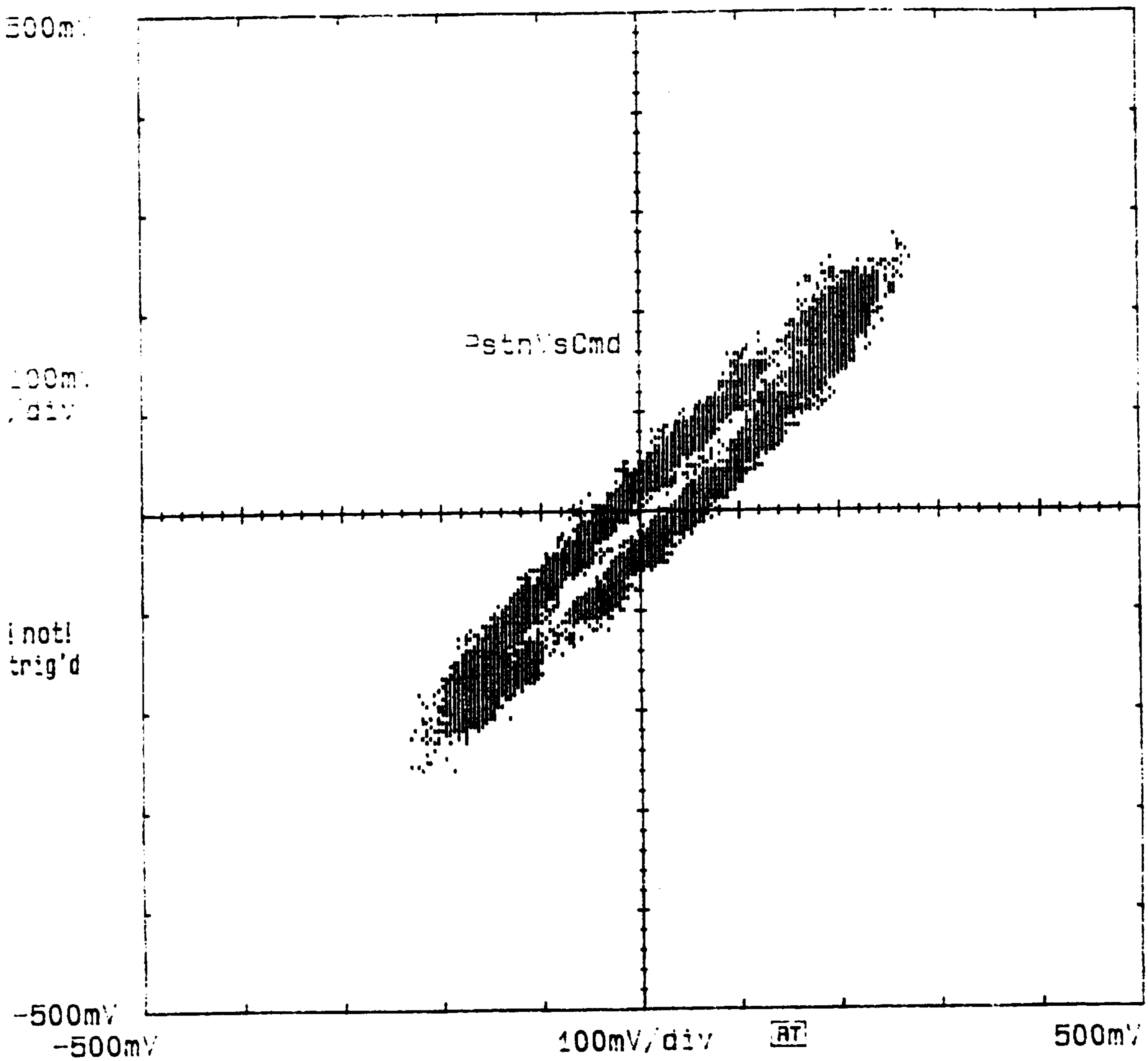
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 15:33:13

.25 Hz
±.5in
2V/in



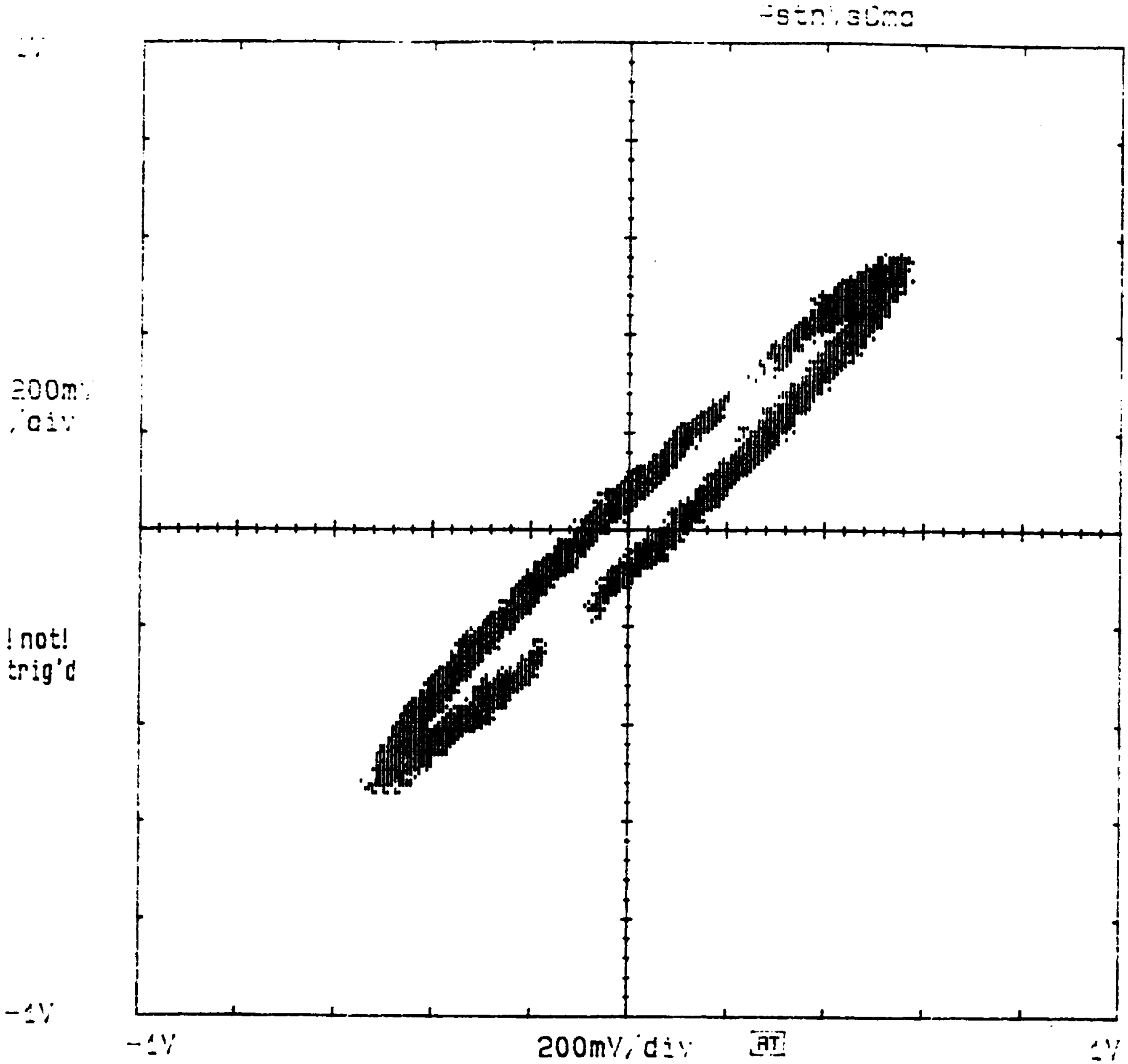
± .1"in
.5 Hz
2V/in

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 15: 45: 17



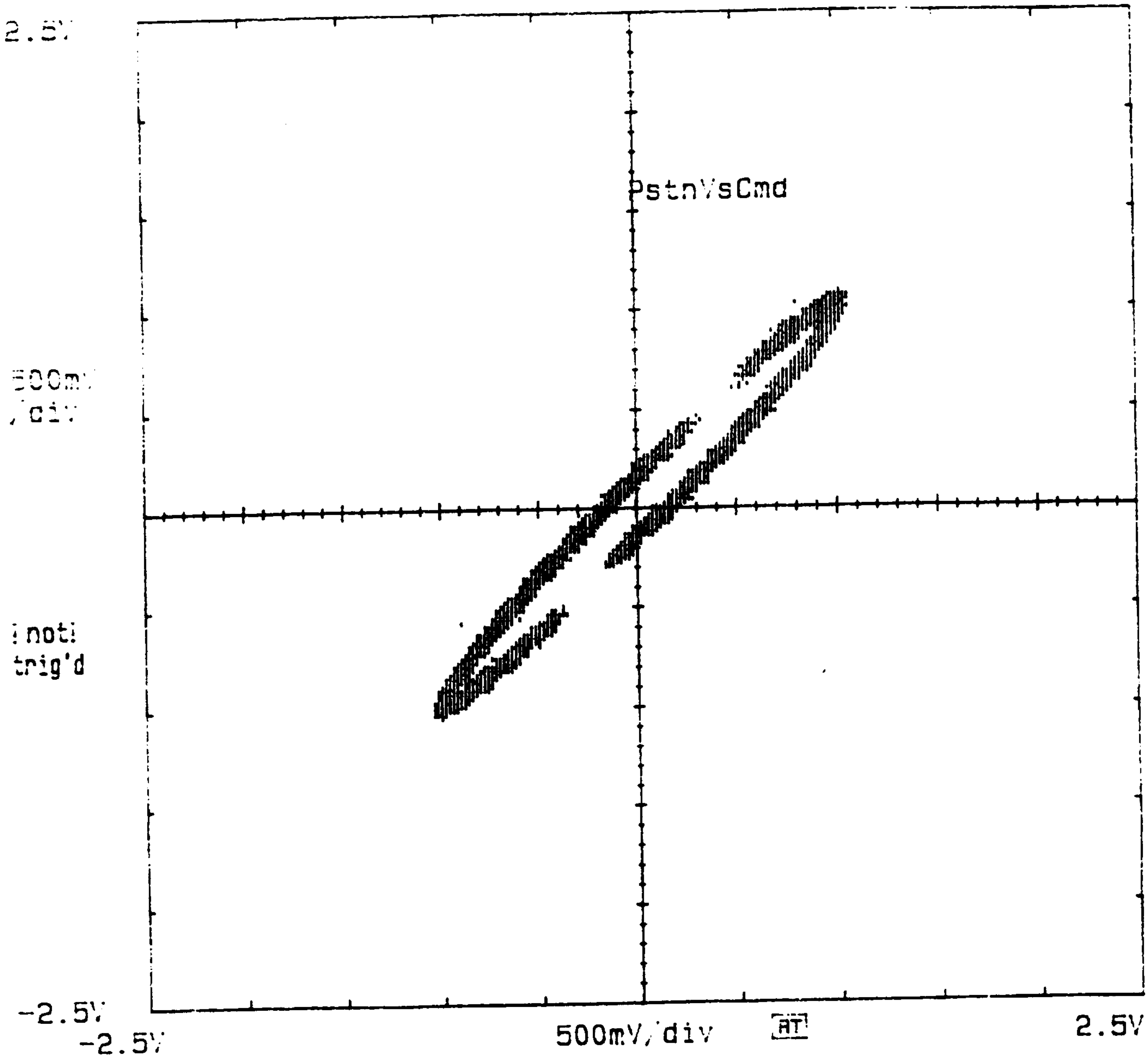
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 16:13:55

±.25in .5Hz
2V/inch



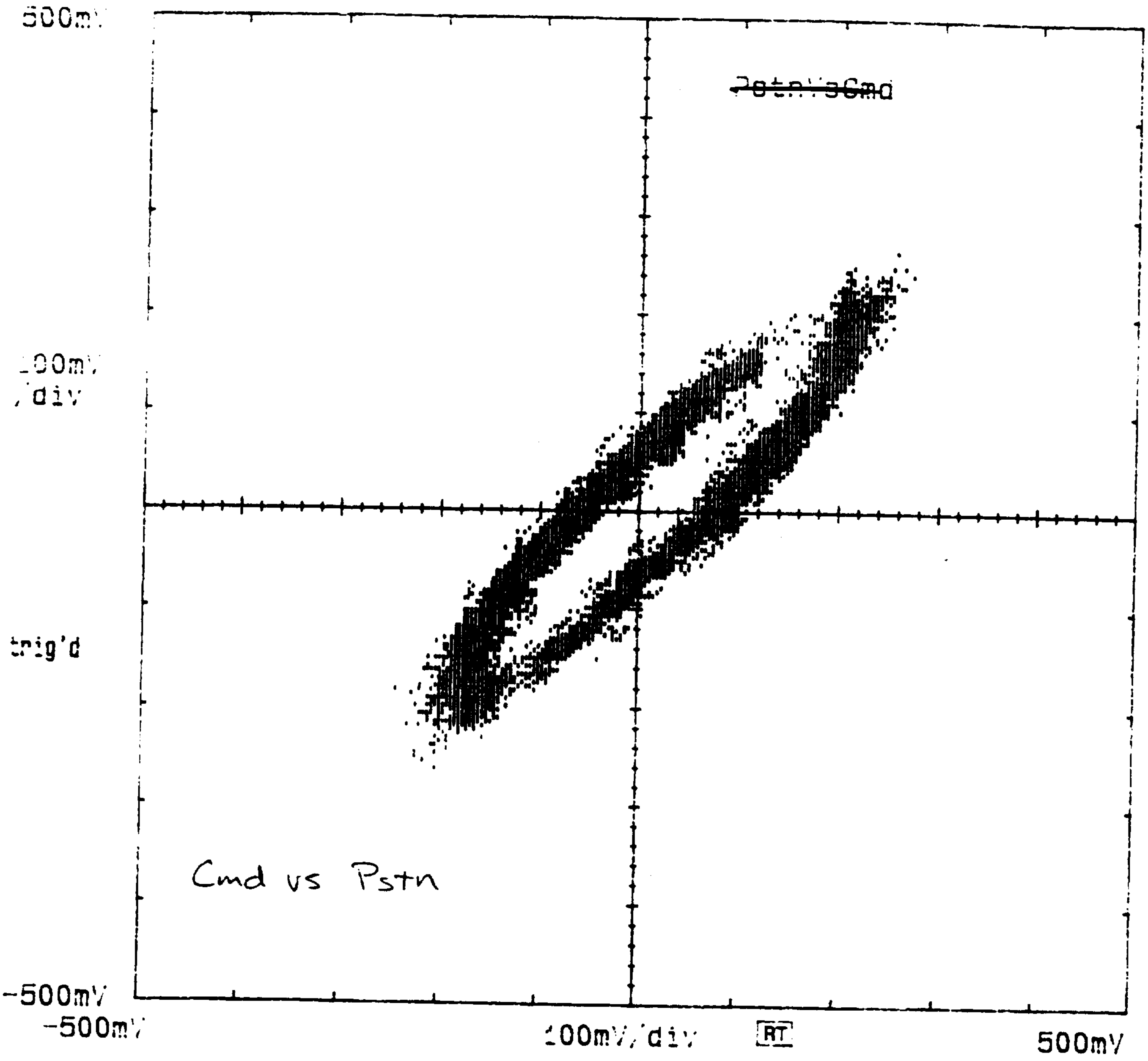
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 31-MAR-94 time: 16:26:55

±.5 in
.5 Hz
2 V/inch



DSA 602 DIGITIZING SIGNAL ANALYZER
date: 1-APR-94 time: 8: 10: 42

≡ .1 in
1Hz
2V/in



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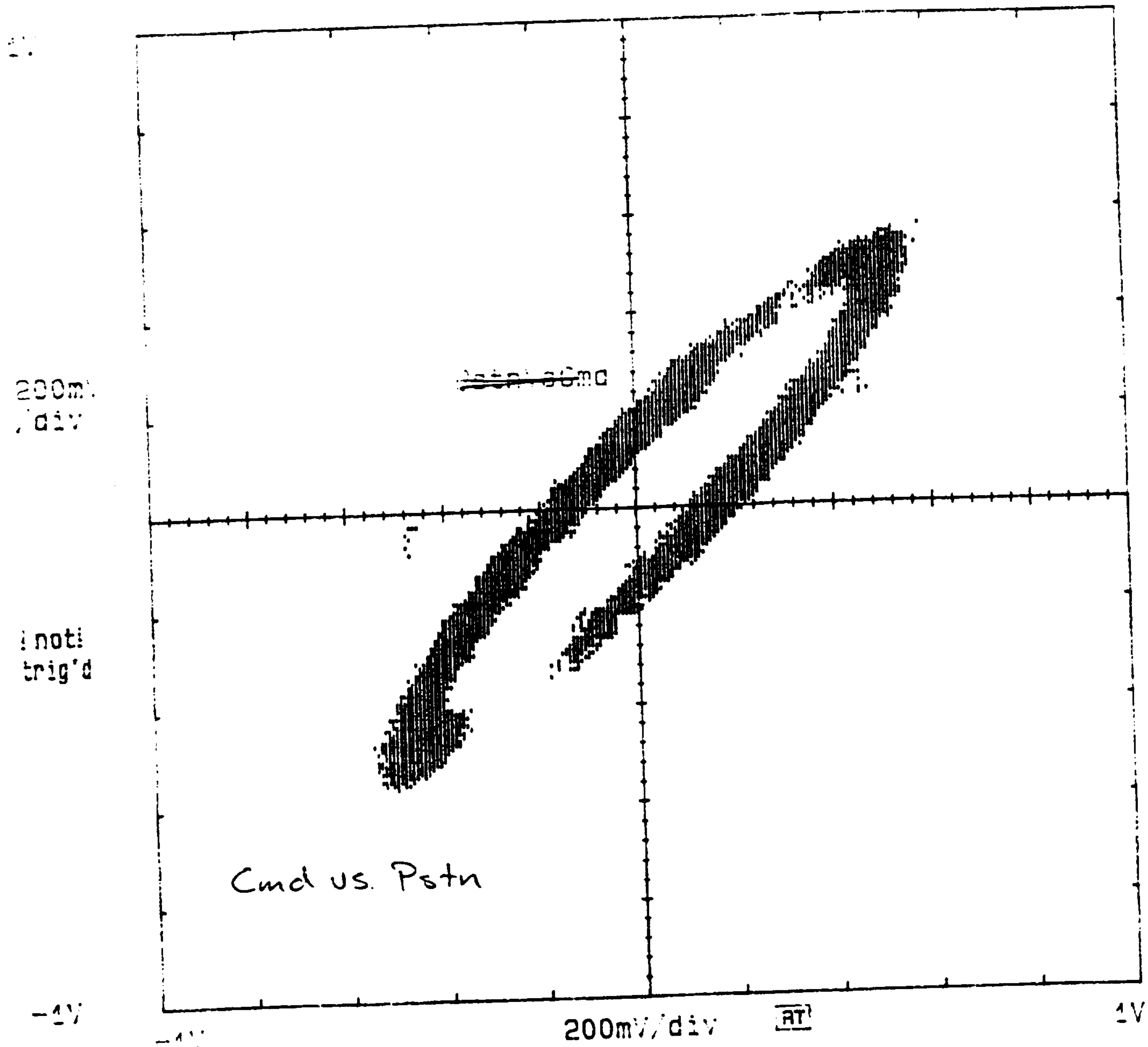
I .25in
1 Hz
2V/in



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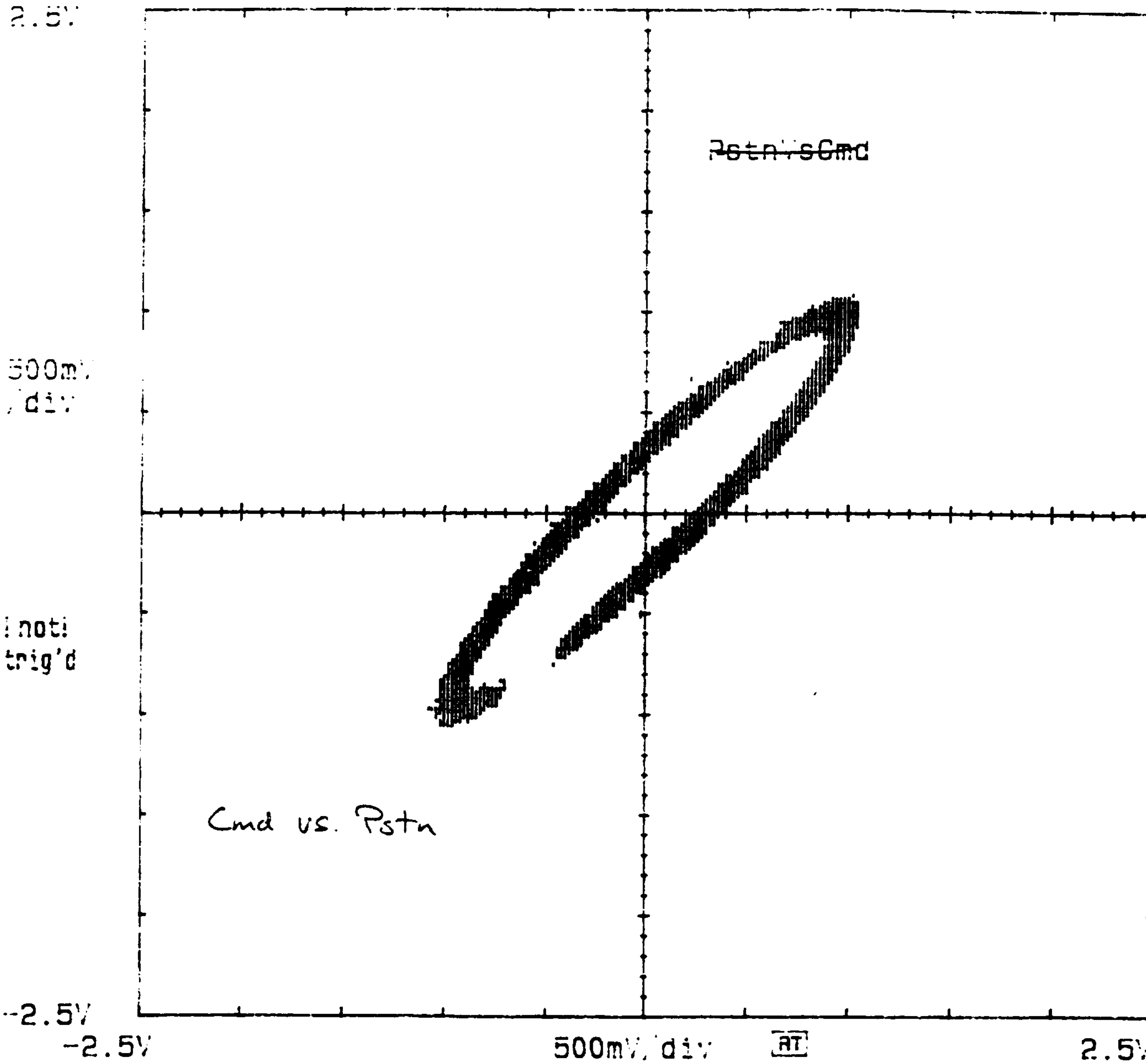
± .5in
1 Hz
2V/in



± .1in
2Hz
2V/in

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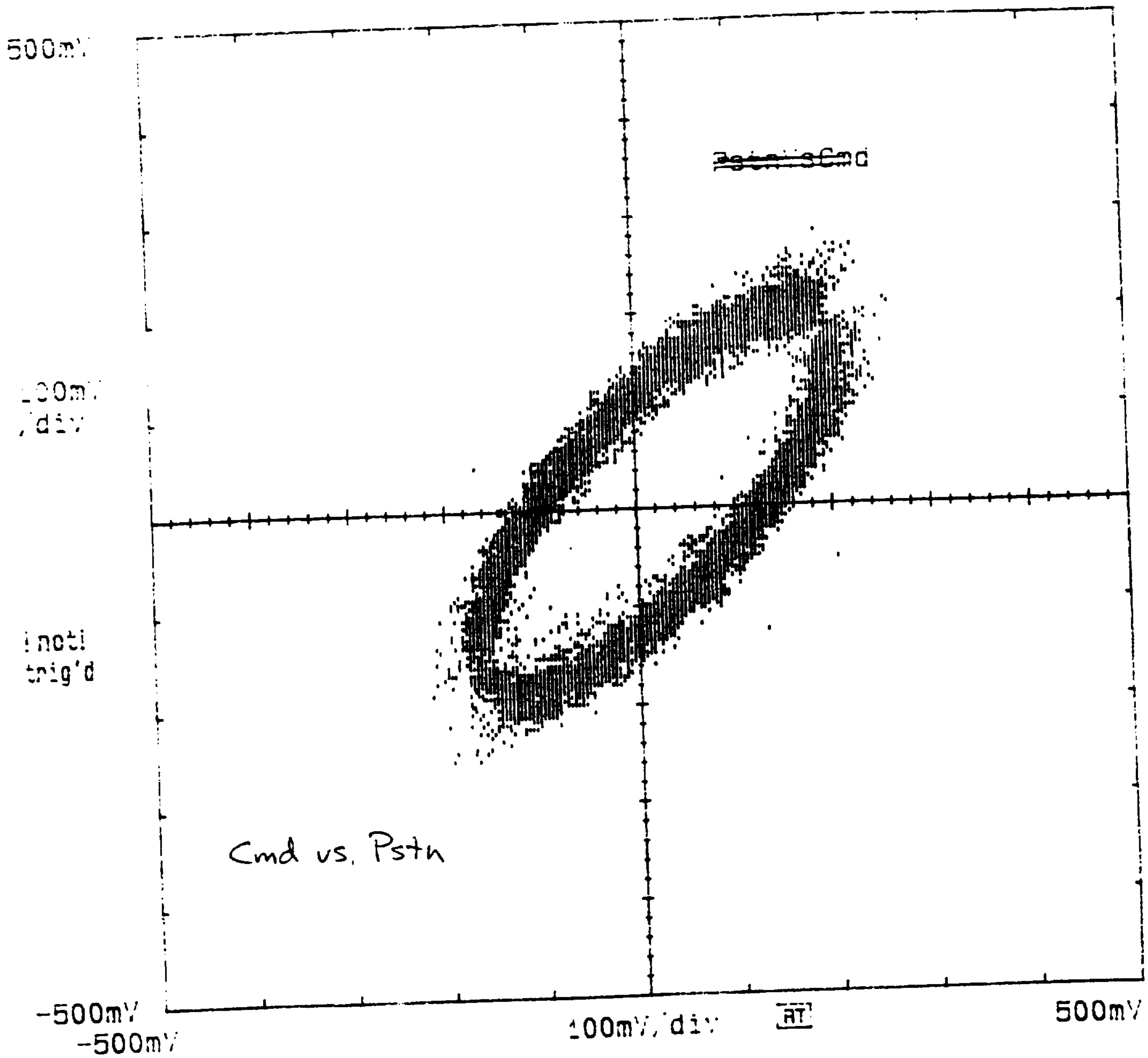

±.25in
2Hz
2V/in

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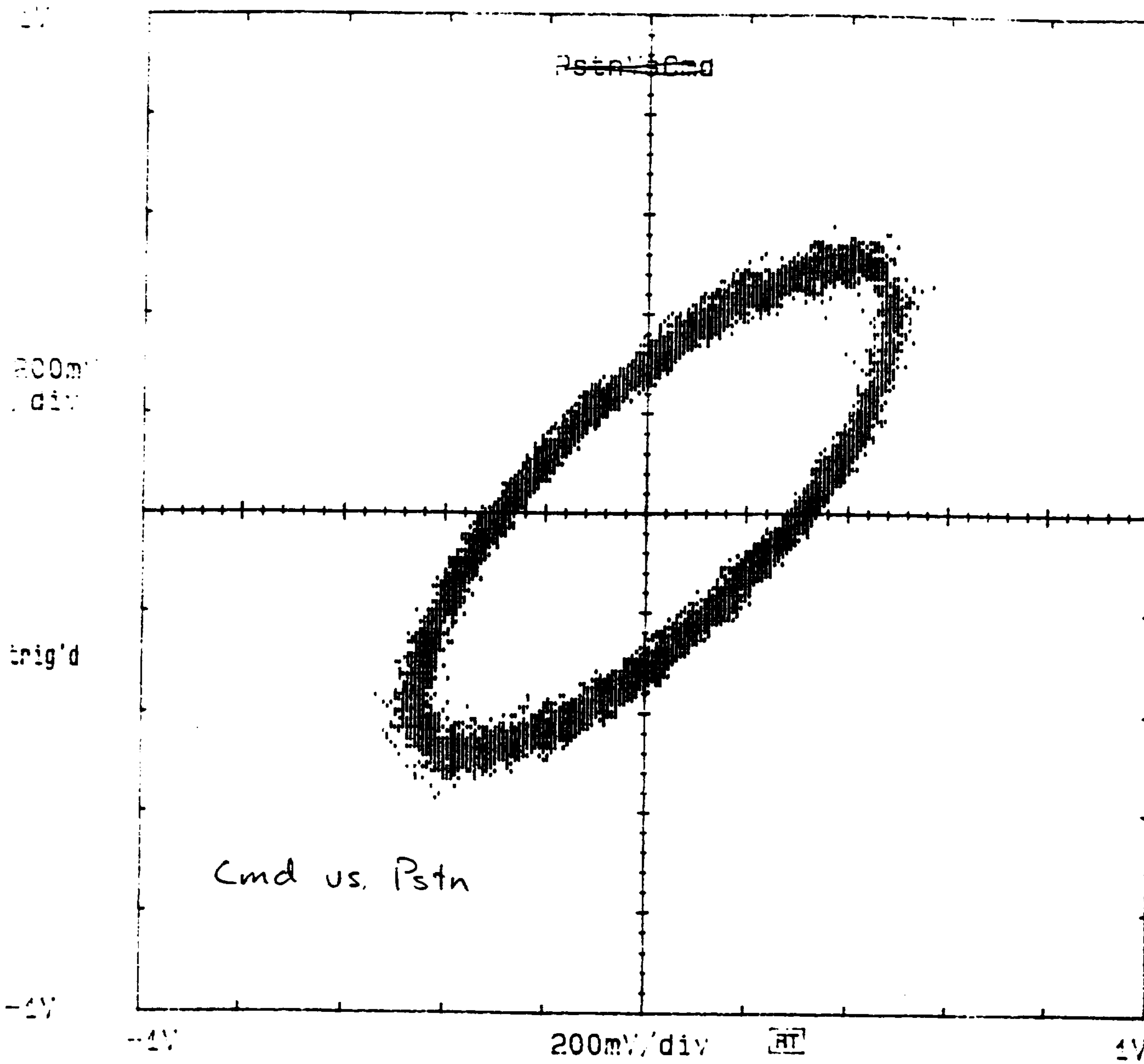

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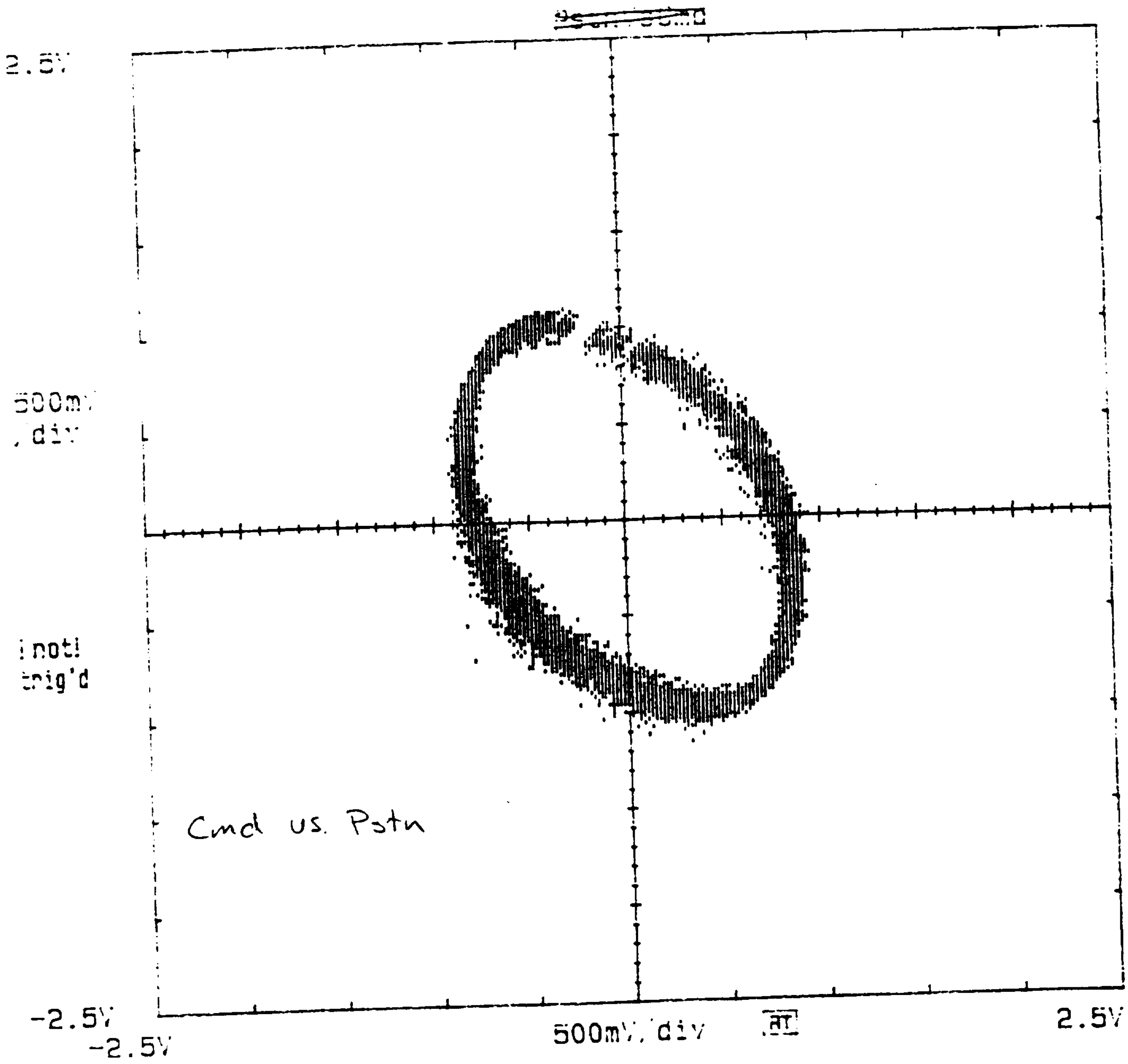
±.5in
2Hz
2V/in



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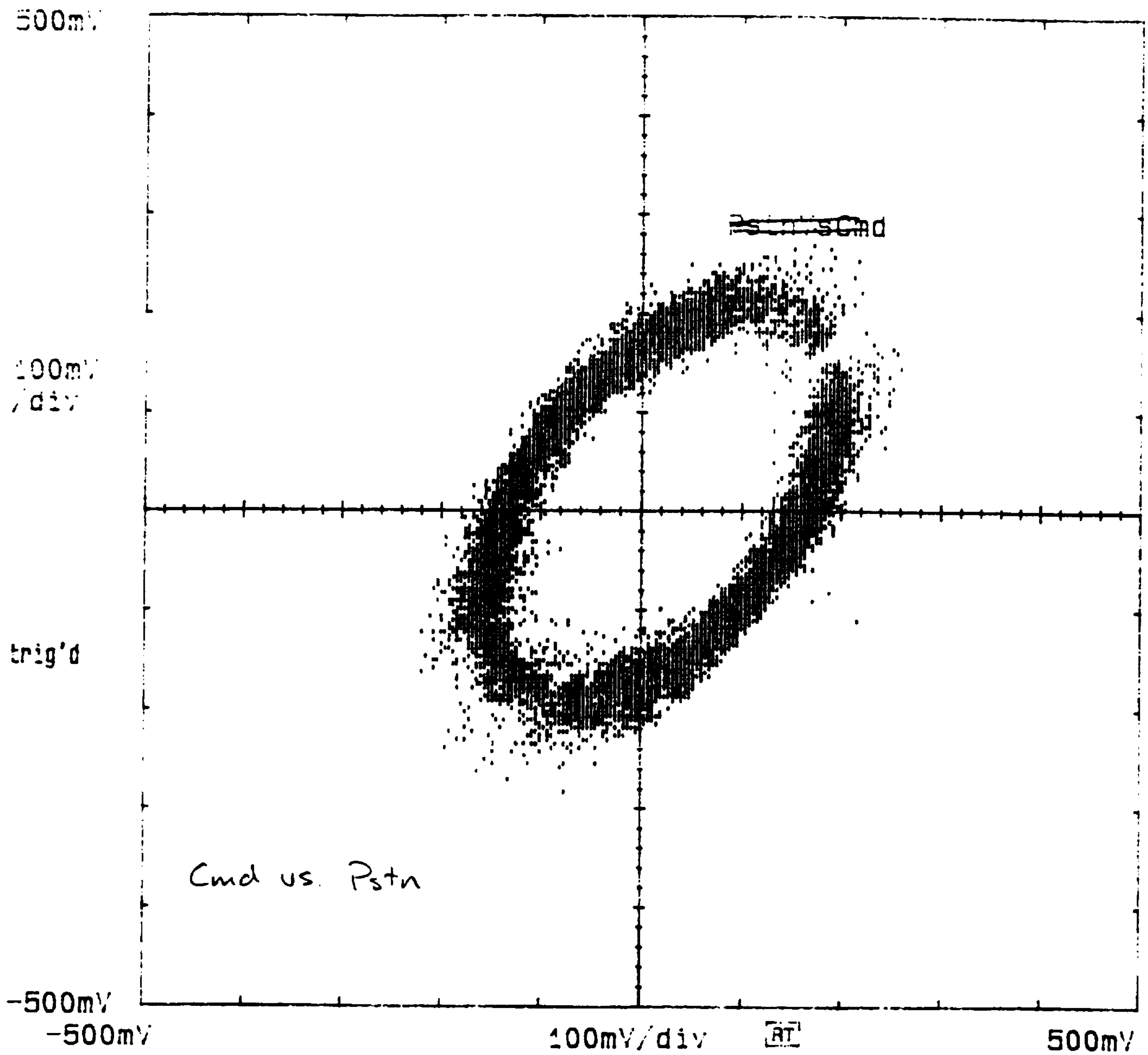
±.1in
3Hz
2V/inch



± .25in
3HZ
2V/in

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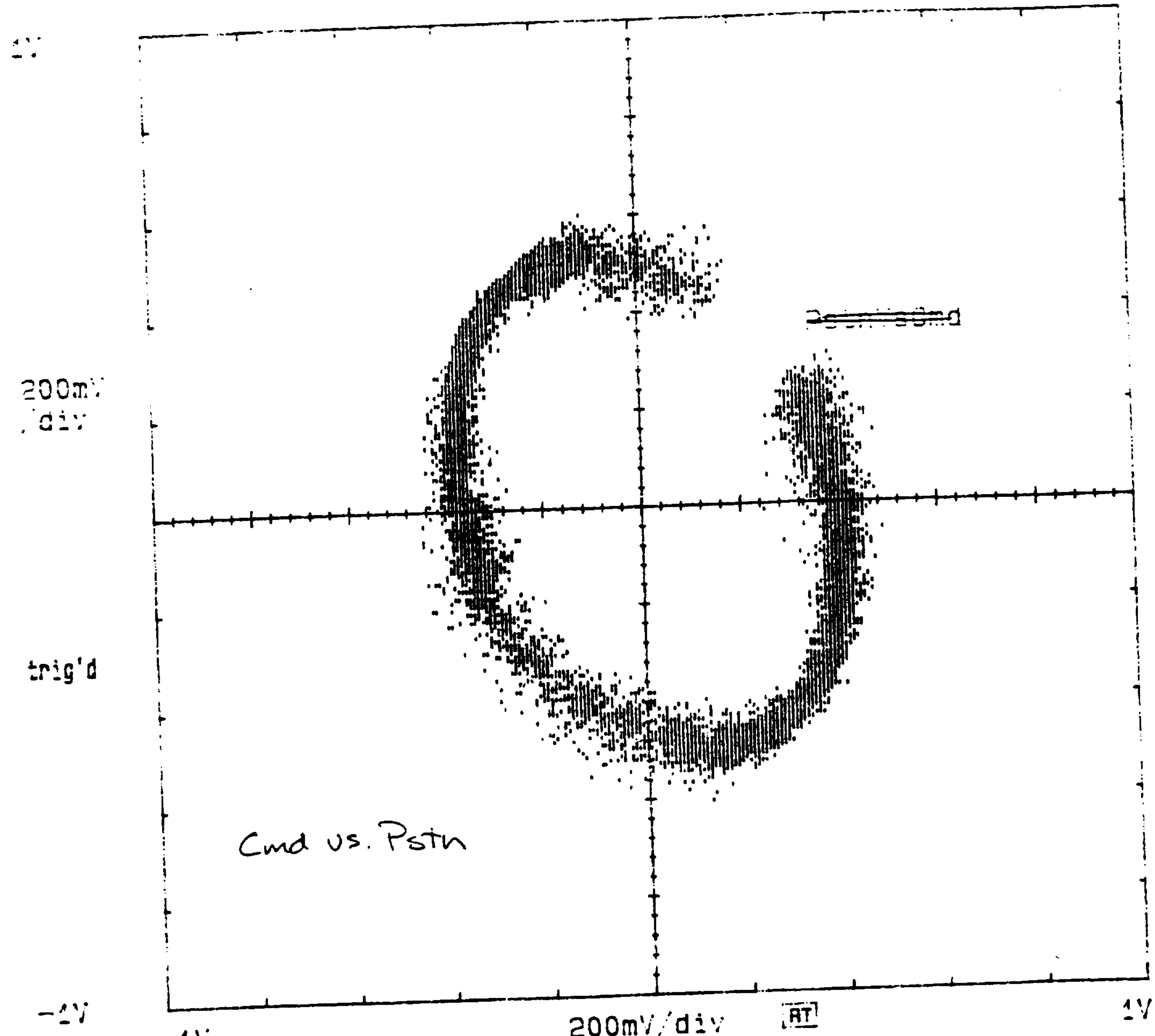

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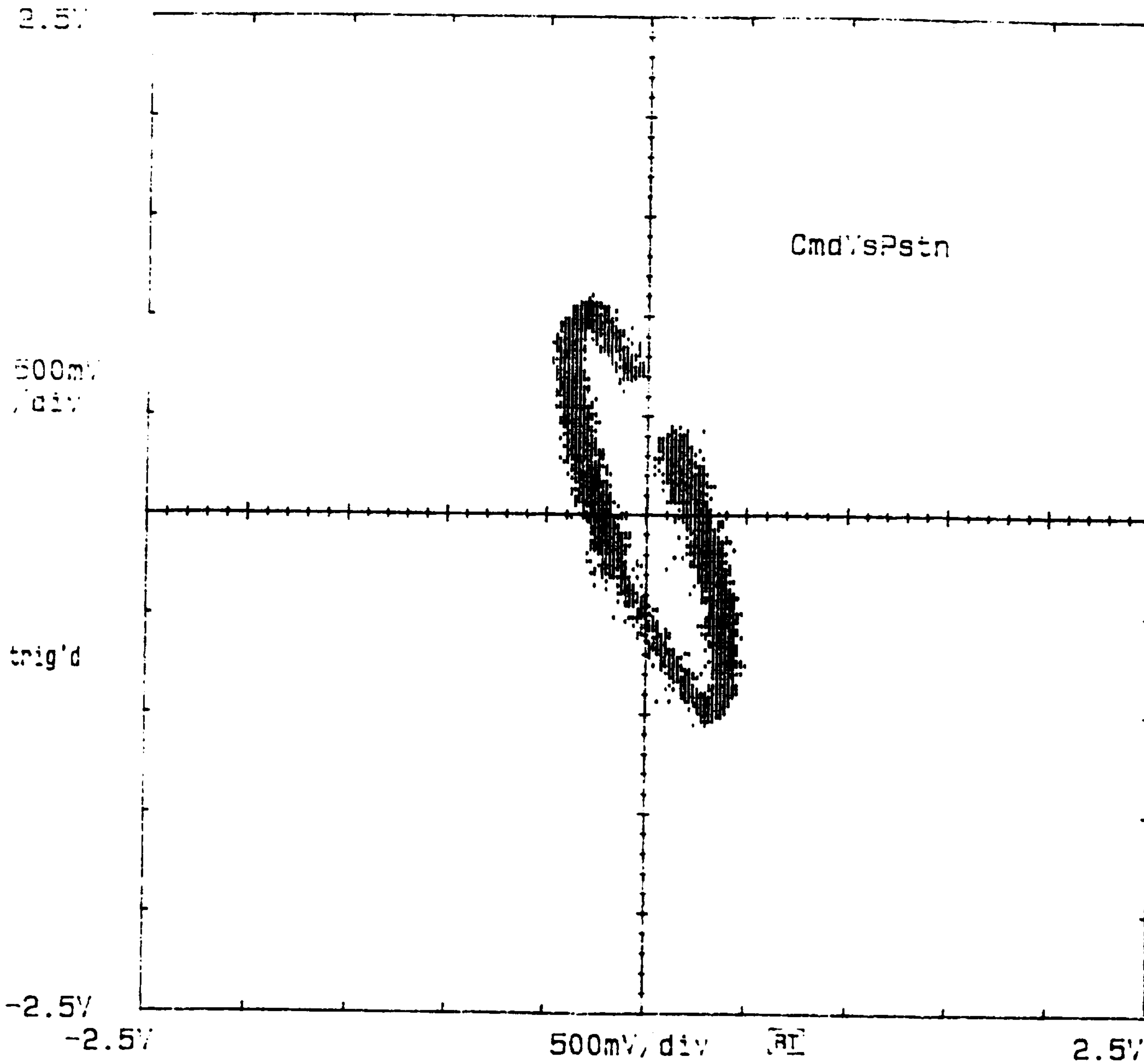
±.5in
3Hz
2V/in



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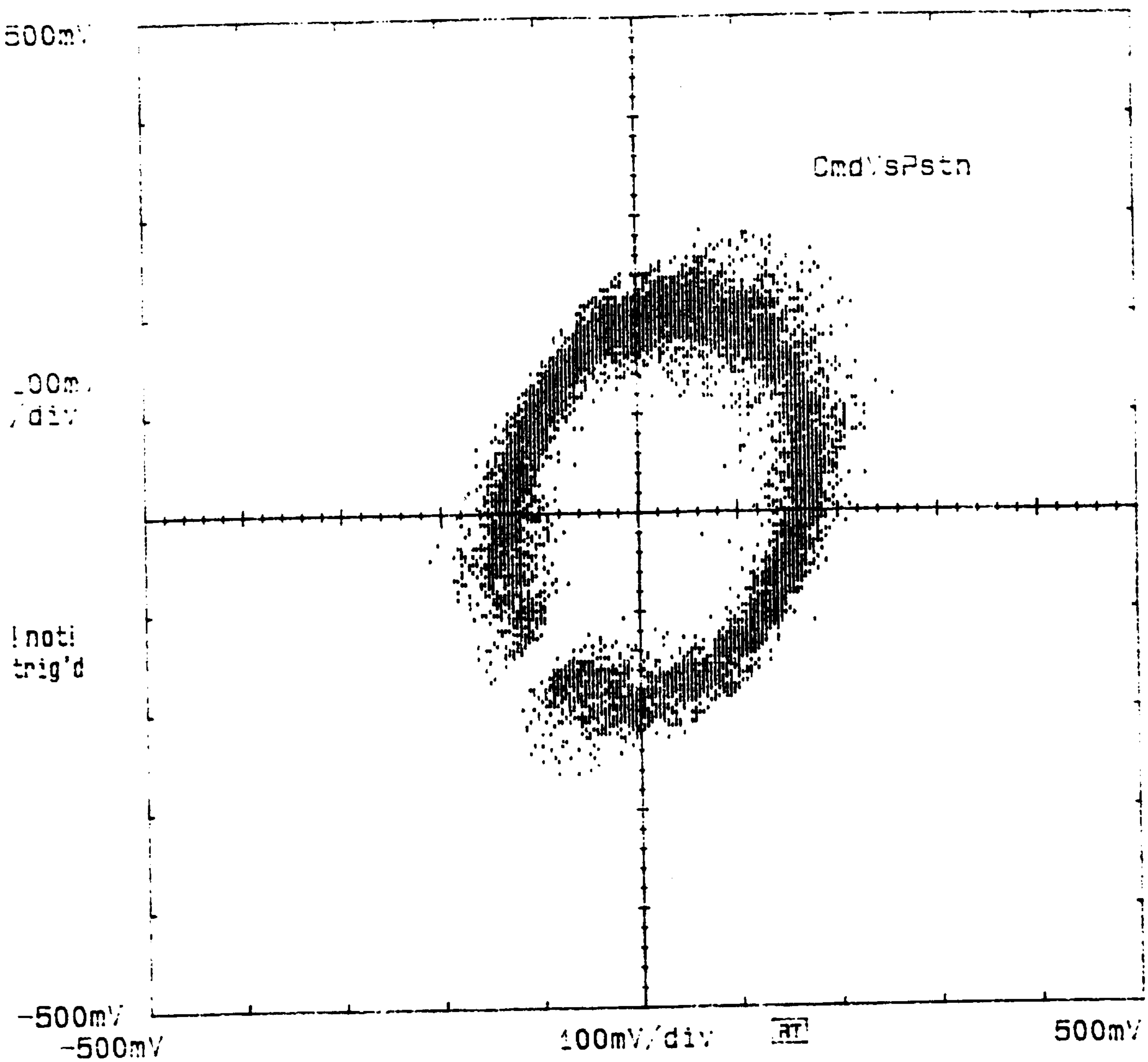
±.1in
4HZ
2V/in



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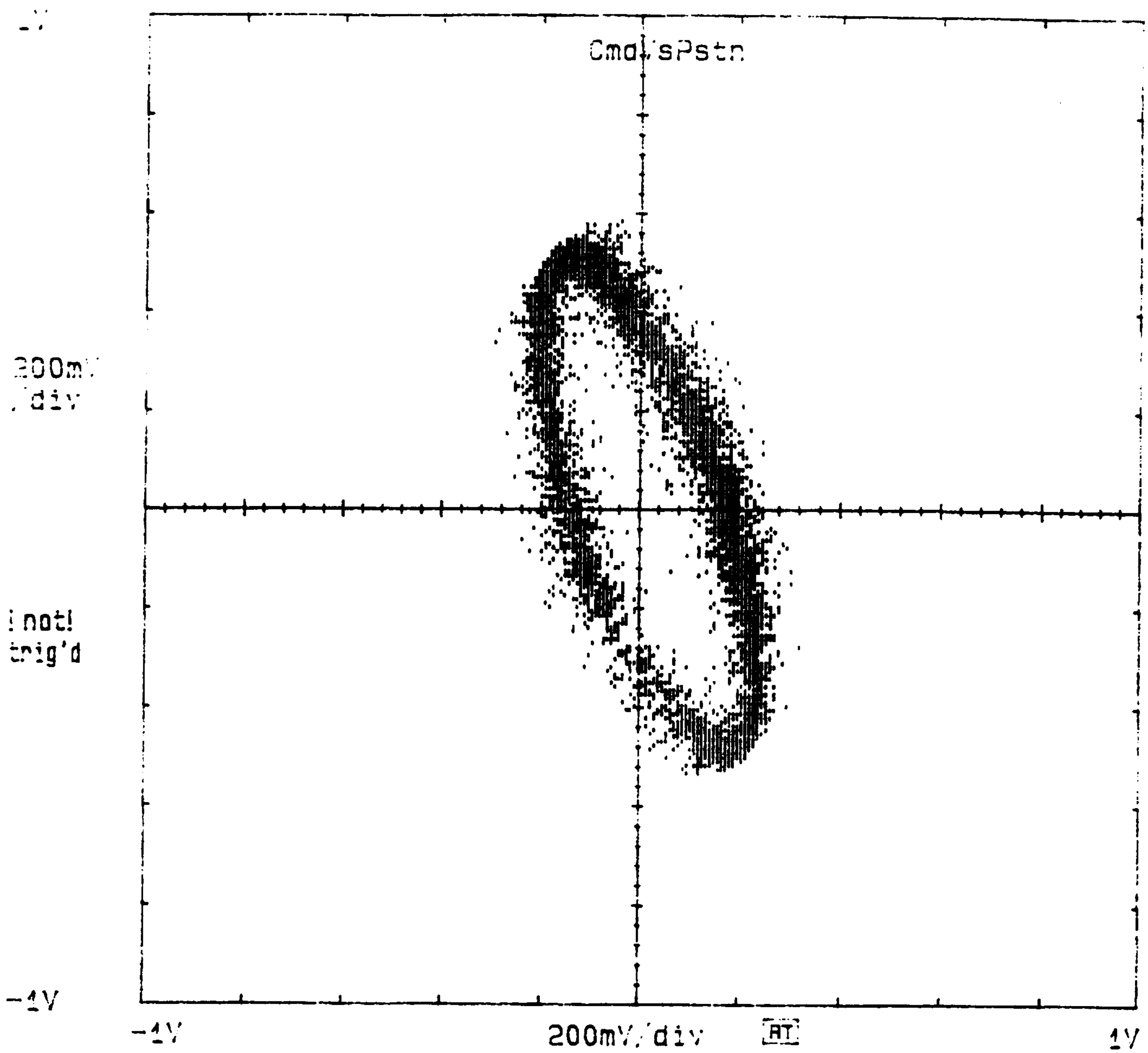
± .25in
4Hz
2V/in



±.5 in
4HZ
2V/in

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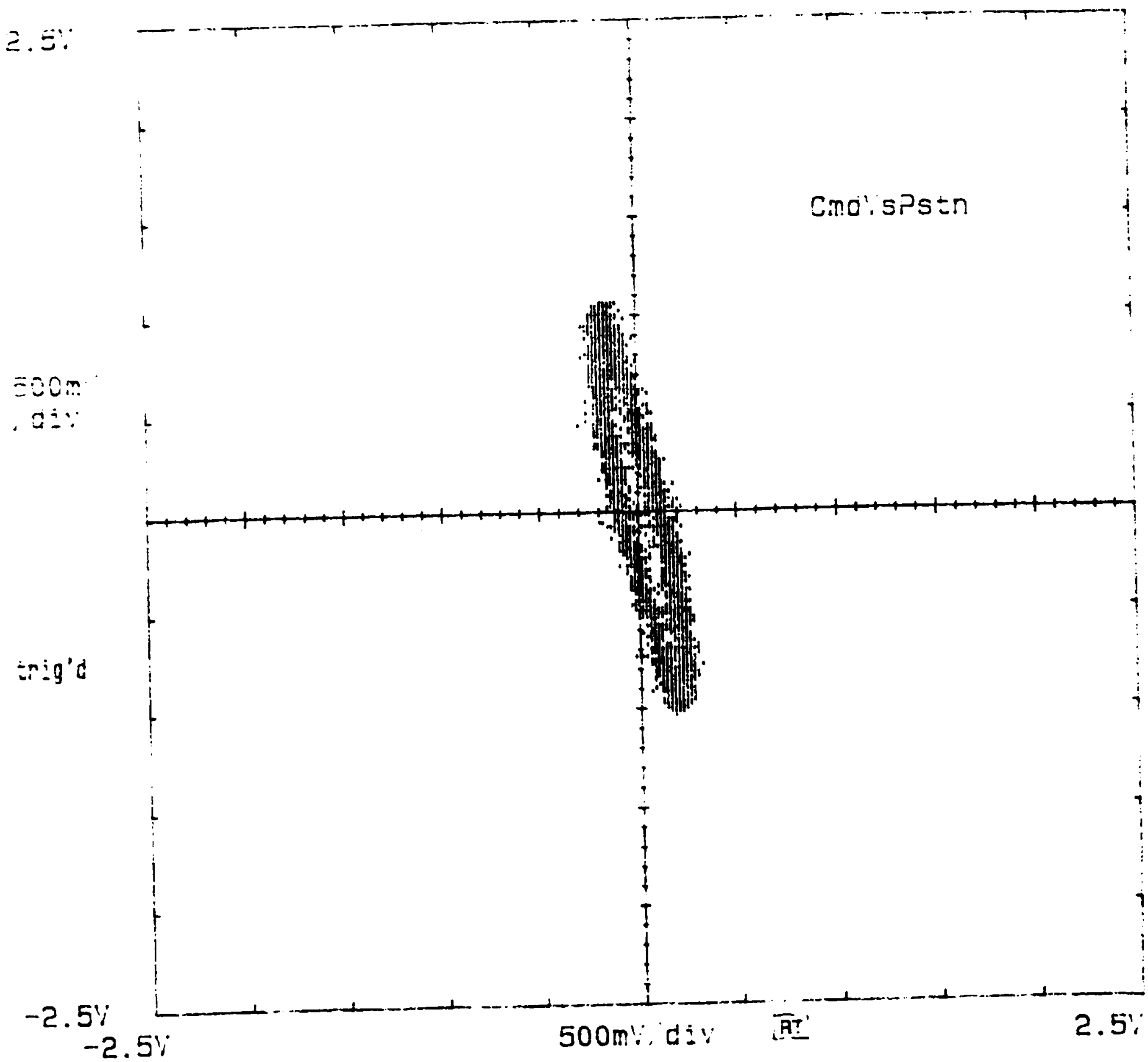

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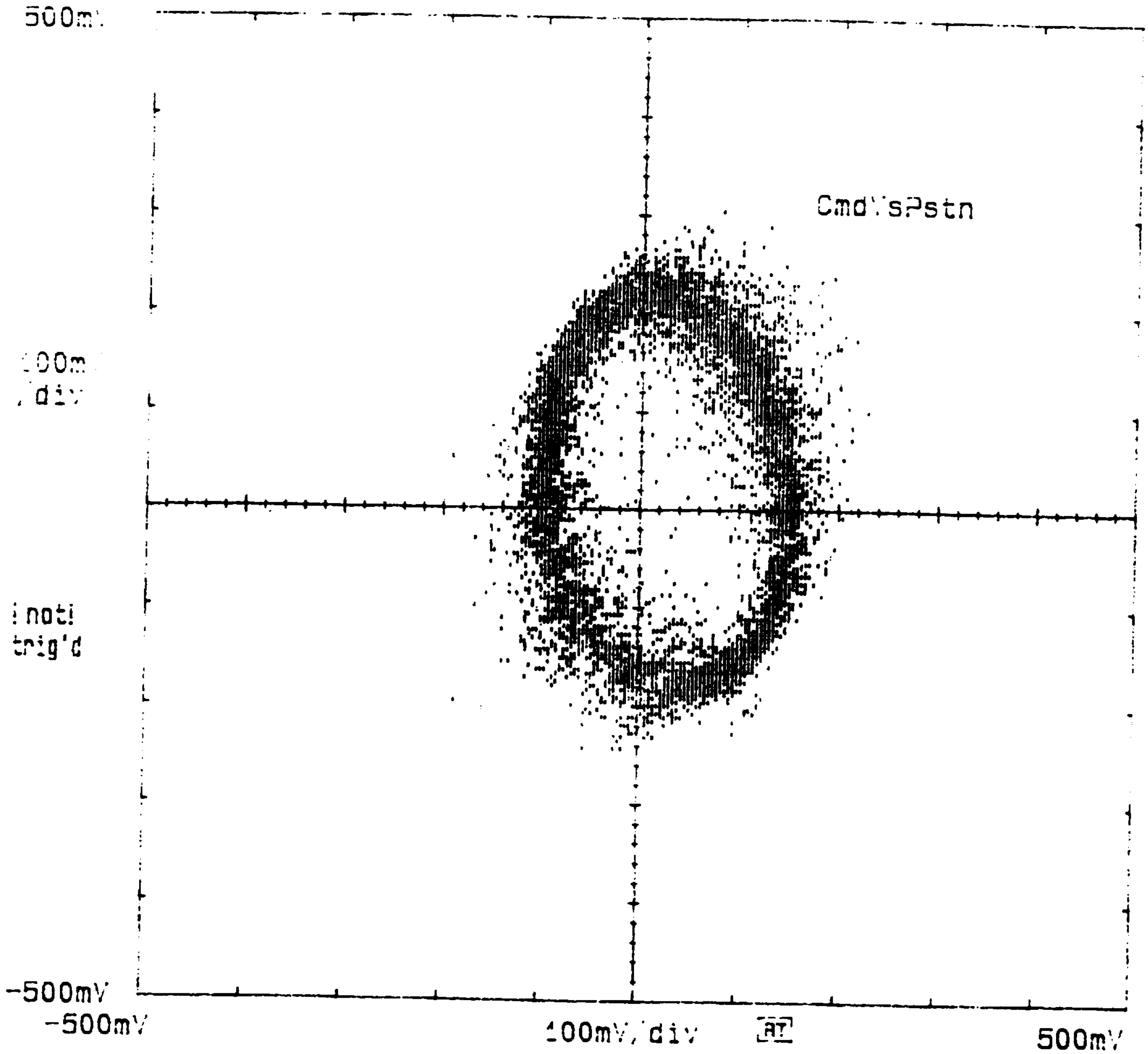
±.1in
5Hz
2V/in



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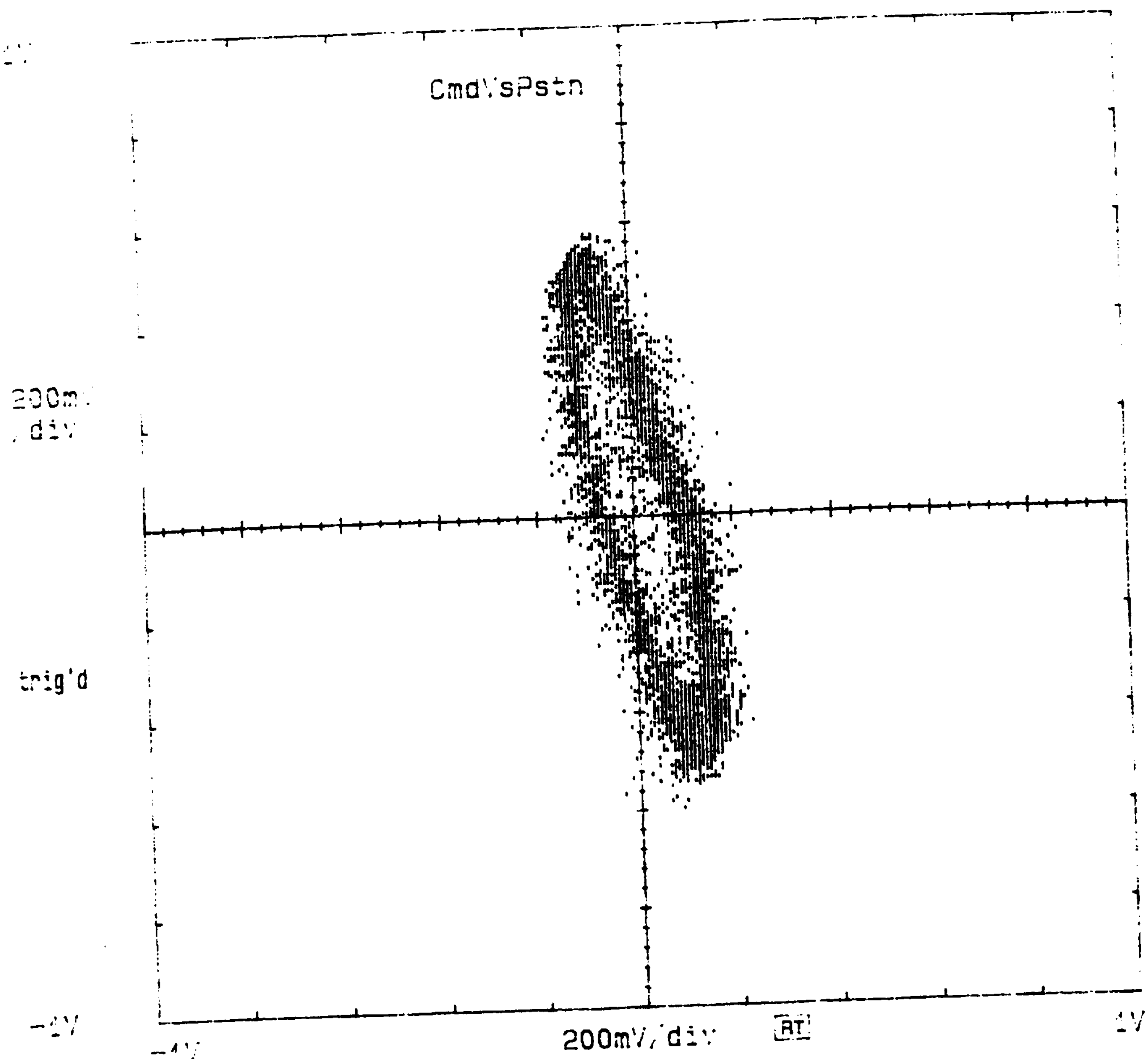
±.25 in
5Hz
2V/in



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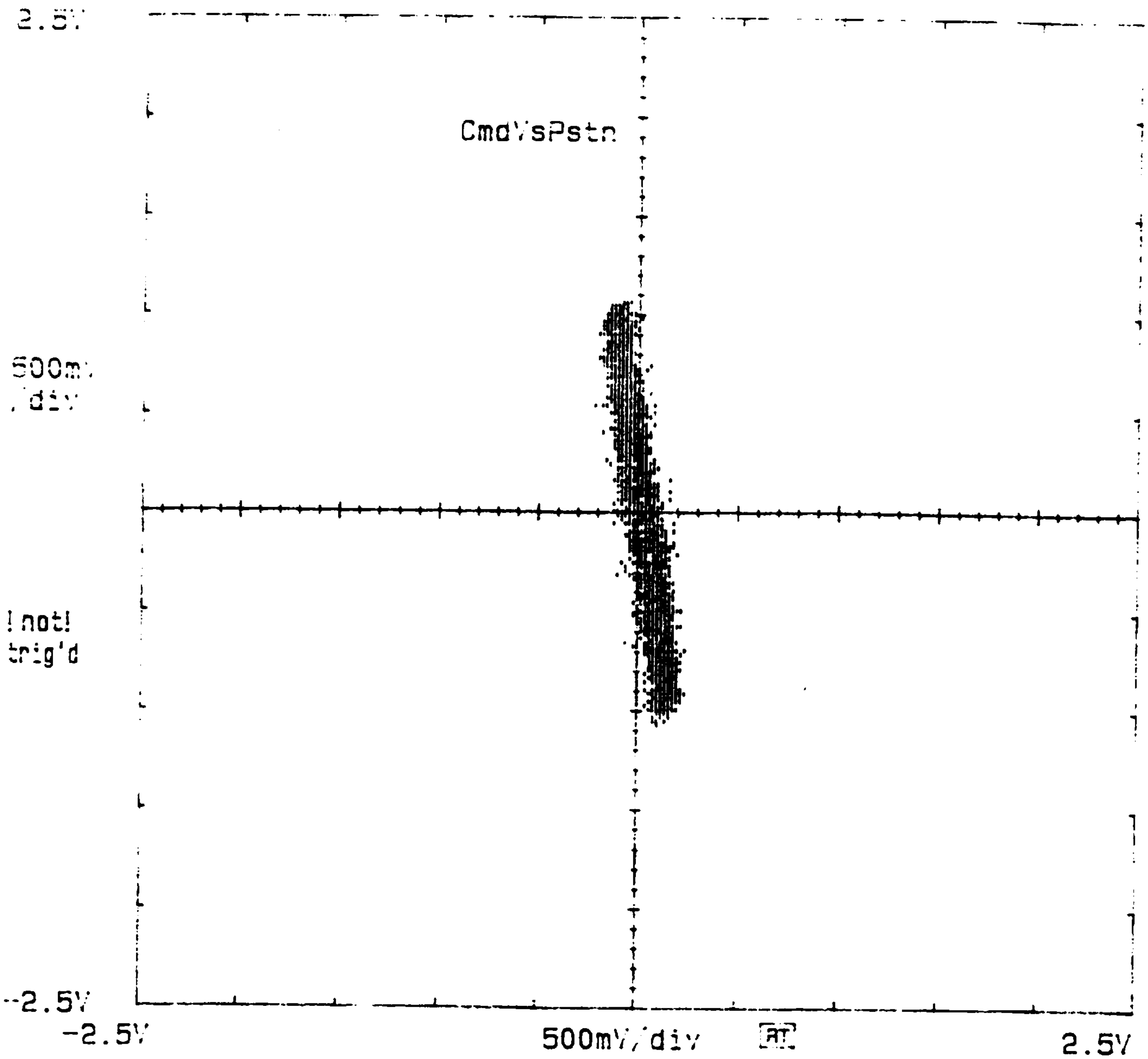
± .5 in
5 Hz
2V/in



±, lin
6Hz
2V/in

DSA 602 DIGITIZING SIGNAL ANALYZER
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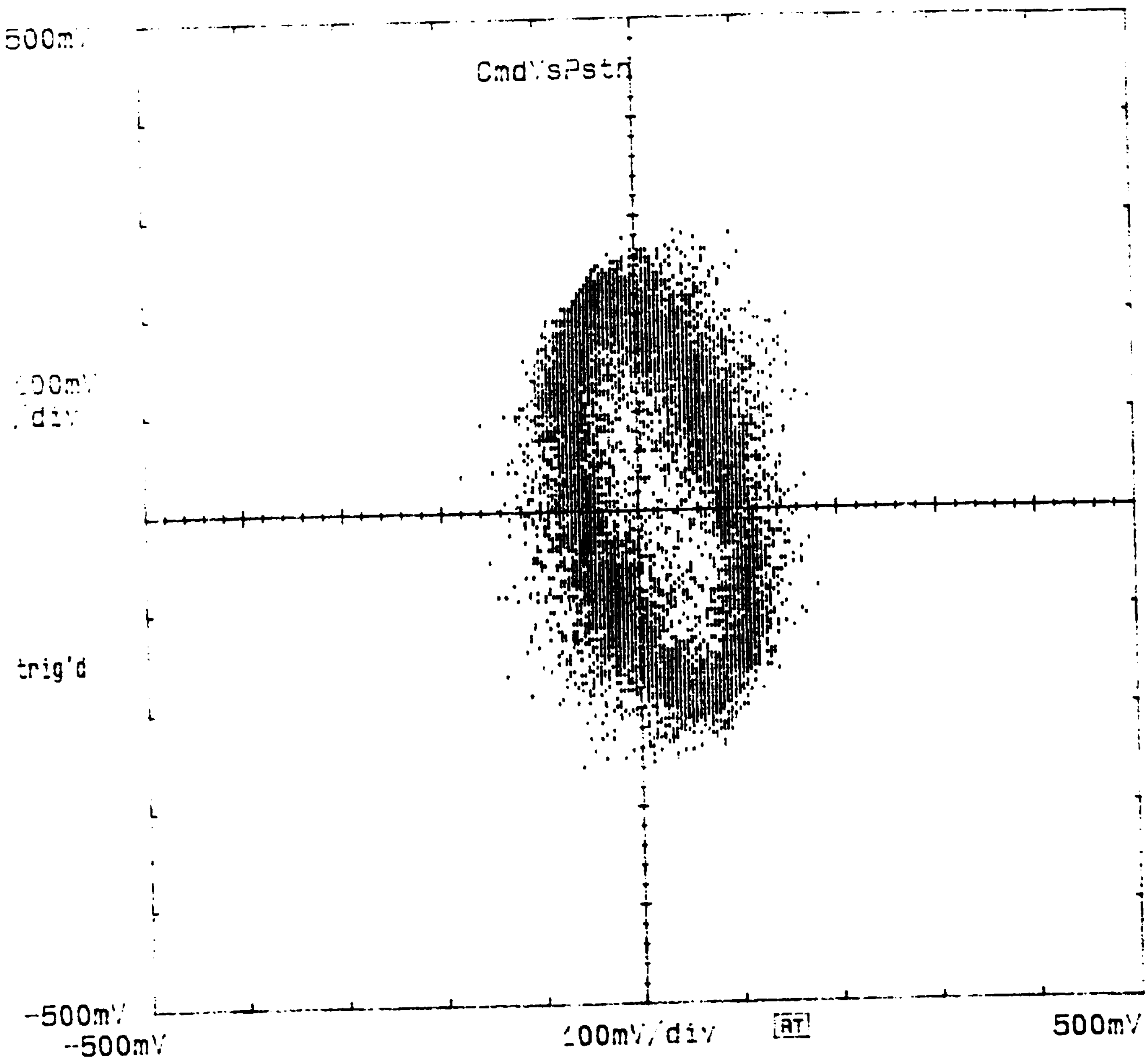

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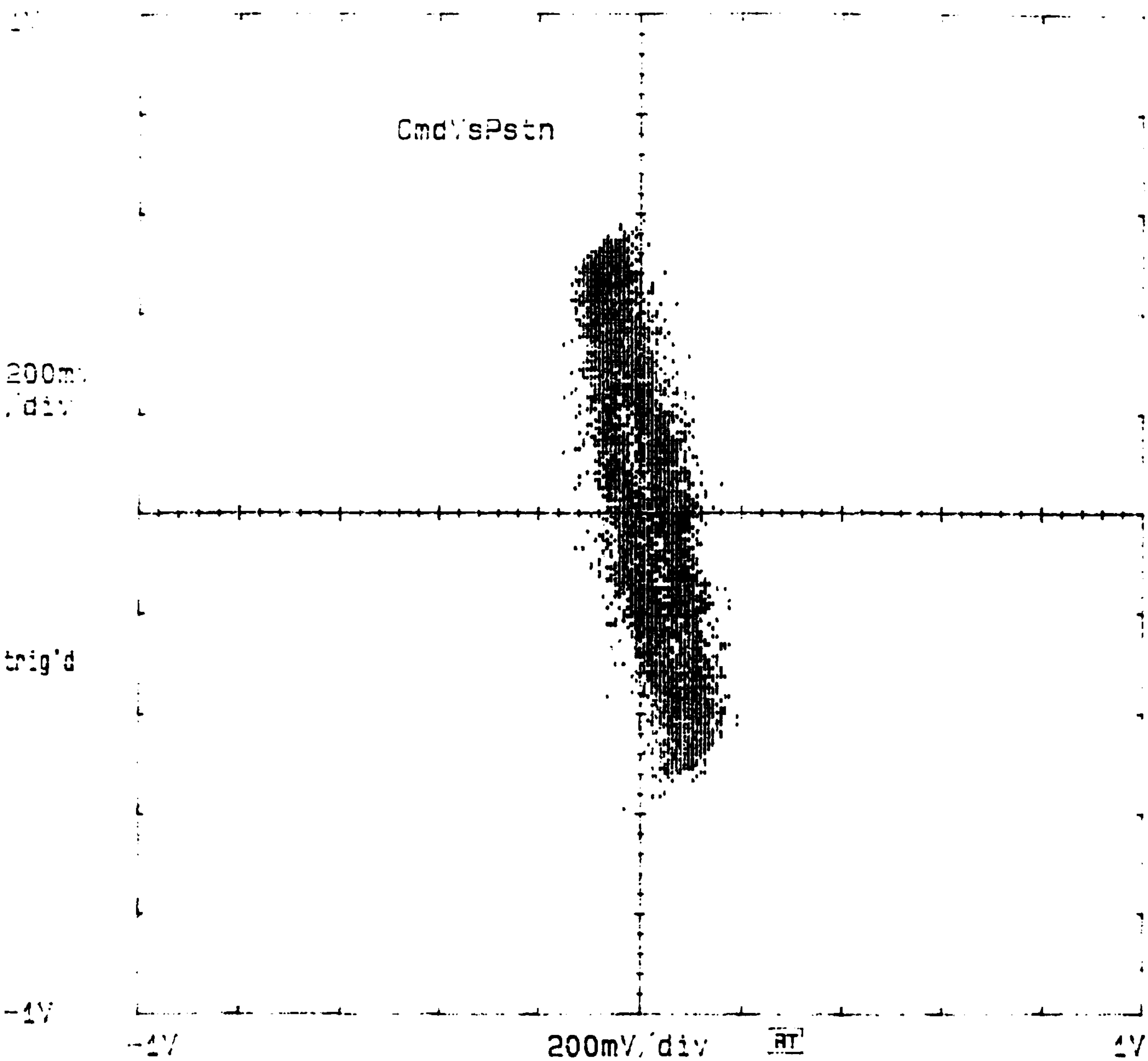
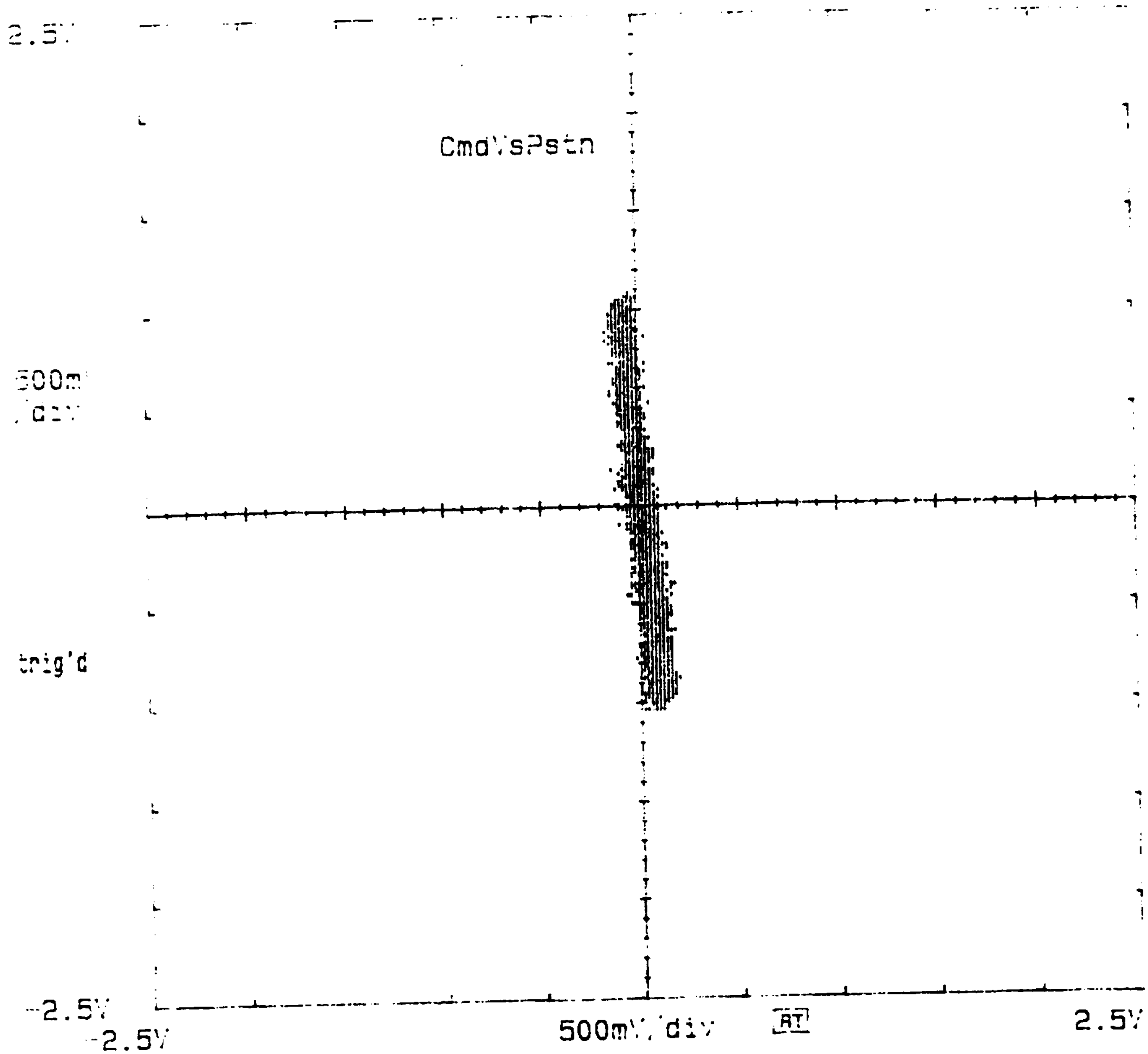
I .25in
6Hz
2V/in



DSA 602 DIGITIZING SIGNAL ANALYZER
date: 1-APR-94 time: 13: 48: 16

± .5 in
6Hz
2V/in



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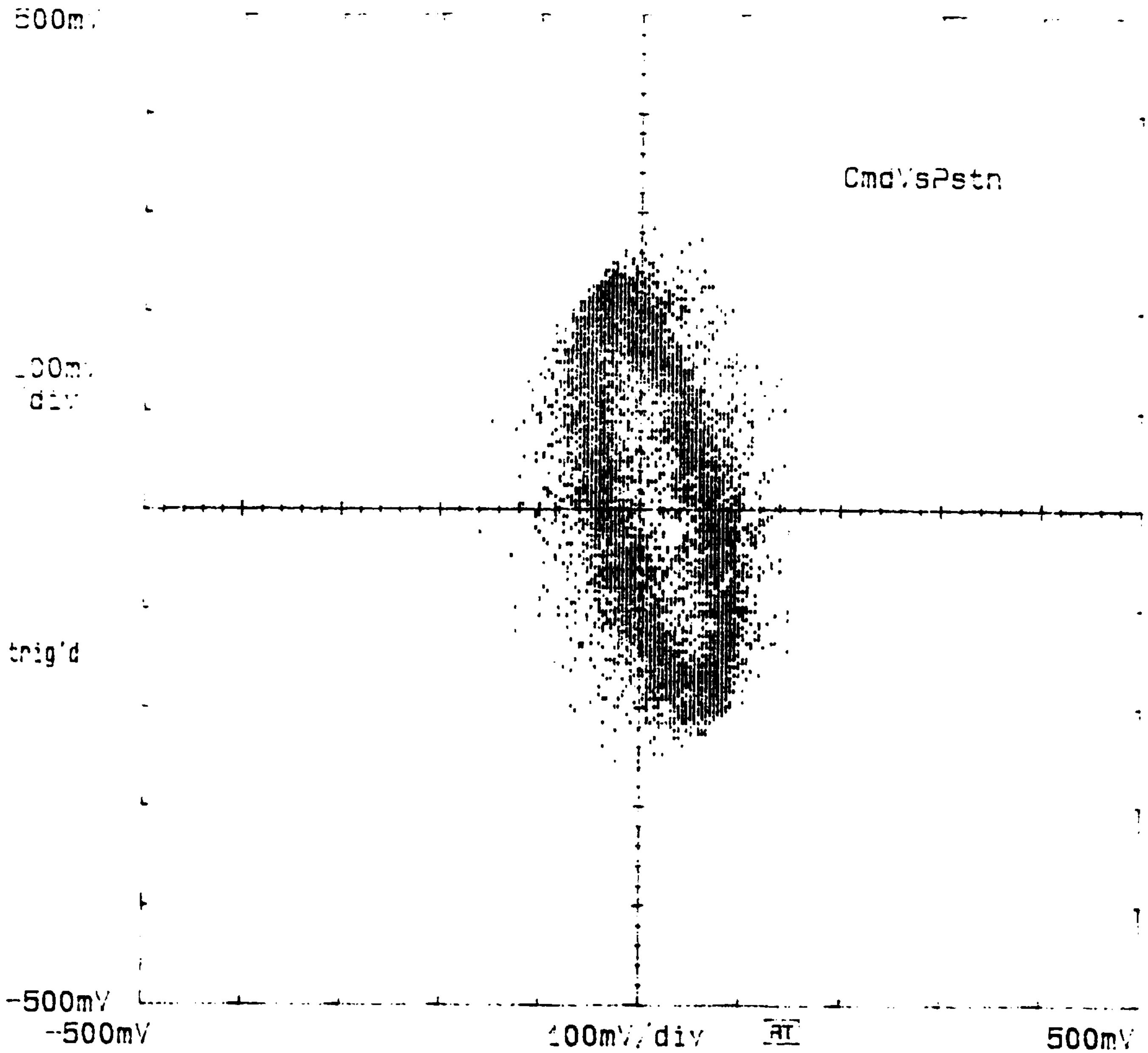
1.1 in
7Hz
2V/in



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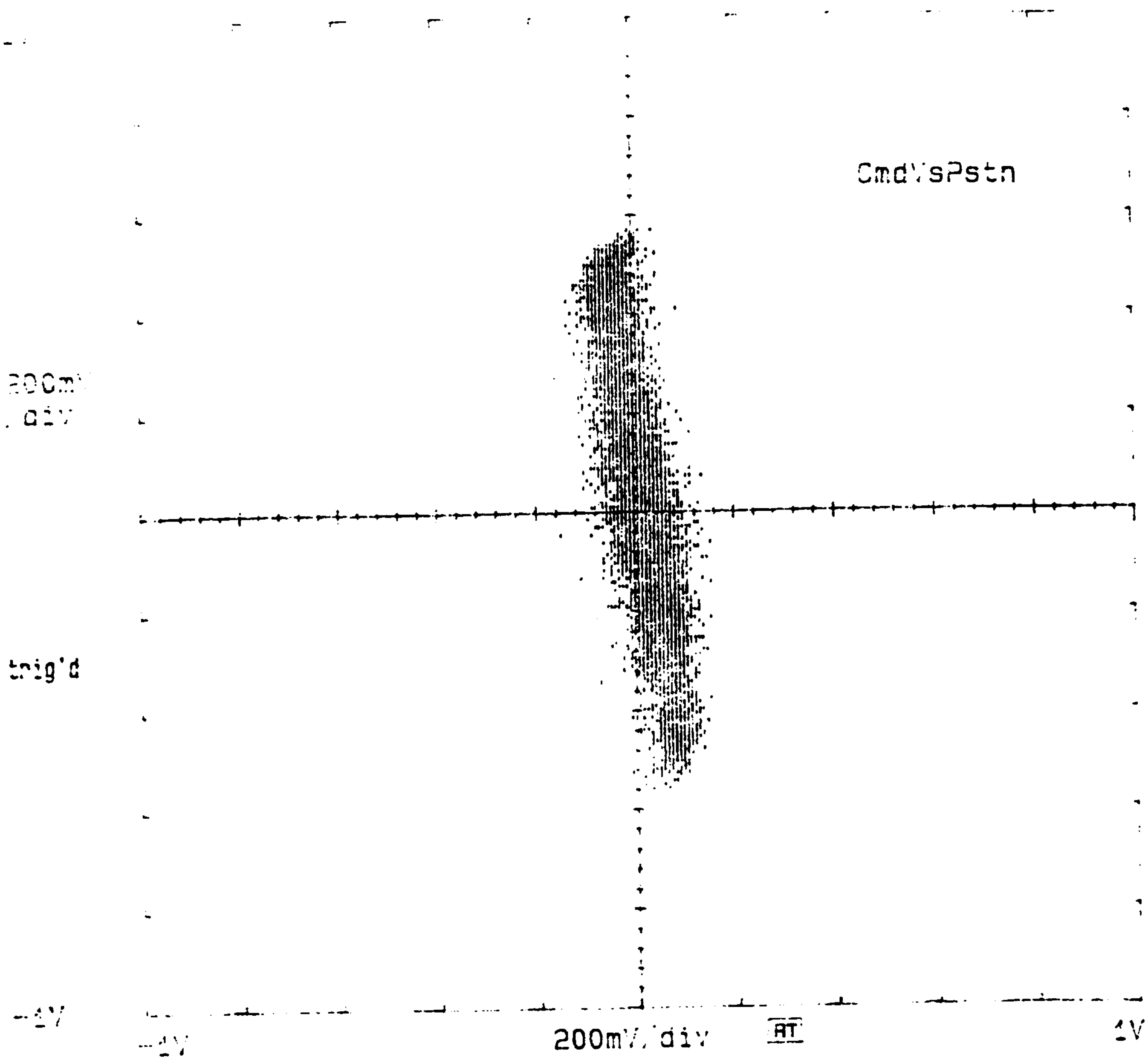
±.25 in
7Hz
2V/in



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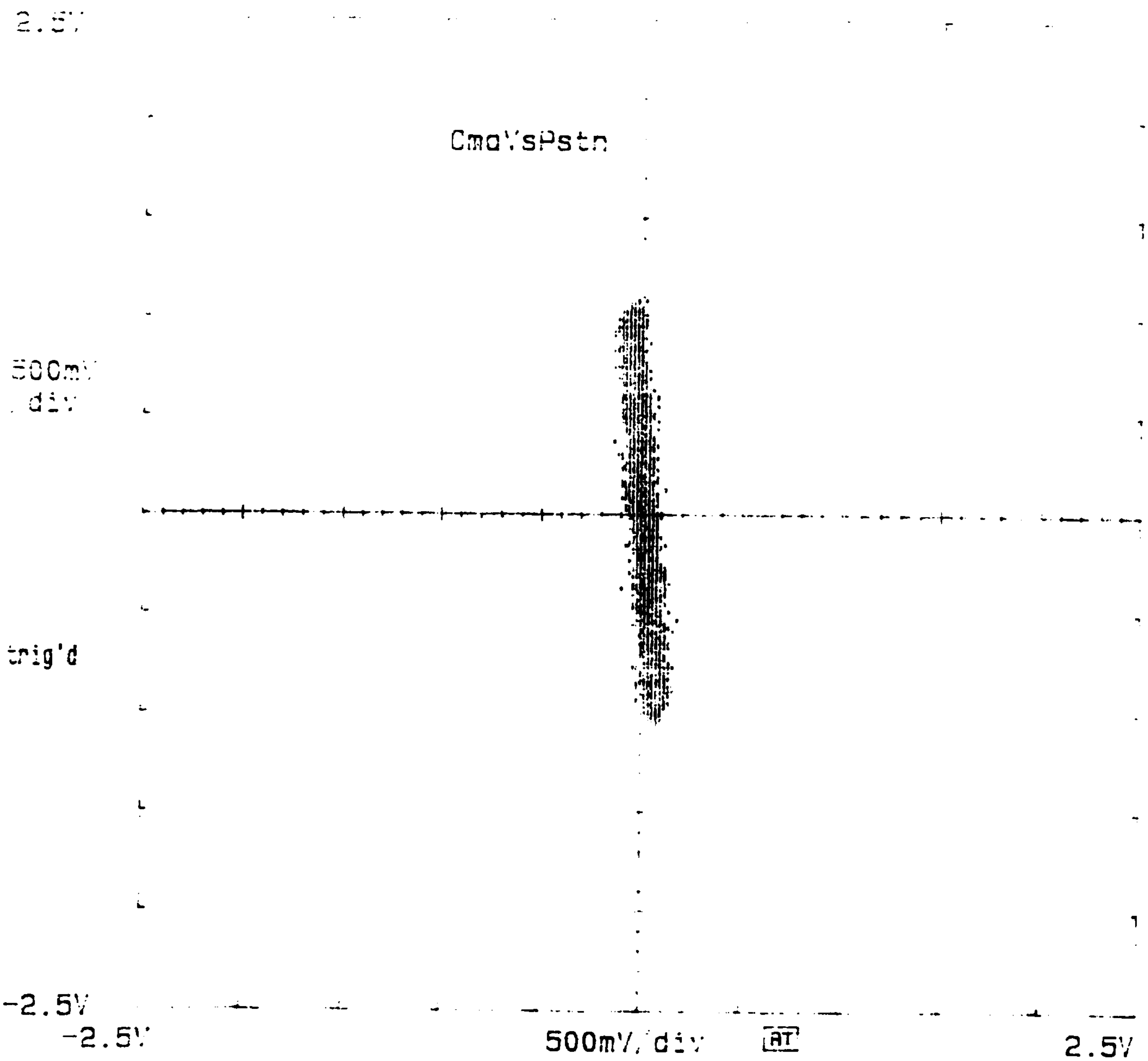
±.5in
7Hz
2V/in



APPENDIX F

Moog Facility Test Procedure

NASA CONTRACT: NAS3-25799

DC MOTOR CONTROLLER

SYSTEM TEST PLAN; MOOG FACILITY

Prepared by:____________________
Chris Fulmer

Principal Engineer:____________________
Ken Schreiner

Program Lead:____________________
Pat Klement

TABLE OF CONTENTS

1.0 SYSTEM DESCRIPTION

This Electro-Mechanical Actuation system utilizes a DC resonant motor controller and an induction motor powered linear actuator capable of up to 70 HP output. The system's power source is either a 300 VDC power supply, used for laboratory testing, or a 300 VDC battery. Control of the system is accomplished via a computer terminal which is an integral part of the system. The EMA Monitor Program controls all aspects of the systems operation. System testing is performed on an actuator inertial test stand for determination of frequency and phase response, and on a load table for determination of velocity/load curves.

1.1 CONTROLLER

This controller utilizes field oriented control to determine the phase current values necessary to drive the induction machine to a commanded speed value. The controller also requires two position feedback sensors when used with a linear actuator. The first is a rotary position sensor which is mounted on the motor shaft and provides rotor angle and speed feedback. The second is a linear position sensor which determines the amount of actuator extension or retraction.

Field-oriented control relies on equations generated from a d-q (direct-quadrature) axis model of the induction machine. Figure 1-1 illustrates the equivalent circuit of the induction machine. When the rotor flux is aligned with the d-axis, the d-axis component of the current, i^e_{ds}, is decoupled and becomes the flux producing current. At this point the q-axis component, i^e_{qs}, may be used to control torque or speed as illustrated by the following equations:

$$T = \frac{3}{4}\,\frac{p\,L_m \lambda^{e*}_{dr}}{L_r}\, i^{e*}_{qs} \qquad \omega_s = \frac{R_r L_m}{L_r \lambda^{e*}_{dr}}\, i^{e*}_{qs} \qquad \lambda^{e*}_{dr} = L_m i^{e*}_{ds}$$: assumes i^{e*}_{ds} constant.

The user definable variable needed to calculate these formulas are:

- R_r = Rotor Resistance
- L_m = Mutual Inductance
- L_r = Rotor Inductance
- P = Number Of Poles
- $i^e_{ds}{}^*$ = d-Axis Current In Synchronous Frame

Figure 1-2 shows the block diagram of the system. A comparison of the commanded actuator position to the actual actuator position produces an error signal. This error signal is used by the software algorithms to generate the required field oriented control motor currents that move the motor/actuator and eliminate the position error. The rotor angle feedback and the actuator force feedback signals are used by the algorithms to determine the appropriate command signals. Motor current regulation is performed using computer software by comparing the actual motor currents from phase A and B feedback currents to the commanded phase currents. The resulting current error is used to determine the power switching sequence which ultimately controls the motors phase currents.

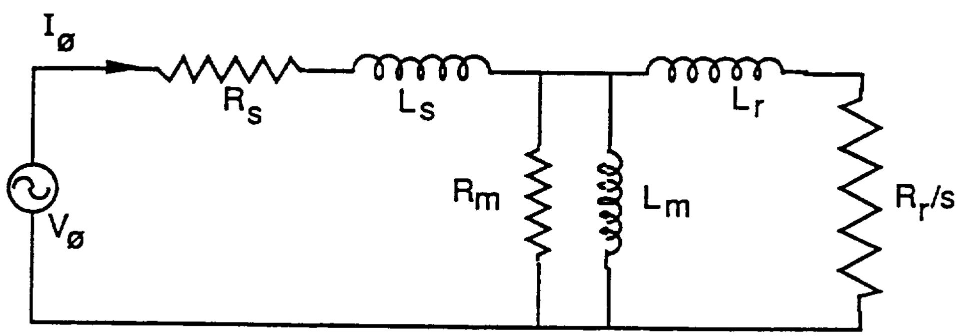


Figure 1-1: Induction Machine Equivalent Circuit For Field Orientation Operation

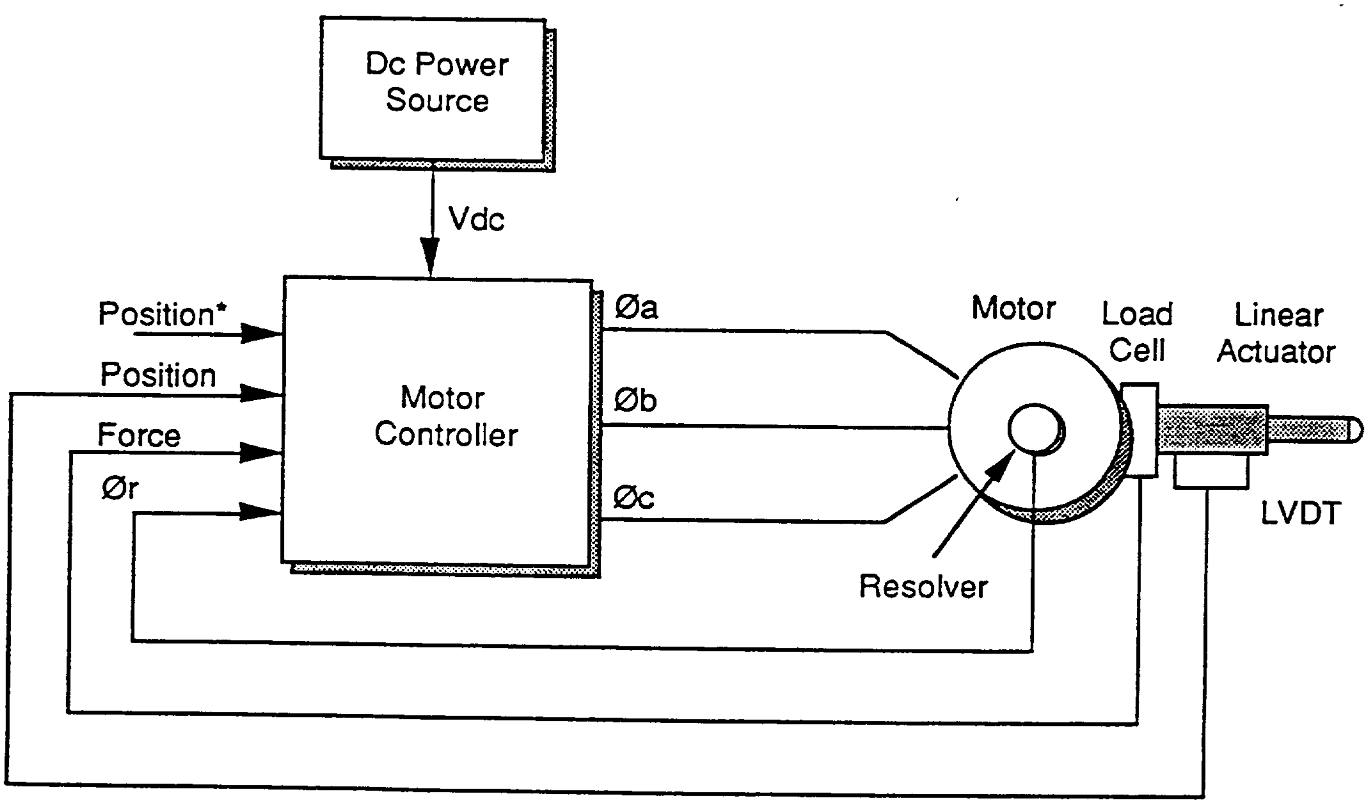


Figure 1-2: Motor Controller Block Diagram

1.2 MOTOR

The motor that is integrated into the MOOG built actuator is a 70 Hp induction machine developed by Sundstrand for NASA contract number NAS3-25799, task order 1 and EMA ADP 2402.

1.3 ACTUATOR TEST STAND

The actuator test stands used for this sequence of tests are of two types. The first provides an inertial load to the actuator system that represents the load typical of the Space Shuttle's Main engine. The second test stand provides a load to the actuator system that may be adjusted to values between zero and 55,000 pounds. The actuator may thus be tested at varying velocities and loads up to the maximum rated load of 55,000 pounds.

2.0 TEST PLAN DESCRIPTION

2.1 OBJECTIVE

This test plan was developed to provide a method of testing the DC link resonant motor controller and the motor/actuator system. The objective of the testing is to determine system capabilities including the system frequency and phase response, and maximum output power.

2.2 MEASUREMENTS

The testing requires measurement of several parameters including actuator commanded position, actuator actual position, actuator load and actuator velocity. The following paragraphs indicate proposed measurement methods for all quantities of interest as well as proposed equipment.

2.2.1 FREQUENCY AND PHASE RESPONSE

The frequency and phase response shall be measured on the inertial test stand by comparing the commanded signal to the actuator output. The commanded and actual actuator positions are available as signal outputs from the motor controller. The inertial test stand also provides the actual position information. A strip chart recorder shall be used to record the measurement data.

2.2.2 FORCE

Force shall be measured using the in-line force transducer on the MOOG force-velocity test stand.

2.2.3 VELOCITY

Velocity shall be measured using the instrumentation on the MOOG force-velocity test stand. The velocity is also displayed on the motor controller's computer monitor.

2.2.4 TEMPERATURE

There are two temperature measurement points within the system. One is part of the heat exchanger system and indicates the temperature of the coolant in the cold plate. The second temperature measurement point is a thermocouple embedded within the motor stator. This temperature is monitored using a temperature meter to ensure that the temperature does not exceed the maximum operating parameters during testing.

2.2.5 ACTUATOR POSITION

The actuator position is measured by the LVDT (Linear Variable Displacement Transducer) mounted in the actuator's housing. The signal from this device is processed by the Controllers computer software and is available as an output to the strip chart recorder.

2.3 TESTS

The testing is performed on two different test stands:

2.3.1 ACTUATOR INERTIAL TESTING

This series of tests measures the frequency response, phase response and step response of the entire system, with the actuator operating on an inertial test stand.

2.3.2 ACTUATOR VELOCITY/FORCE TESTING

This series of tests measures the maximum power output of the system, with the actuator operating in a hydraulically loaded test stand.

3.0 TEST PLAN PROCEDURES

3.1 ACTUATOR INERTIAL FREQUENCY/PHASE RESPONSE TEST

1. Install the actuator in the inertial test stand and power up the motor controller.
2. Initialize the controller.
3. Apply the specified SINUSOIDAL command (see table) for a ten cycle minimum.
4. Plot the position vs. command on an X-Y plot.
5. Record the position and command signals on a strip chart recorder.
6. Power down the DC power source.
7. Power down or reset motor controller.

TEST #	FREQUENCY (HZ)	AMPLITUDE (IN) ZERO TO PEAK
1	0.05	1, 2 and 5.0
2	0.25	0.1, 0.25 and 0.5
3	0.5	0.1, 0.25 and 0.5
4	1.0	0.1, 0.25 and 0.5
5	2.0	0.1, 0.25 and 0.5
6	3.0	0.1, 0.25 and 0.5
7	4.0	0.1, 0.25 and 0.5
8	5.0	0.1, 0.25 and 0.5
9	6.0	0.1, 0.25 and 0.5
10	8.0	0.1, 0.25 and 0.5

3.2 ACTUATOR STEP RESPONSE TEST

1. Install the actuator in the inertial test stand and power up the motor controller.
2. Initialize controller.
3. Apply the specified STEP command (see table) for a five cycle minimum.
4. Record the position and command signals on a strip chart recorder.
5. Power down the DC power source.
6. Power down or reset motor controller.

TEST #	FREQUENCY (HZ)	AMPLITUDE (IN) PEAK TO PEAK
1	0.3	0.25
2	0.3	0.5
3	0.3	1.0
4	0.3	2.0
5	0.3	4.0
6	0.3	6.0
7	0.3	8.0
8	0.3	10.0
9	0.3	11.0

3.3 ACTUATOR FORCE/VELOCITY TEST

1. Install the actuator in the Force/Velocity test stand and power up motor controller.

2. Initialize controller.

3 Apply the specified command (see table) for a five cycle minimum at the specified load.

4. Record the commanded and actual actuator position, and velocity on a strip chart recorder.

5. Power down the DC power source.

6. Power down or reset motor controller.

TEST #	ACTUATOR LOAD (K-lbs.)	POSITION COMMAND (±in)
1	5	5.5
2	12	5.5
3	17	5.5
4	24	5.5
5	27	5.5
6	42	5.5
7	50	5.5
8	53	5.5
9	55	5.5

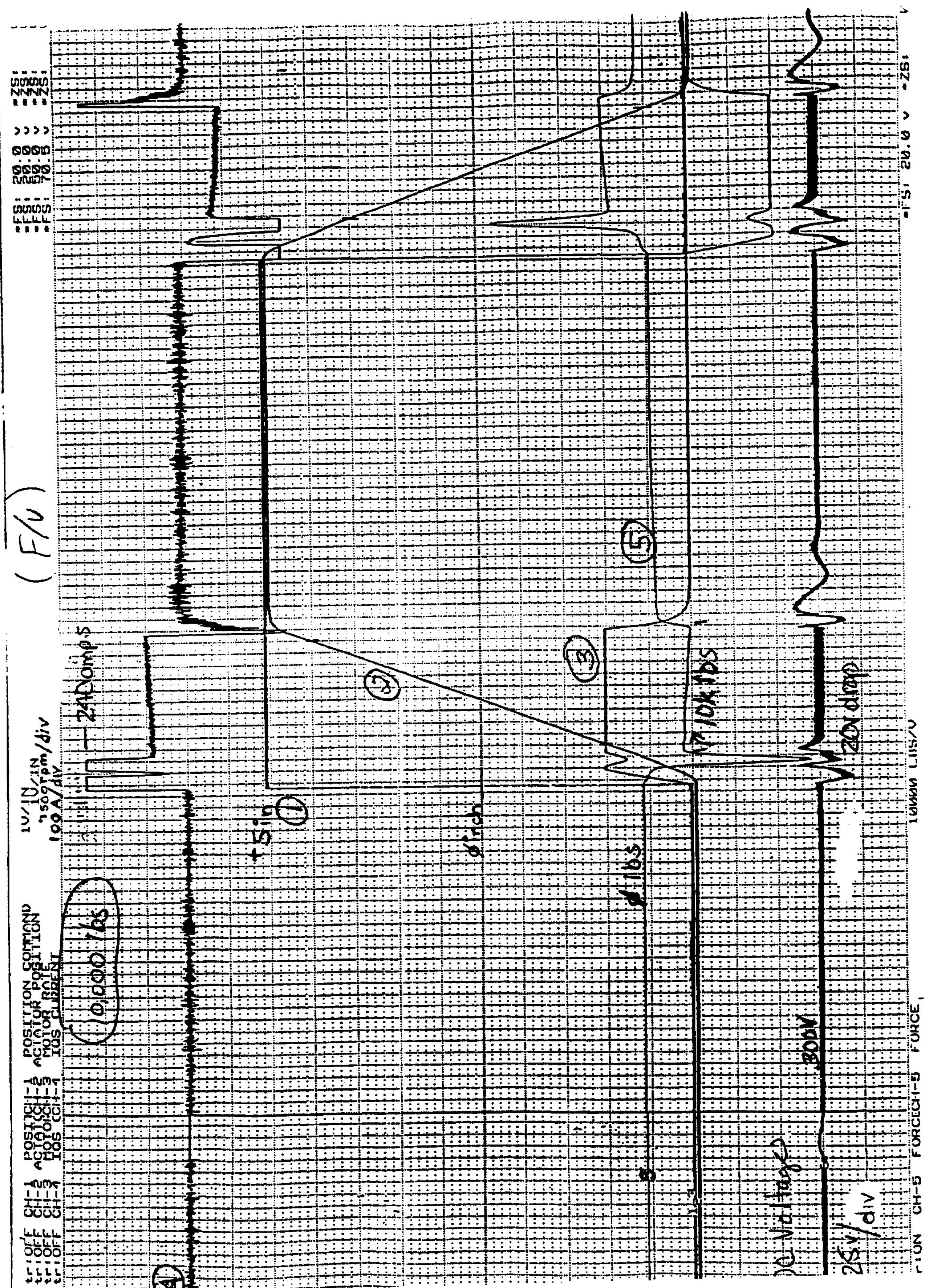
APPENDIX G

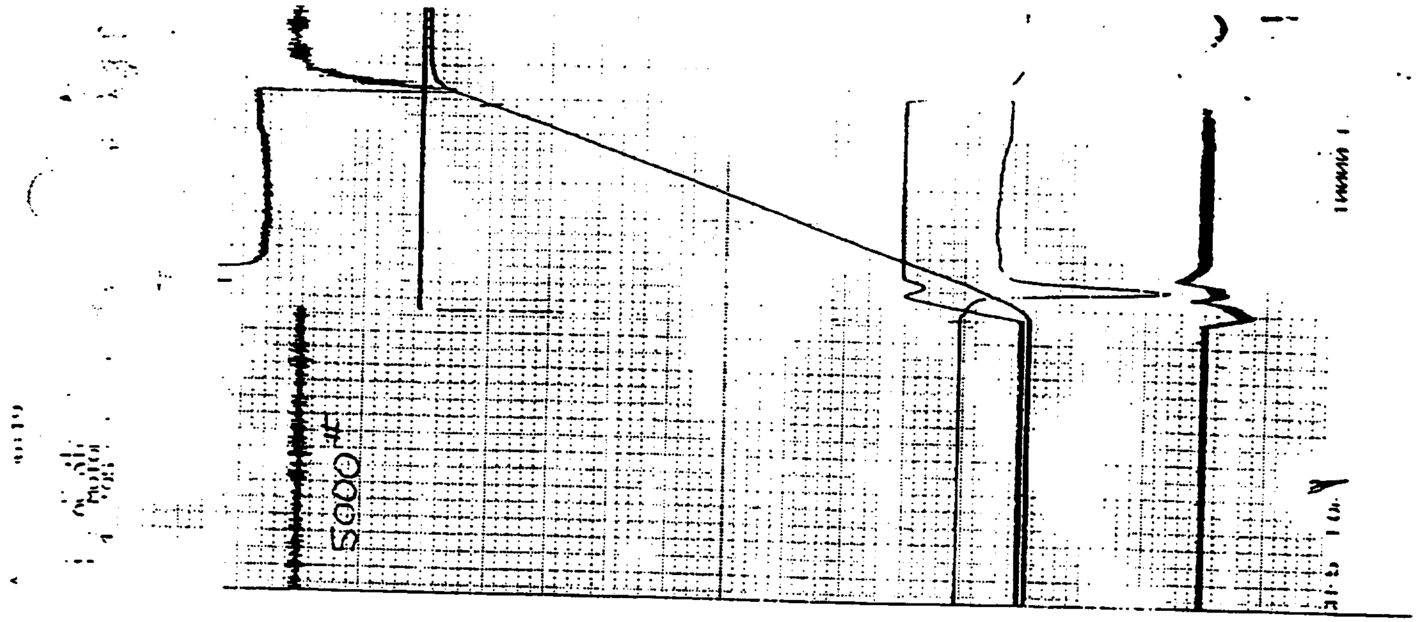
MOOG FACILITY TEST DATA

The no load test data was recorded under the following conditions:

- Kp = 13.0, Ki = 0.1, and Kr = 50.0 unless otherwise noted.
- Command and Position scales are equal on the strip charts unless otherwise noted.

SECTION 1 – FORCE-VELOCITY TEST DATA


POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
IOS CURRENT
ANALOG REAL TIME
FORCE
(F/V)
10,000 lbs
+5 in
Ø inch
Ø lbs
10K lbs
2400 amps
20 V/div
25 V/div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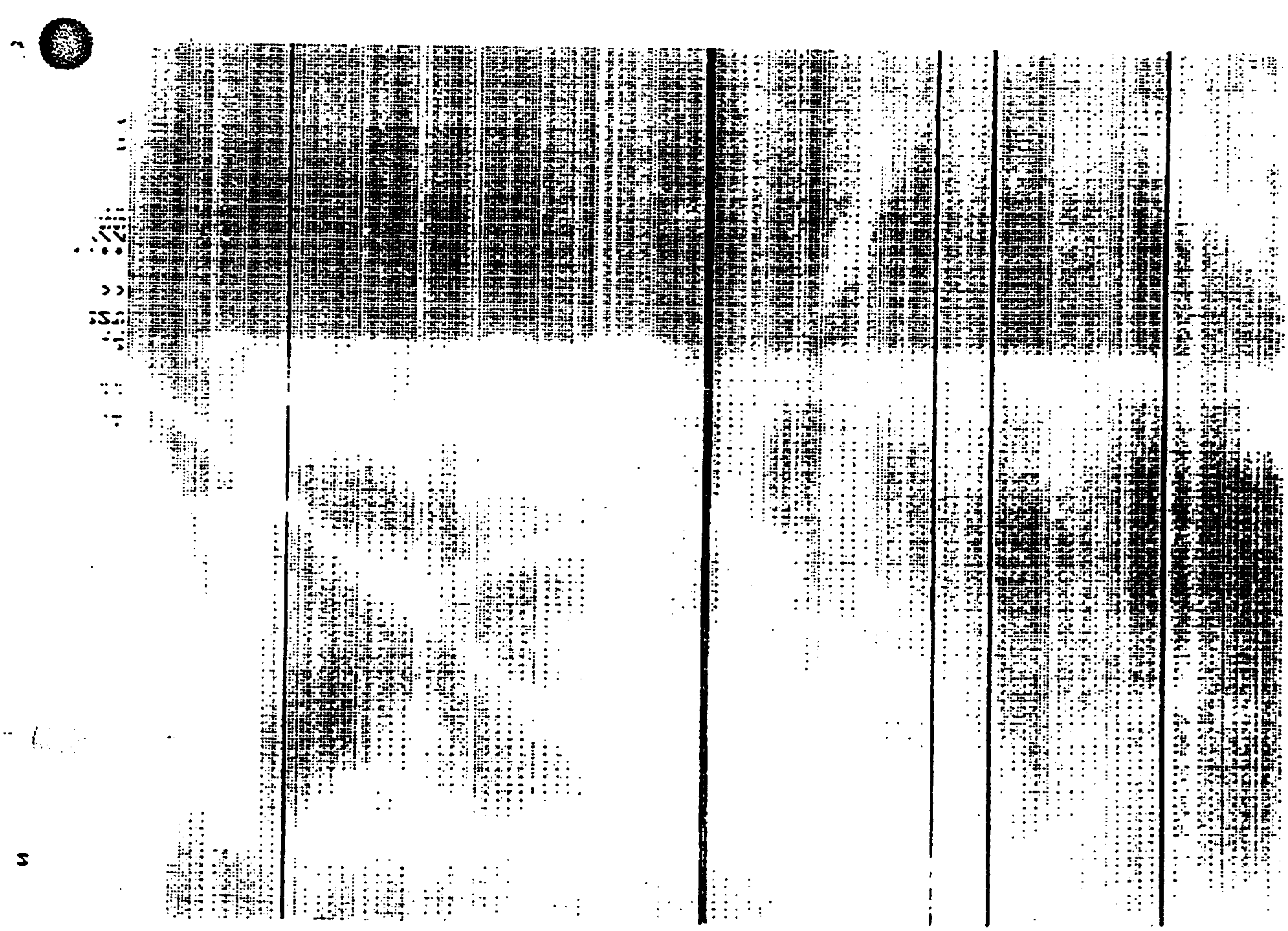
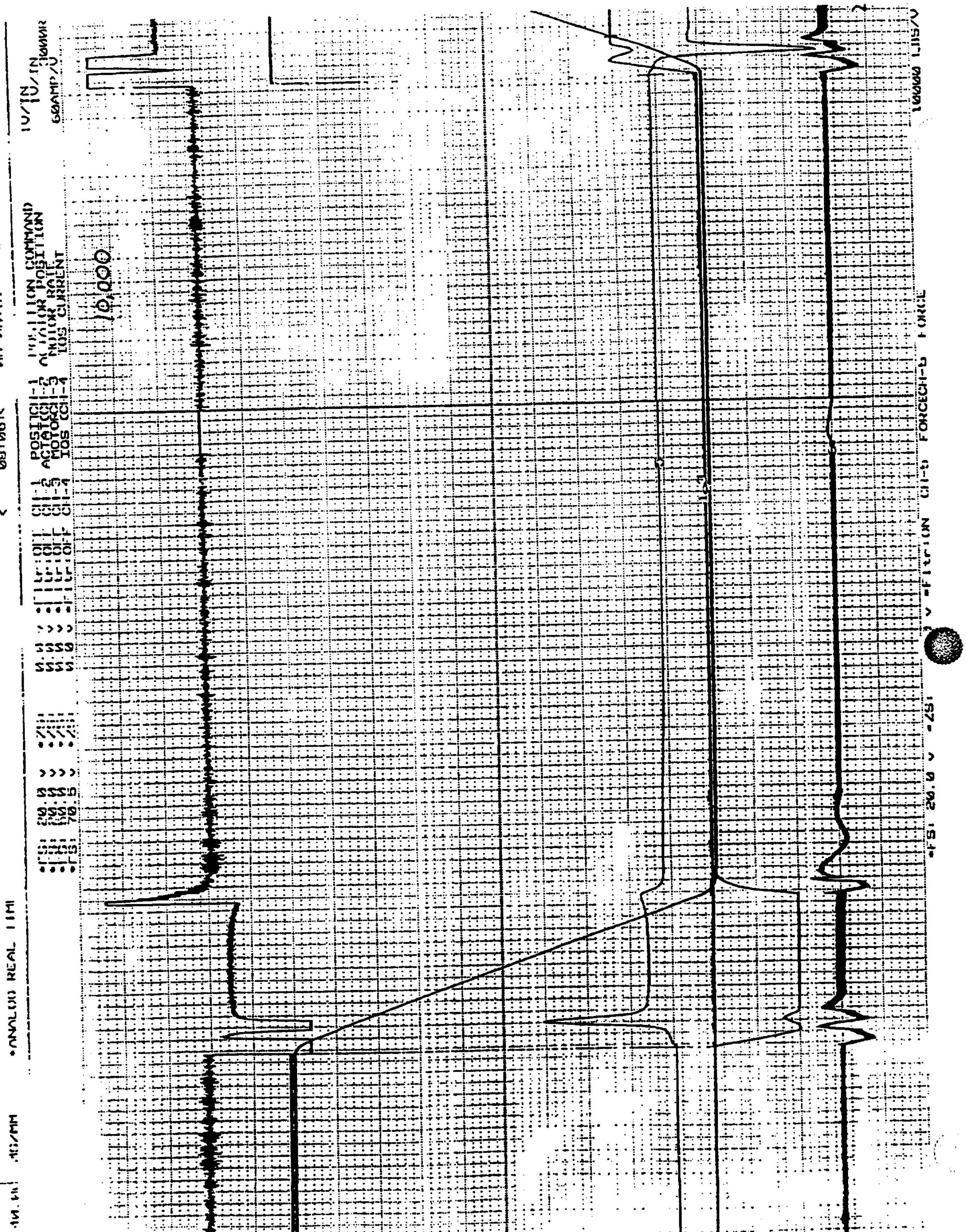
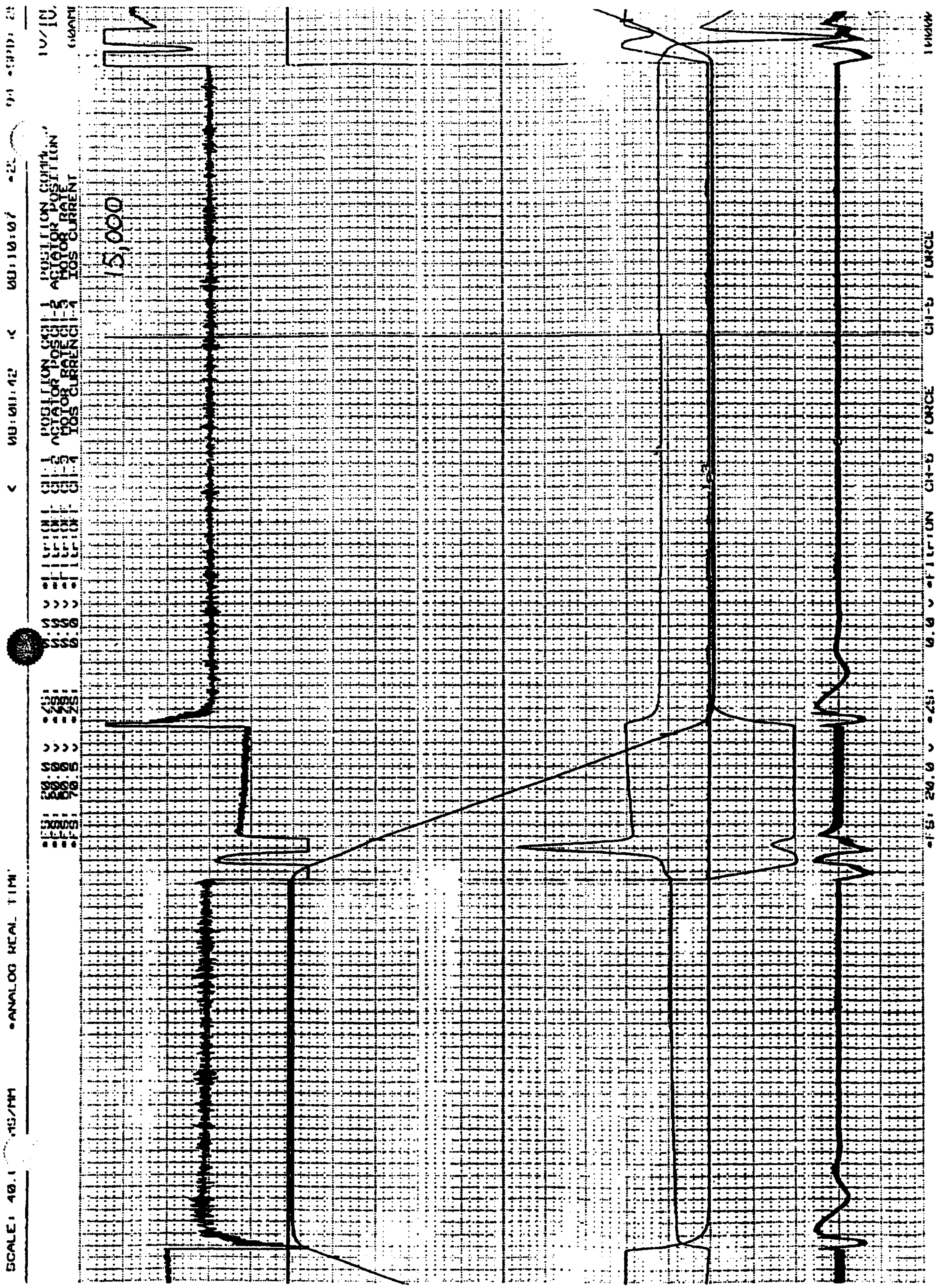
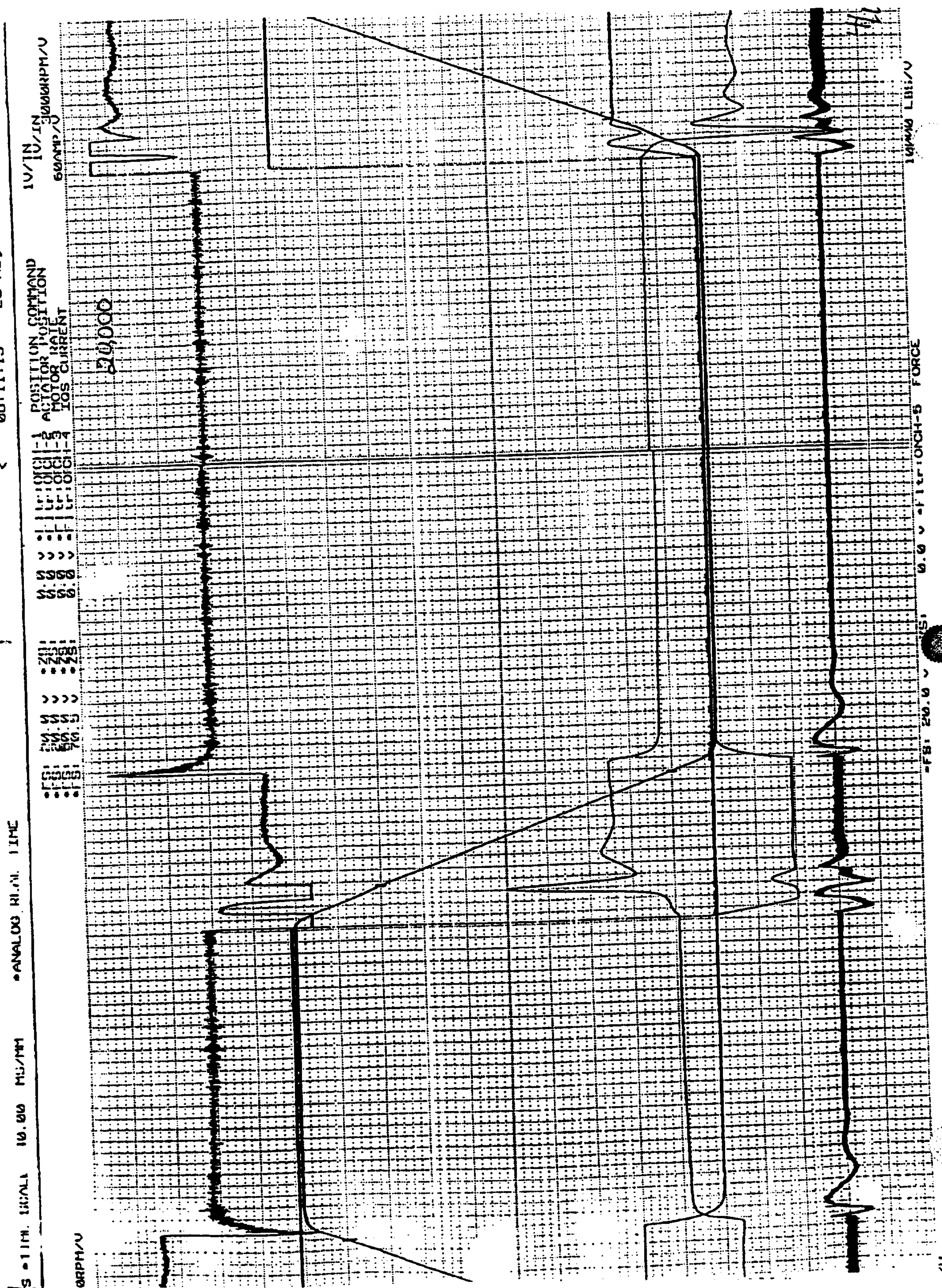
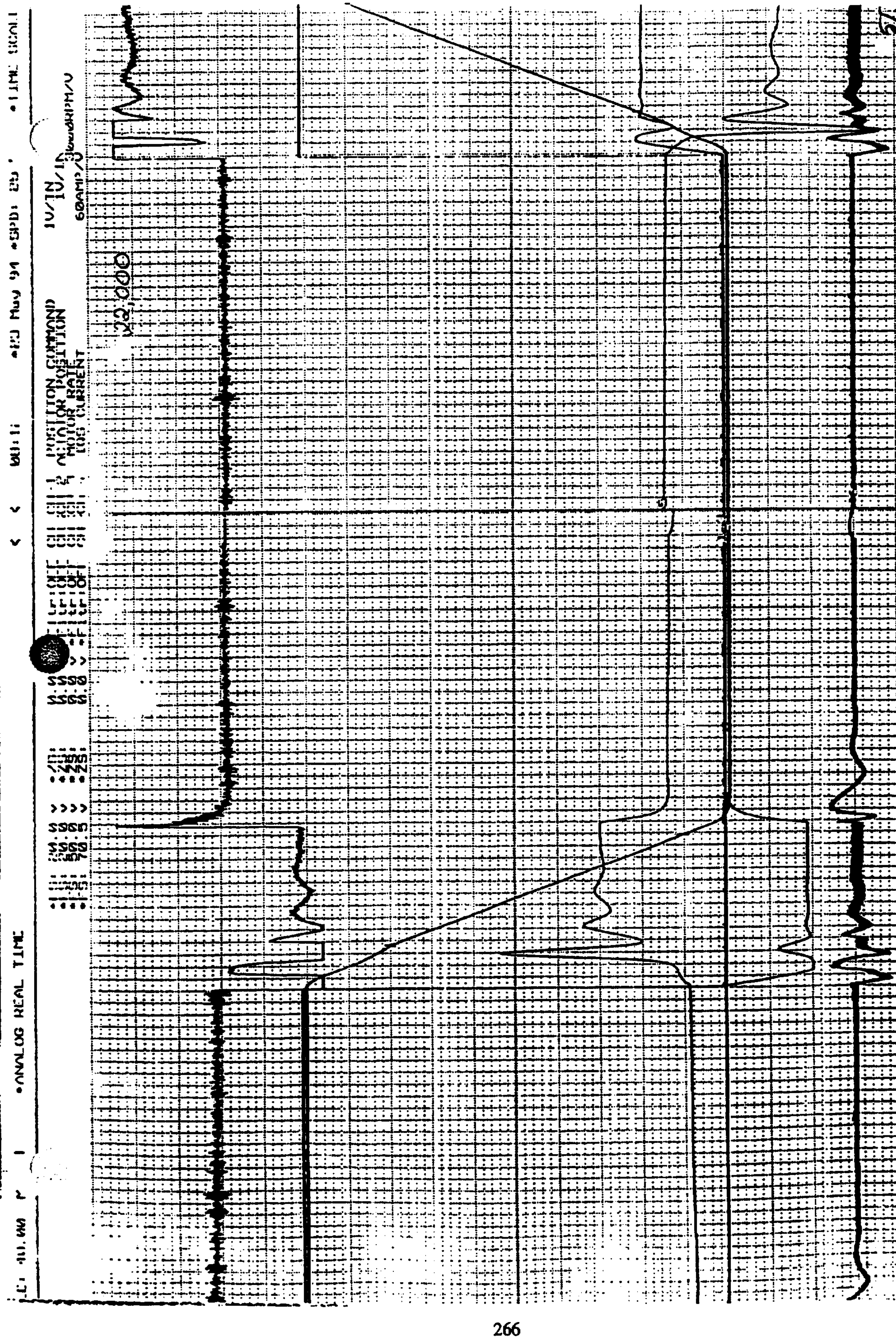


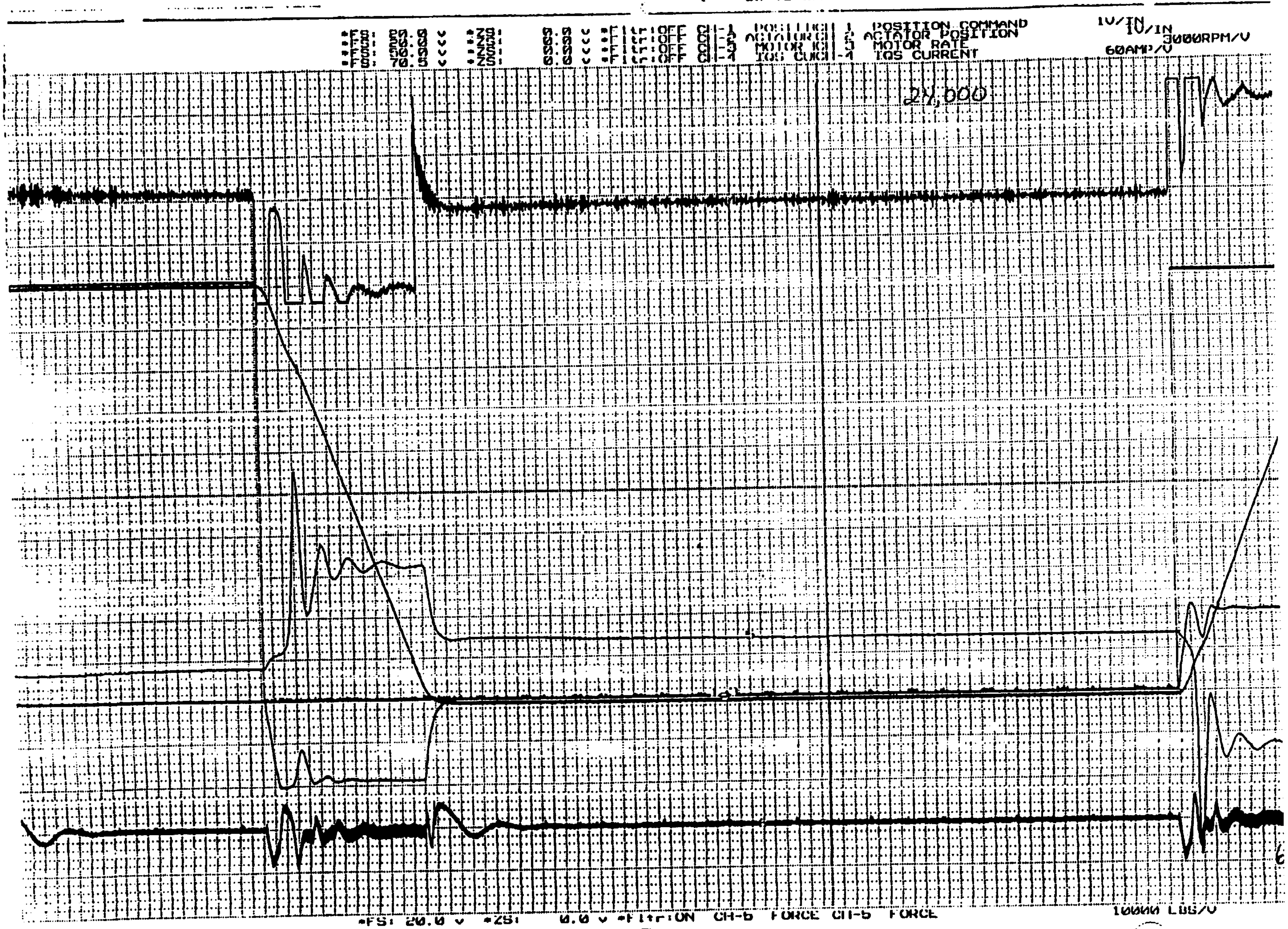

ANALOG REAL TIME
POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
IOS CURRENT
FORCE


SCALE: 40.1
•ANALOG REAL TIME
POSITION COMM.
ACTUATOR POSITION
MOTOR RATE
IOS CURRENT
15,000
CH-5 FORCE
CH-6 FORCE



*ANALOG REAL TIME
00:11:19
*23 May 91 *SPD:
MM/S *TIME
10.00 MS/MM
POSITION COMMAND
ACTATOR POSITION
MOTOR RATE
IOS CURRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
20,000
FORCE
10000 LBS/V


ANALOG REAL TIME
POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
LOG CURRENT
22,000
FORCE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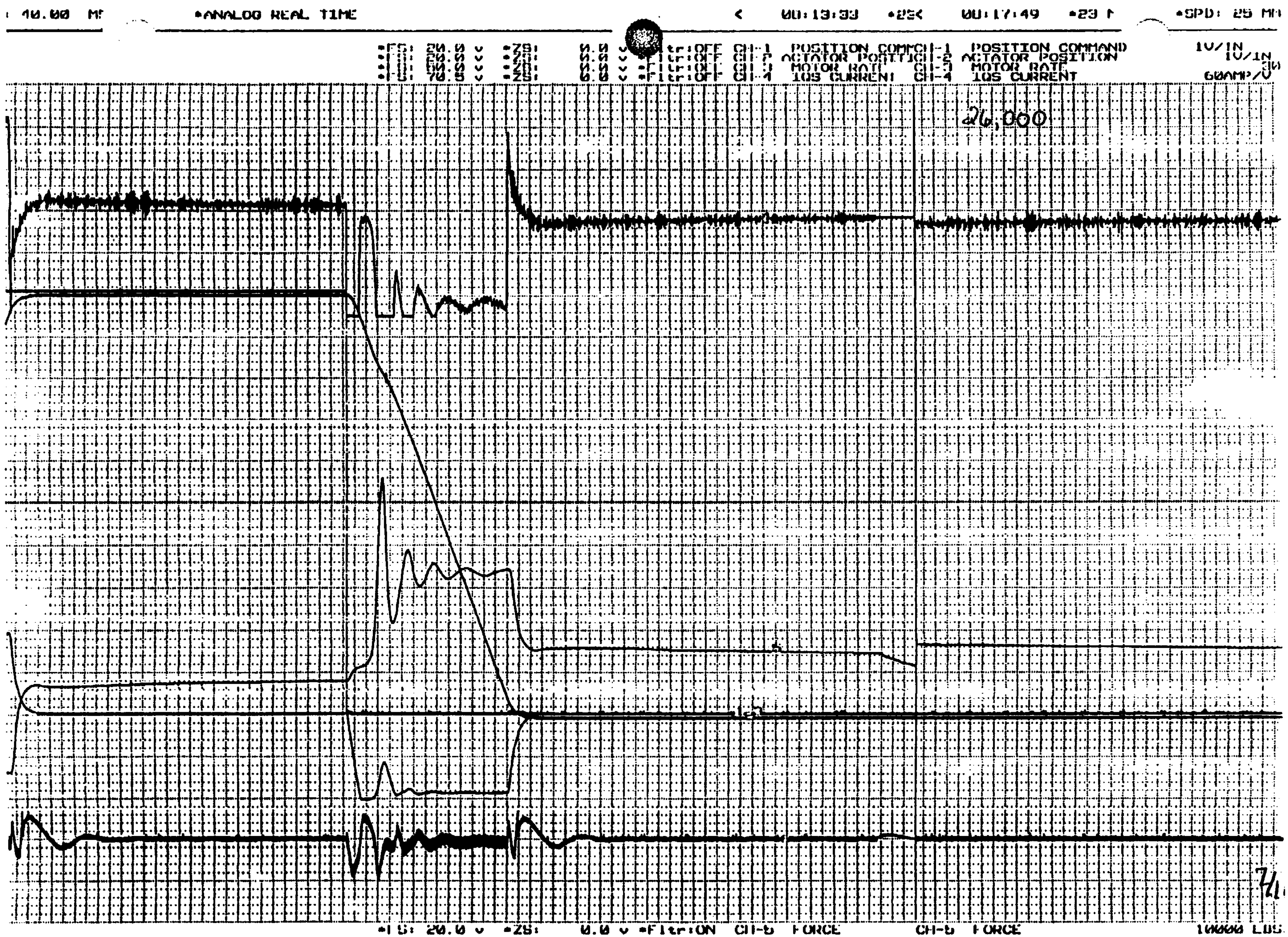
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-2 ACTATOR POSITION 10/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
24,000
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-6 FORCE CH-6 FORCE 10000 LBS/V


40.00 MS
*ANALOG REAL TIME
< 00:13:33 *25< 00:17:49 *23 > *SPD: 25 MM
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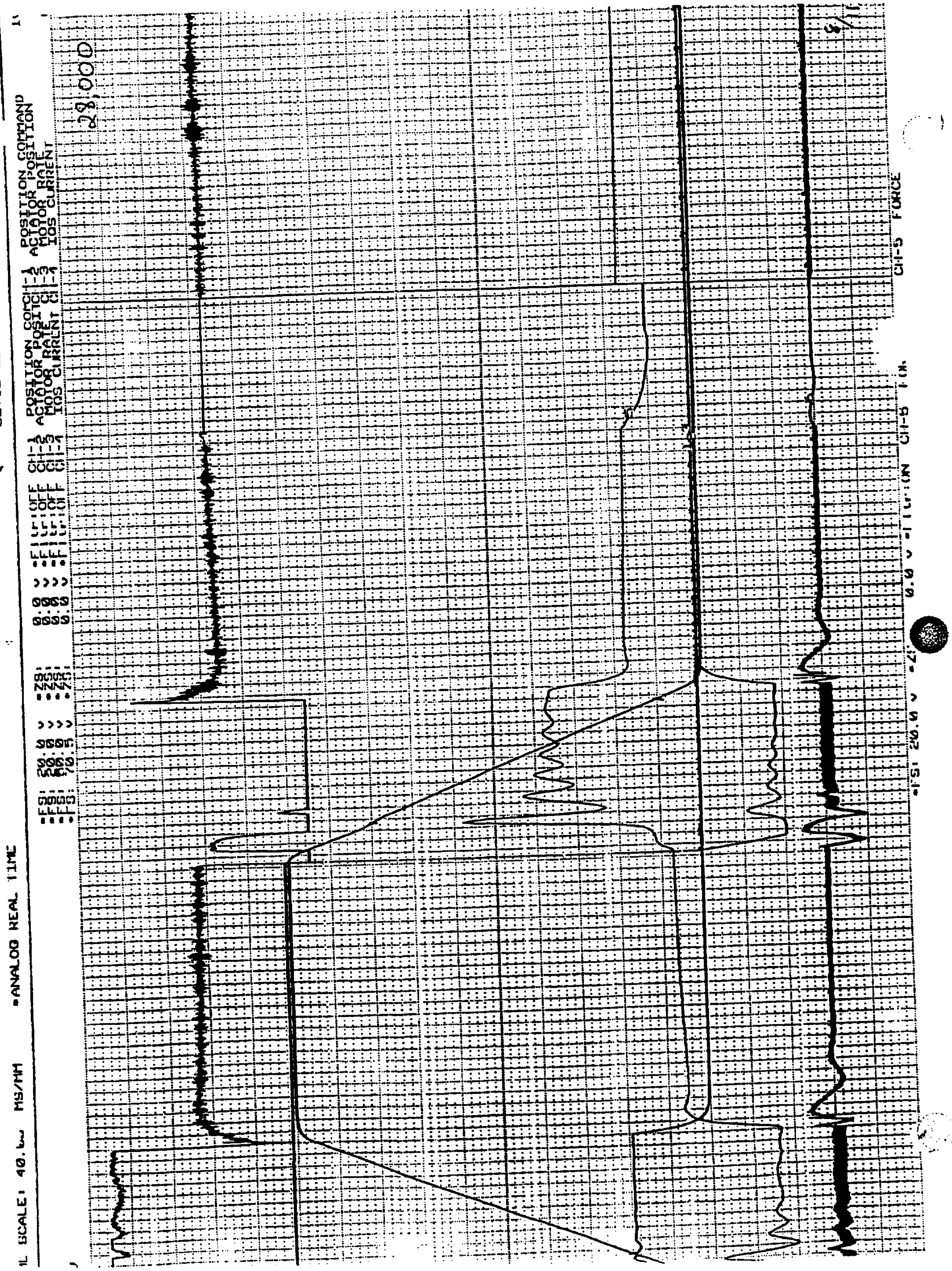
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-2 ACTATOR POSITICH-2 ACTATOR POSITION 1V/IN
*FS: 60.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE CH-3 MOTOR RATE
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 1QS CURRENT CH-4 1QS CURRENT 60AMP/V
26,000
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-6 FORCE CH-6 FORCE 10000 LBS
7/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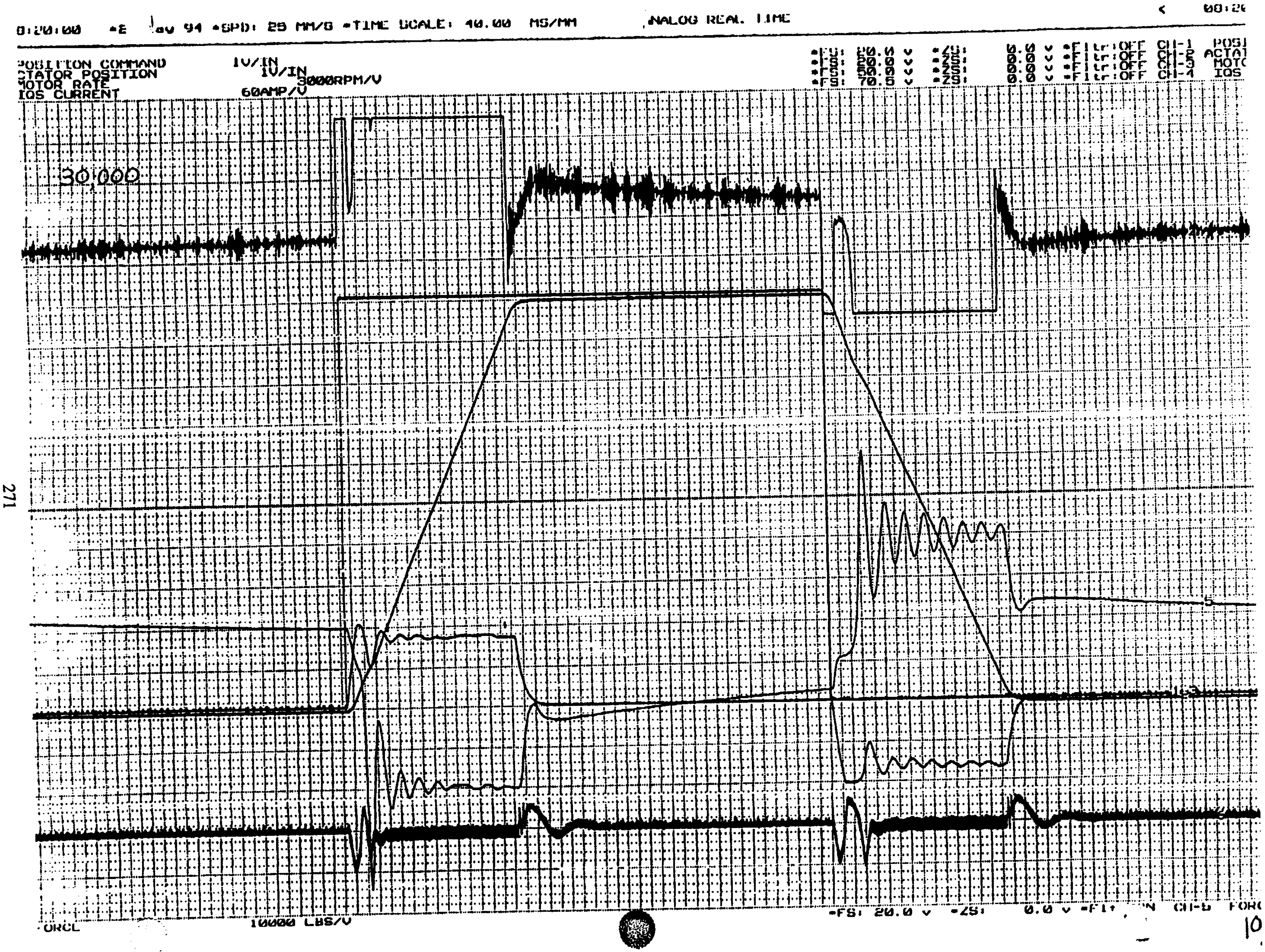
*ANALOG REAL TIME
08:10:00
08:10:51
POSITION COMMAND
ACTATOR POSITION
MOTOR RATE
IOS CURRENT
CH-5 FORCE
28,000

MM/S •TIM ALE: 40.00 MS/MM
•ANALOG REAL TIME
00:19:01
•SPD: 25
•FS: 20.0 v •ZS: 0.0 v •Fltr:OFF CH-1 POSITION COMMAND
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-2 ACTATOR POSITION
•FS: 60.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IOS CURRENT
1V/IN
1V/IN
60AMP/V
1000RPM/V
LBS/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE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STATOR POSITION 1V/IN
MOTOR RATE 3000RPM/V
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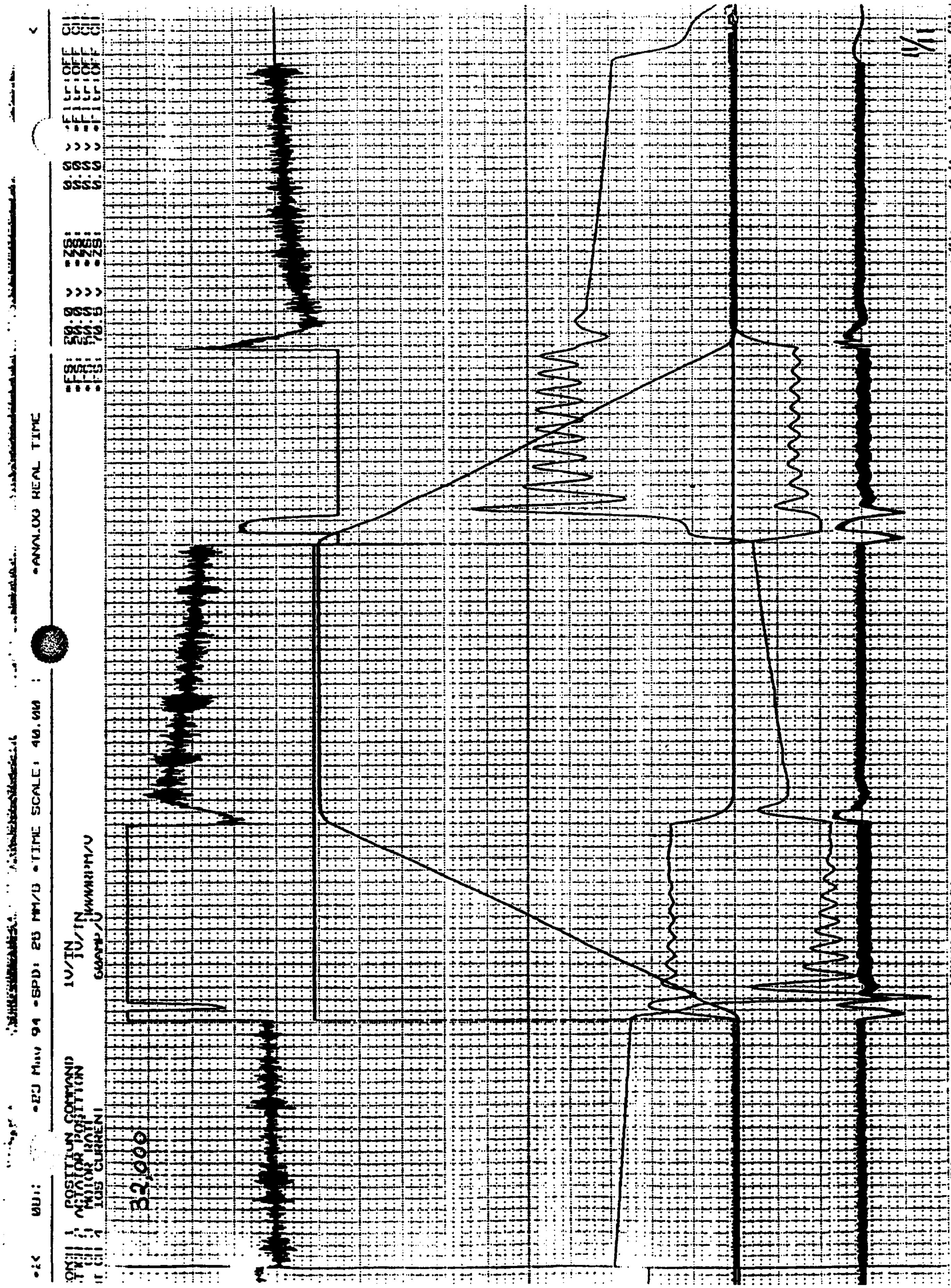
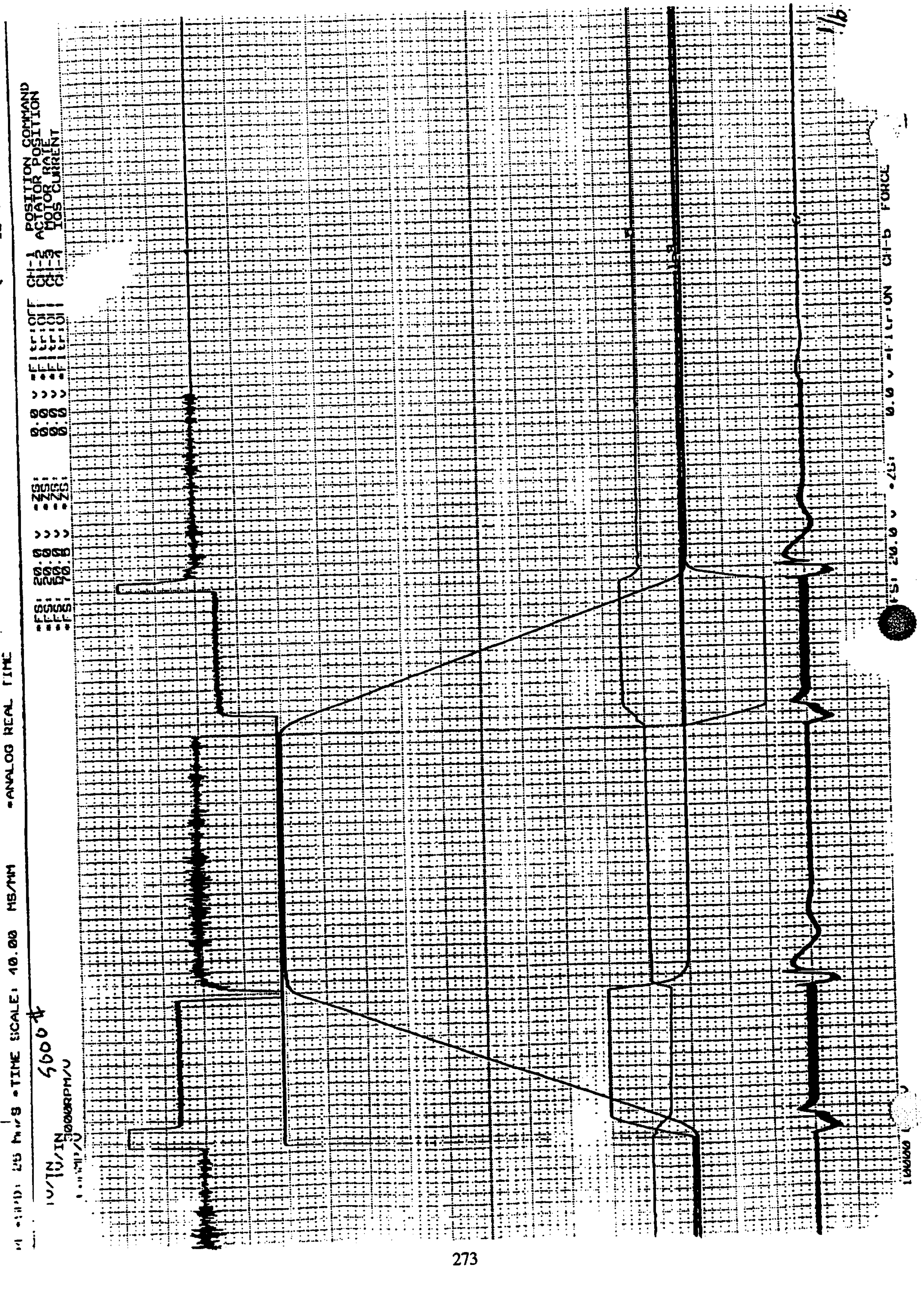
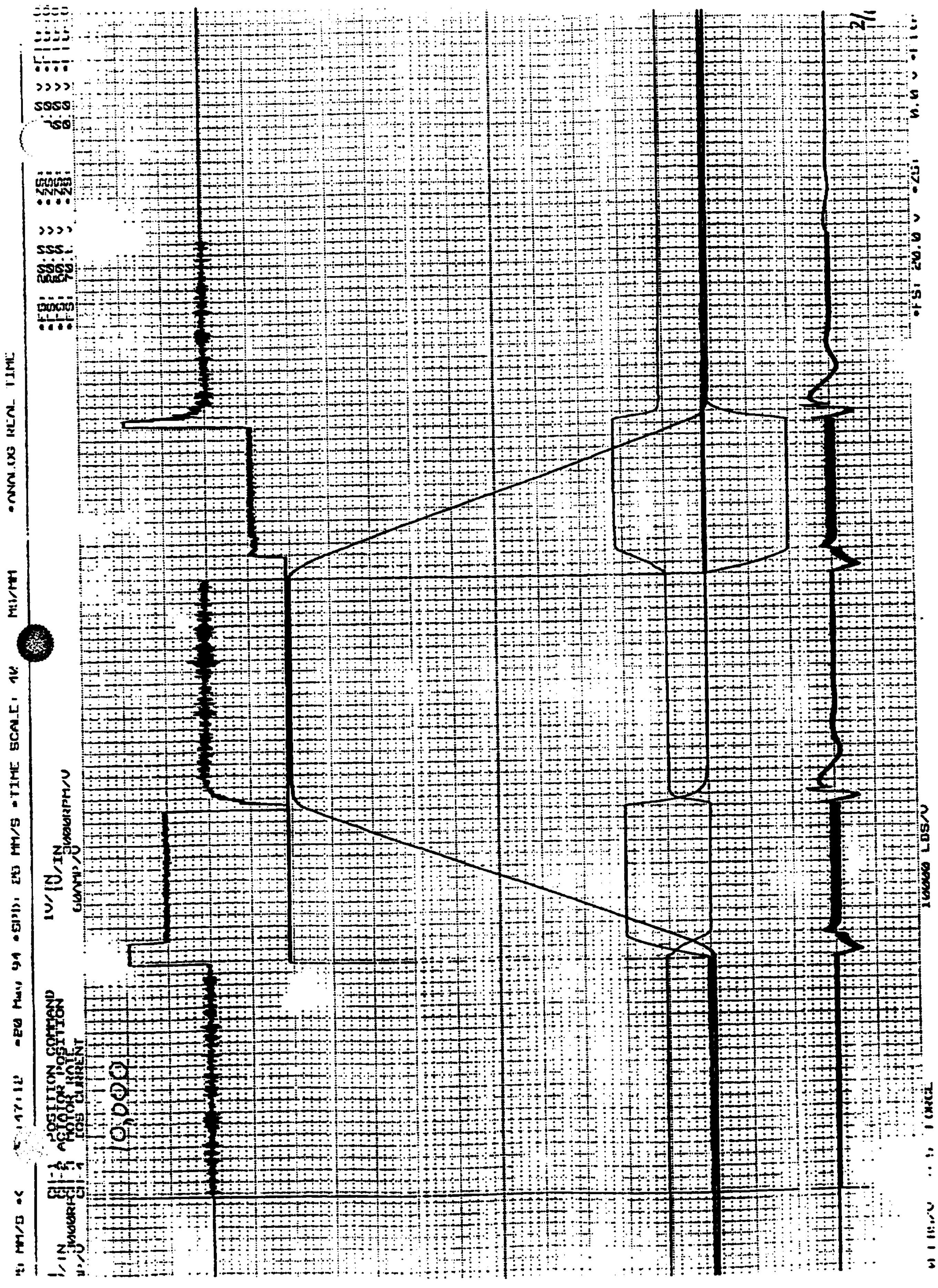
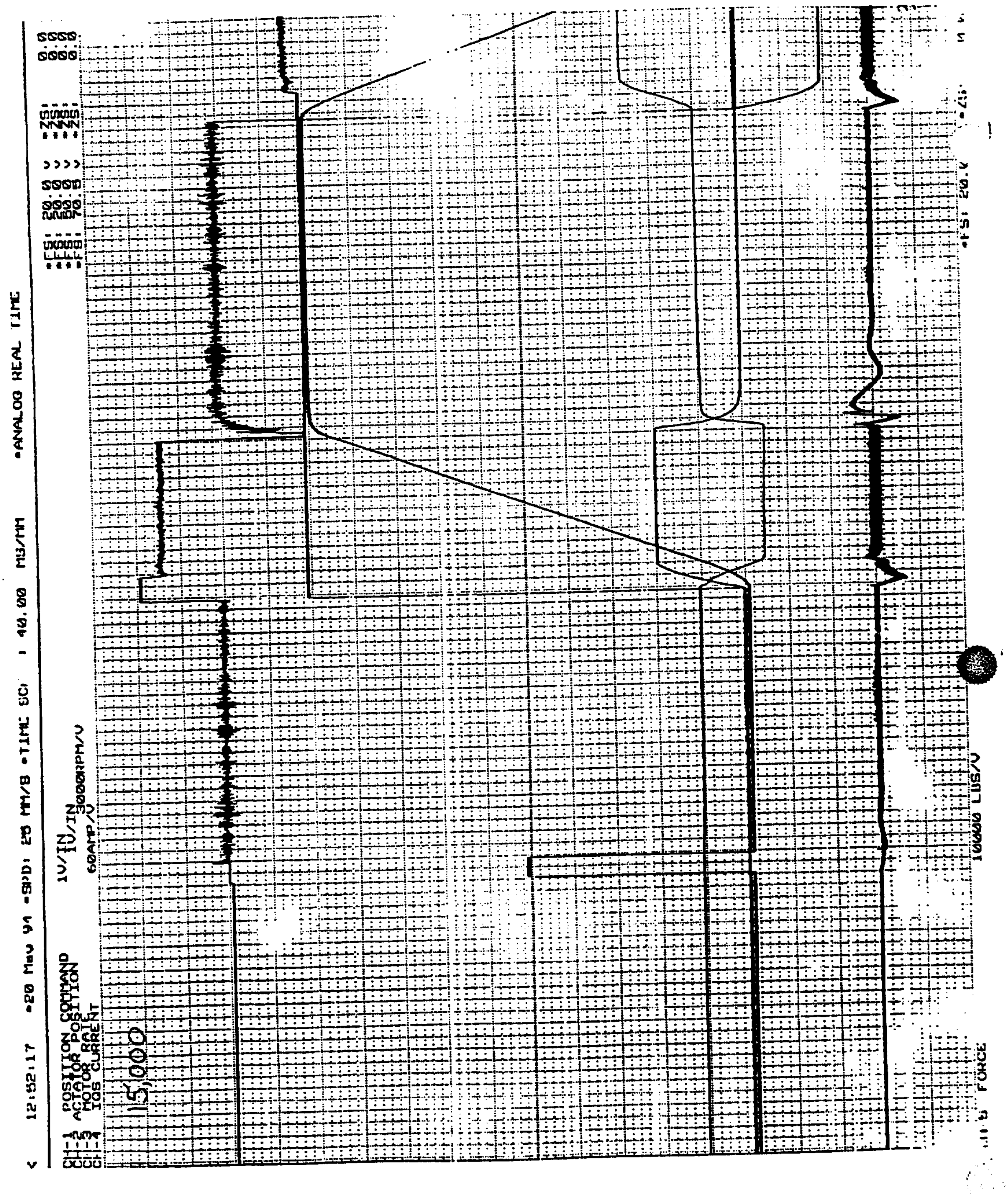
30,000
10000 LBS/V
ANALOG REAL TIME


POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
105 CURRENT
32,000
ANALOG REAL TIME
CH-5 FORCE

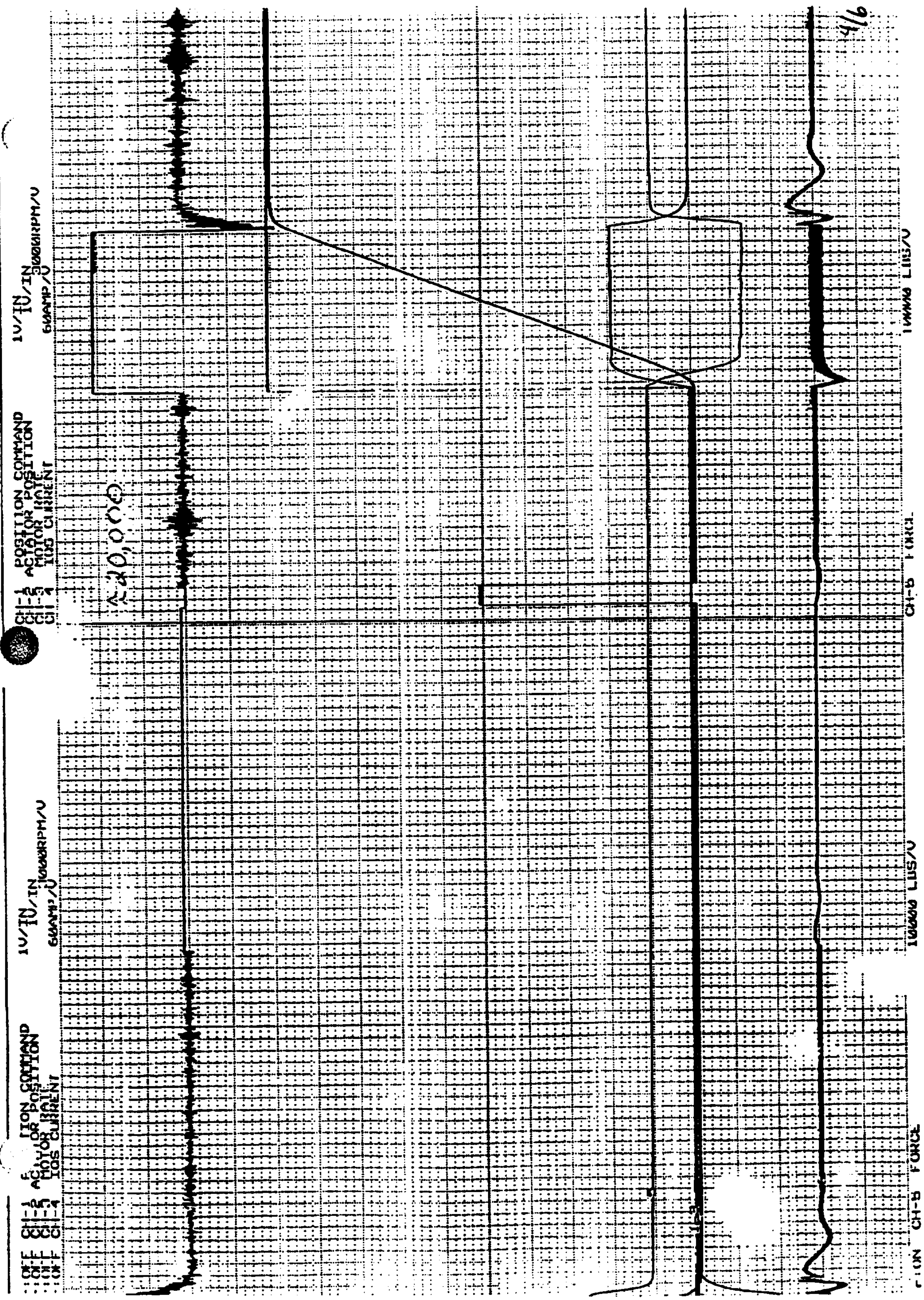

*TIME SCALE: 10.00 MS/MM
*ANALOG REAL TIME
12:46:07
*20 May 91
CH-1 POSITION COMMAND
CH-2 ACTATOR POSITION
CH-3 MOTOR RATE
CH-4 IGS CURRENT
CH-6 FORCE
5600#
3000RPM/V

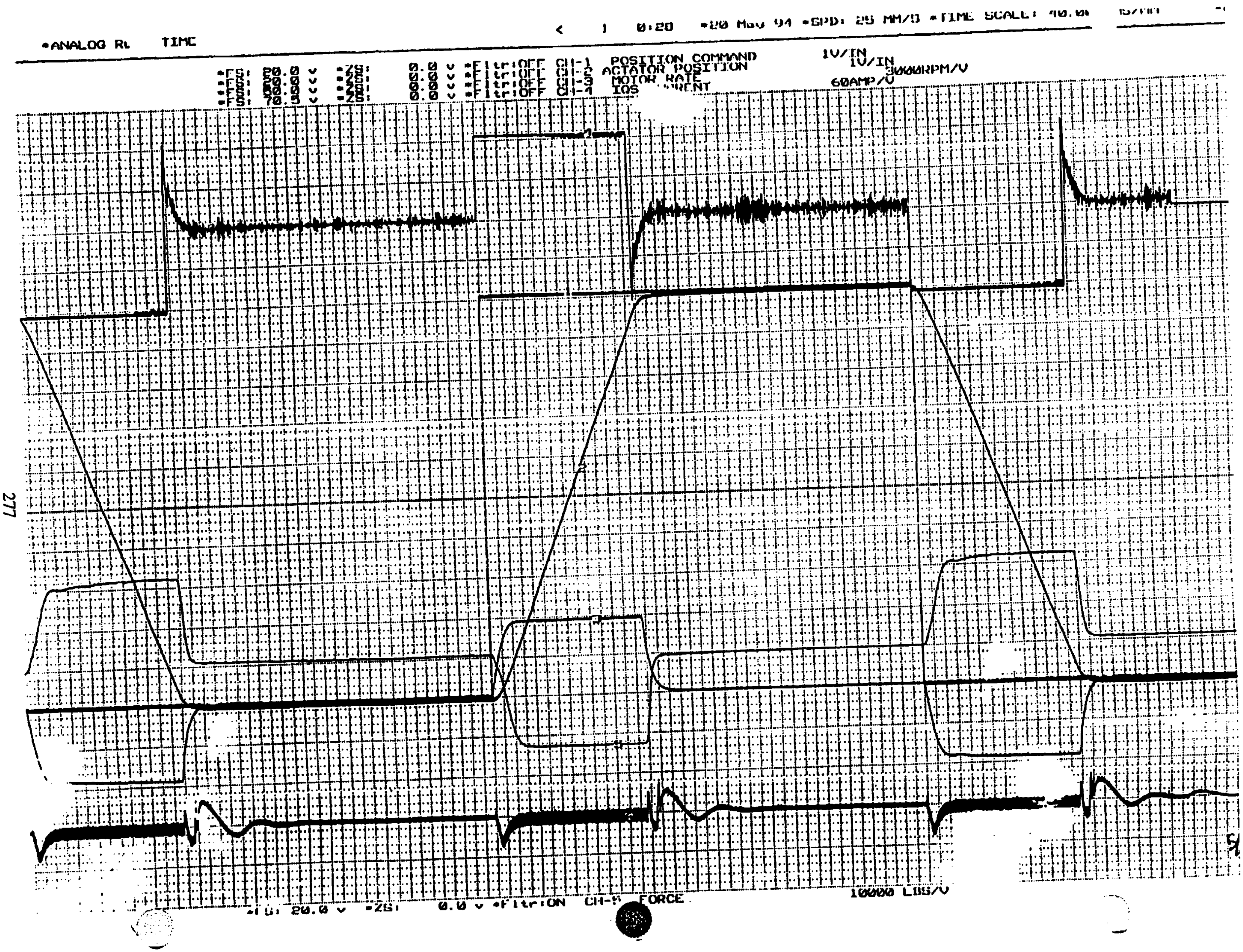


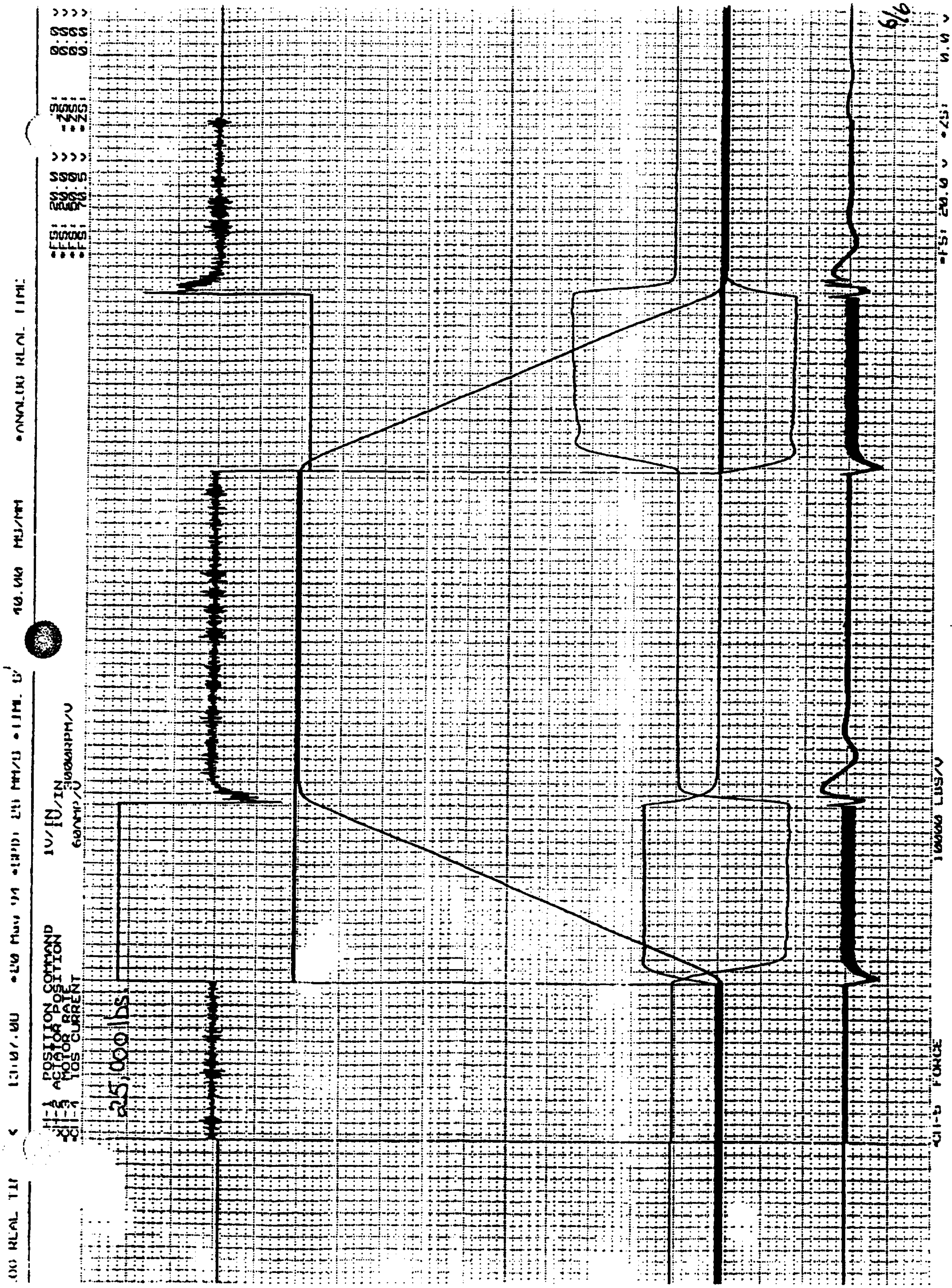
ANALOG REAL TIME
POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
IOS CURRENT
FORCE
100000 LBS/V



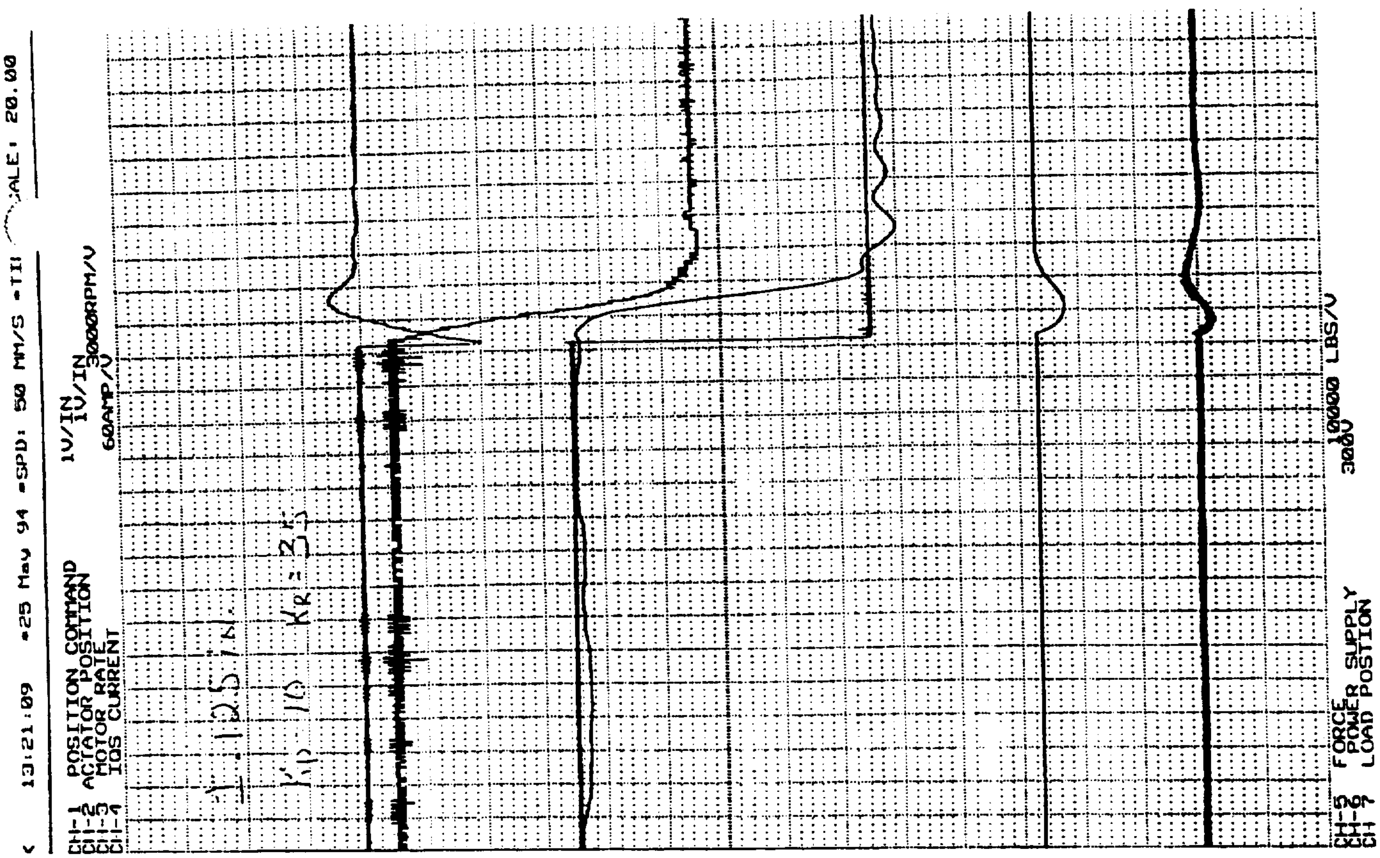
12:52:17 •20 May 94 •SPD: 25 MM/S •TIME SC: 1 10.00 MS/MM •ANALOG REAL TIME
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IGS CURRENT 60AMP/V
15,000
FORCE 10000 LBS/V

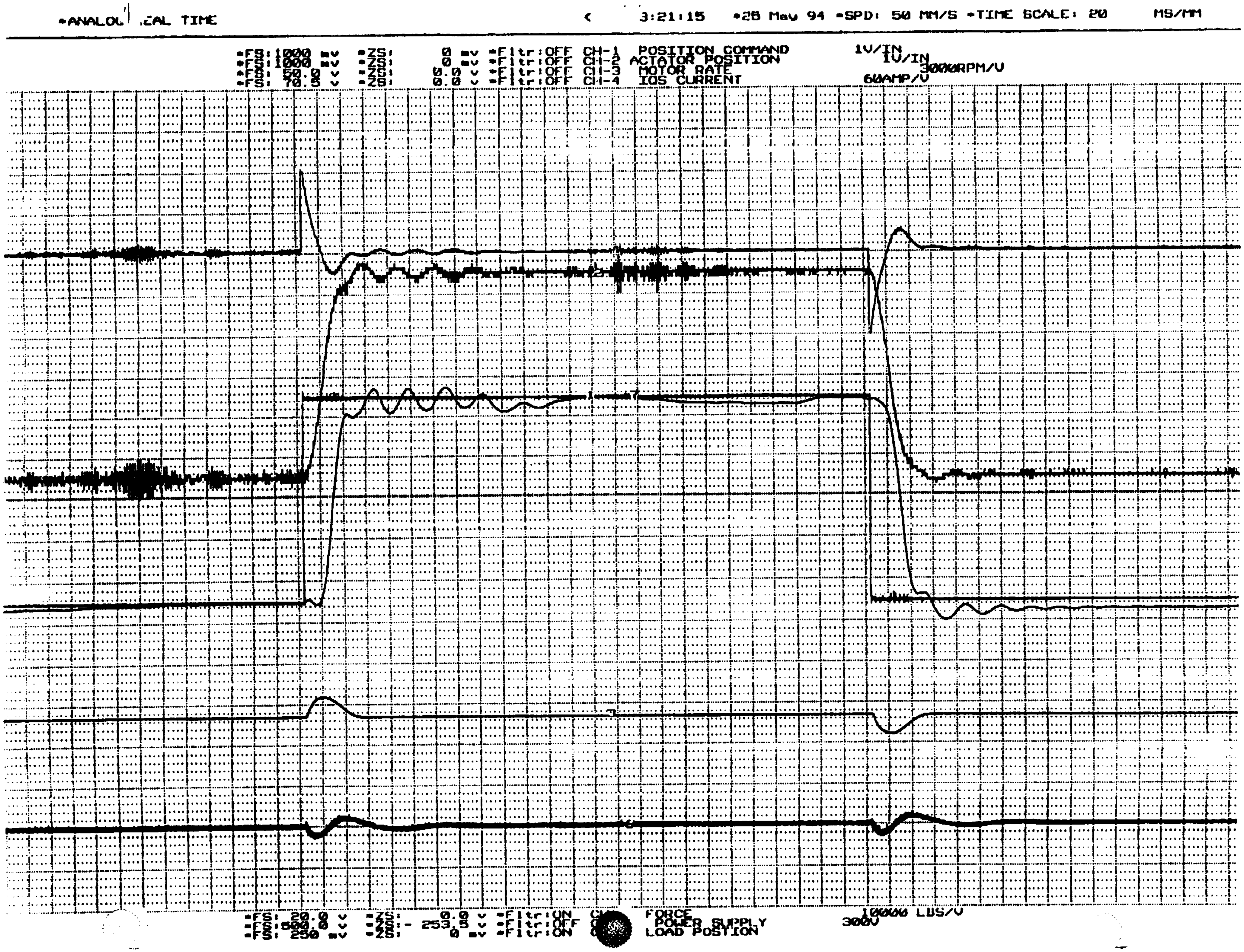

•28 May 91 •SPD: 25 MM/S •TIME SCALE: 10.
CH-1
CH-2 ACTUATOR POSITION
CH-3 MOTOR RATE
CH-4 IGS CURRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
CH-6 FORCE
10000 LBS/V
13:00:17 •28 May 91 •SPD: 25 MM/S •TIME 10.00 MS
CH-1 POSITION COMMAND
CH-2 ACTUATOR POSITION
CH-3 MOTOR RATE
CH-4 IGS CURRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
~20,000
CH-6 FORCE
10000 LBS/V
4/6

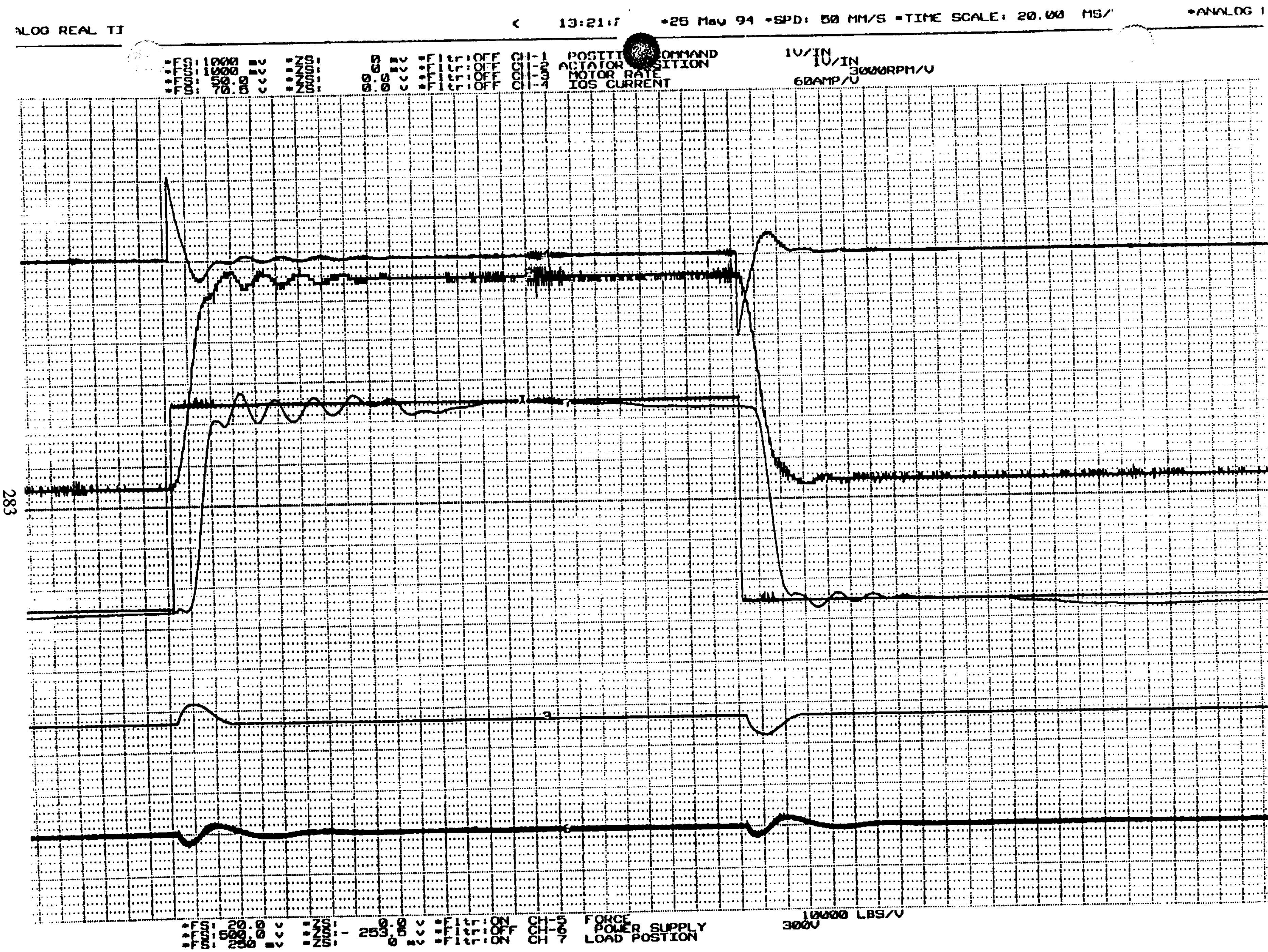

*ANALOG Rι TIME
< 1 0:20 *20 May 94 *SPD: 25 MM/S *TIME SCALE: 40.0
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IOS 60AMP/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE 10000 LBS/V


POSITION COMMAND
ACTATOR POSITION
MOTOR RATE
TOS CURRENT
25,000 lbs.
FORCE
10000 LBS/V

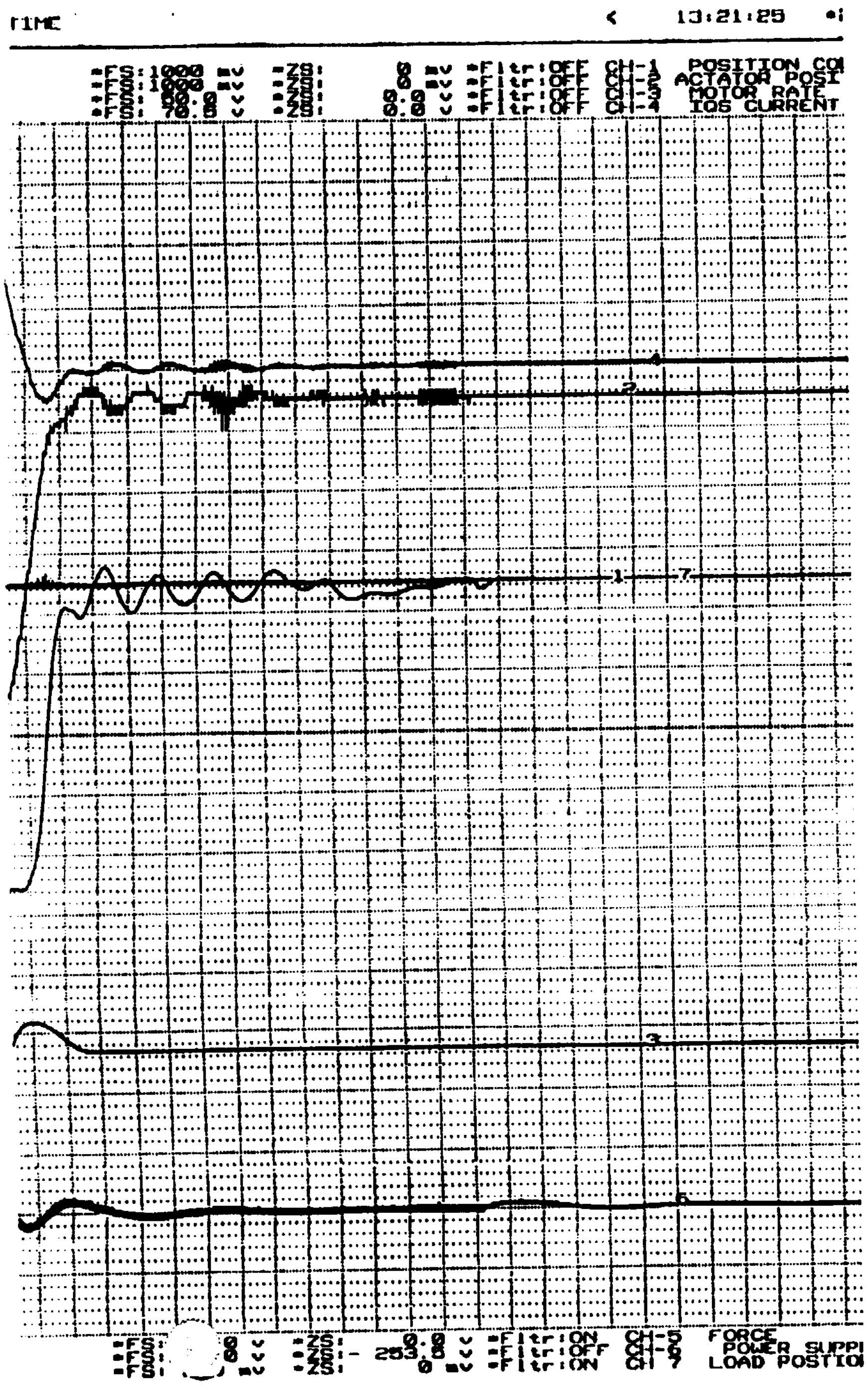
SECTION 2 – STEP RESPONSE TEST DATA

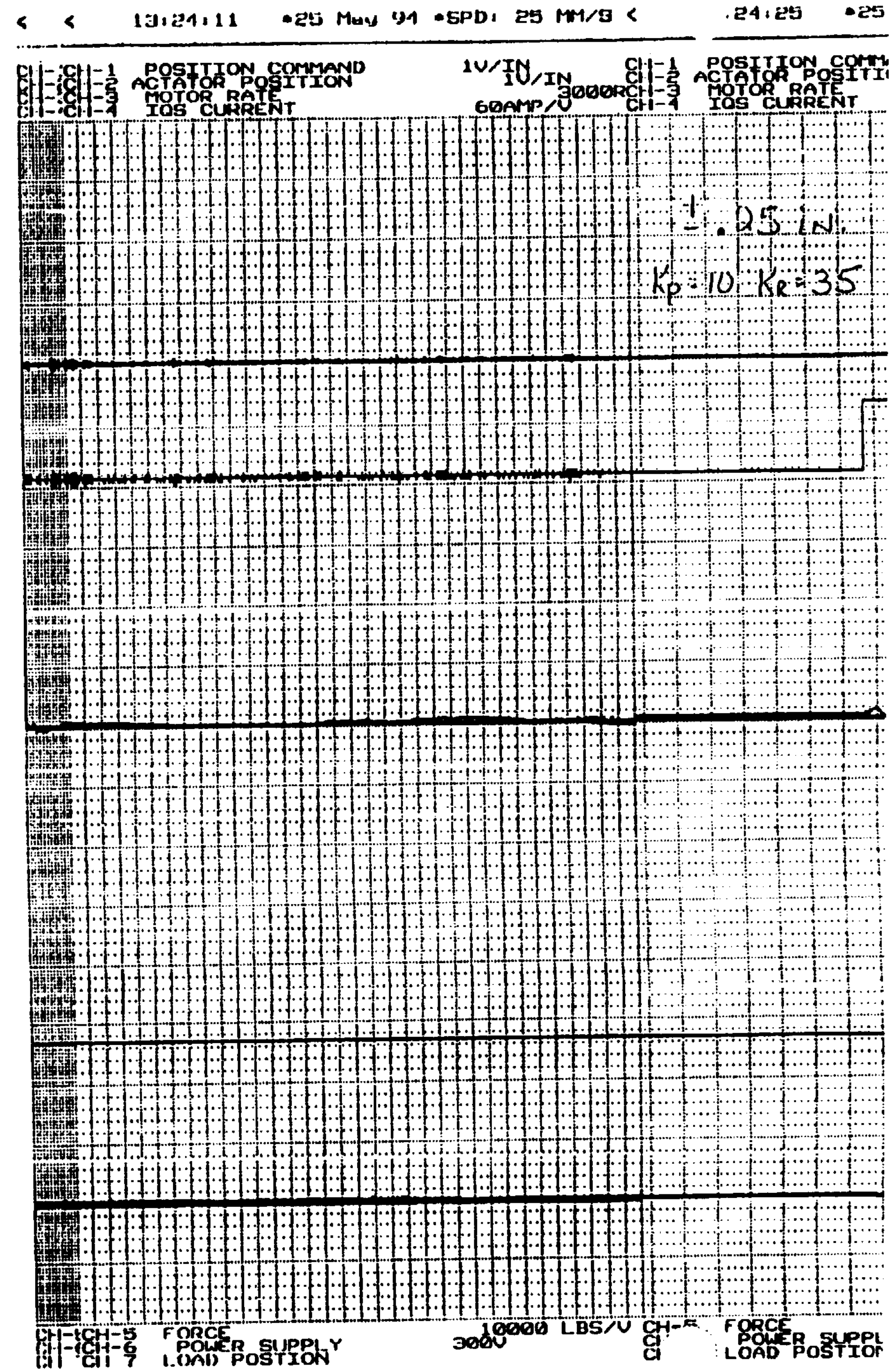

13:21:09 •25 May 94 •SPD: 50 MM/S •TI
ALE: 20.00
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IQS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
CH-6 POWER SUPPLY 300V
CH 7 LOAD POSTION

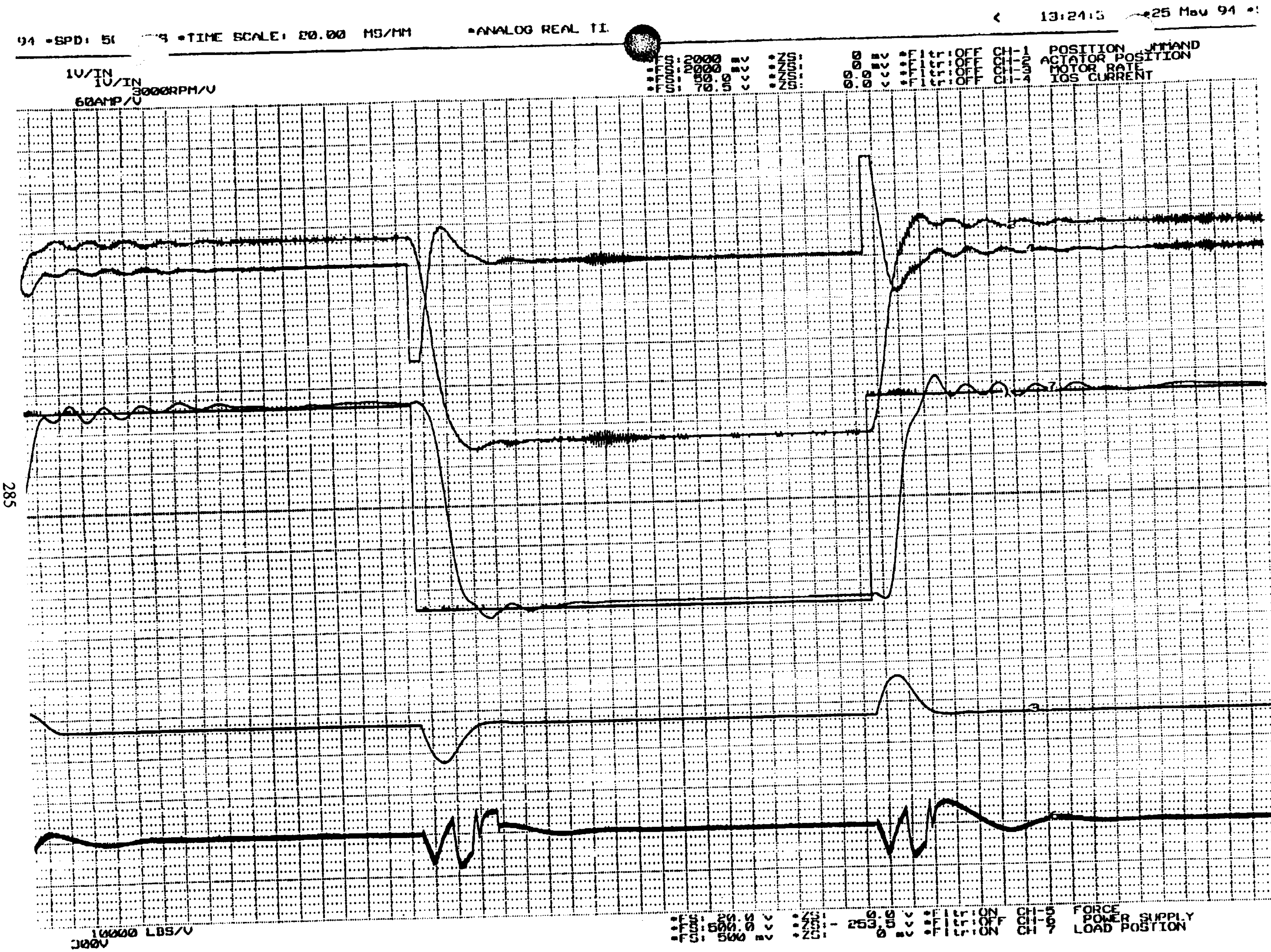

*ANALOG REAL TIME
3:21:15 *28 May 94 *SPD: 50 MM/S *TIME SCALE: 20 MS/MM
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IOS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON FORCE 10000 LBS/V
*FS:500.0 v *ZS:- 253.5 v *Fltr:OFF POWER SUPPLY 300V
*FS: 250 mv *ZS: 0 mv *Fltr:ON LOAD POSITION

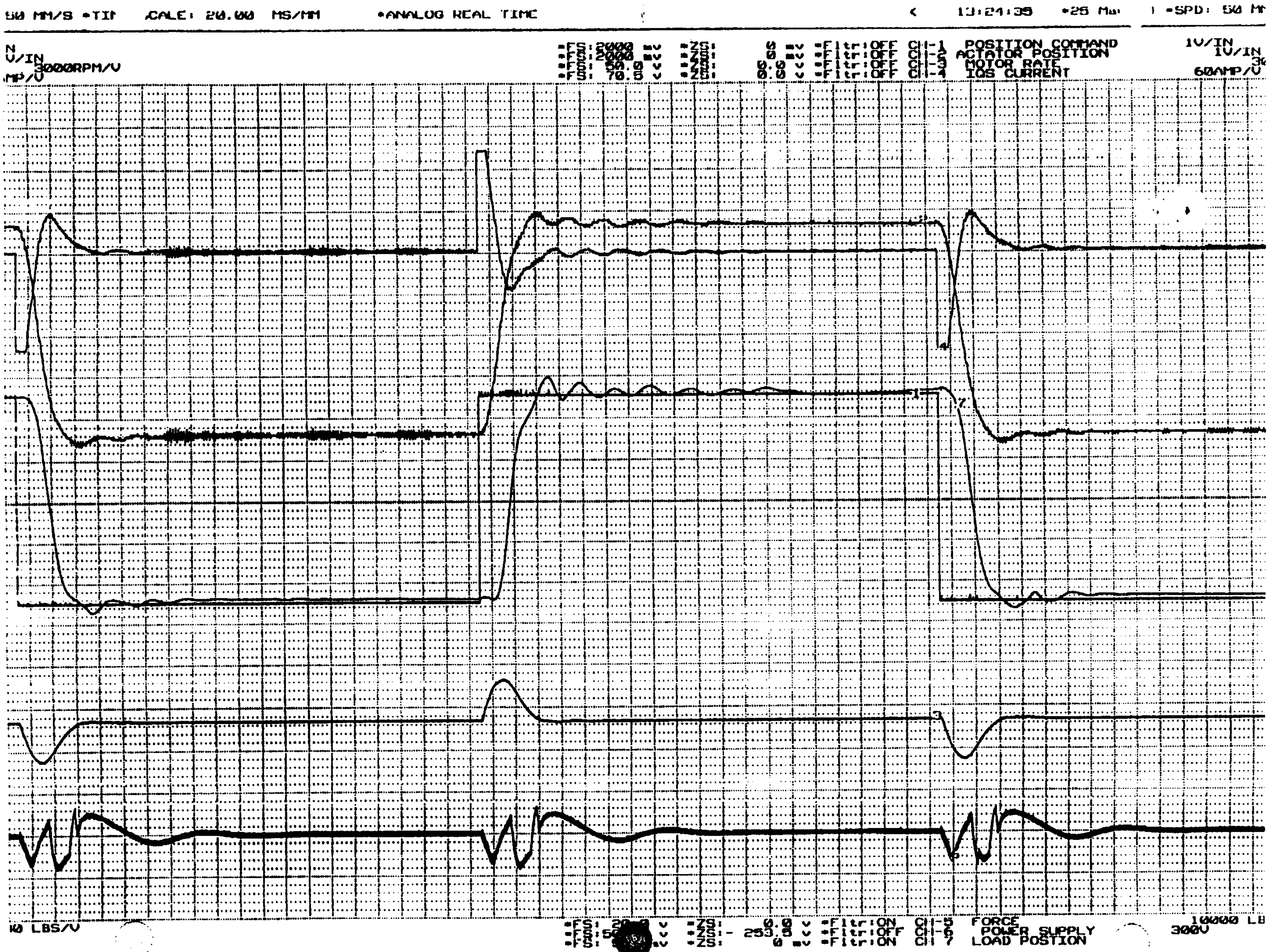


ALOG REAL TI
< 13:21:? *25 May 94 *SPD: 50 MM/S *TIME SCALE: 20.00 MS/
*ANALOG I
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IOS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE 10000 LBS/V
*FS:500.0 v *ZS:- 253.5 v *Fltr:OFF CH-6 POWER SUPPLY 300V
*FS: 250 mv *ZS: 0 mv *Fltr:ON CH 7 LOAD POSTION

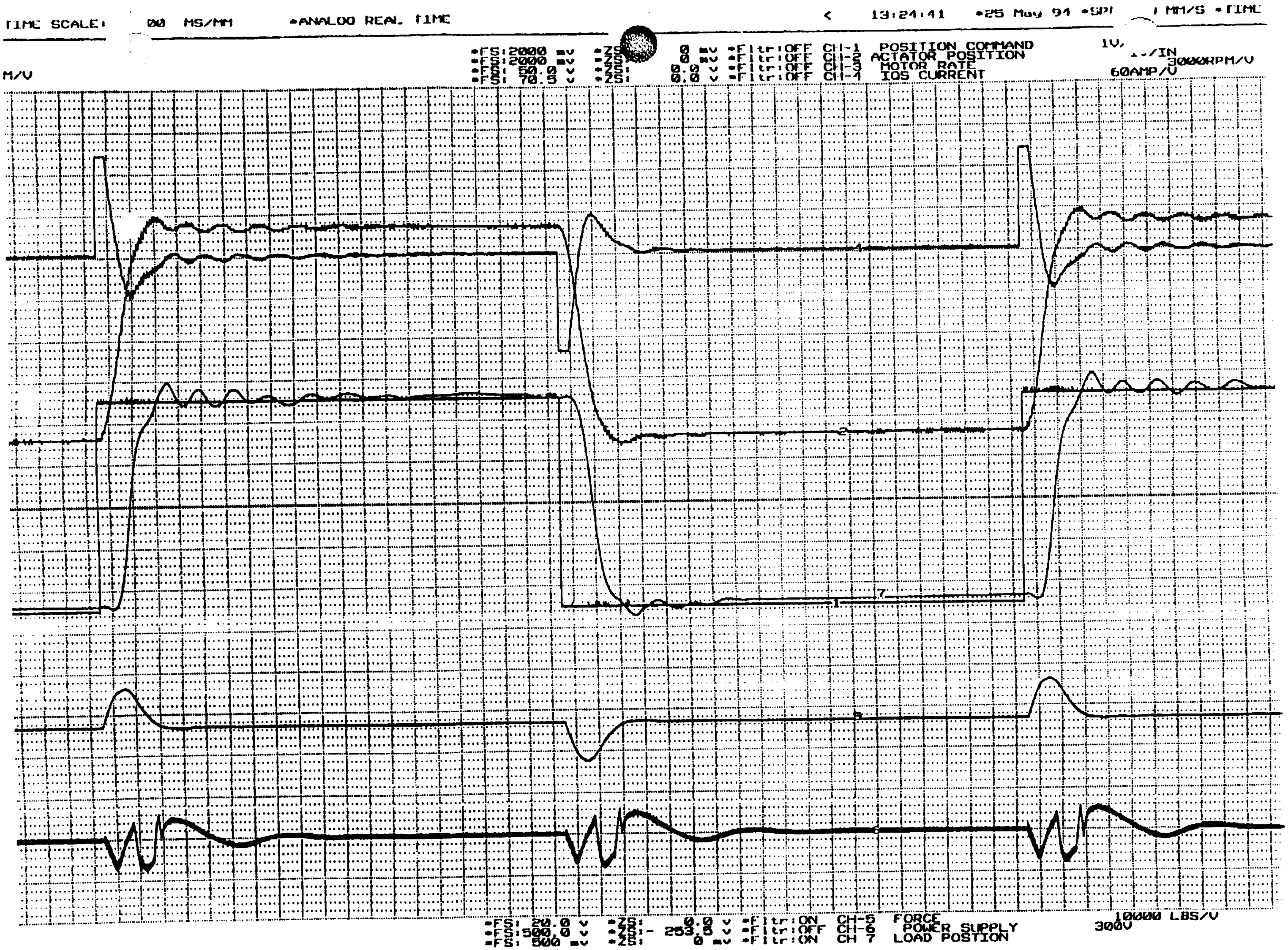

TIME
13:21:25
FS:1000 mV ZS: 0 mV Fltr:OFF CH-1 POSITION CO
FS:1000 mV ZS: 0 mV Fltr:OFF CH-2 ACTATOR POSI
FS: 50.0 V ZS: 0.0 V Fltr:OFF CH-3 MOTOR RATE
FS: 70.0 V ZS: 0.0 V Fltr:OFF CH-4 IOS CURRENT
Fltr:ON CH-5 FORCE
Fltr:OFF CH-6 POWER SUPP
Fltr:ON CH 7 LOAD POSTIO


13:24:11 25 May 94 SPD: 25 MM/S
24:25
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000R
CH-4 IOS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
CH-6 POWER SUPPLY 300V
CH 7 LOAD POSTION
± .25 IN.
Kp = 10 KR = 35

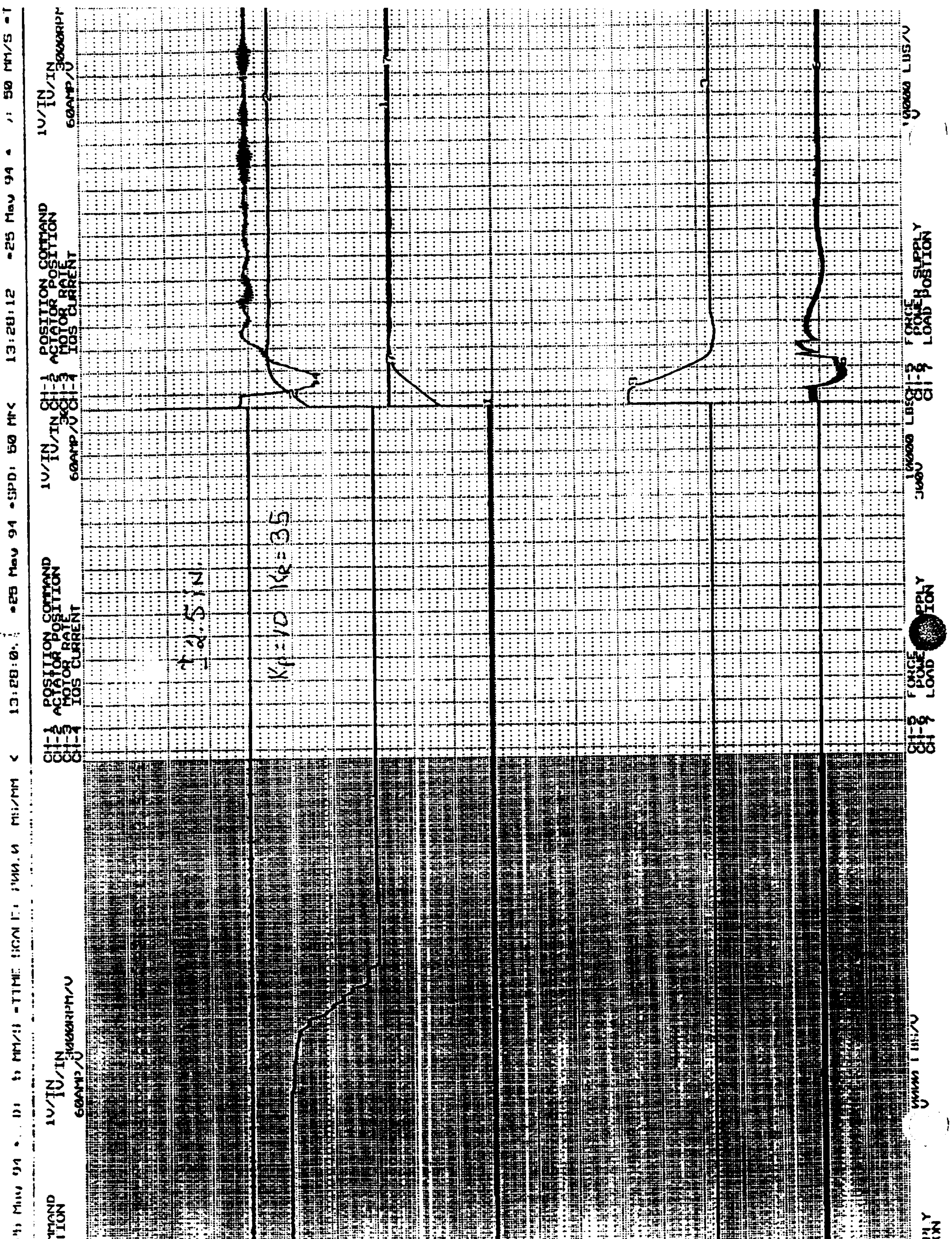

94 •SPD: 50 •TIME SCALE: 20.00 MS/MM •ANALOG REAL TI
13:24:5 25 May 94
•FS:2000 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND
•FS:2000 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTATOR POSITION
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE
•FS:500.0 v •ZS:- 253.5 v •Fltr:OFF CH-6 POWER SUPPLY
•FS: 500 mv •ZS: 0 mv •Fltr:ON CH 7 LOAD POSTION
10000 LBS/V
300V

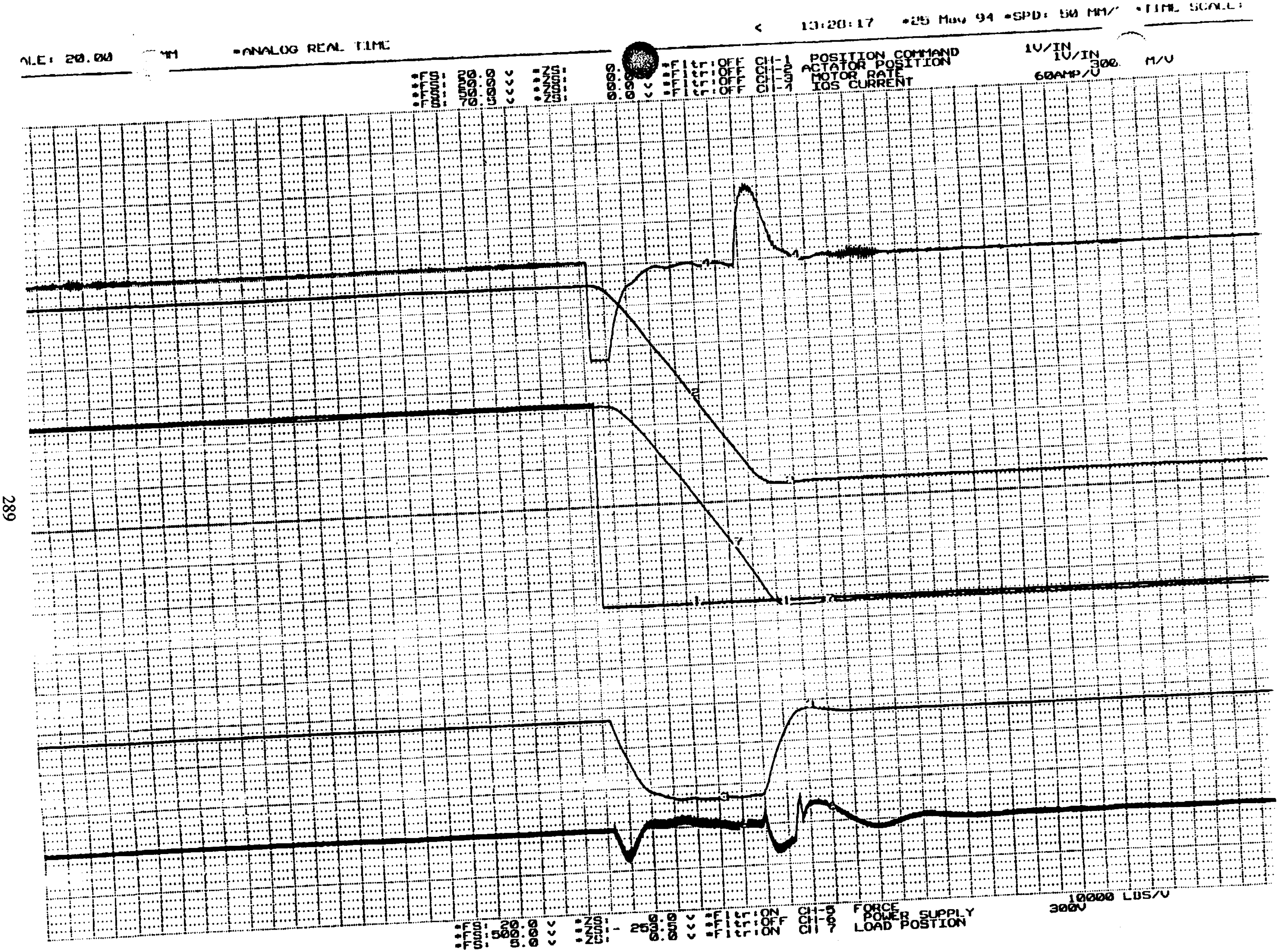


50 MM/S •TIM CALE: 20.00 MS/MM •ANALOG REAL TIME < 13:24:35 •25 Ma 1 •SPD: 50 MM
•FS:2000 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND 1V/IN
•FS:2000 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRENT 60AMP/V
3000RPM/V
LBS/V
•ZS: 0.0 v •Fltr:ON CH-5 FORCE 10000 LB
•ZS:- 253.5 v •Fltr:OFF CH-6 POWER SUPPLY 300V
•ZS: 0 mv •Fltr:ON CH 7 LOAD POSTION



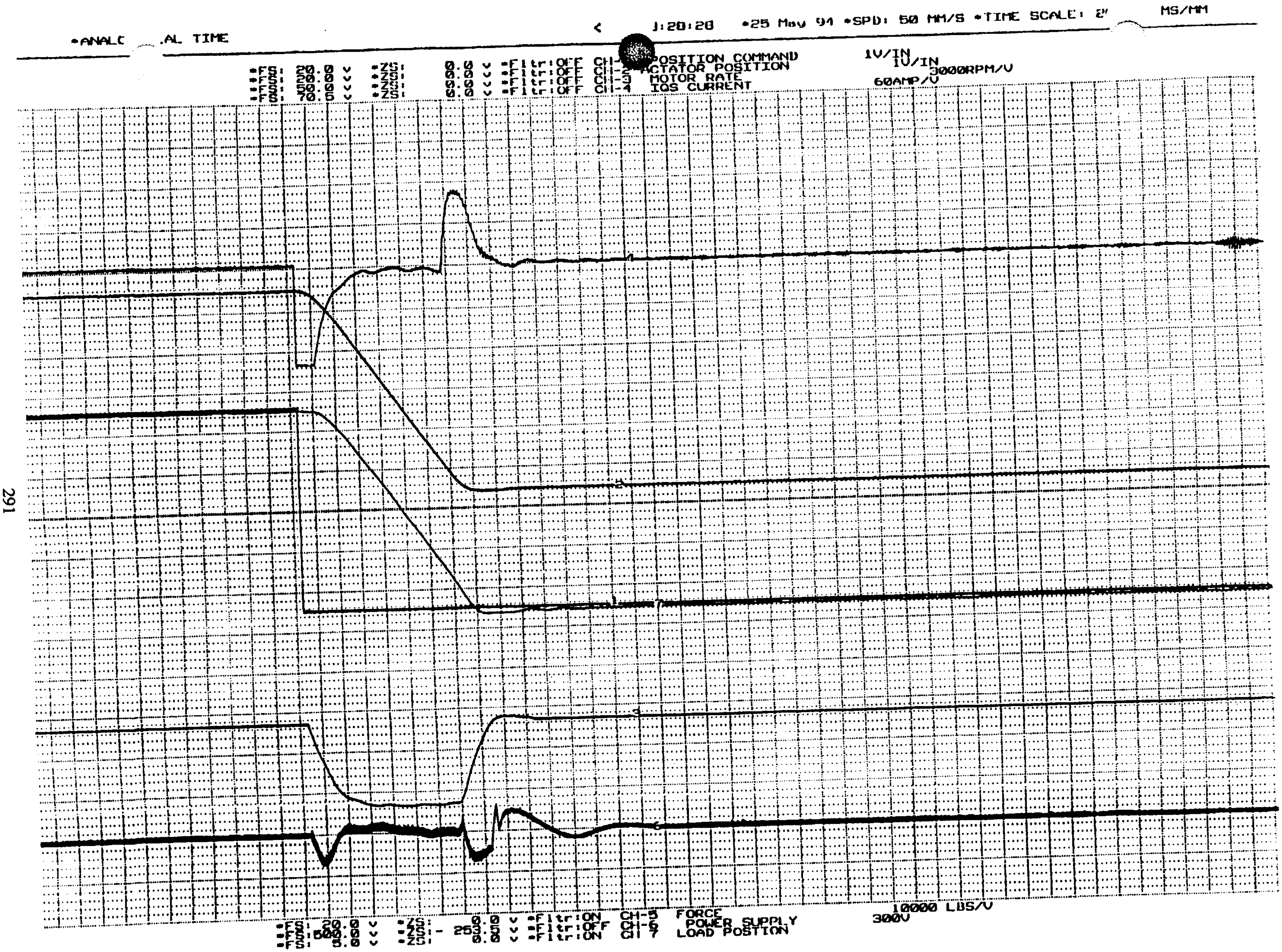
TIME SCALE: 00 MS/MM
*ANALOG REAL TIME
13:24:41
*25 May 94
MM/S *TIME
*FS:2000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND
*FS:2000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT
3000RPM/V
60AMP/V
M/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE
*FS:500.0 v *ZS:- 253.5 v *Fltr:OFF CH-6 POWER SUPPLY
*FS: 500 mv *ZS: 0 mv *Fltr:ON CH 7 LOAD POSTION
10000 LBS/V
300V

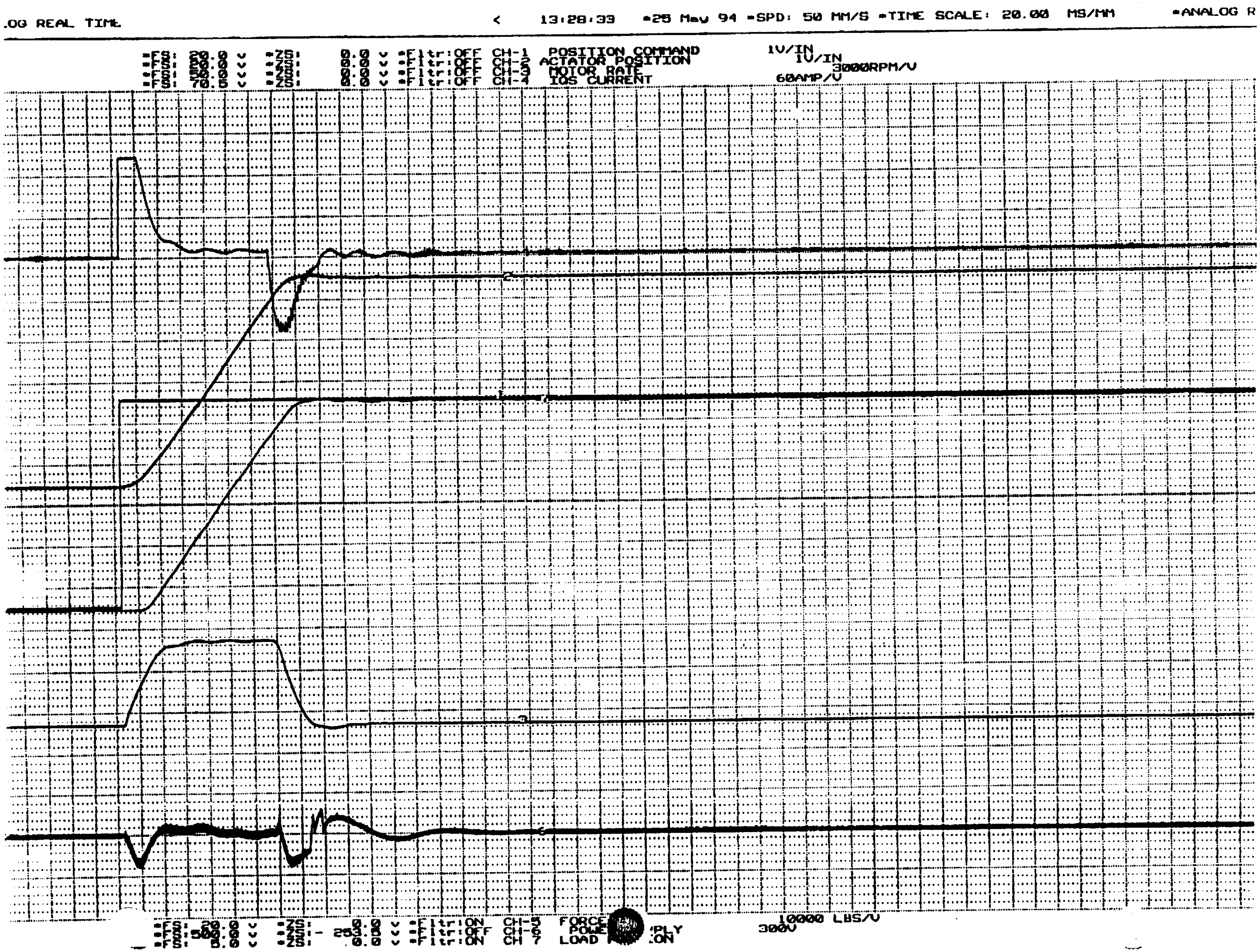

13:28:12
•25 May 94
50 MM/S
CH-1 POSITION COMMAND
CH-2 ACTATOR POSITION
CH-3 MOTOR RATE
CH-4 IOS CURRENT
1V/IN
1V/IN
3000RPM
60AMP/V
CH-5 FORCE
CH-9 POWER SUPPLY
CH-7 LOAD POSTION
10000 LBS/V
13:28:0
•28 May 94
SPD: 50 MM/S
±2.5 IN
Kp=10 Kr=35

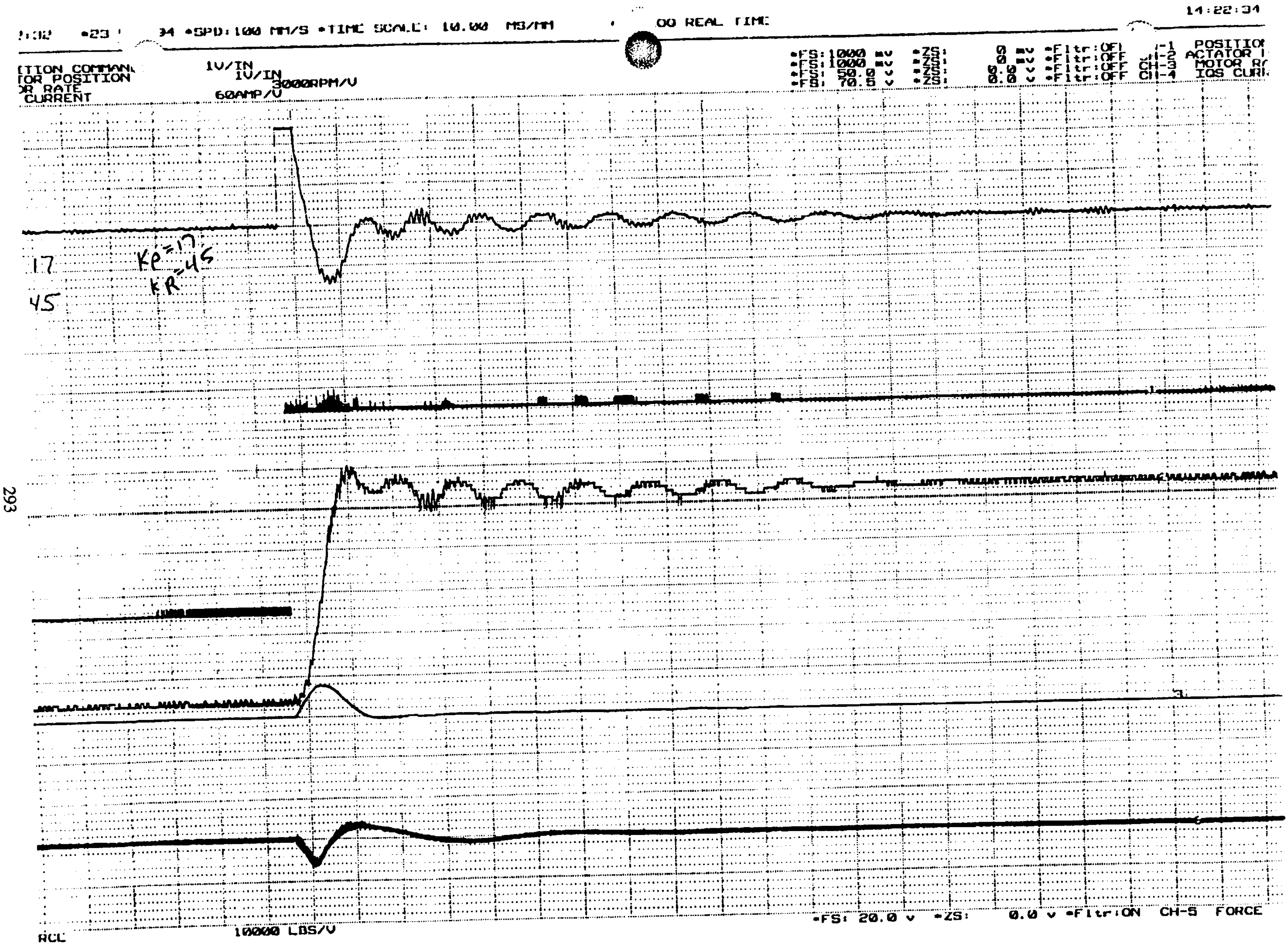


ALE: 20.00 MM
*ANALOG REAL TIME
13:20:17 *25 May 94 *SPD: 50 MM/ *TIME SCALE:
*FS: 20.0 V *ZS: 0.0 V *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS: 20.00 V *ZS: 0.00 V *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.00 V *ZS: 0.0 V *Fltr:OFF CH-3 MOTOR RATE 300. M/V
*FS: 70.5 V *ZS: 0.0 V *Fltr:OFF CH-4 IOS CURRENT 60AMP/V
*FS: 20.0 V *ZS: 0.0 V *Fltr:ON CH-5 FORCE 10000 LBS/V
*FS:500.0 V *ZS:- 253.5 V *Fltr:OFF CH-6 POWER SUPPLY 300V
*FS: 5.0 V *ZS: 0.0 V *Fltr:ON CH 7 LOAD POSTION

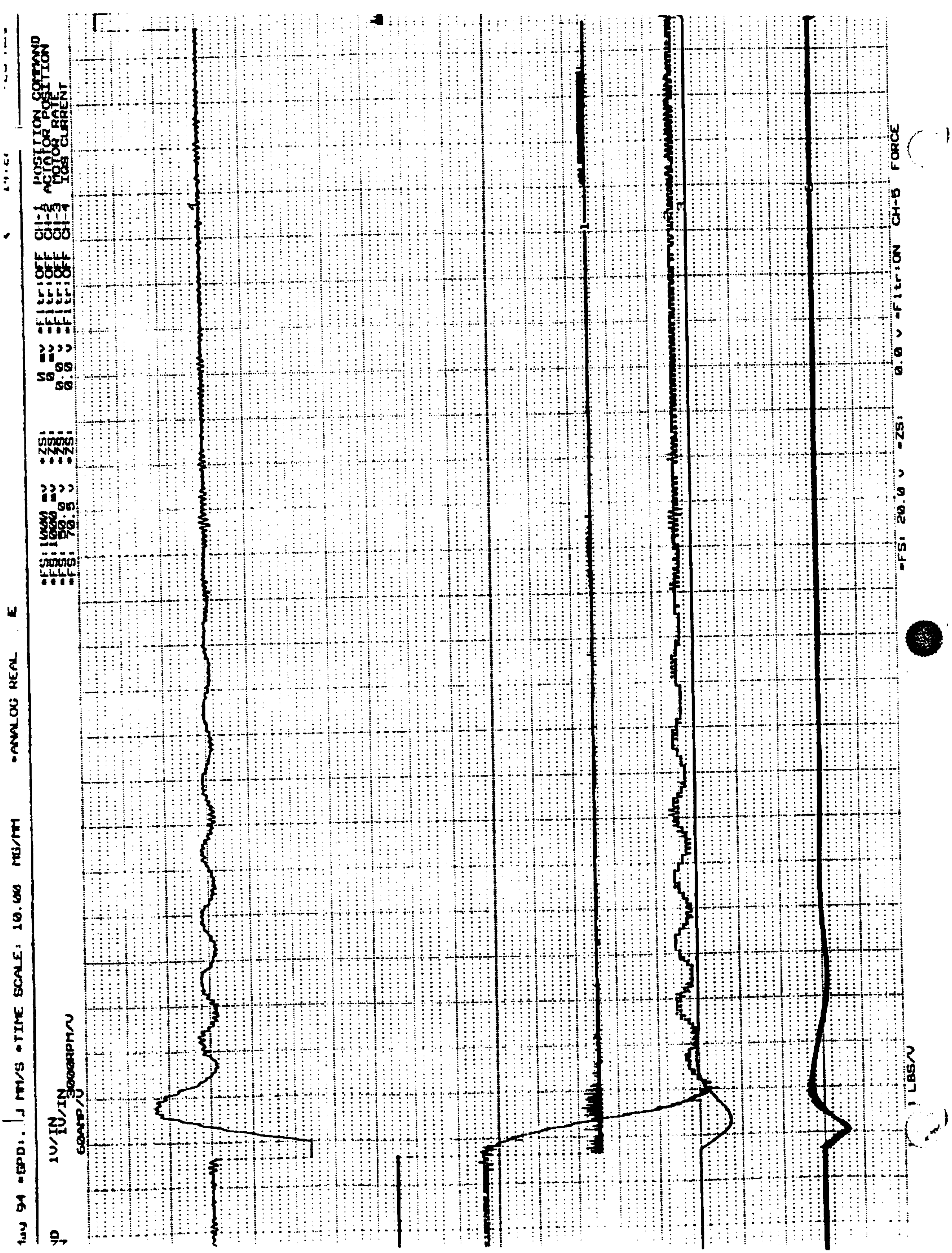

00 MS/MM *ANALOG REAL TIME < 13:20:23 *25 May 94 *SPD: 50 MM/S *TIME ALE: 20.00
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v CH-5 FORCE 10000 LBS/V
*FS:500.0 v *ZS:- 253.5 v CH-6 POWER SUPPLY 300V
*FS: 5.0 v *ZS: 0.0 v CH 7 LOAD POSTION

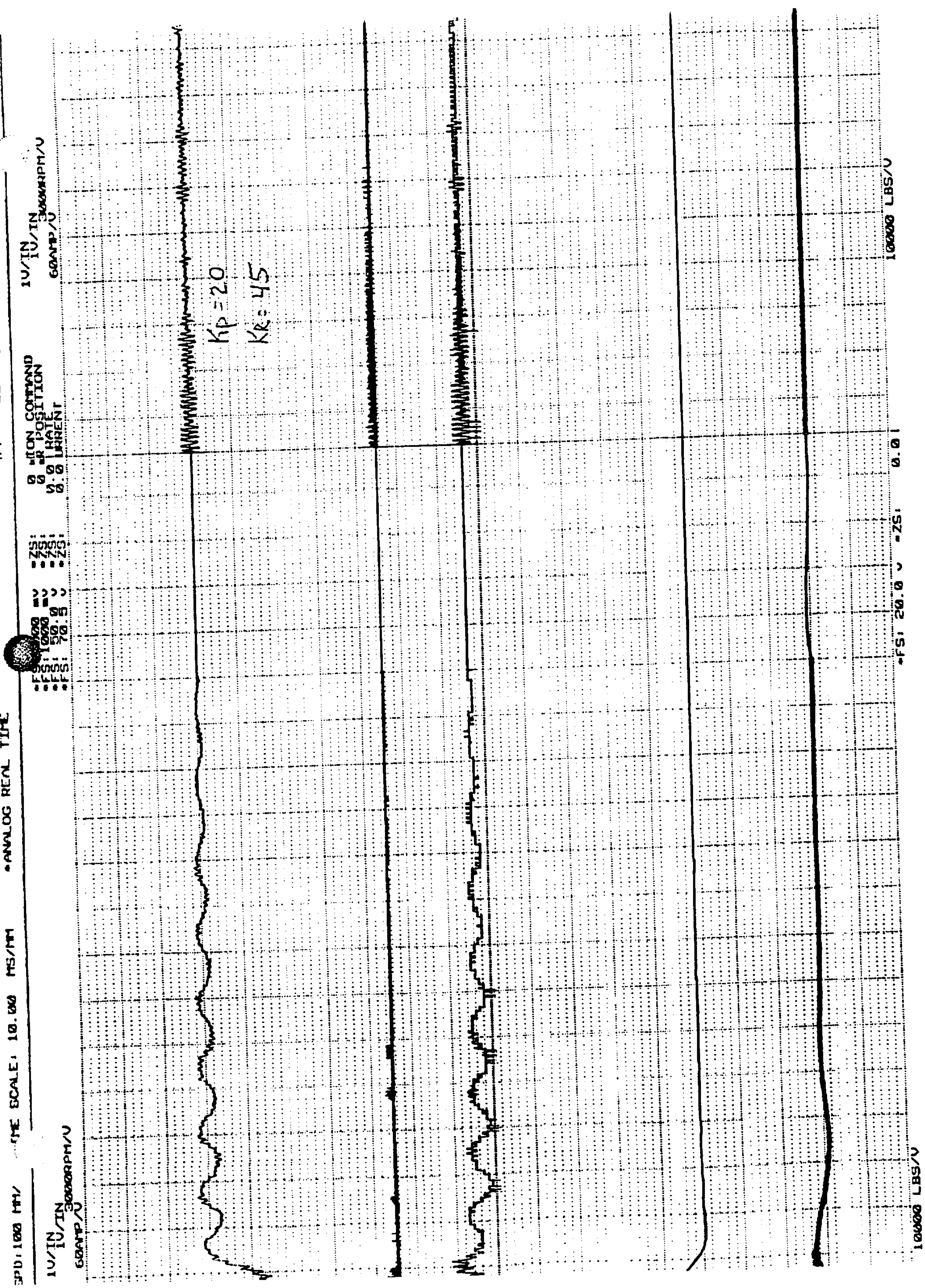

*ANALC .AL TIME
J:20:20 *25 May 94 *SPD: 50 MM/S *TIME SCALE: 2 MS/MM
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS: 20.0 v *ZS: 0.0 v *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE 10000 LBS/V
*FS: 500.0 v *ZS: - 253.5 v *Fltr:OFF CH-6 POWER SUPPLY 300V
*FS: 5.0 v *ZS: 0.0 v *Fltr:ON CH 7 LOAD POSTION

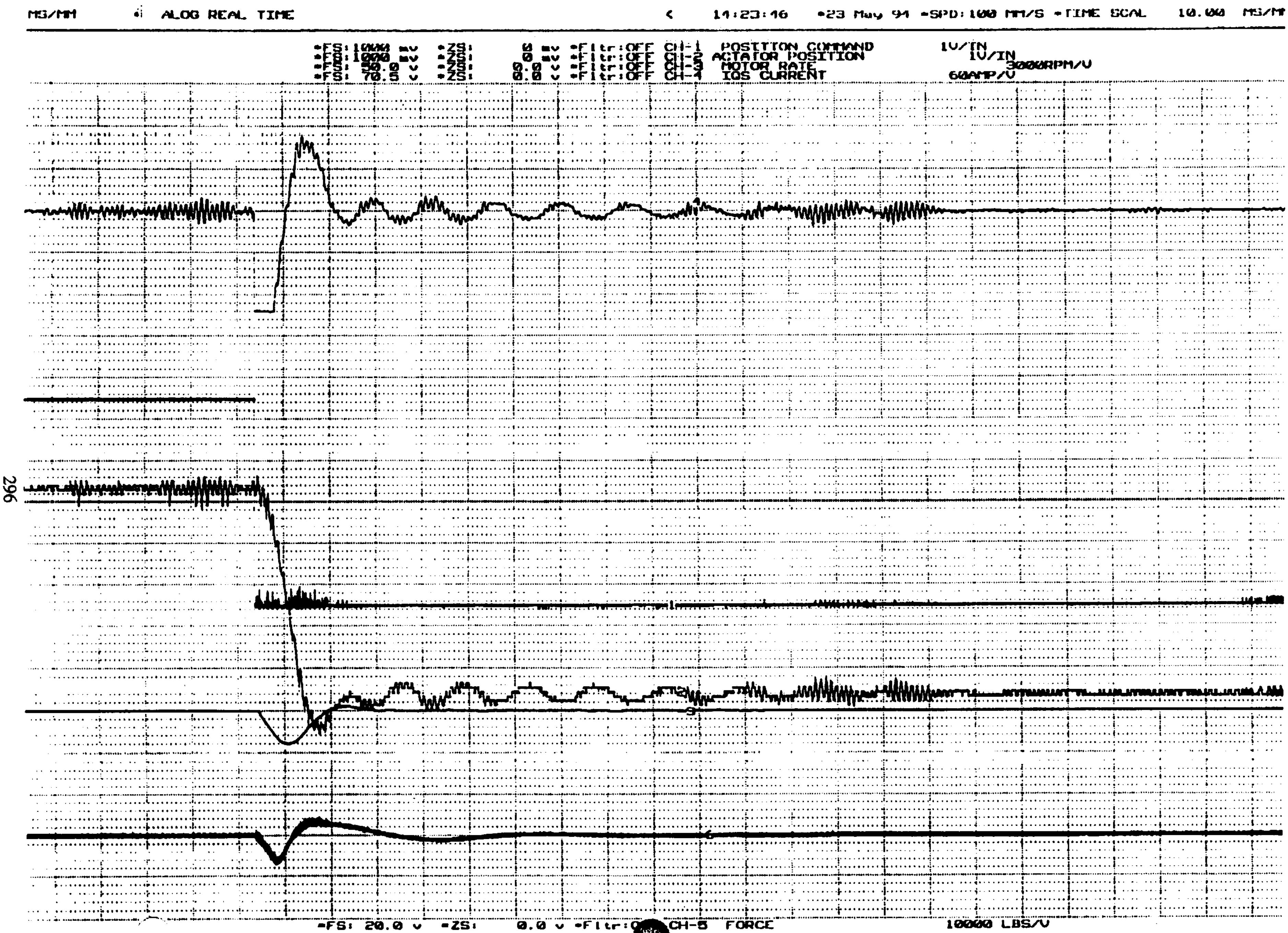

.OG REAL TIME
13:28:33 ▪25 May 94 ▪SPD: 50 MM/S ▪TIME SCALE: 20.00 MS/MM ▪ANALOG R
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IOS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
300V
LOAD

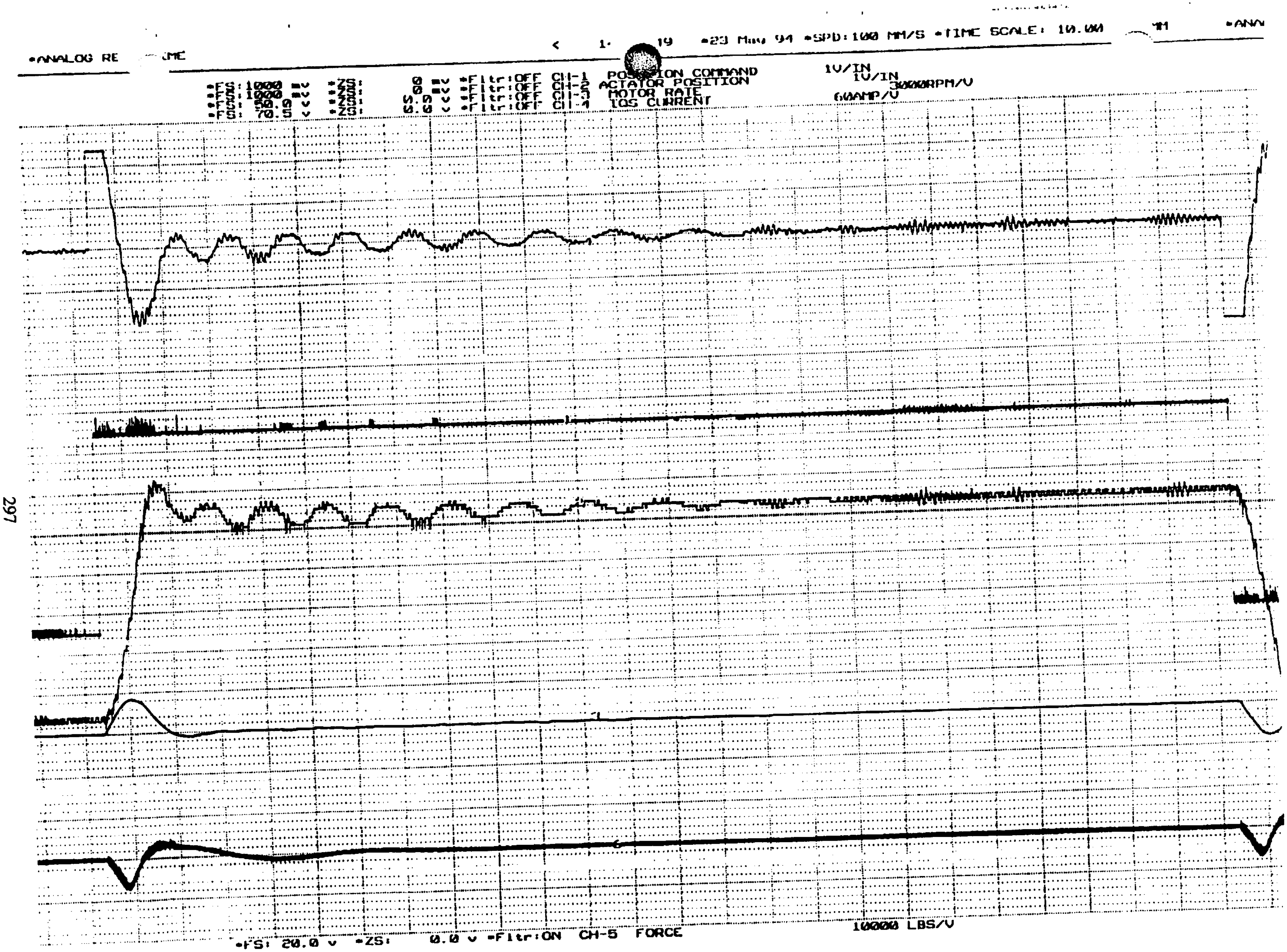


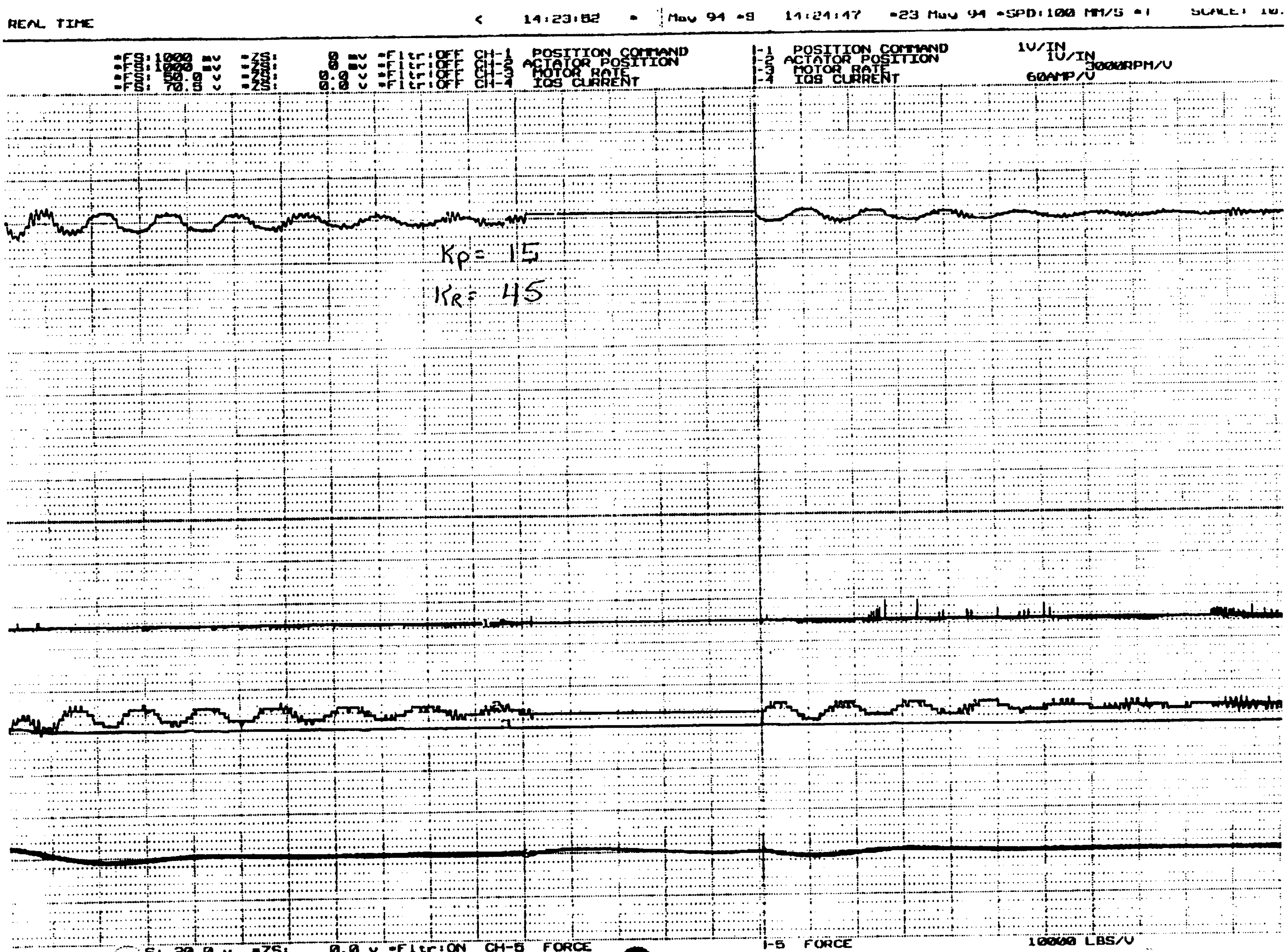
14:22:34
?:32 •23 ' 34 •SPD:100 MM/S •TIME SCALE: 10.00 MS/MM
OO REAL TIME
TION COMMAN
TOR POSITION
OR RATE
CURRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
•FS:1000 mv •ZS: 0 mv •Fltr:OFF -1 POSITIO
•FS:1000 mv •ZS: 0 mv •Fltr:OFF -2 ACTATOR
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR R
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CUR
Kp=17
KR=45
17
45
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE
ACL
10000 LBS/V

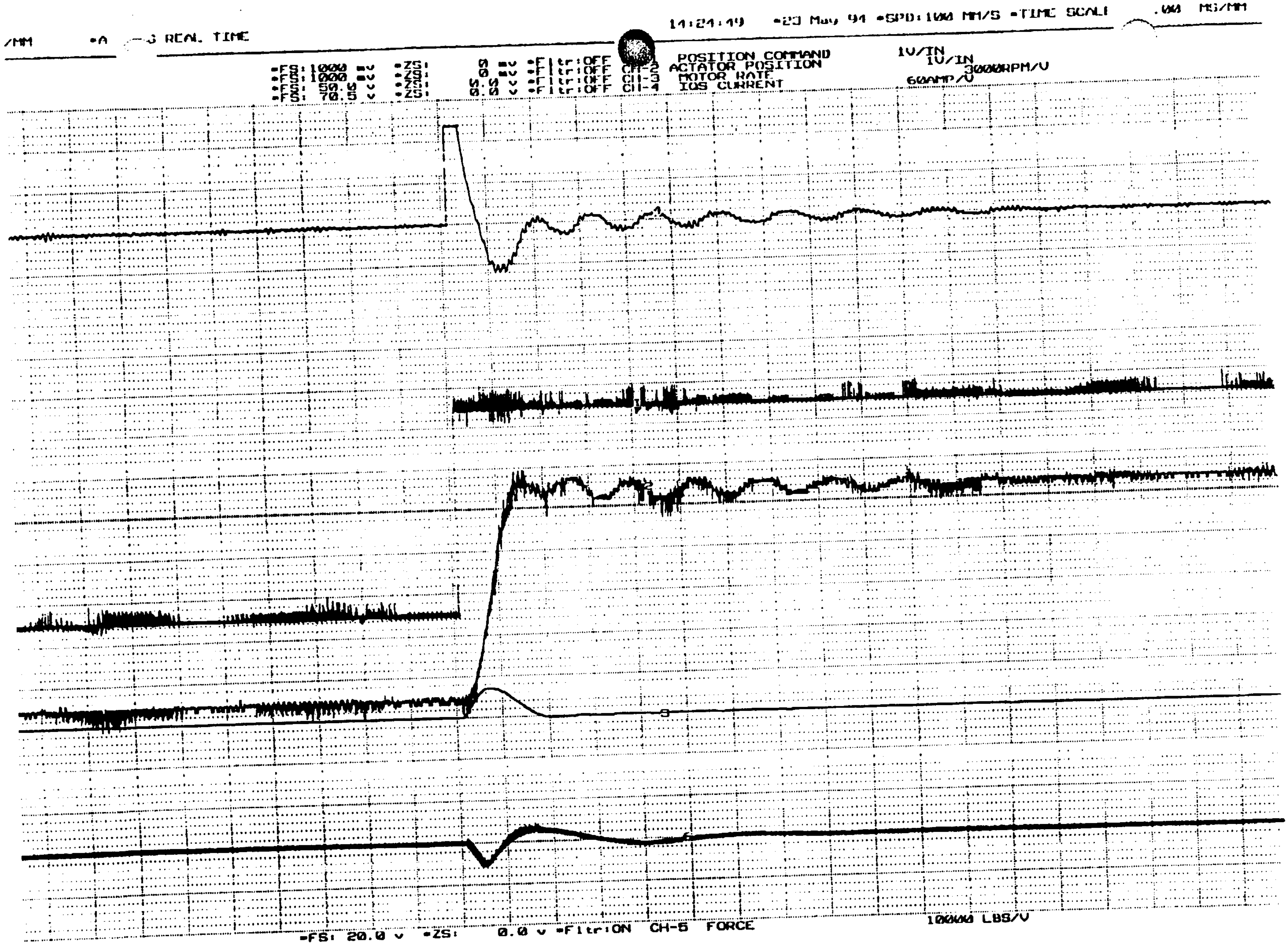

•TIME SCALE: 10.00 MS/MM
•ANALOG REAL
CH-1 POSITION COMMAND
CH-2 ACTATOR POSITION
CH-3 MOTOR RATE
CH-4 IGBS CURRENT
CH-5 FORCE
10V/IN
10V/IN
3000RPM/V
60AMP/V
LBS/V

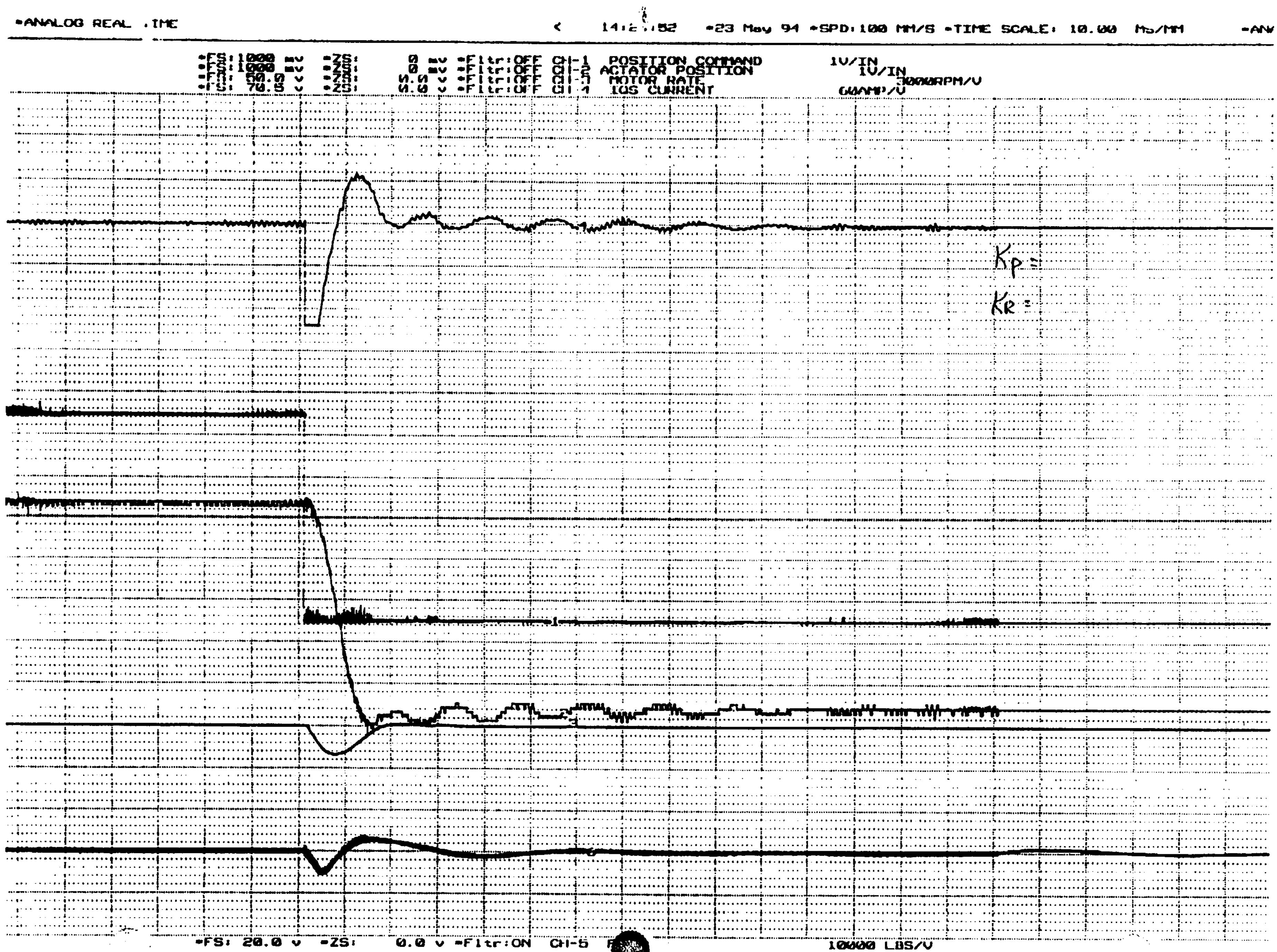

SPD:100 MM/
TIME SCALE: 10.00 MS/MM
ANALOG REAL TIME
23 May 94
SPD:100 MM/S
SCALE: 10
Kp=20
KR=45
10000 LBS/V
FS: 20.0 V
ZS: 0.0
10000 LBS/V

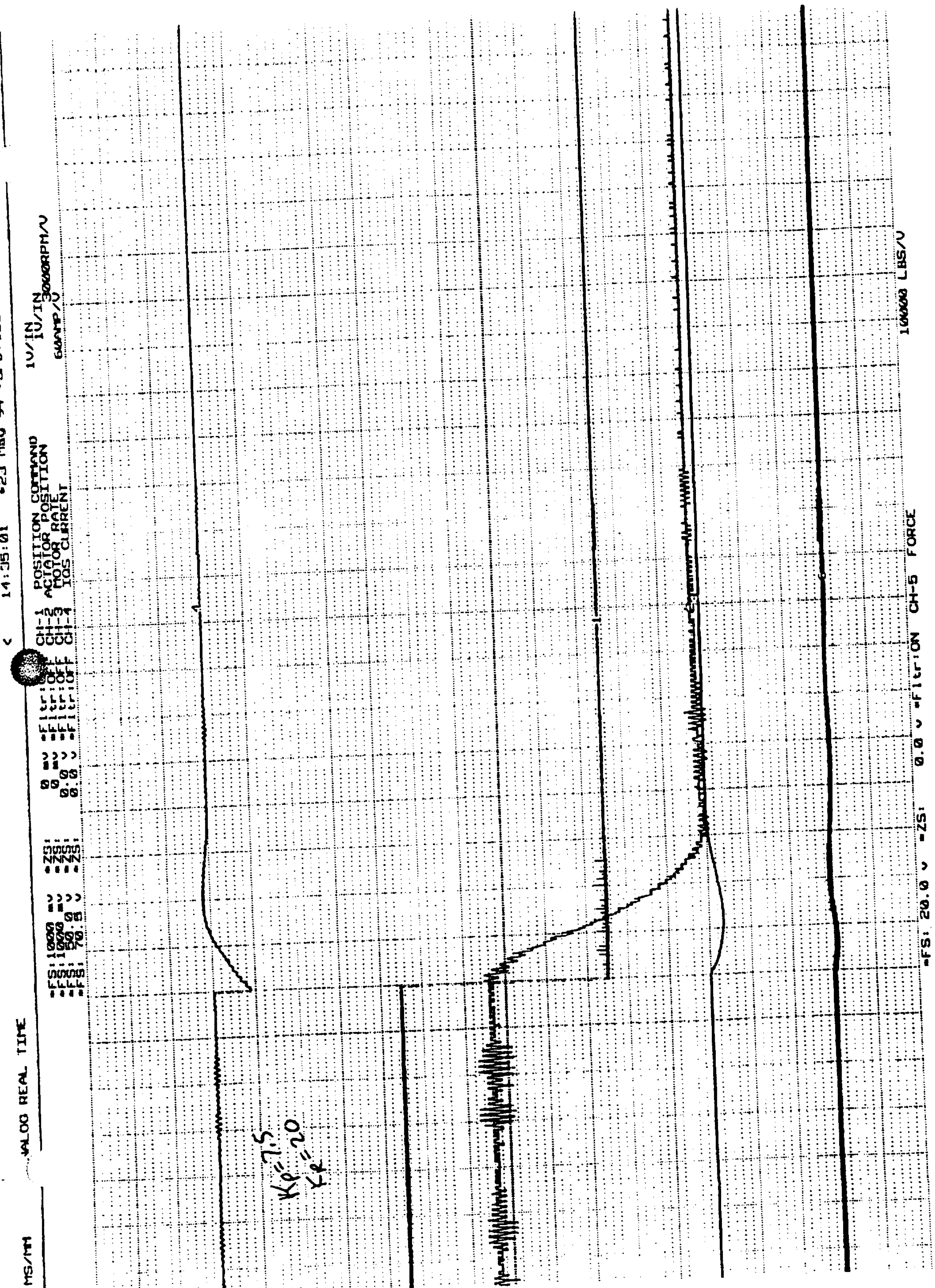

MS/MM ALOG REAL TIME
< 14:23:46 *23 May 94 *SPD:100 MM/S *TIME SCAL 10.00 MS/MM
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v CH-5 FORCE 10000 LBS/V

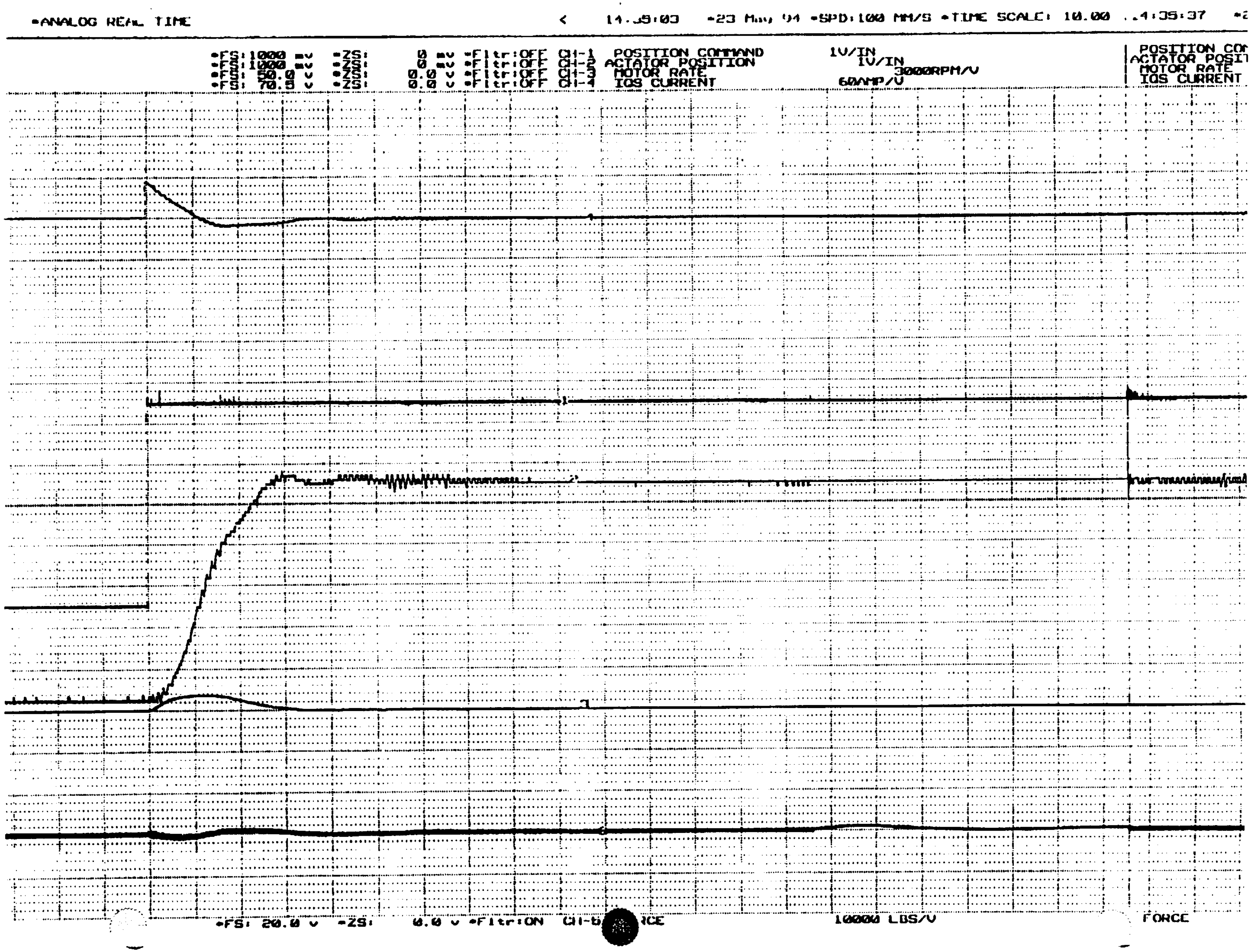

*ANALOG RE ME
< 1· 19 *23 May 94 *SPD:100 MM/S *TIME SCALE: 10.00
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE 10000 LBS/V

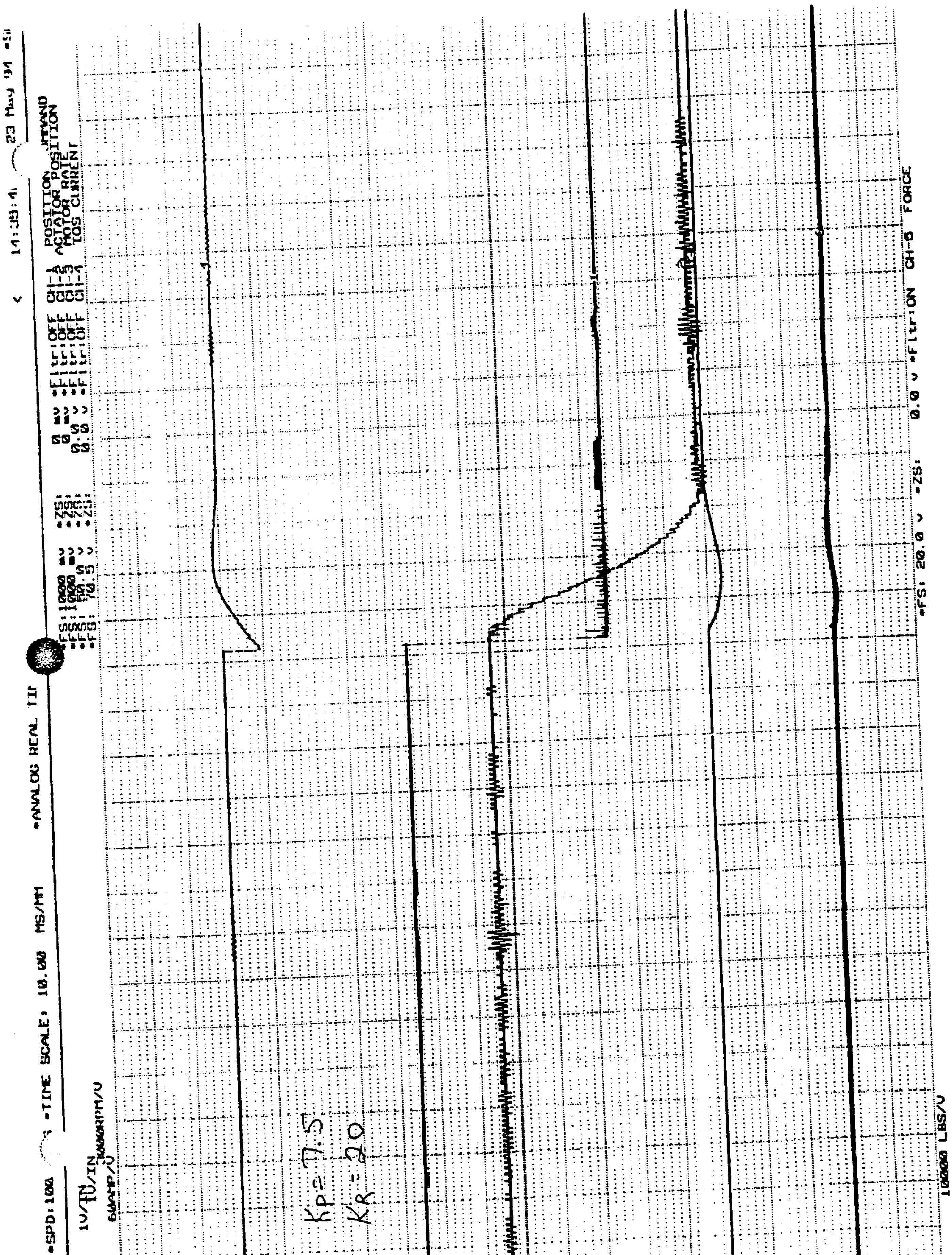

REAL TIME
< 14:23:82 * May 94 *9 14:24:47 *23 May 94 *SPD:100 MM/S *1 SCALE: 10.
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT
I-1 POSITION COMMAND 1V/IN
I-2 ACTATOR POSITION 1V/IN
I-3 MOTOR RATE 3000RPM/V
I-4 IQS CURRENT 60AMP/V
Kp= 15
KR= 45
S: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE
I-5 FORCE 10000 LBS/V

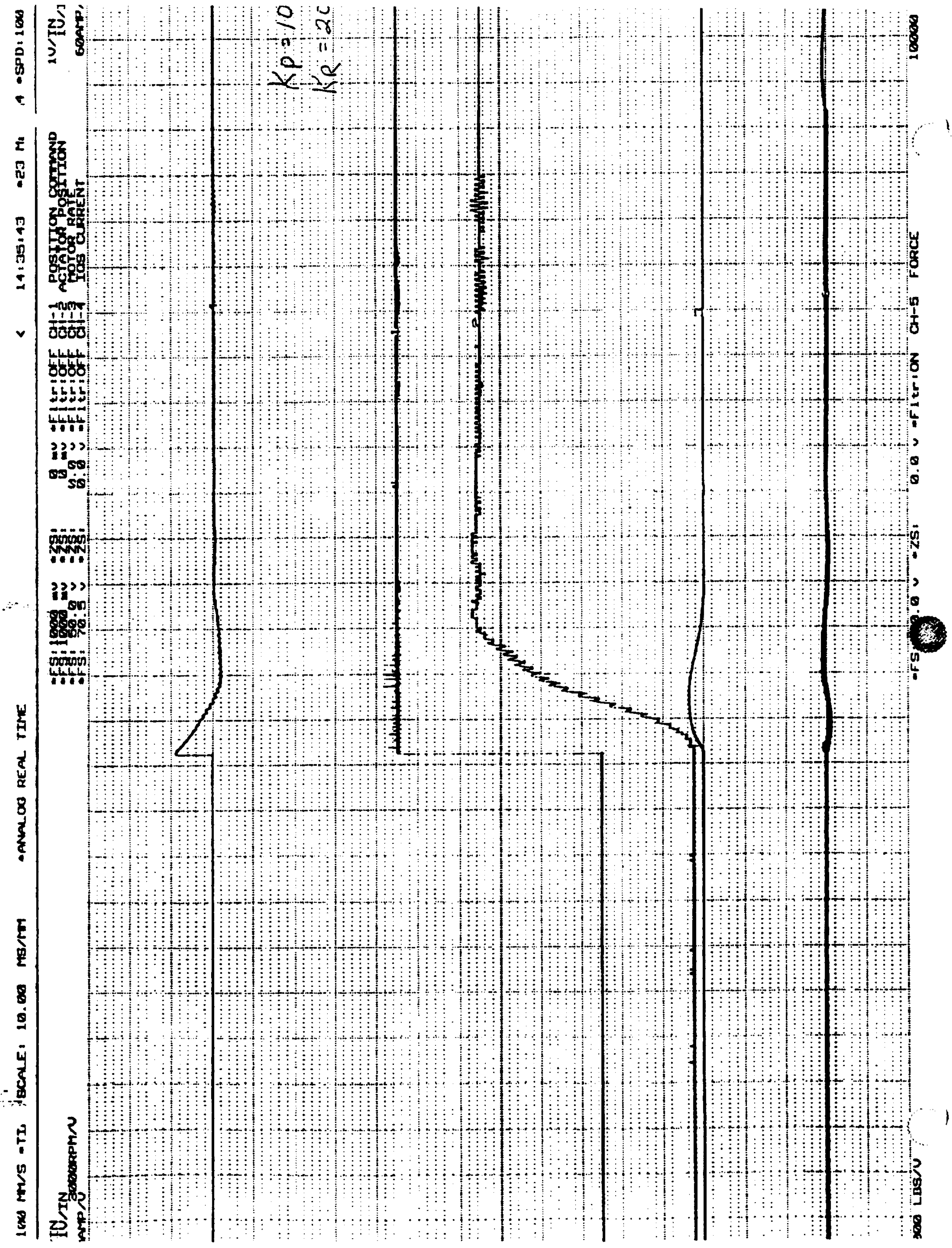

14:24:49 •23 May 94 •SPD:100 MM/S •TIME SCALE .00 MS/MM
/MM •A —3 REAL TIME
•FS:1000 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND 1V/IN
•FS:1000 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
•FS: 50.0 v •ZS: 5.0 v •Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRENT 60AMP/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE 10000 LBS/V

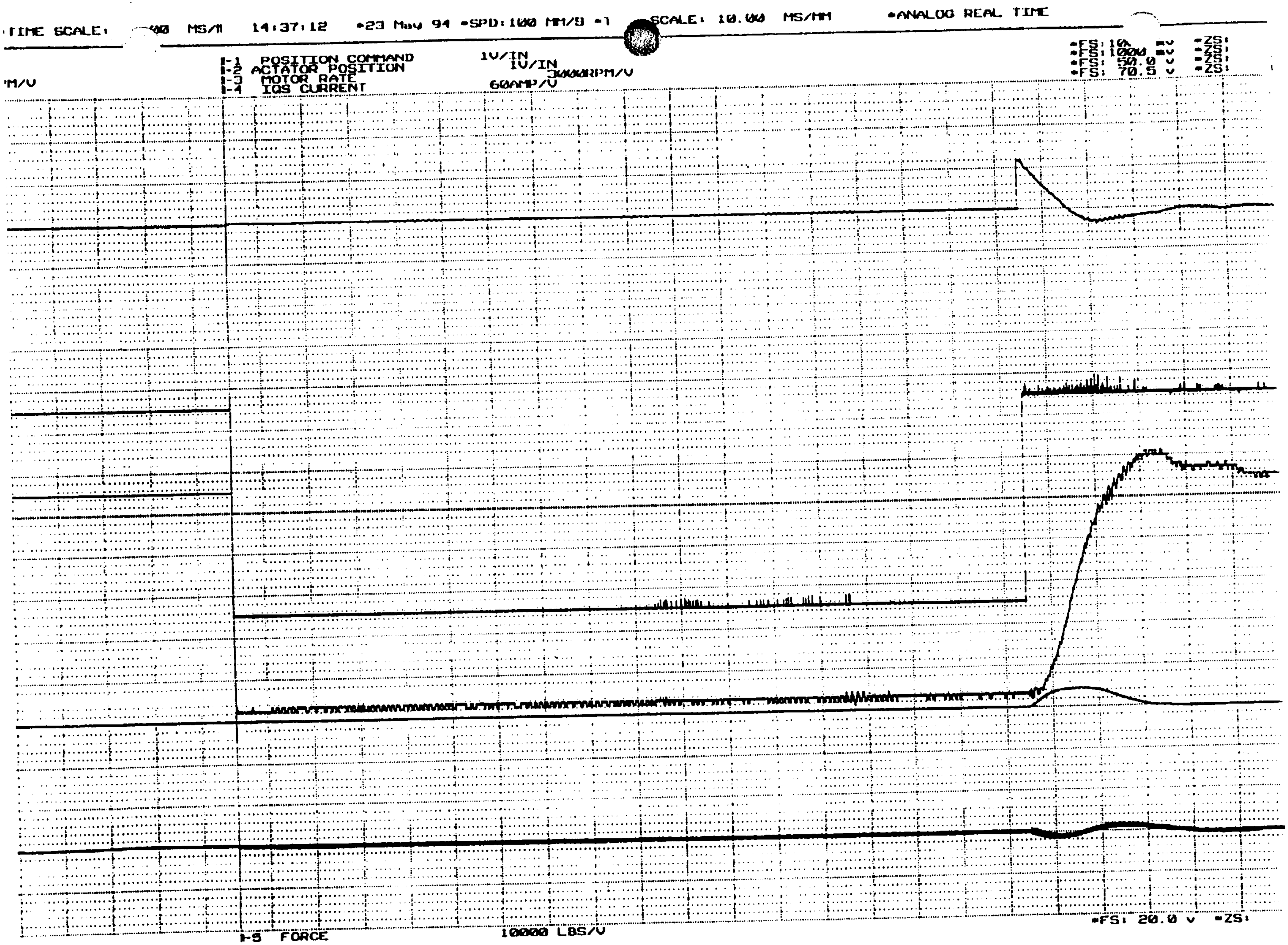

*ANALOG REAL TIME
14:2 :52 *23 May 94 *SPD:100 MM/S *TIME SCALE: 10.00 Ms/MM
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS:1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
Kp =
KR =
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5
10000 LBS/V

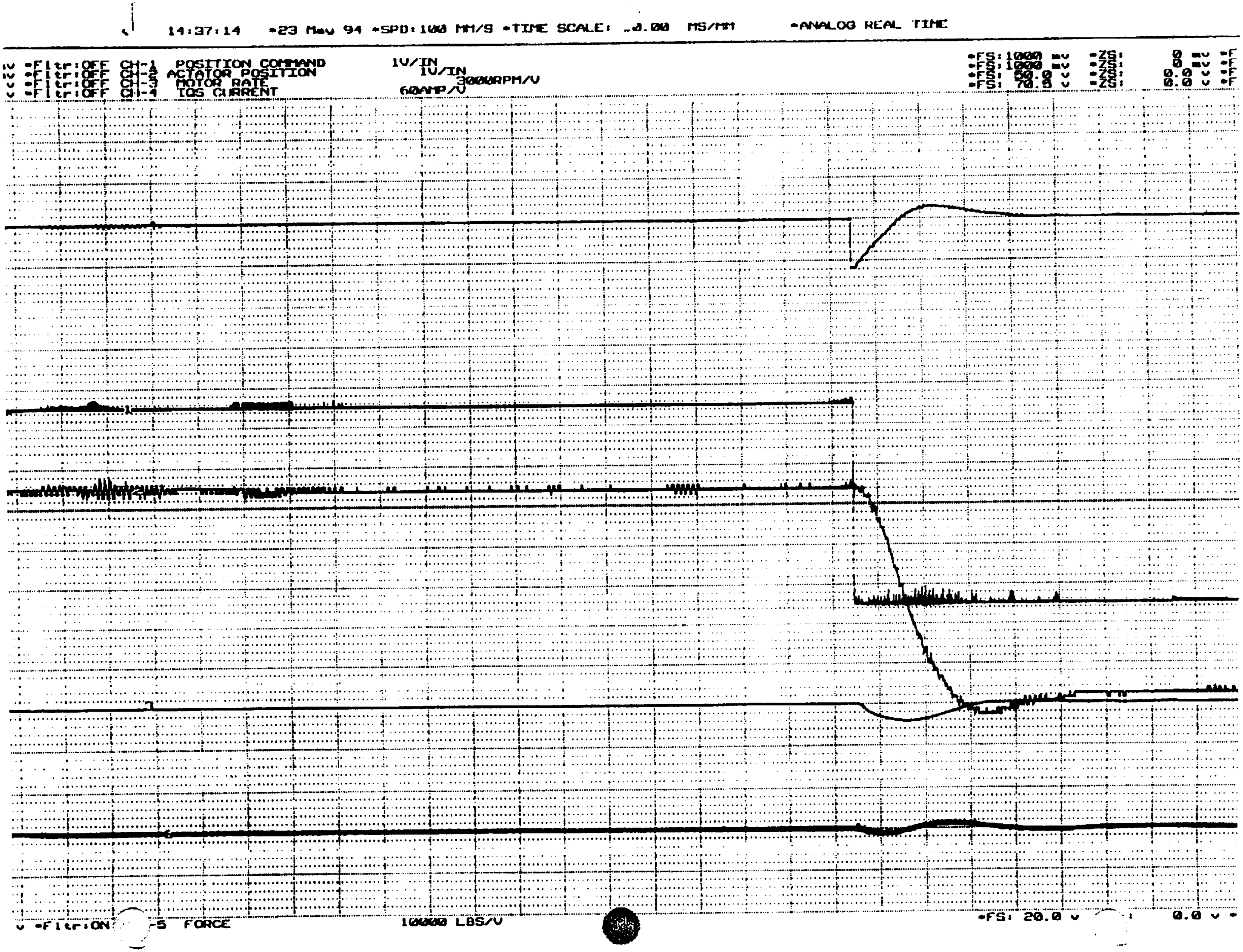

MS/MM
ANALOG REAL TIME
14:35:01 •23 May 94 •SPD:100 MM/S •TIME 5
10.00 MS/
•FS:1000 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND 1V/IN
•FS:1000 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTUATOR POSITION 1V/IN
•FS: 50.0 v •ZS: 0.00 v •Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
•FS: 70.0 v •ZS: 0.00 v •Fltr:OFF CH-4 IQS CURRENT 60AMP/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE 10000 LBS/V
Kp=7.5
Kr=20

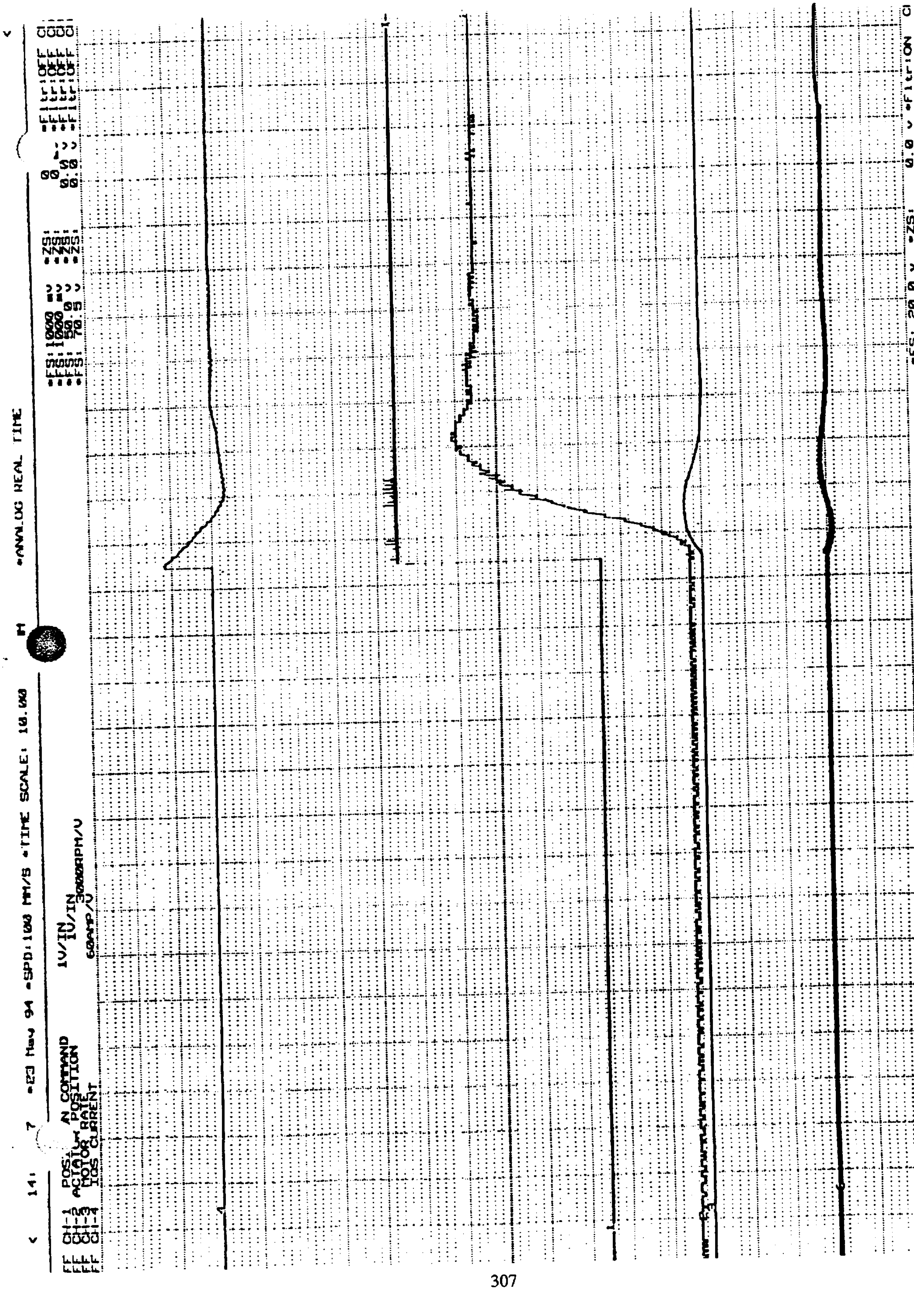

•ANALOG REAL TIME
14:59:03 •23 May 94 •SPD:100 MM/S •TIME SCALE: 10.00 14:35:37
•FS:1000 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND 1V/IN
•FS:1000 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IOS CURRENT 60AMP/V
POSITION COM
ACTATOR POSIT
MOTOR RATE
IOS CURRENT
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON
10000 LBS/V
FORCE

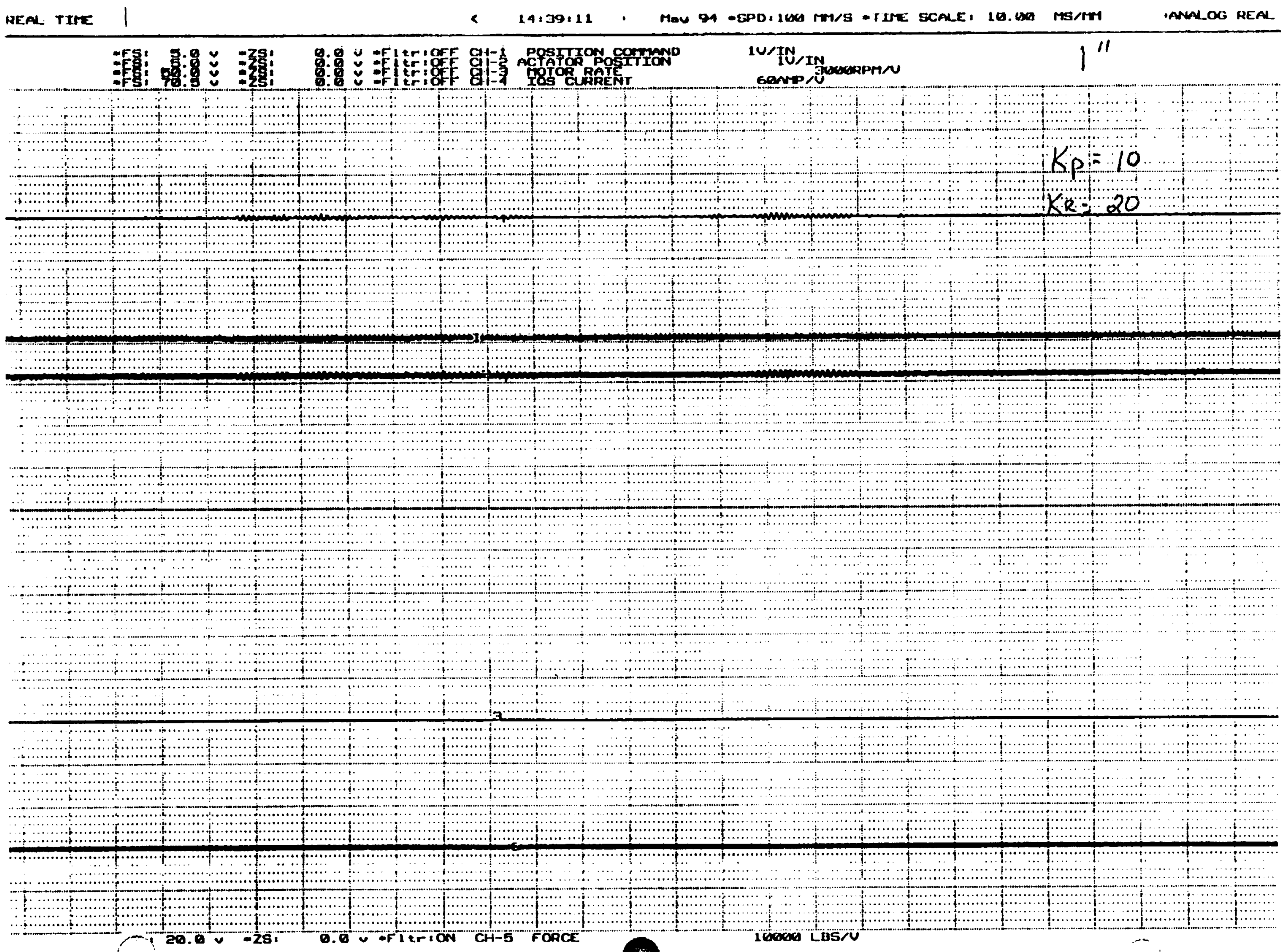

•TIME SCALE: 10.000 MS/MM
•ANALOG REAL TI
23 May 94
POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
IOS CURRENT
CH-5 FORCE
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON
10000 LBS/V
60AMP/V
Kp = 7.5
KR = 20

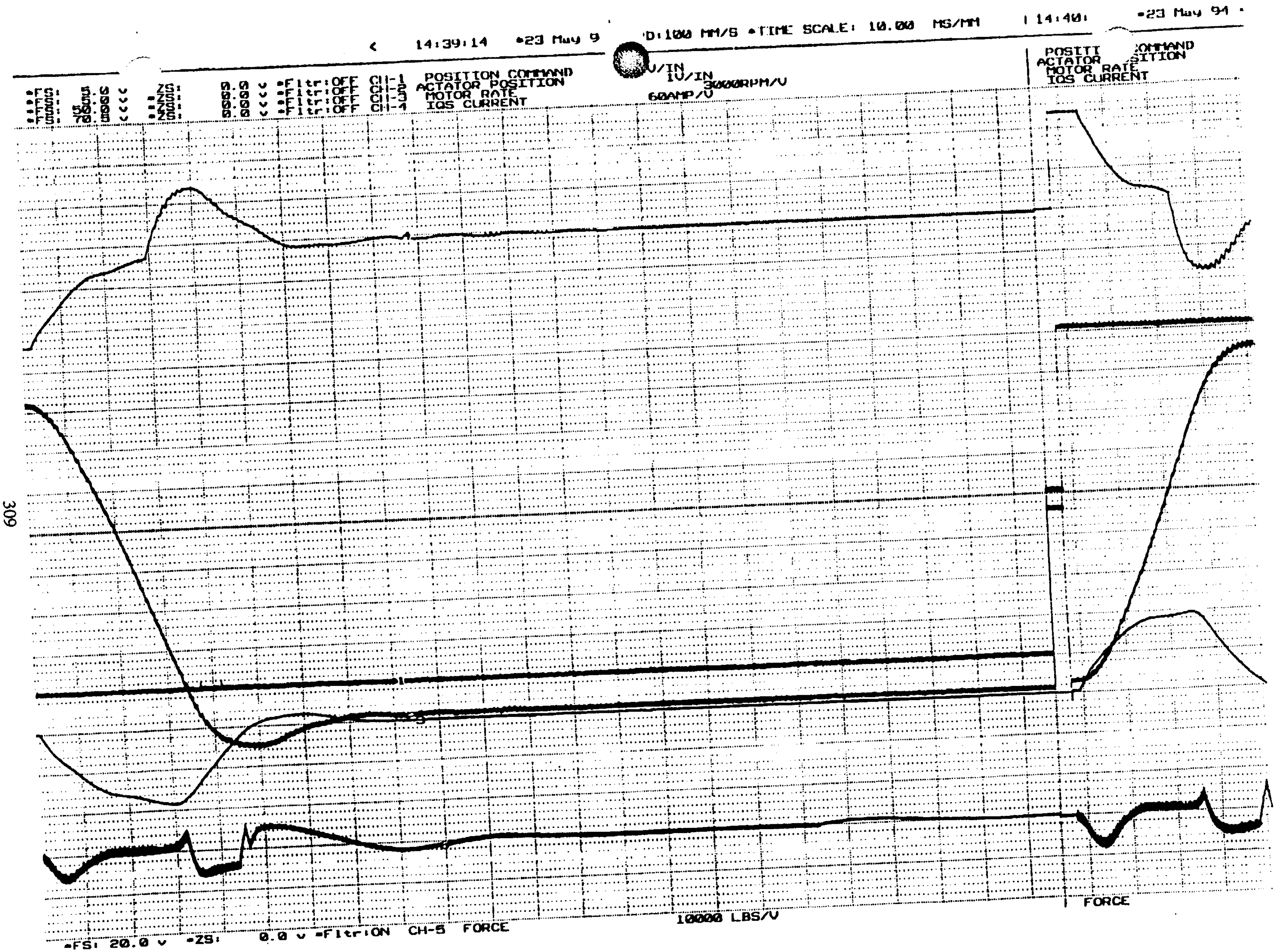

100 MM/S •TI SCALE: 10.00 MS/MM •ANALOG REAL TIME
14:35:43 •23 Mt •SPD:100
POSITION COMMAND
ACTATOR POSITION
MOTOR RATE
IGS CURRENT
CH-5 FORCE
Kp=10
KR=20
100000
500 LBS/V

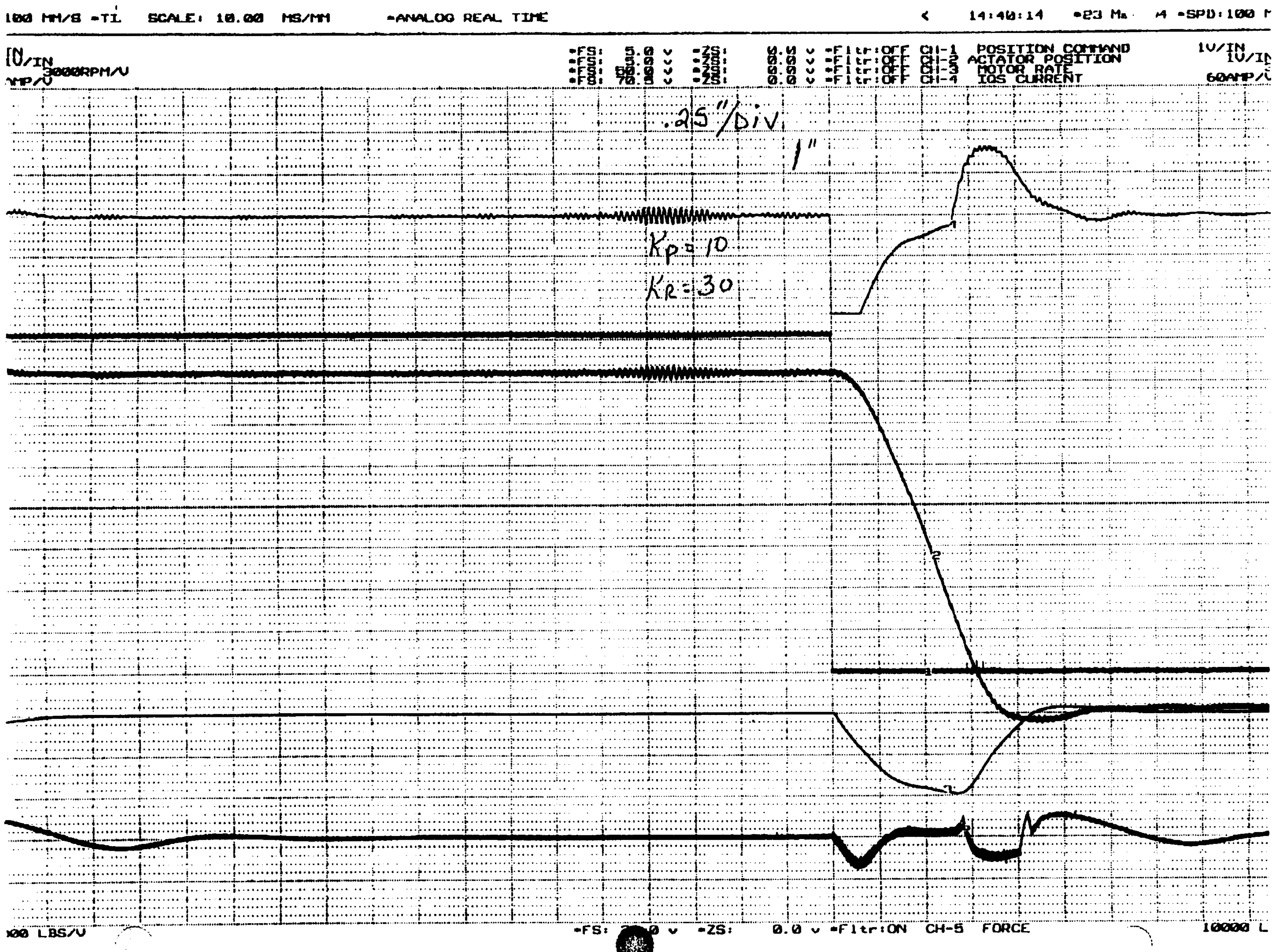

TIME SCALE: MS/M 14:37:12 *23 May 94 *SPD:100 MM/S *1 SCALE: 10.00 MS/MM *ANALOG REAL TIME
M/V
1-1 POSITION COMMAND 1V/IN
1-2 ACTATOR POSITION 1V/IN
1-3 MOTOR RATE 3000RPM/V
1-4 IQS CURRENT 60AMP/V
*FS: 10 mv *ZS:
*FS: 1000 mv *ZS:
*FS: 50.0 v *ZS:
*FS: 70.5 v *ZS:
1-5 FORCE 10000 LBS/V
*FS: 20.0 v *ZS:

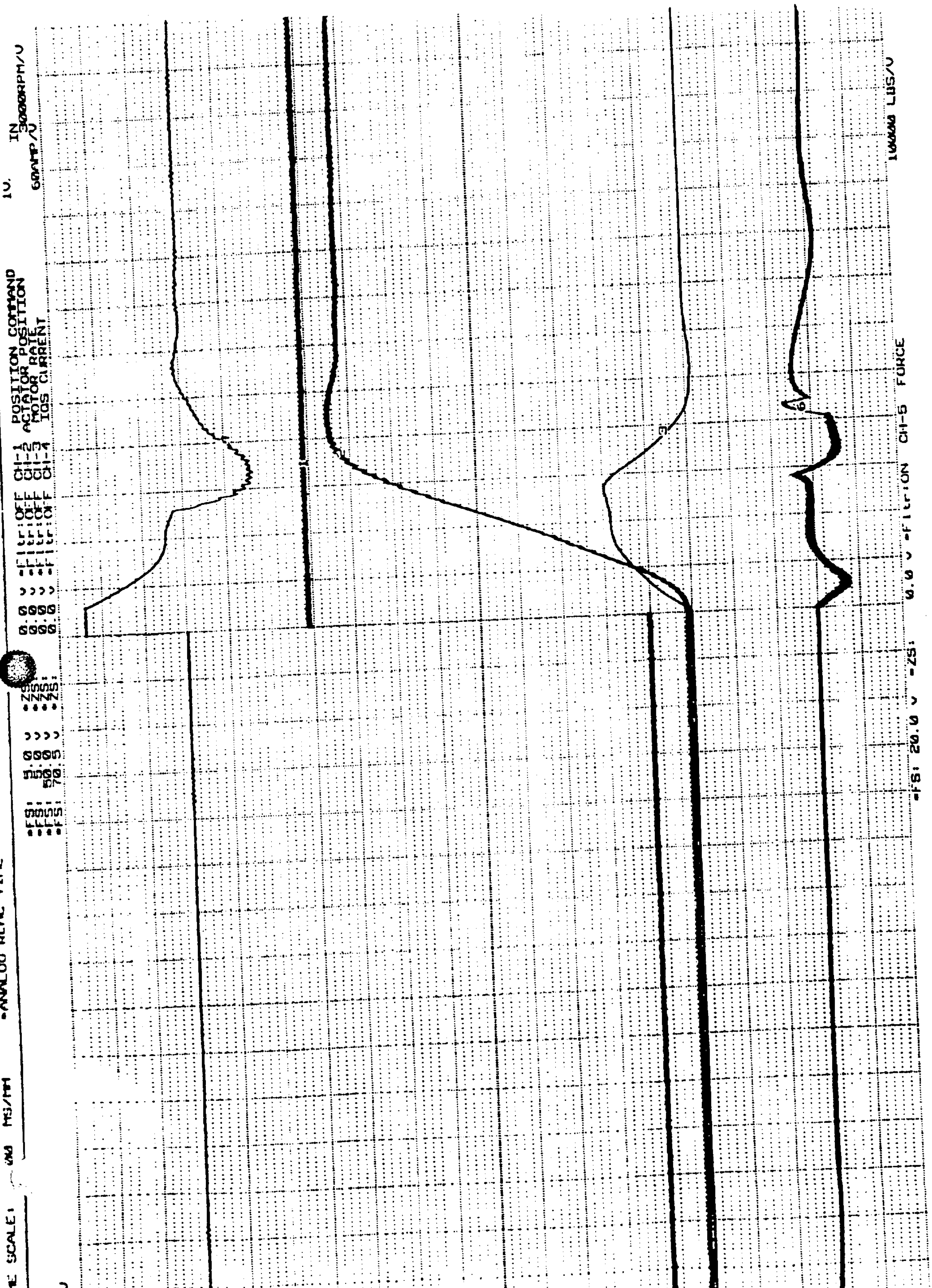

14:37:14 •23 May 94 •SPD:100 MM/S •TIME SCALE: _0.00 MS/MM •ANALOG REAL TIME
•Fltr:OFF CH-1 POSITION COMMAND 1V/IN
•Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
•Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
•Fltr:OFF CH-4 IOS CURRENT 60AMP/V
•FS:1000 mv •ZS: 0 mv •F
•FS:1000 mv •ZS: 0 mv •F
•FS: 50.0 v •ZS: 0.0 v •F
•FS: 70.5 v •ZS: 0.0 v •F
•Fltr:ON -5 FORCE 10000 LBS/V •FS: 20.0 v 0.0 v

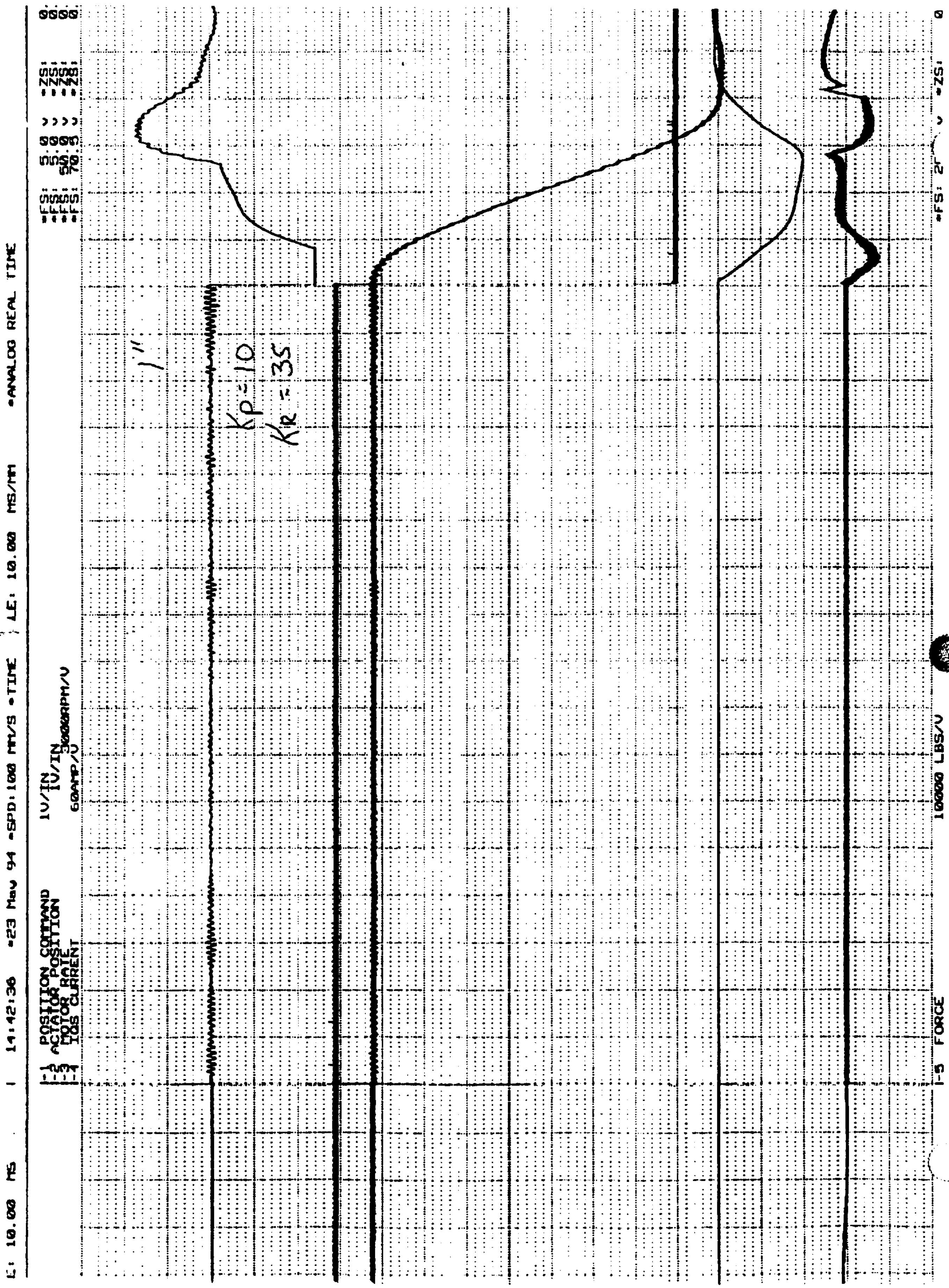

*23 May 94 *SPD:100 MM/S *TIME SCALE: 10.00
*ANALOG REAL TIME
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTUATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IDS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON


REAL TIME
< 14:39:11 · May 94 •SPD:100 MM/S •TIME SCALE: 10.00 MS/MM
•ANALOG REAL
•FS: 5.0 v •ZS: 0.0 v •Fltr:OFF CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IOS CURRENT 60AMP/V
1"
Kp = 10
KR = 20
20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE 10000 LBS/V

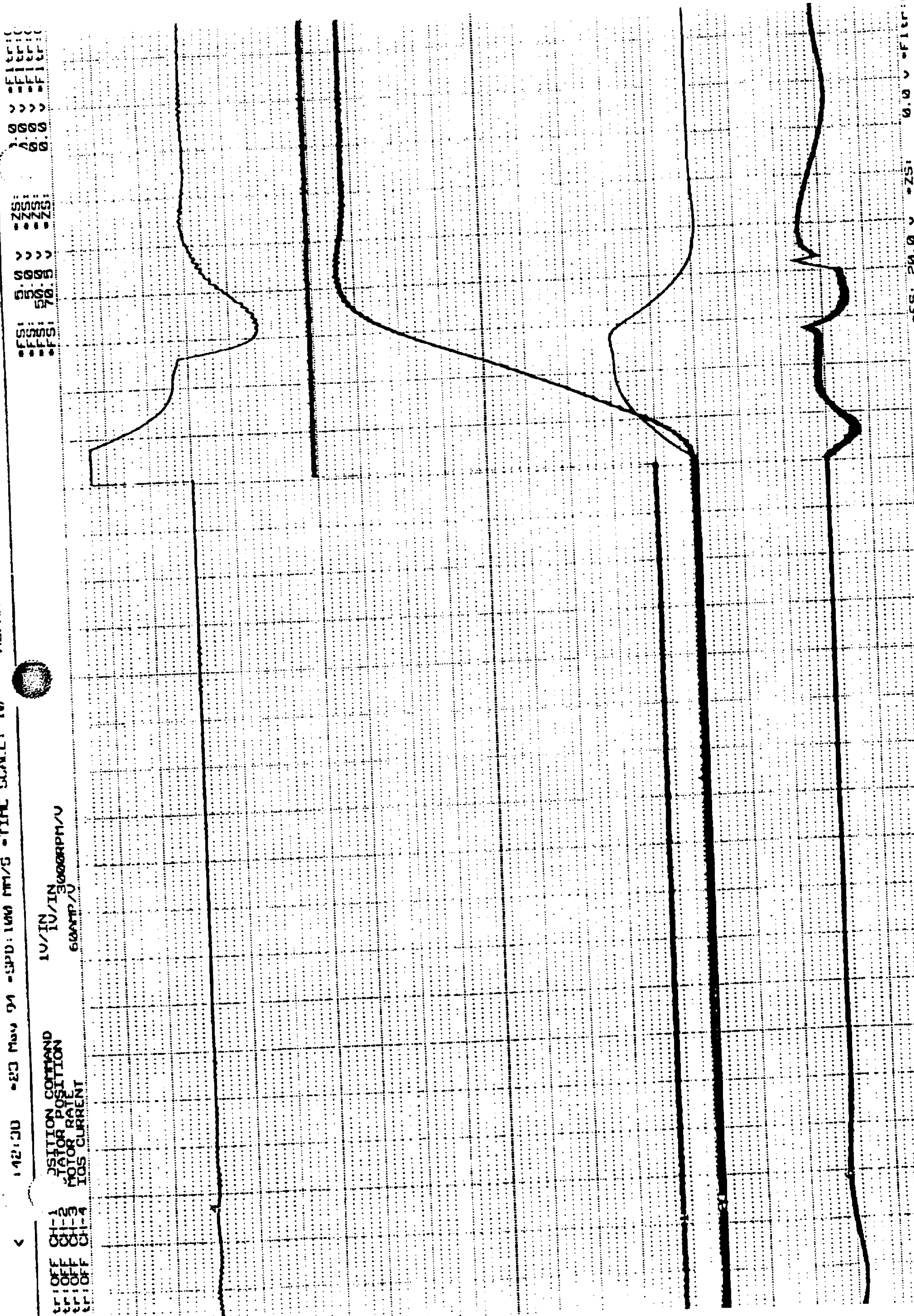

< 14:39:14 •23 May 9
'D:100 MM/S •TIME SCALE: 10.00 MS/MM
| 14:40:
•23 May 94 •
•FS: 5.0 v •ZS: 0.0 v •Fltr:OFF CH-1 POSITION COMMAND
•FS: 5.000 v •ZS: 0.00 v •Fltr:OFF CH-2 ACTATOR POSITION
•FS: 50.00 v •ZS: 0.00 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.0 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRENT
V/IN
1V/IN
3000RPM/V
60AMP/V
POSITI COMMAND
ACTATOR SITION
MOTOR RATE
IQS CURRENT
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE
10000 LBS/V
FORCE


100 MM/S -T1 SCALE: 10.00 MS/MM -ANALOG REAL TIME
14:40:14 -23 Ms 4 -SPD:100
-FS: 5.0 v -ZS: 0.0 v -Fltr:OFF CH-1 POSITION COMMAND 1V/IN
-FS: 5.0 v -ZS: 0.0 v -Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
-FS: 50.0 v -ZS: 0.0 v -Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
-FS: 70.0 v -ZS: 0.0 v -Fltr:OFF CH-4 IQS CURRENT 60AMP/V
.25"/Div
1"
Kp = 10
KR = 30
LBS/V
-ZS: 0.0 v -Fltr:ON CH-5 FORCE
10000

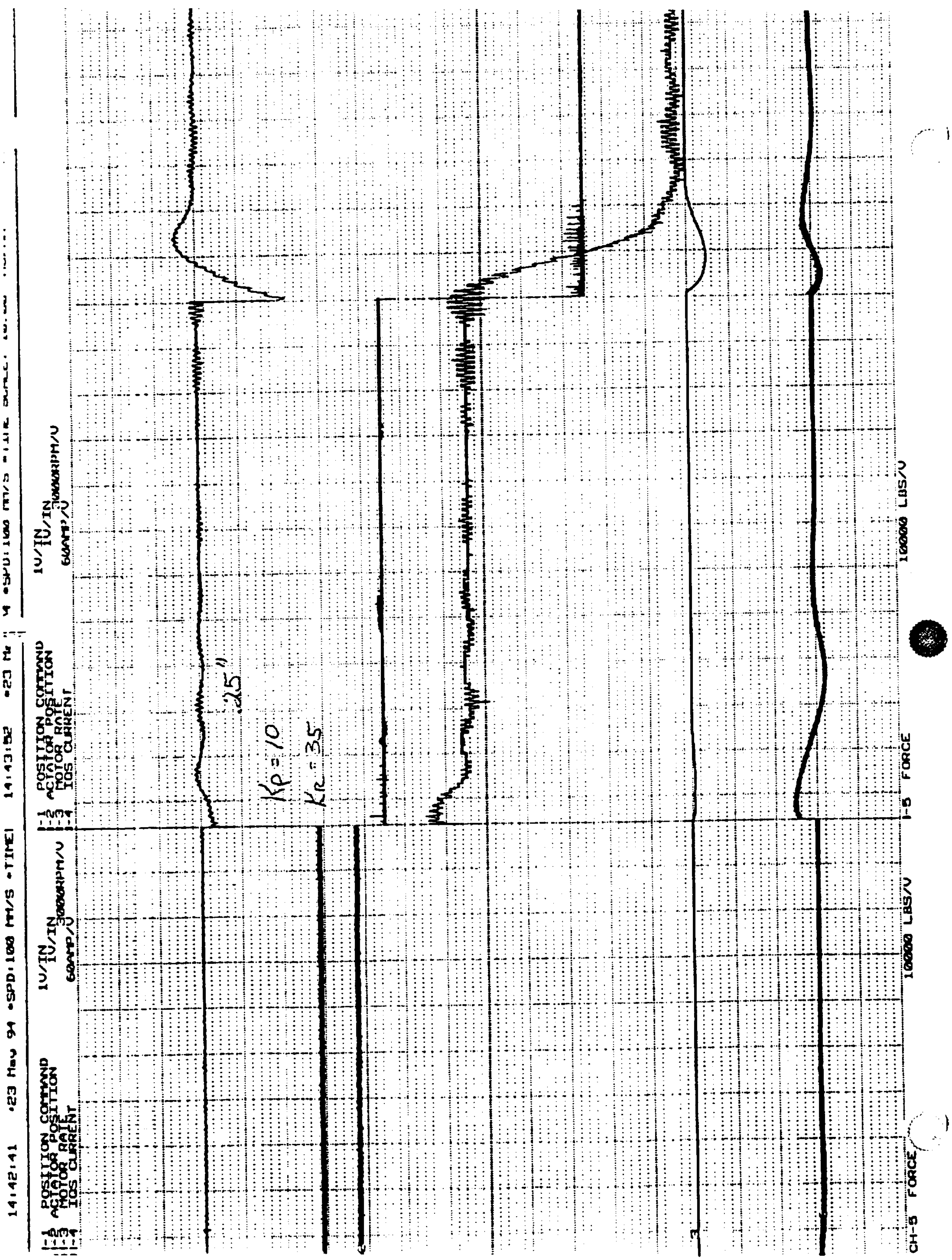

TIME SCALE: 00 MS/MM
•ANALOG REAL TIME
14:40:16 •23 May 94 •SPD
MM/S •TIME
•FS: 5.0 v •ZS: 0.0 v •Fltr:OFF CH-1 POSITION COMMAND
•FS: 5.0 v •ZS: 0.0 v •Fltr:OFF CH-2 ACTATOR POSITION
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRENT
10.
IN
3000RPM/V
60AMP/V
M/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE
10000 LBS/V



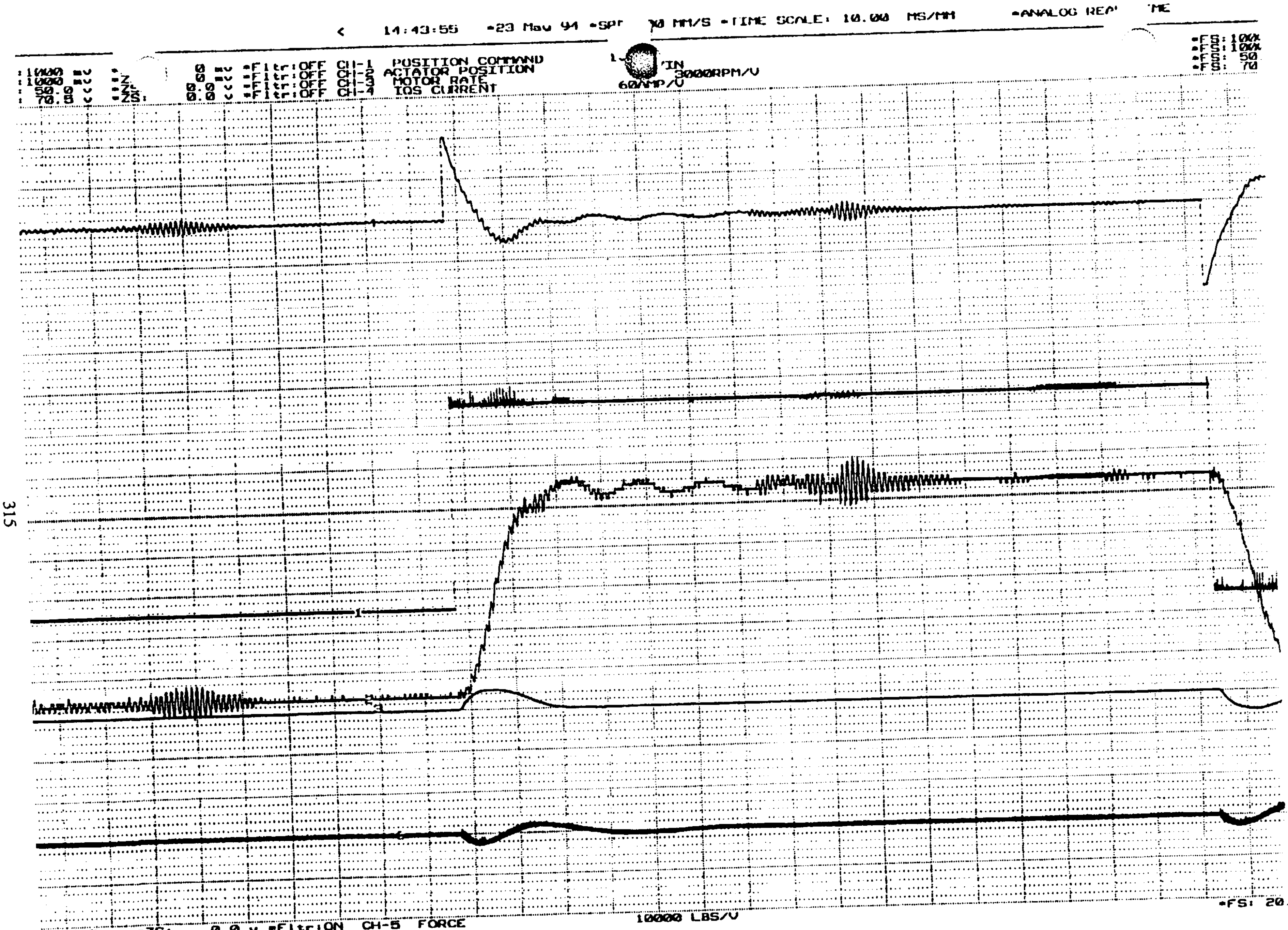
C: 10.00 MS | 14:42:36 *23 May 94 *SPD:100 MM/S *TIME | LE: 10.00 MS/MM *ANALOG REAL TIME
1-1 POSITION COMMAND 1V/IN
1-2 ACTATOR POSITION 1V/IN
1-3 MOTOR RATE 3000RPM/V
1-4 IQS CURRENT 60AMP/V
1-5 FORCE 10000 LBS/V
*FS: 5.00 V *ZS: 0
*FS: 5.00 V *ZS: 0
*FS: 50.0 V *ZS: 0
*FS: 70.0 V *ZS: 0
Kp = 10
KR = 35
1"

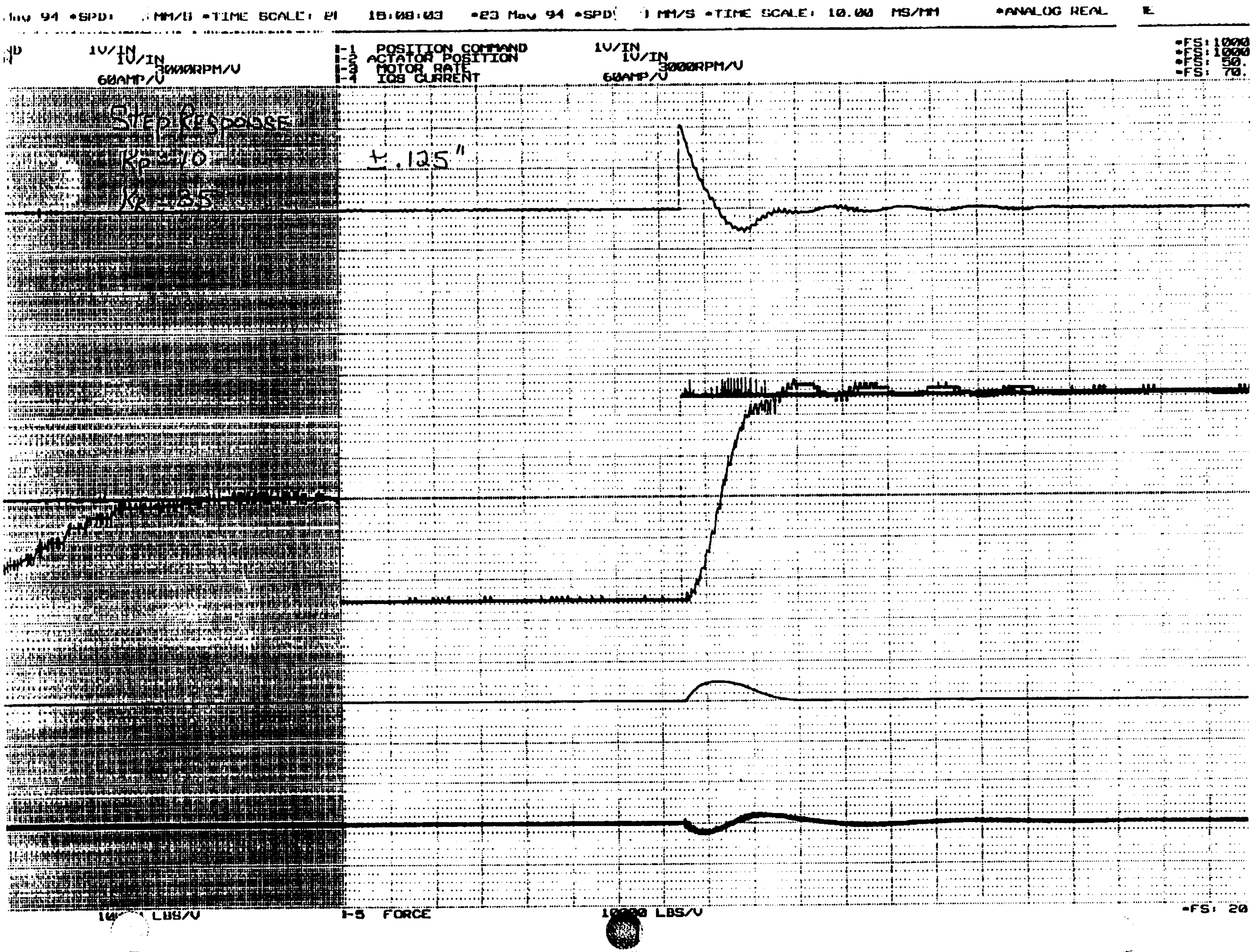


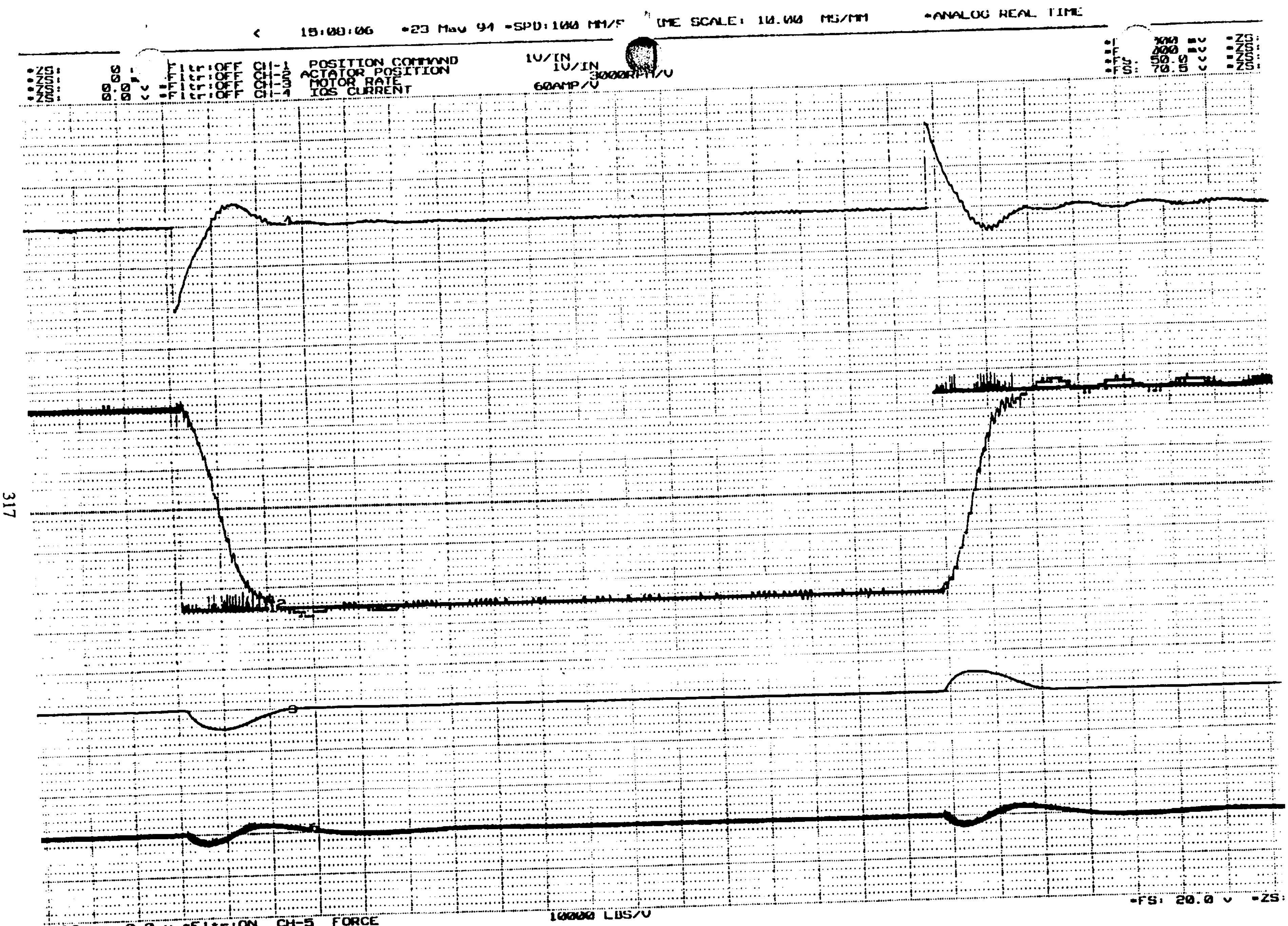
POSITION COMMAND 1V/IN
ACTUATOR POSITION 1V/IN
MOTOR RATE 3000RPM/V
IGS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
ANALOG REAL TIME

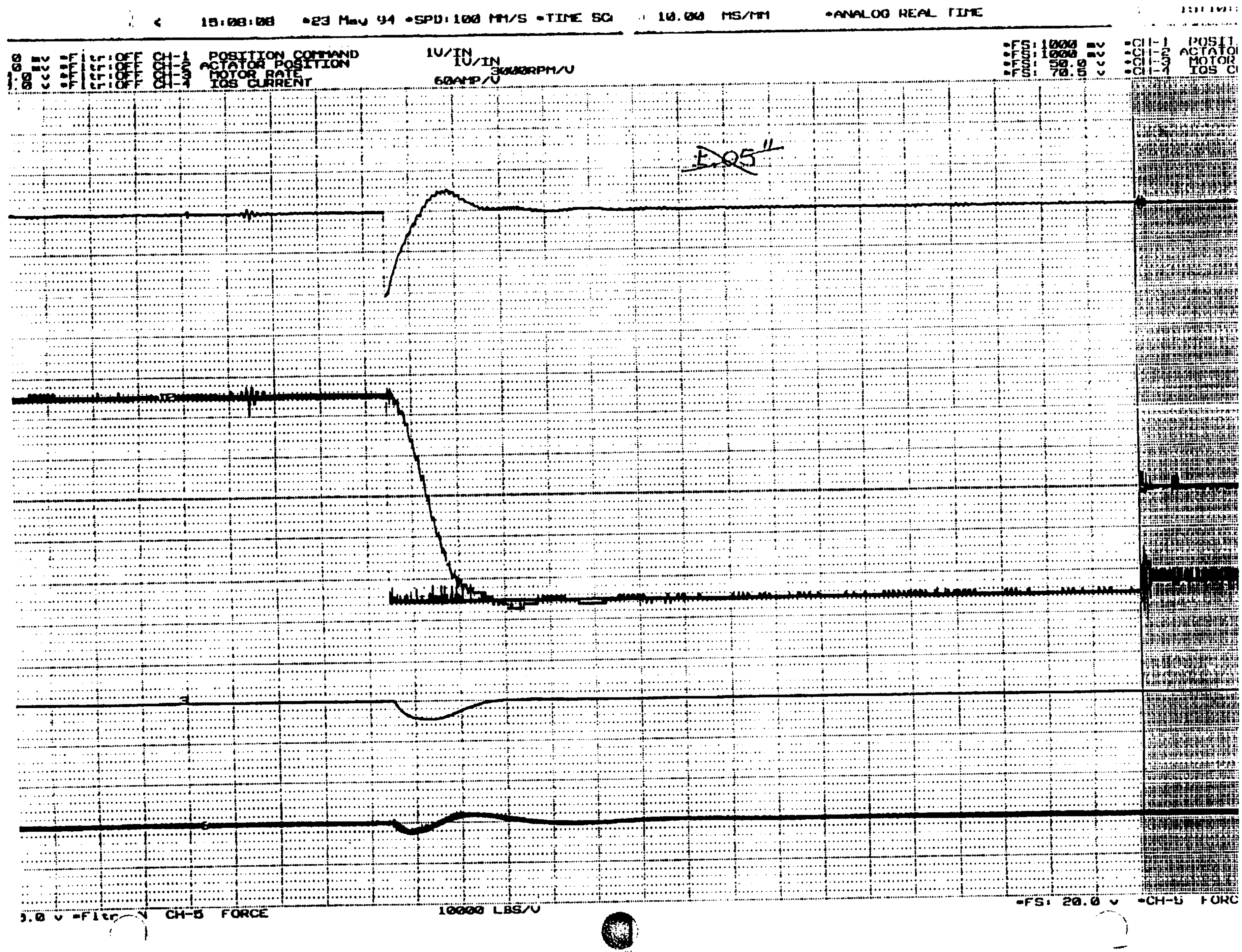


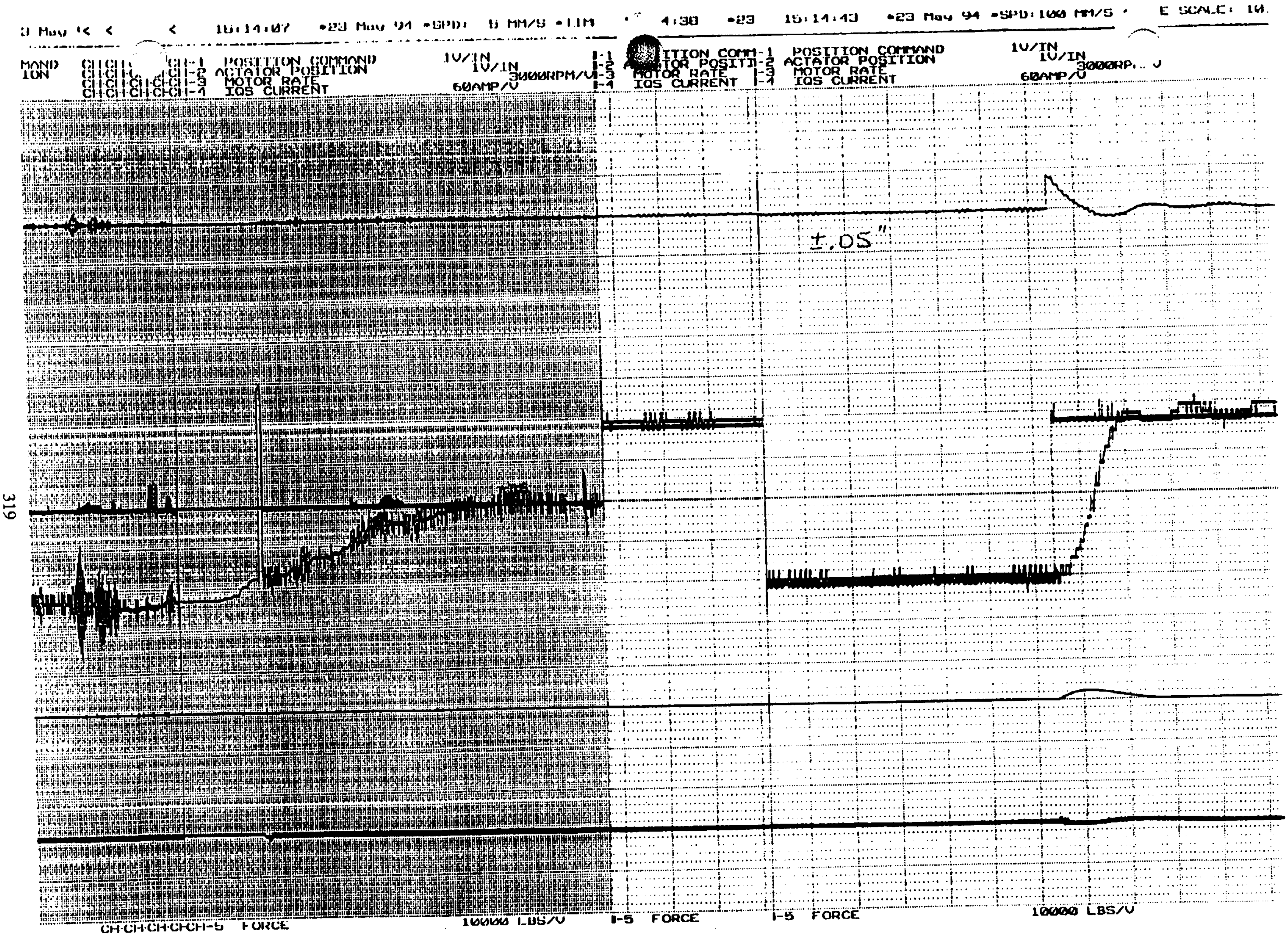
14:42:41 •23 May 94 •SPD:100 MM/S •TIME!
1-1 POSITION COMMAND 10V/IN
1-2 ACTATOR POSITION 10V/IN
1-3 MOTOR RATE 3000RPM/V
1-4 IOS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
14:43:52 •23 Ma
1-1 POSITION COMMAND 10V/IN
1-2 ACTATOR POSITION 10V/IN
1-3 MOTOR RATE 3000RPM/V
1-4 IOS CURRENT 60AMP/V
1-5 FORCE 10000 LBS/V
.25"
Kp = 10
Kr = 35


14:43:55 =23 May 94 =Spr 70 MM/S =TIME SCALE: 10.00 MS/MM =ANALOG REA' ME
:1000 mv =Z 0 mv =Fltr:OFF CH-1 POSITION COMMAND
:1000 mv =Z 0 mv =Fltr:OFF CH-2 ACTATOR POSITION
: 50.0 v =Z 0.0 v =Fltr:OFF CH-3 MOTOR RATE
: 70.5 v =ZS: 0.0 v =Fltr:OFF CH-4 IQS CURRENT
IN
3000RPM/V
60AMP/V
=FS: 10%
=FS: 10%
=FS: 50
=FS: 70
: 20.0 v =ZS: 0.0 v =Fltr:ON CH-5 FORCE
10000 LBS/V
=FS: 20

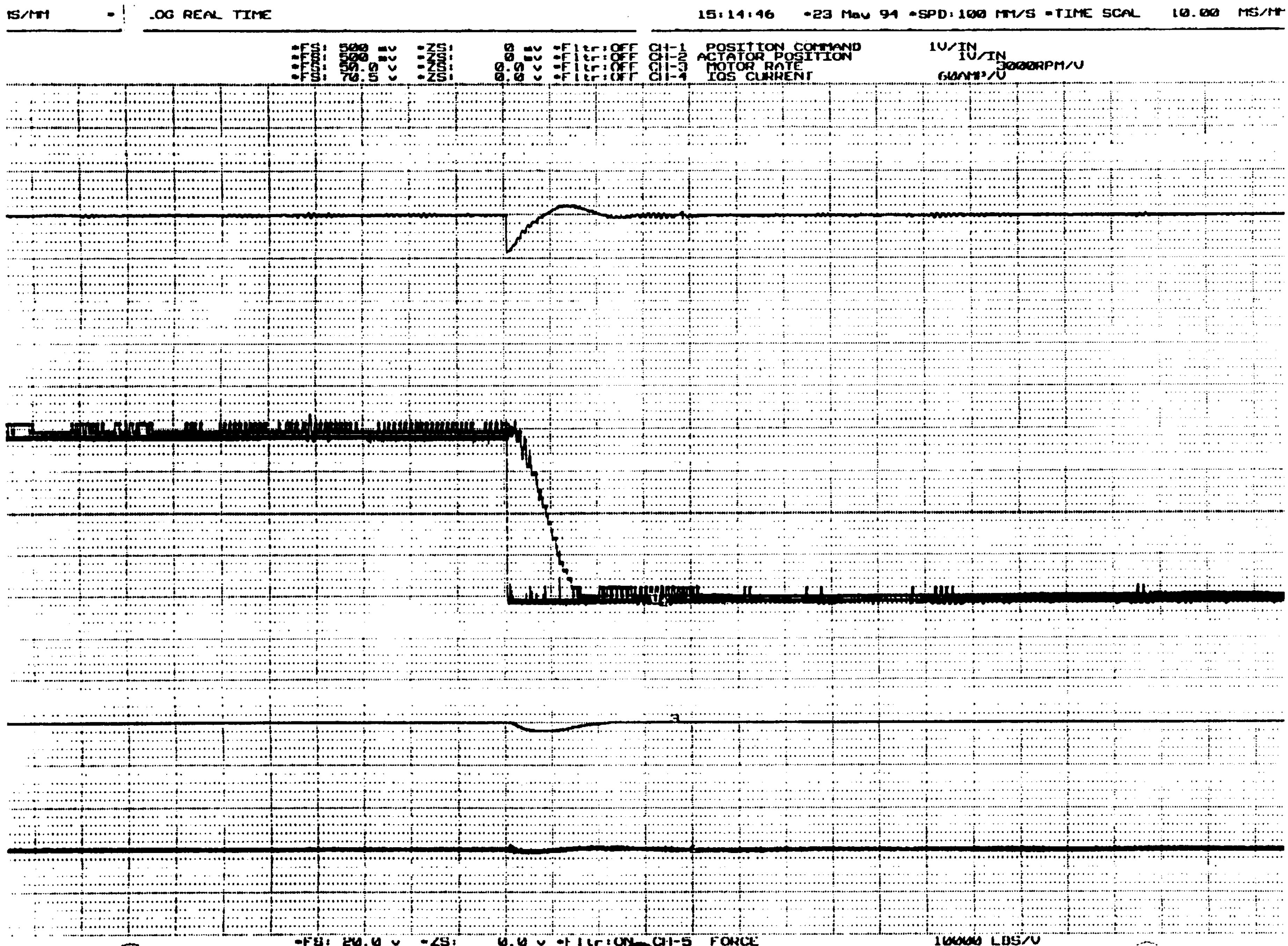

15:08:03 *23 May 94 *SPD: 1 MM/S *TIME SCALE: 10.00 MS/MM *ANALOG REAL
I-1 POSITION COMMAND 1V/IN
I-2 ACTATOR POSITION 1V/IN
I-3 MOTOR RATE 3000RPM/V
I-4 IQS CURRENT 60AMP/V
*FS:1000
*FS:1000
*FS: 50.
*FS: 70.
Step Response
±.125"
I-5 FORCE
10000 LBS/V
*FS: 20


15:00:06 •23 May 94 •SPD:100 MM/S TIME SCALE: 10.00 MS/MM •ANALOG REAL TIME
Fltr:OFF CH-1 POSITION COMMAND 1V/IN
Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
•Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
•Fltr:OFF CH-4 IOS CURRENT 60AMP/V
•ZS: 0.0 v •Fltr:ON CH-5 FORCE 10000 LBS/V
•FS: 20.0 v •ZS:


15:08:08 *23 May 94 *SPD:100 MM/S *TIME SC 10.00 MS/MM *ANALOG REAL TIME
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IOS CURRENT 60AMP/V
*FS:1000 mv
*FS:1000 mv
*FS: 50.0 v
*FS: 70.5 v
±.05"
CH-5 FORCE
10000 LBS/V
*FS: 20.0 v

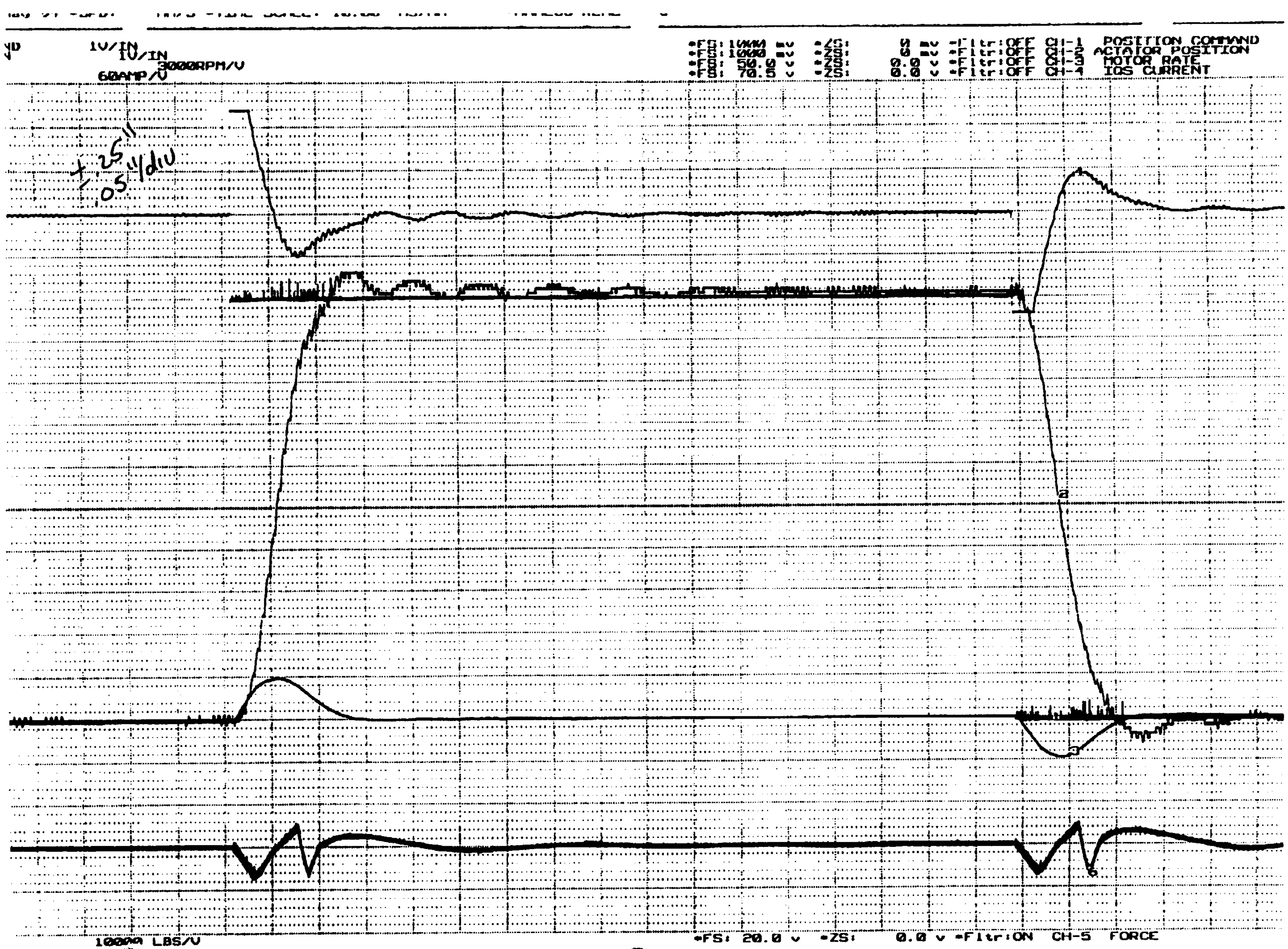


15:14:07 •23 May 94 •SPD: 5 MM/S
4:30 •23 15:14:43 •23 May 94 •SPD:100 MM/S
SCALE: 10.
CH-1 POSITION COMMAND 1V/IN
CH-2 ACTATOR POSITION 1V/IN
CH-3 MOTOR RATE 3000RPM/V
CH-4 IQS CURRENT 60AMP/V
CH-5 FORCE 10000 LBS/V
POSITION COMM-1 POSITION COMMAND 1V/IN
ACTATOR POSITI-2 ACTATOR POSITION 1V/IN
MOTOR RATE 1-3 MOTOR RATE
IQS CURRENT 1-4 IQS CURRENT 60AMP/V
1-5 FORCE
1-5 FORCE 10000 LBS/V
±.05"

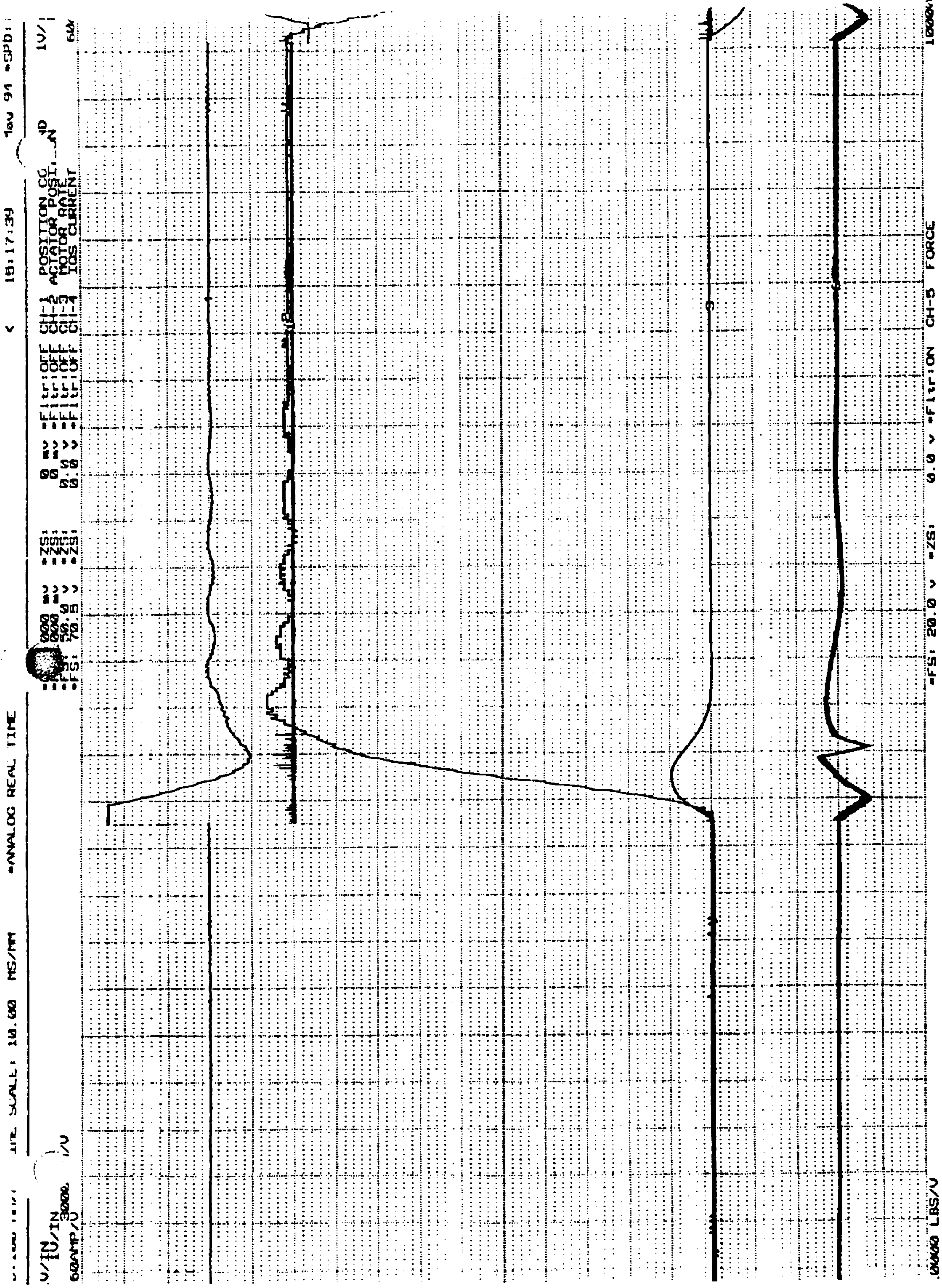


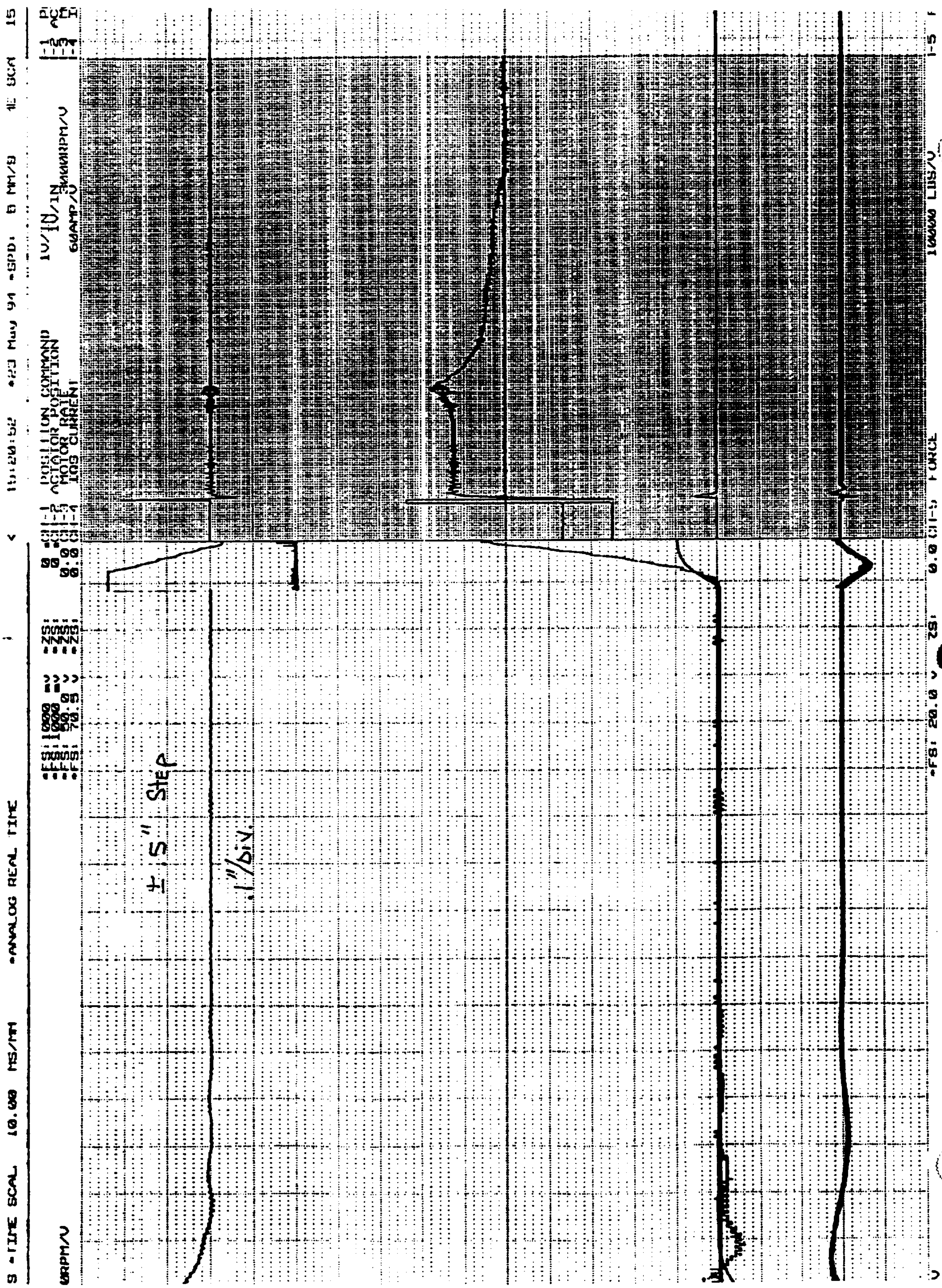
1S/MM
.OG REAL TIME
15:14:46 •23 May 94 •SPD:100 MM/S •TIME SCAL 10.00 MS/MM
•FS: 500 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND 1V/IN
•FS: 500 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRENT 6WAMP/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE 10000 LBS/V

*ANALOG REF ME
< 15 19 *23 May 94 *SPD:100 MM/S *TIME SCALE: 10.00
*FS: 500 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND 1V/IN
*FS: 500 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION 1V/IN
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE 3000RPM/V
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT 60AMP/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE 10000 LBS/V

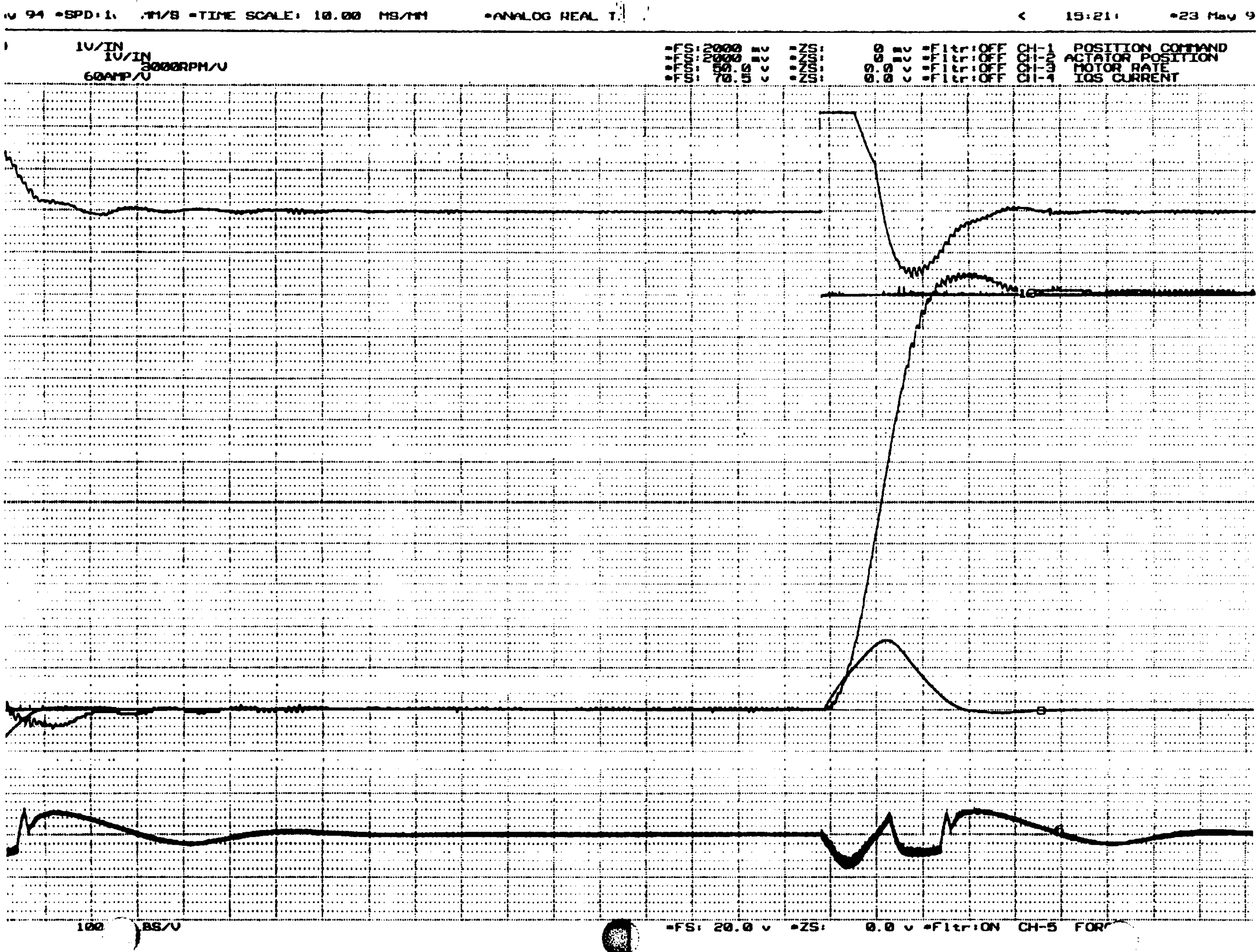


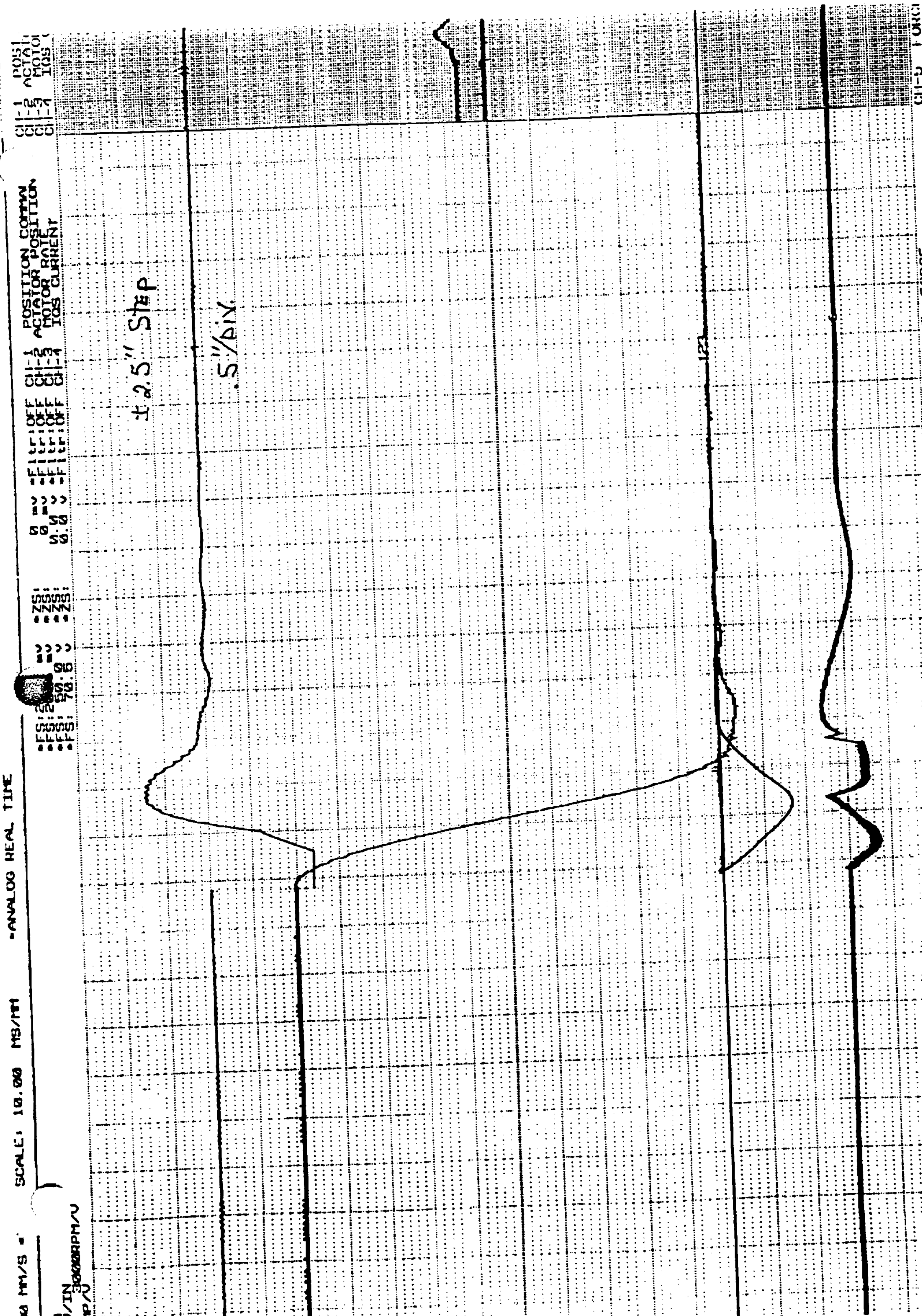
1V/IN
1V/IN
3000RPM/V
60AMP/V
+.25"
.05"/div
*FS: 1000 mv *ZS: 0 mv *Fltr:OFF CH-1 POSITION COMMAND
*FS: 1000 mv *ZS: 0 mv *Fltr:OFF CH-2 ACTATOR POSITION
*FS: 50.0 v *ZS: 0.0 v *Fltr:OFF CH-3 MOTOR RATE
*FS: 70.5 v *ZS: 0.0 v *Fltr:OFF CH-4 IQS CURRENT
10000 LBS/V
*FS: 20.0 v *ZS: 0.0 v *Fltr:ON CH-5 FORCE

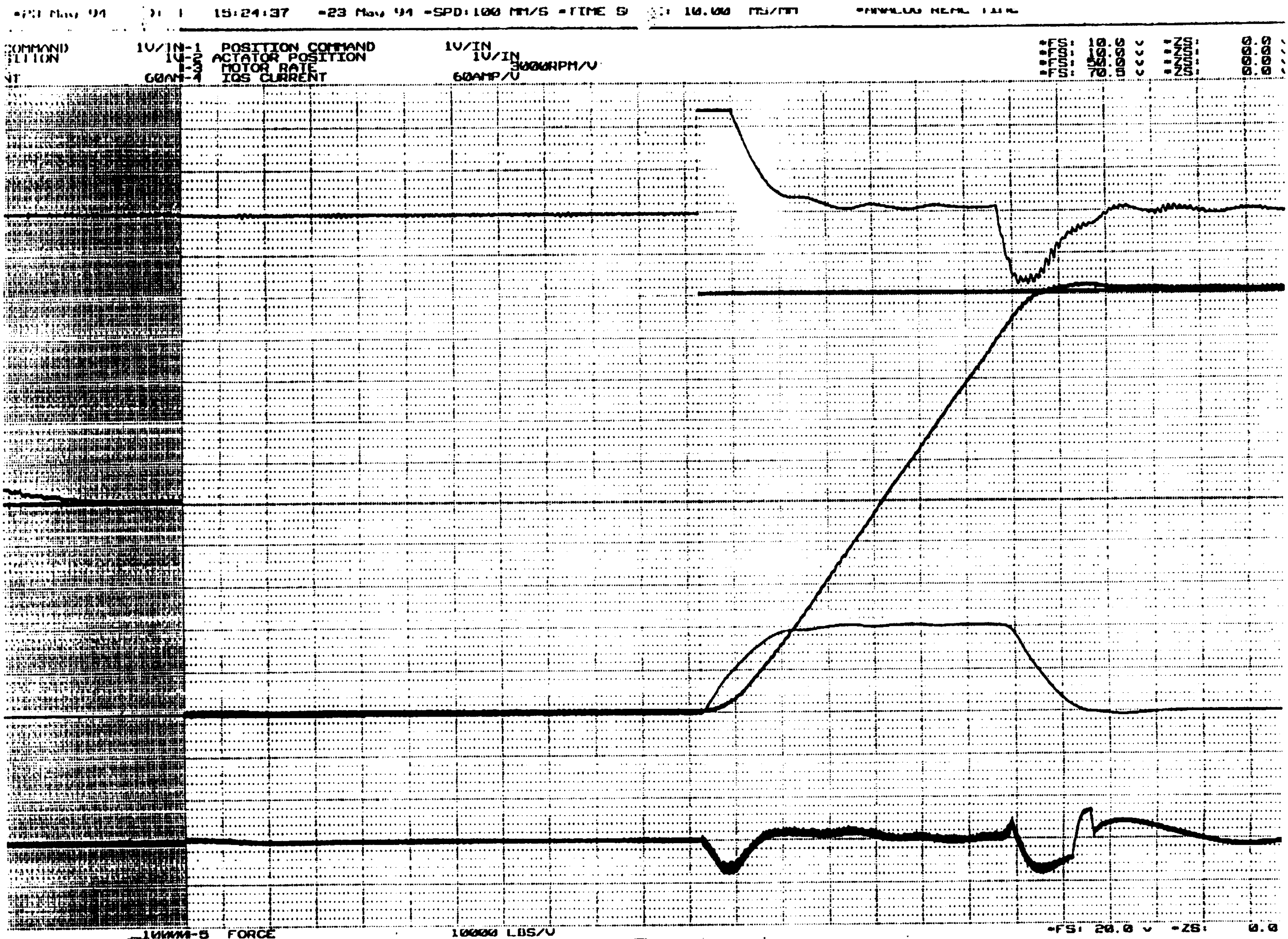

ANALOG REAL TIME
10.00 MS/MM
15:17:39
POSITION CC
MOTOR RATE
IOS CURRENT
CH-5 FORCE

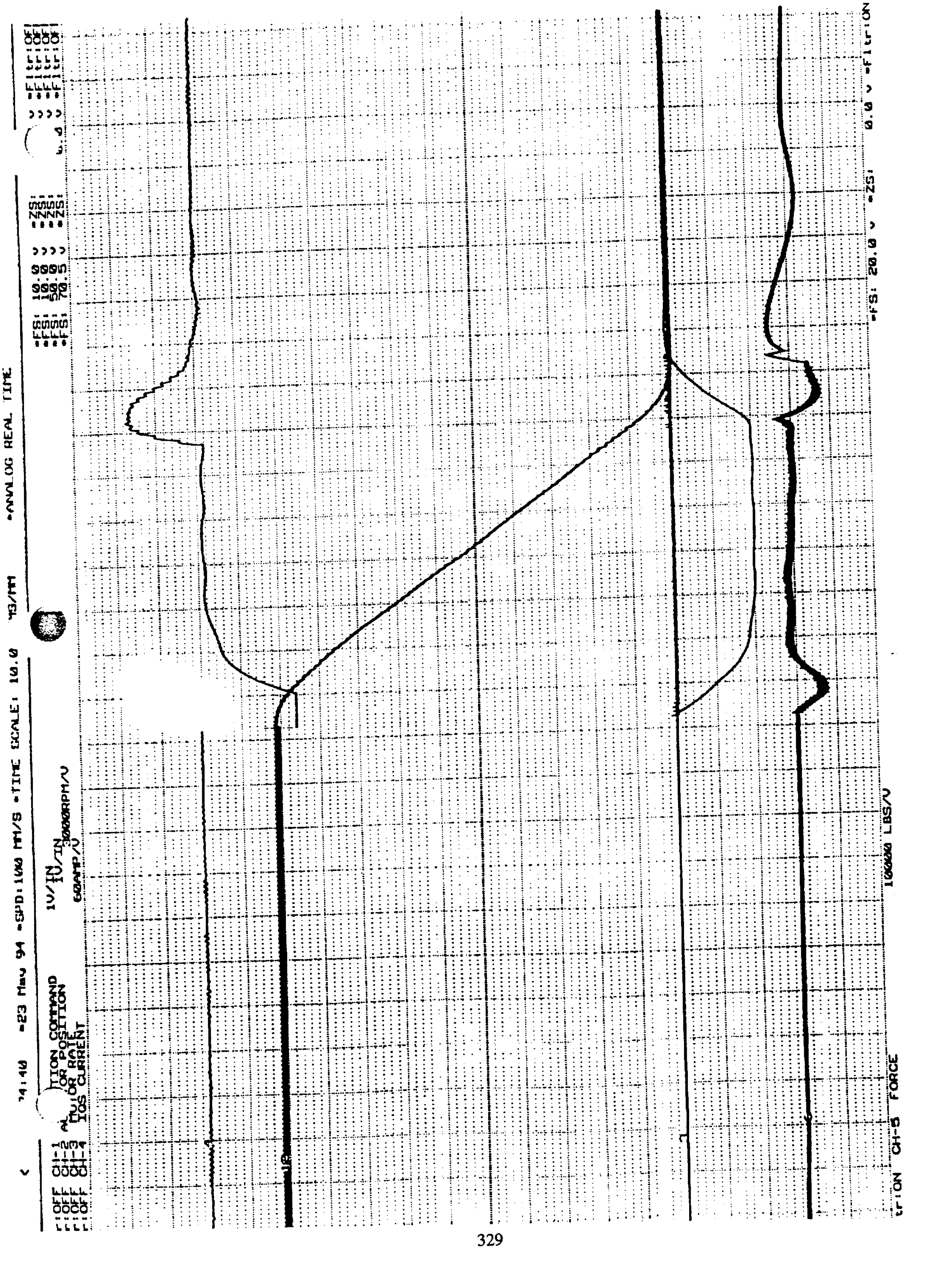

TIME SCAL 10.00 MS/MM
ANALOG REAL TIME
POSITION COMMAND
ACTUATOR POSITION
MOTOR RATE
FORCE
10000 LBS/V
± .5" STEP
.1"/DIV.


•23 May
•SPD:100 MM/S •TIME SCALE: 10.00 MS/MM
•ANV
REAL TIME
15:21:37
ON COMMAND
POSITION
RATE
RRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
•FS:2000 mv •ZS: 5 mv •Fltr:OFF CH-1 POSITION CO
•FS:2000 mv •ZS: 5 mv •Fltr:OFF CH-2 ACTATOR POSI
•FS: 50.0 v •ZS: 5.0 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IOS CURRENT
10000 LBS/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE

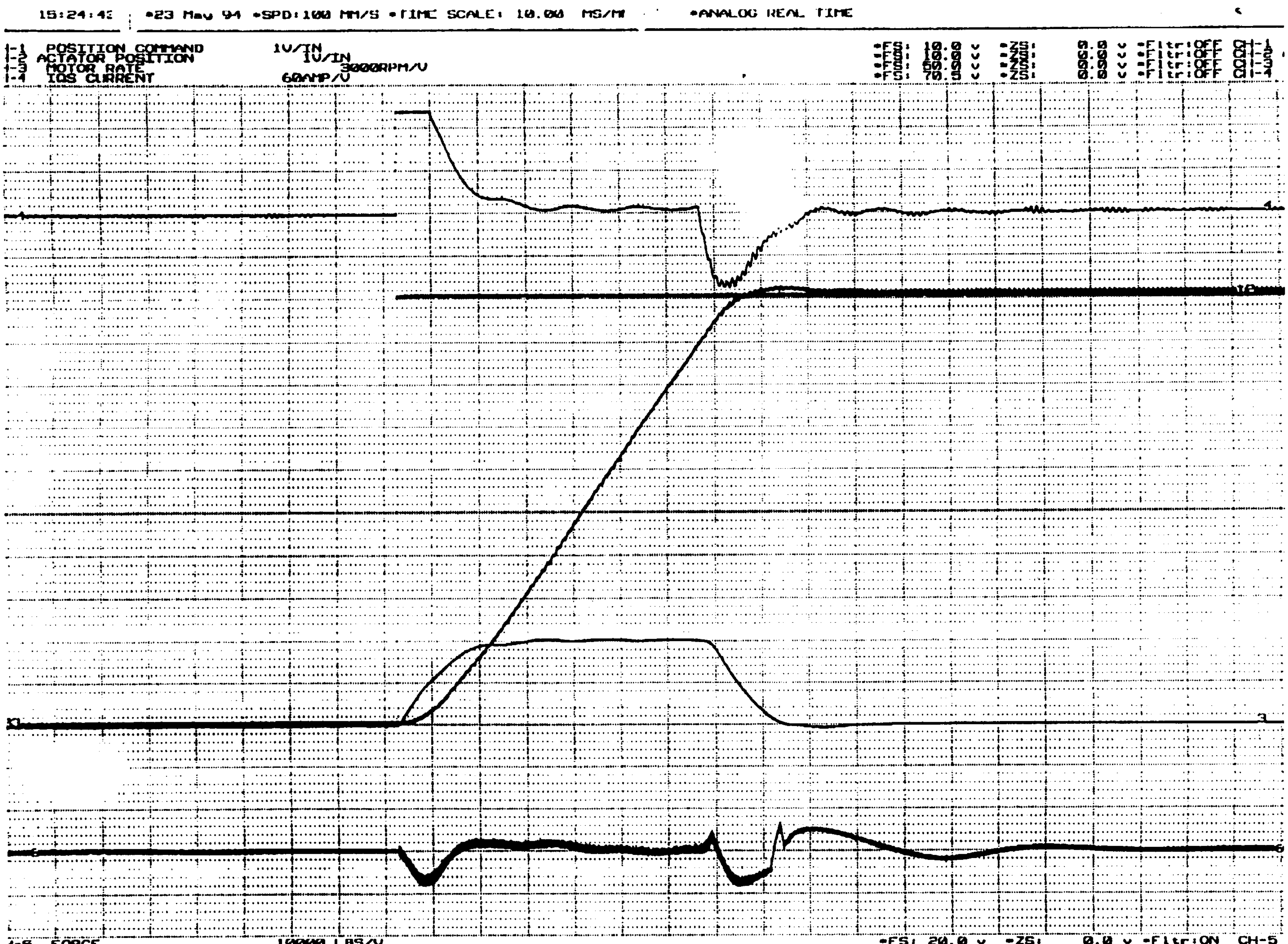

v 94 •SPD:1 MM/S •TIME SCALE: 10.00 MS/MM •ANALOG REAL T. < 15:21: •23 May 9
1V/IN
1V/IN
3000RPM/V
60AMP/V
•FS:2000 mv •ZS: 0 mv •Fltr:OFF CH-1 POSITION COMMAND
•FS:2000 mv •ZS: 0 mv •Fltr:OFF CH-2 ACTATOR POSITION
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RATE
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IOS CURRENT
100 BS/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FOR

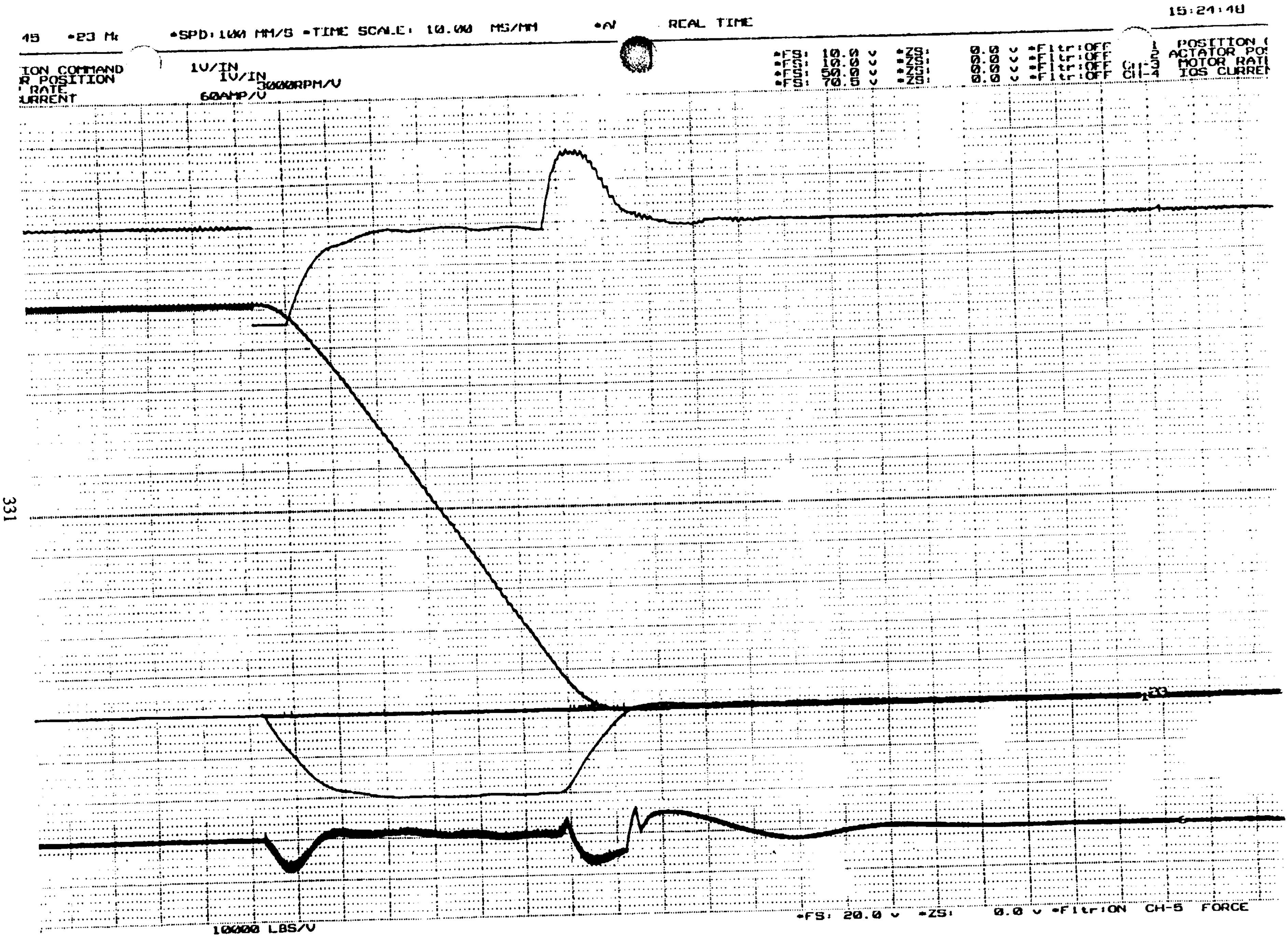

SCALE: 10.00 MS/MM
ANALOG REAL TIME
POSITION COMMAN
ACTATOR POSITION
MOTOR RATE
IQS CURRENT
CH-5 FORCE
±2.5" Step
.5"/DIV


15:24:37 *23 May 94 *SPD:100 MM/S *TIME 10.00 MS/MM
1V/IN-1 POSITION COMMAND 1V/IN
1V-2 ACTATOR POSITION 1V/IN
I-3 MOTOR RATE 3000RPM/V
60AM-4 IQS CURRENT 60AMP/V
*FS: 10.0 v *ZS: 0.0
*FS: 10.0 v *ZS: 0.0
*FS: 50.0 v *ZS: 0.0
*FS: 70.5 v *ZS: 0.0
10WM-5 FORCE 10000 LBS/V
*FS: 20.0 v *ZS: 0.0

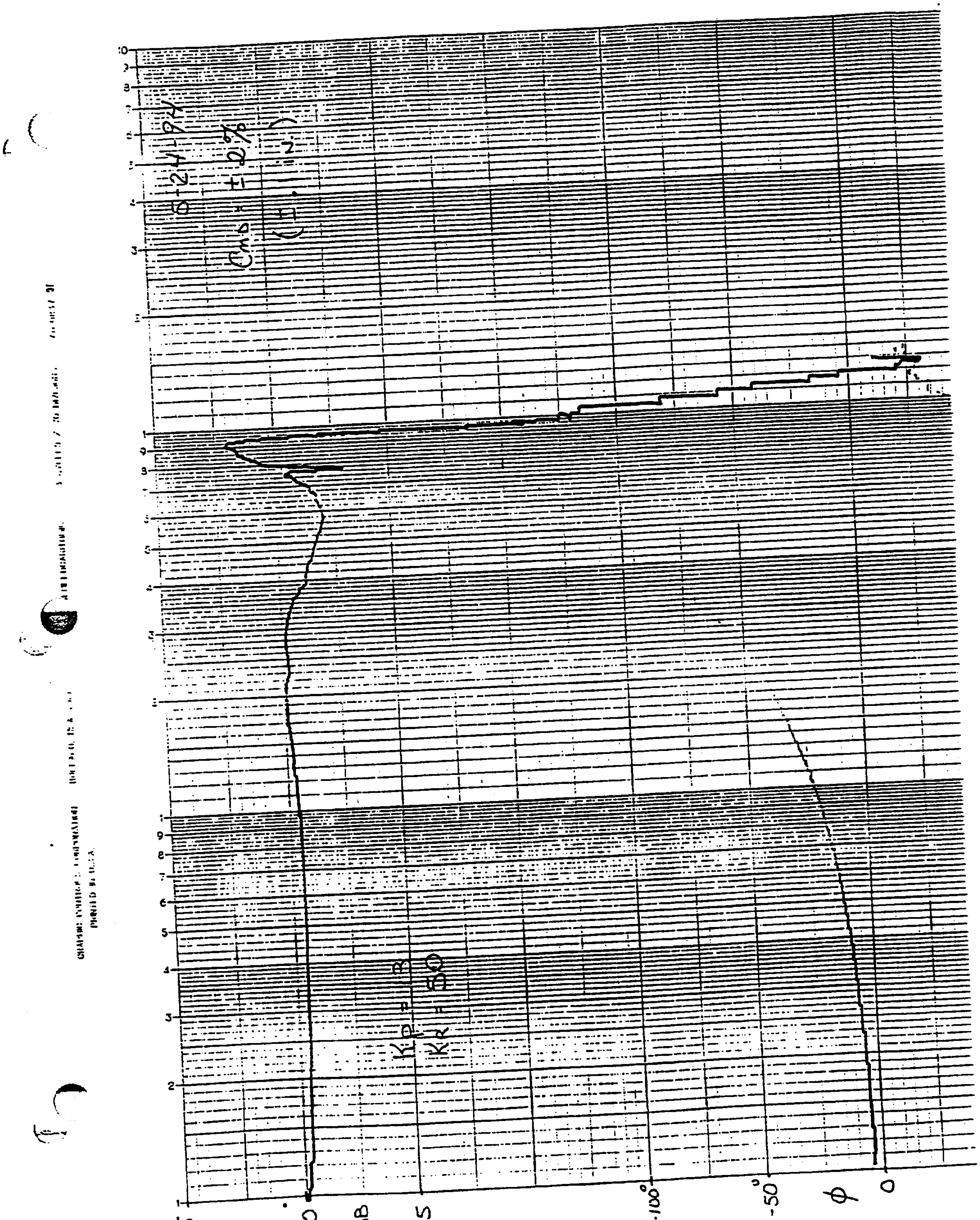


-23 May 94 -SPD:100 MM/S -TIME SCALE: 10.0
-ANALOG REAL TIME
CH-1
CH-2
CH-3
CH-4
TION COMMAND
OR POSITION
OR RATE
IOS CURRENT
1V/IN
10V/IN
60AMP/V
CH-5 FORCE
10000 LBS/V
-FS: 20.0 V -ZS: 0.0 V -Fltr:ON

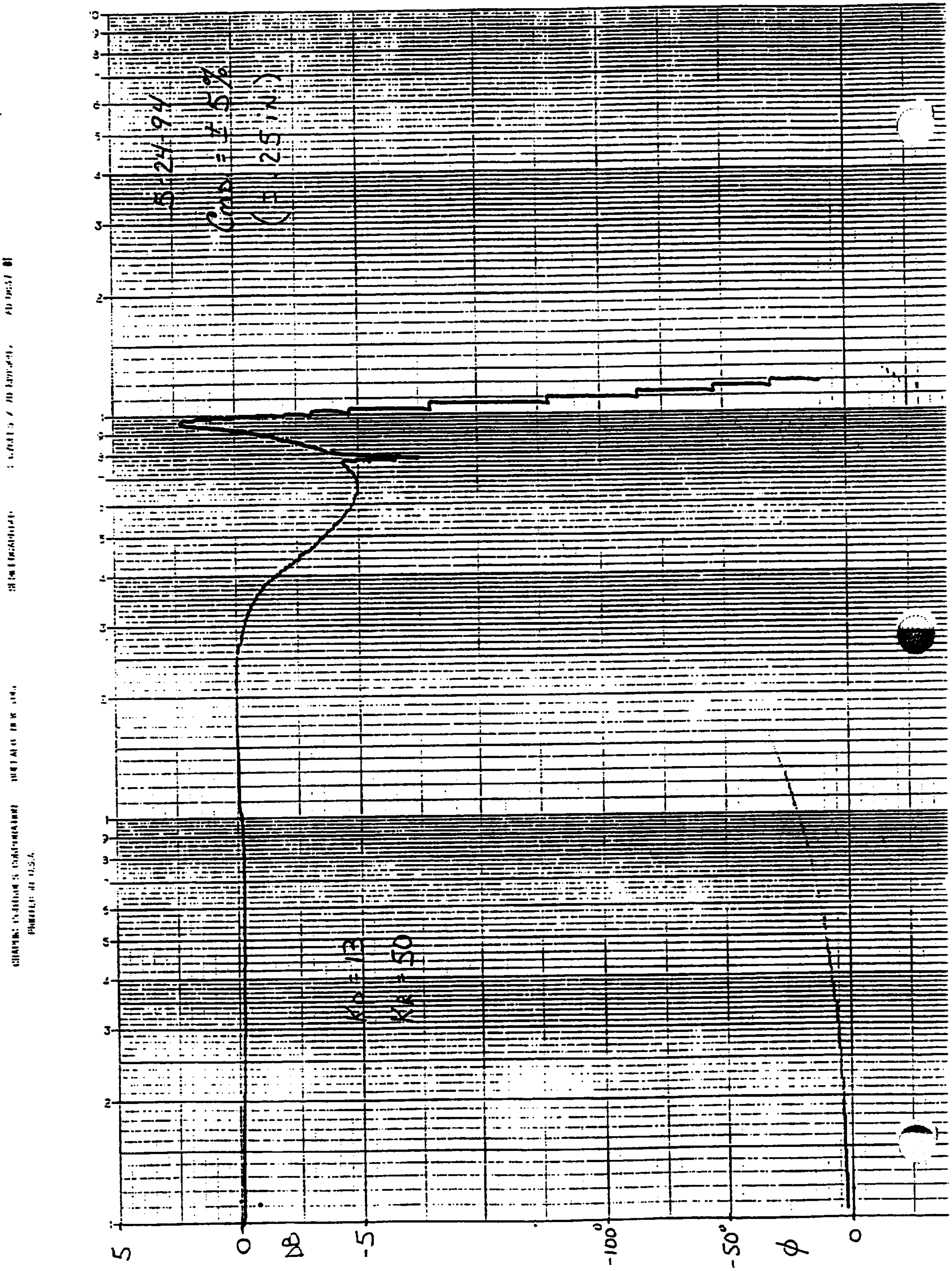

15:24:43
•23 May 94 •SPD:100 MM/S •TIME SCALE: 10.00 MS/M
•ANALOG REAL TIME
1-1 POSITION COMMAND 1V/IN
1-2 ACTATOR POSITION 1V/IN
1-3 MOTOR RATE 3000RPM/V
1-4 IQS CURRENT 60AMP/V
•FS: 10.0 v •ZS: 0.0 v •Fltr:OFF CH-1
•FS: 10.0 v •ZS: 0.0 v •Fltr:OFF CH-2
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4
1-5 FORCE 10000 LBS/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5


15:24:48
45 •23 M
•SPD:100 MM/S •TIME SCALE: 10.00 MS/MM
REAL TIME
ION COMMAND
R POSITION
RATE
URRENT
1V/IN
1V/IN
3000RPM/V
60AMP/V
•FS: 10.0 v •ZS: 0.0 v •Fltr:OFF 1 POSITION
•FS: 10.0 v •ZS: 0.0 v •Fltr:OFF 2 ACTATOR PO
•FS: 50.0 v •ZS: 0.0 v •Fltr:OFF CH-3 MOTOR RAT
•FS: 70.5 v •ZS: 0.0 v •Fltr:OFF CH-4 IQS CURRE
10000 LBS/V
•FS: 20.0 v •ZS: 0.0 v •Fltr:ON CH-5 FORCE

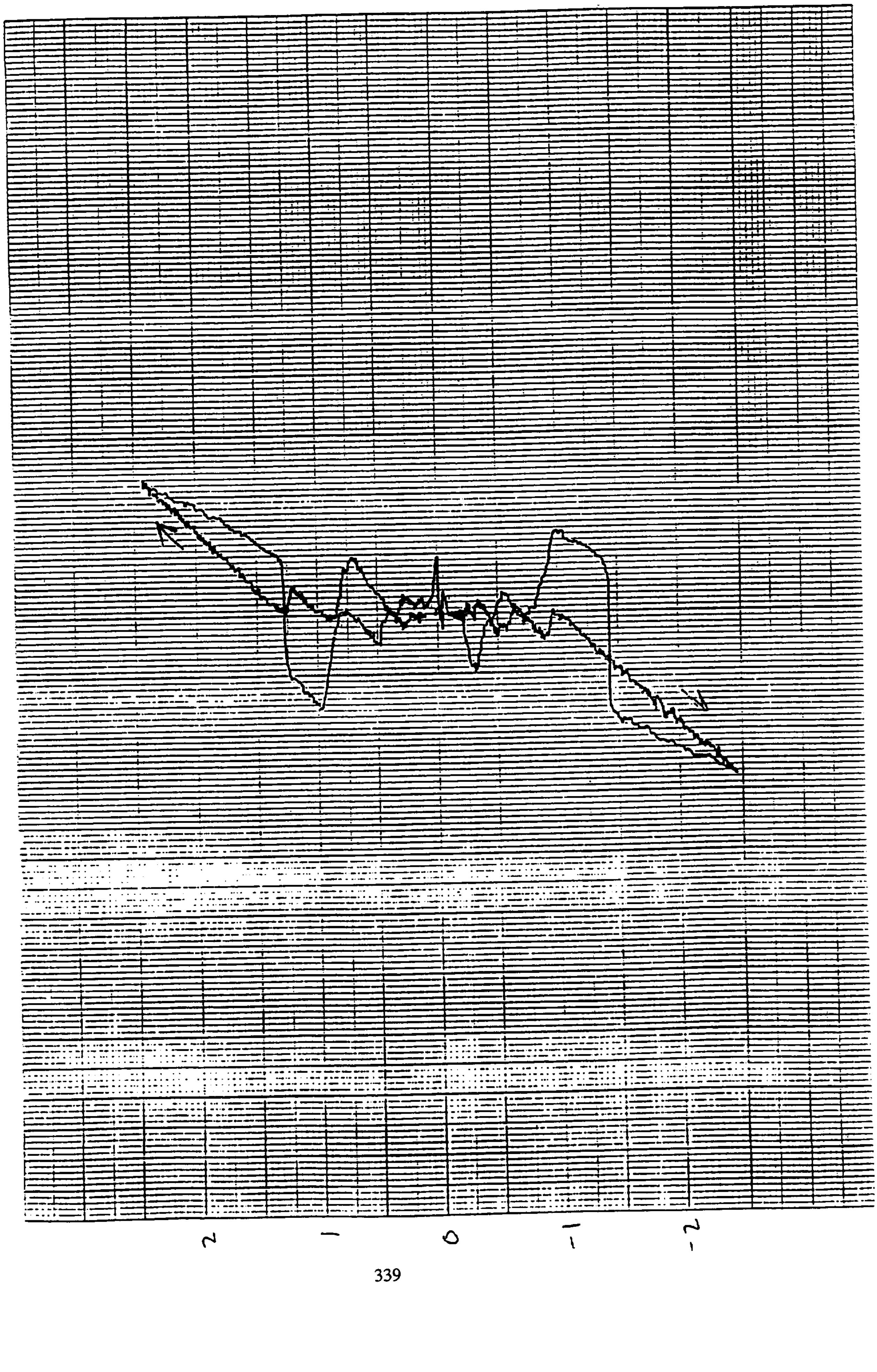
SECTION 3 – FREQUENCY RESPONSE TEST DATA

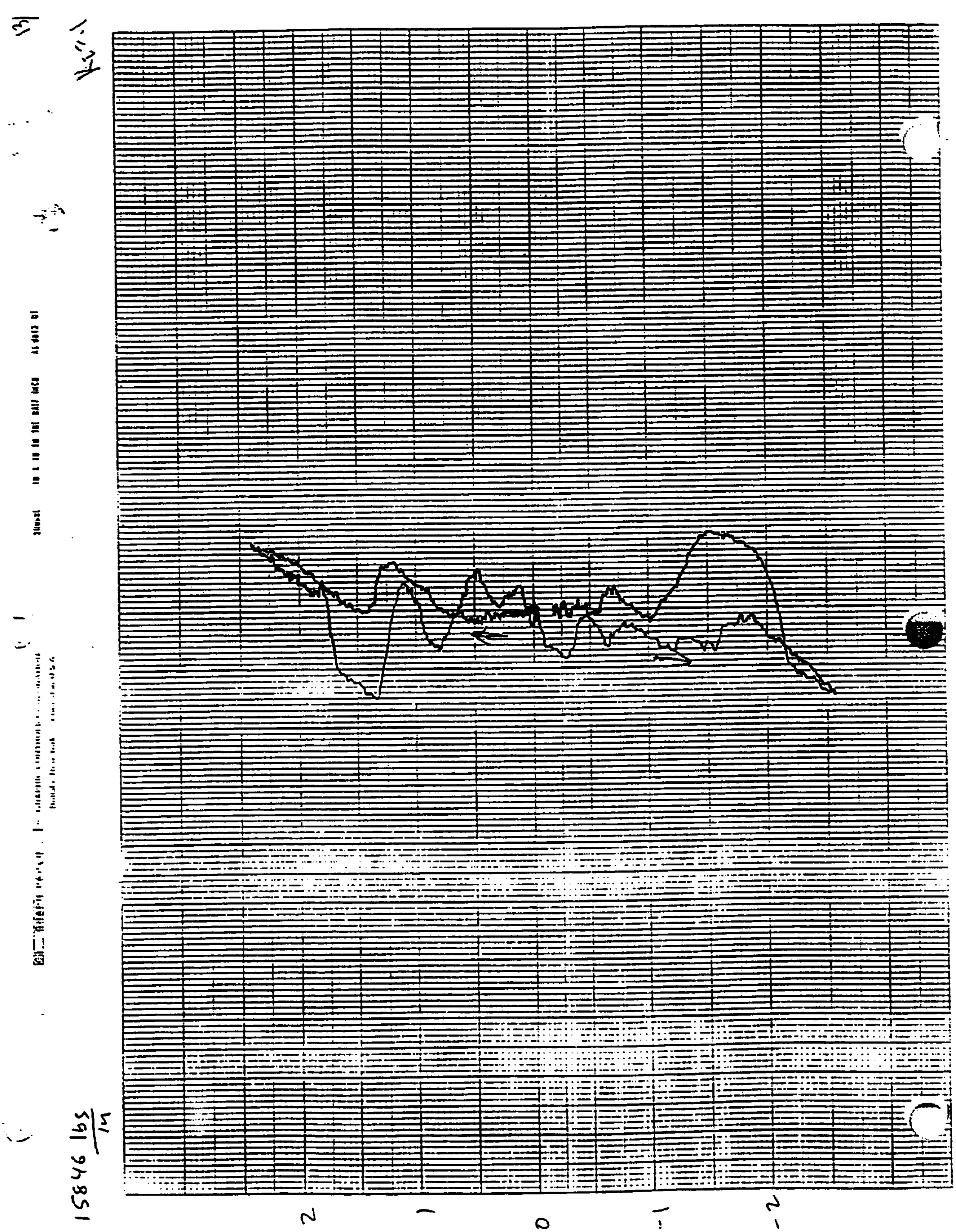


6-24-94
Cmb = ±2%
Kp = 13
Kr = 50
dB
-100°
-50°
φ


5-24-94
Cmd = ± 5%
Kp = 13
KR = 50
5
0
dB
-5
-100°
-50°
φ
0

SECTION 4 – STIFFNESS TEST DATA

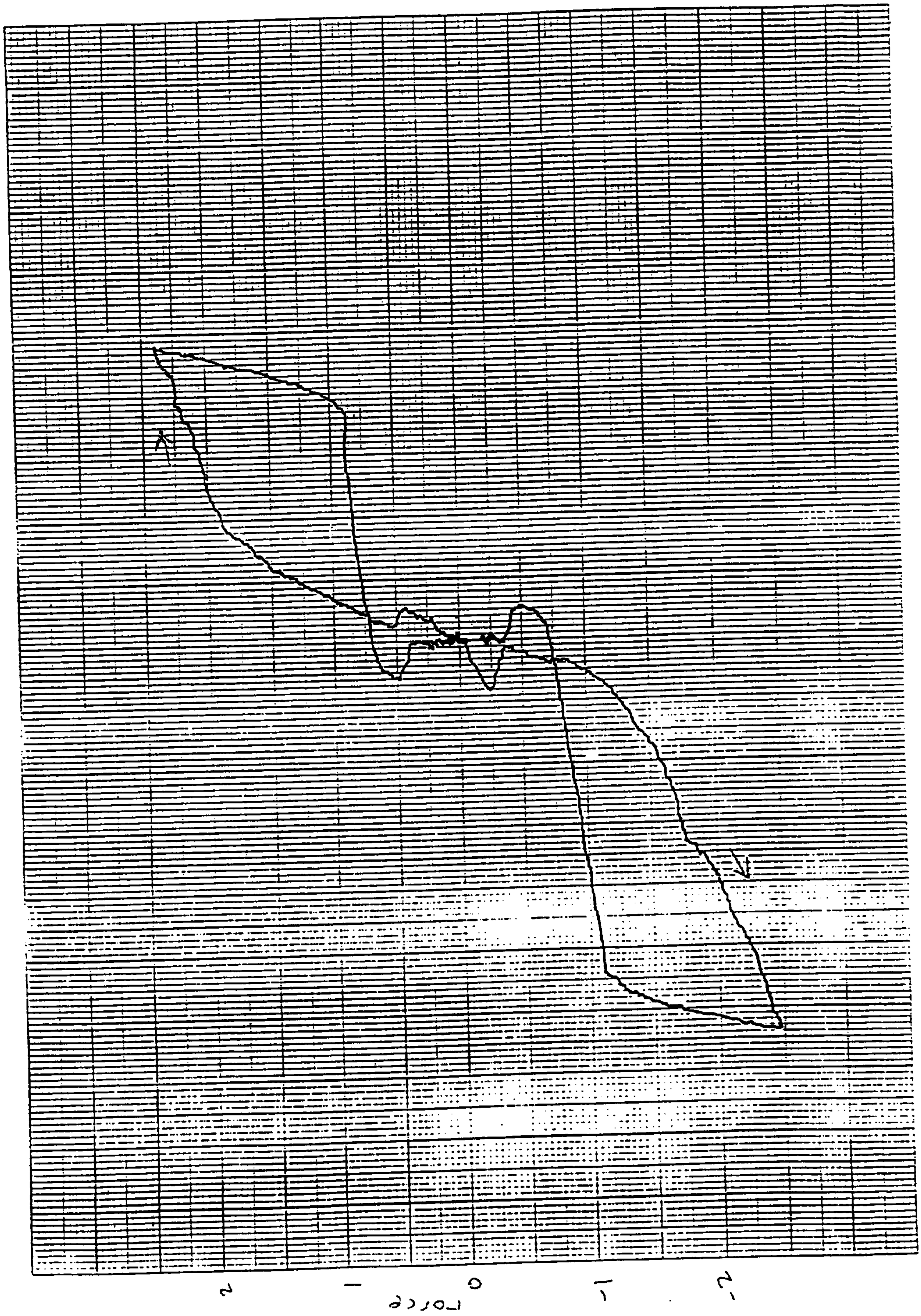


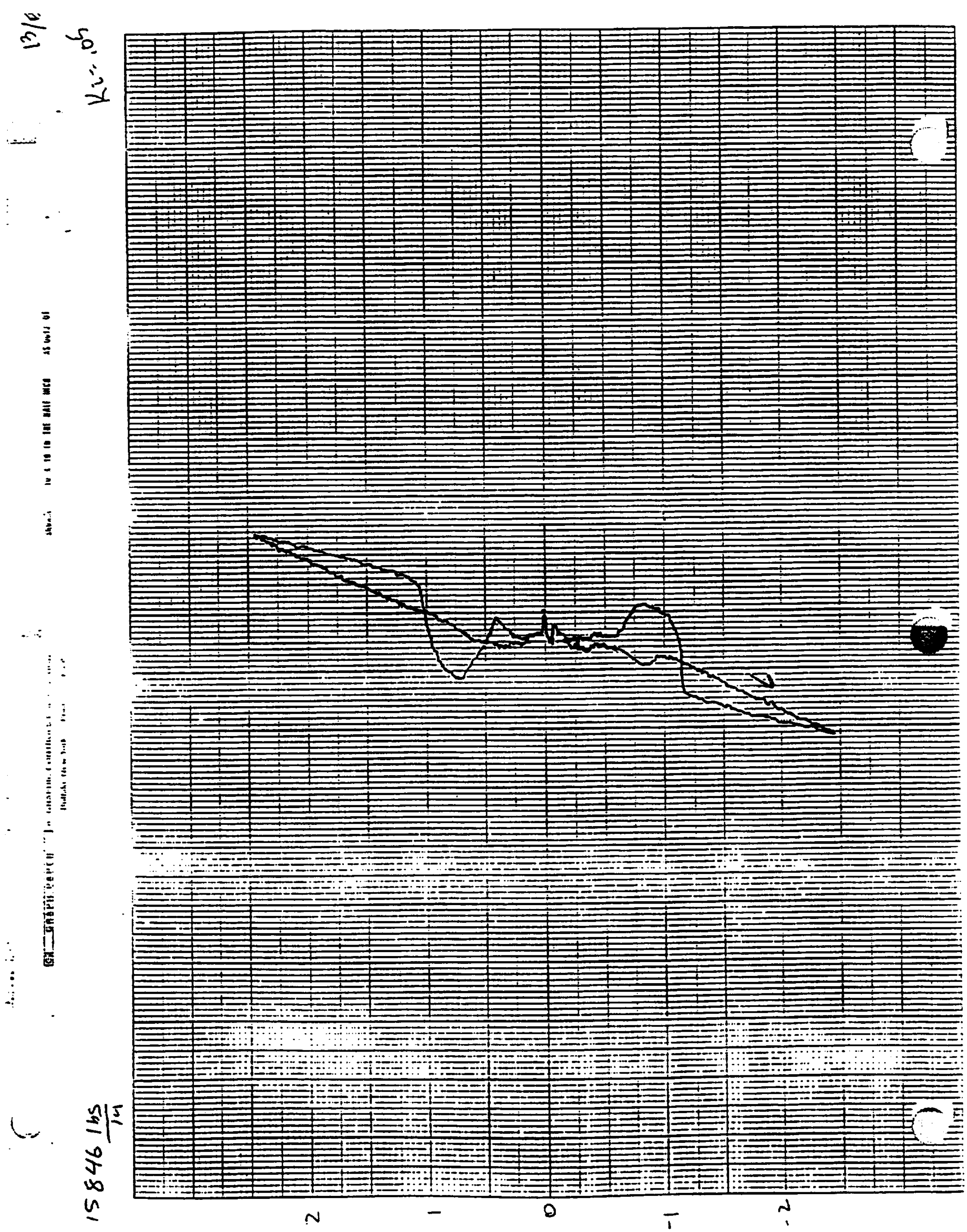

15846 lbs/in
2
1
0
-1
-2

10/35

$K_i = .05$

15846 lbs/inch

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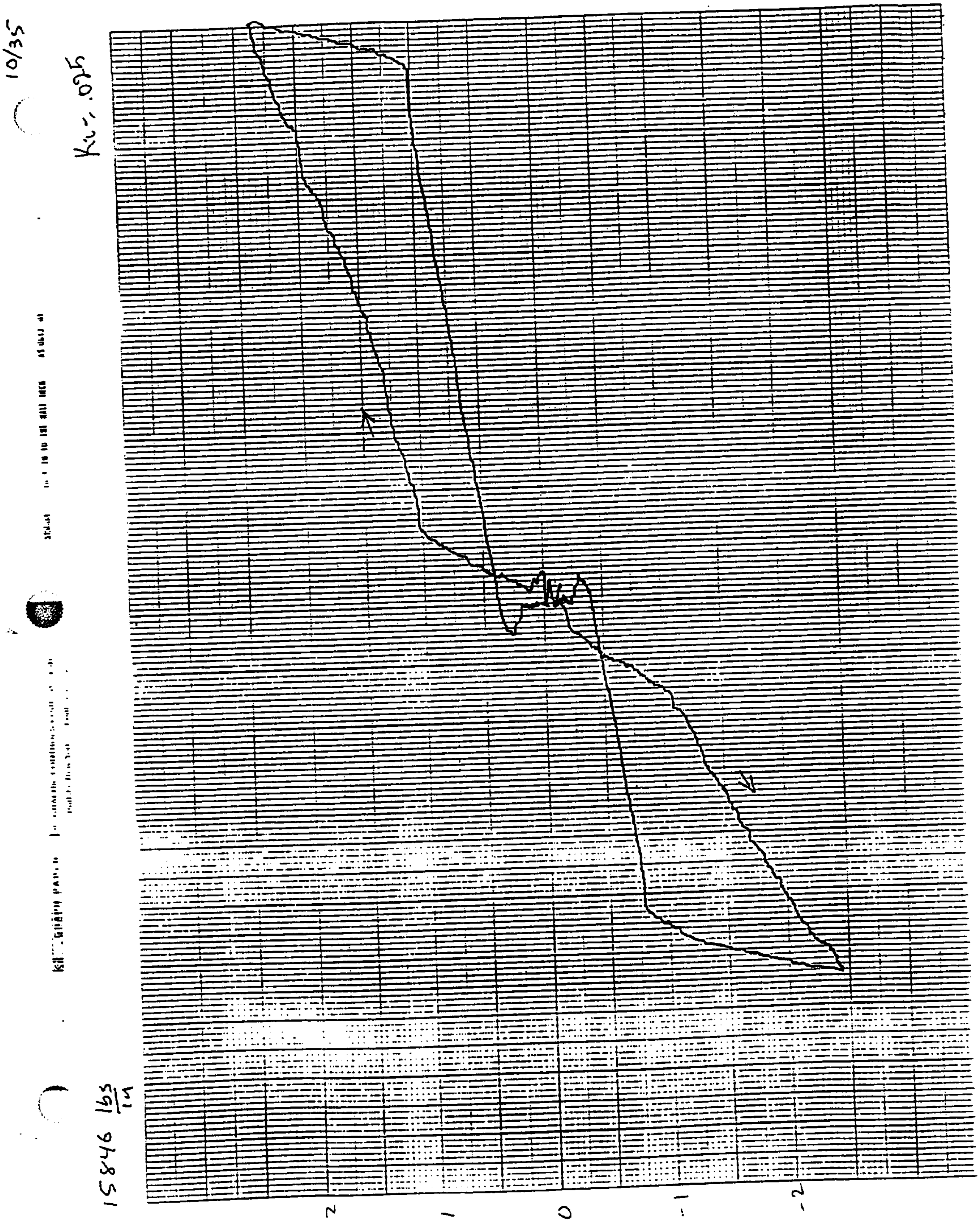
-1
-2


10/35
Ku = .025
15846 lbs/in
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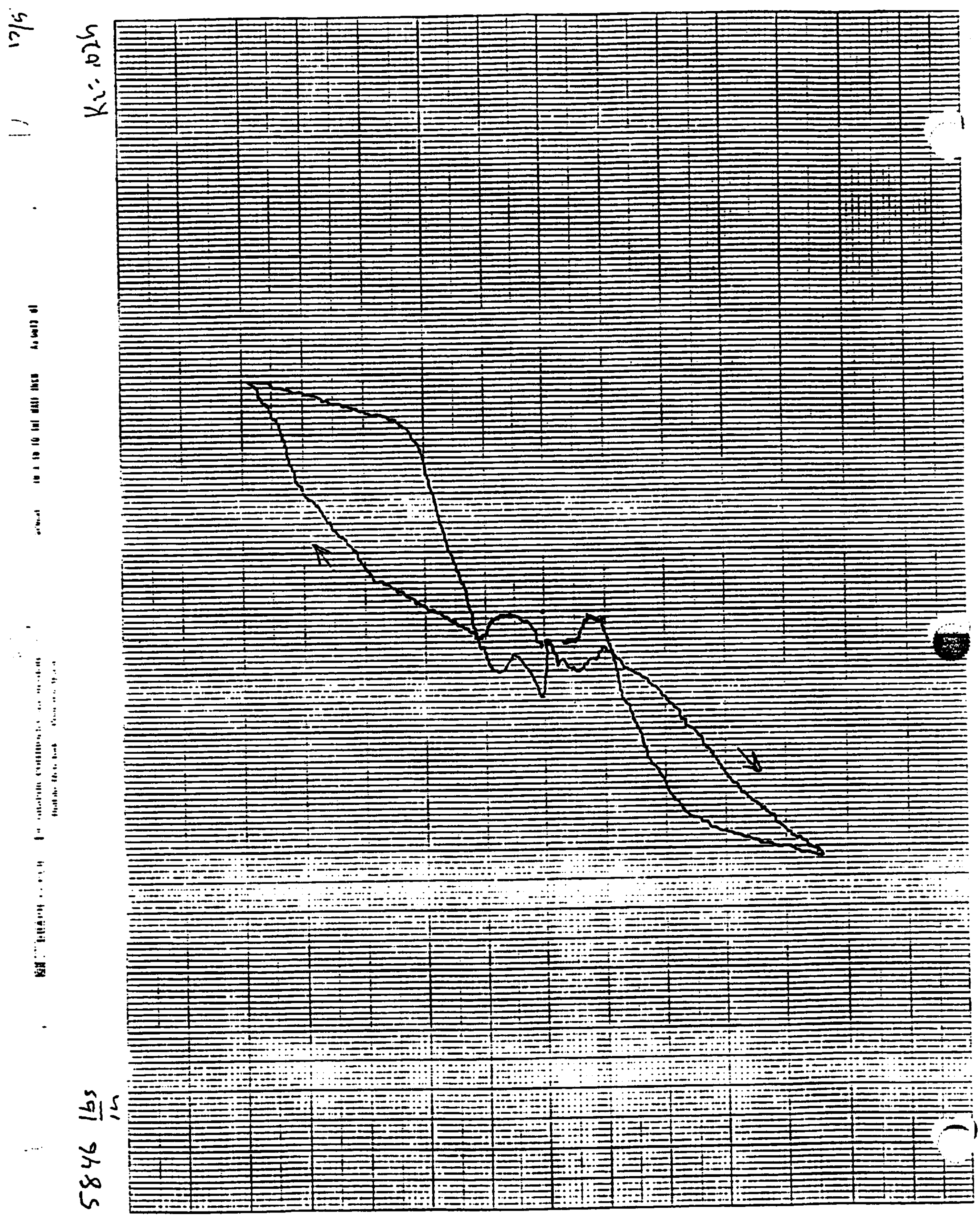
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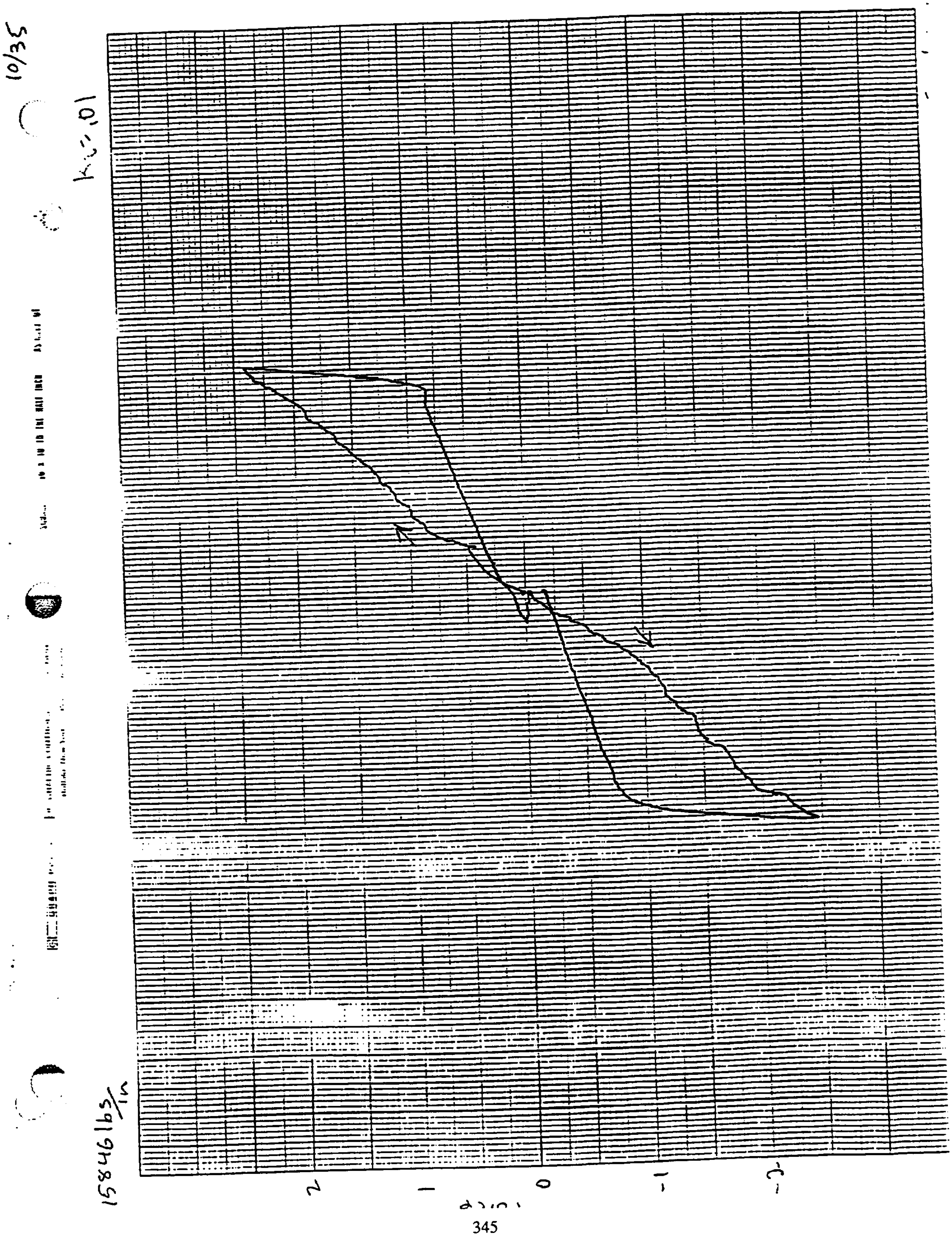
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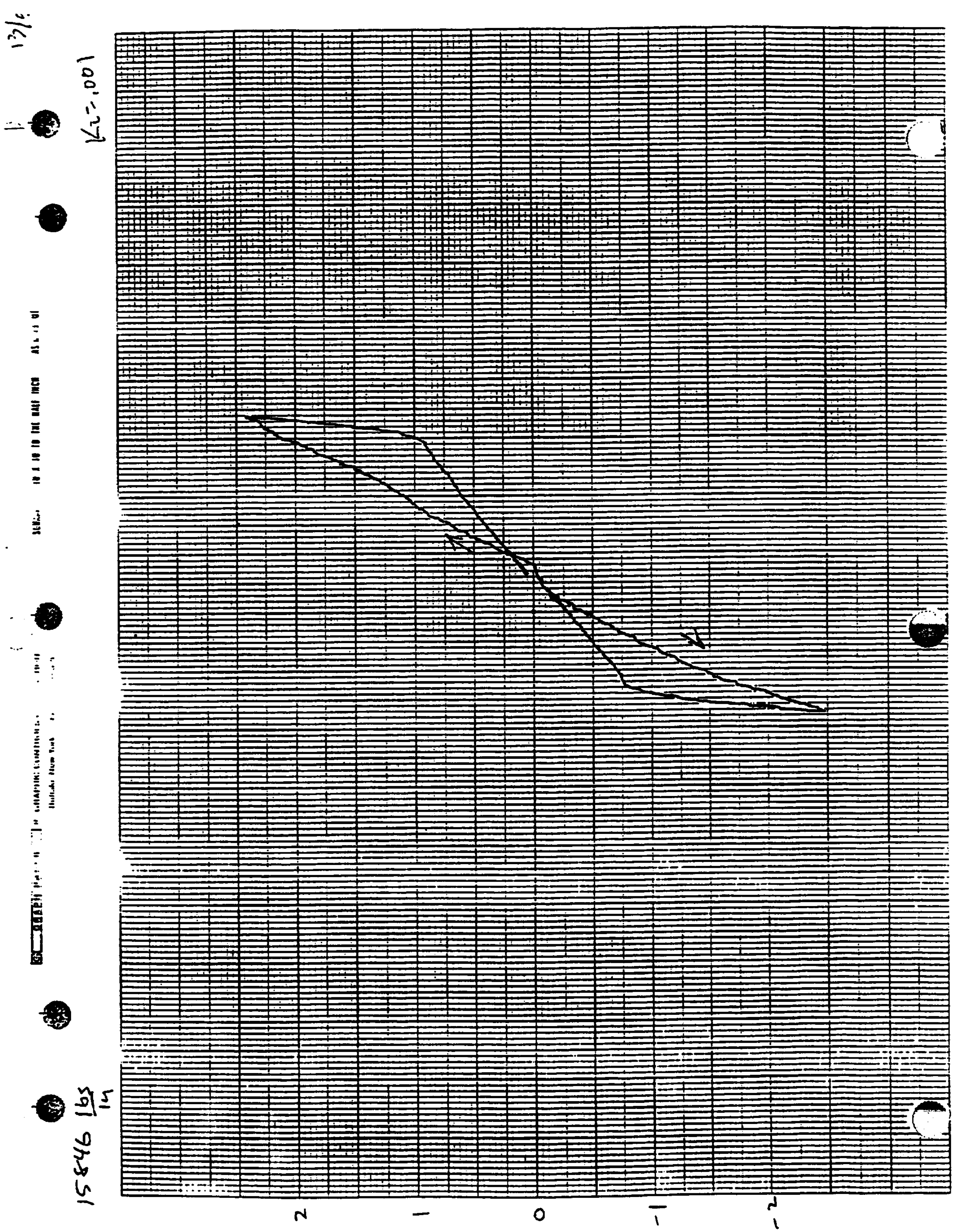
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15846 lbs/in
2
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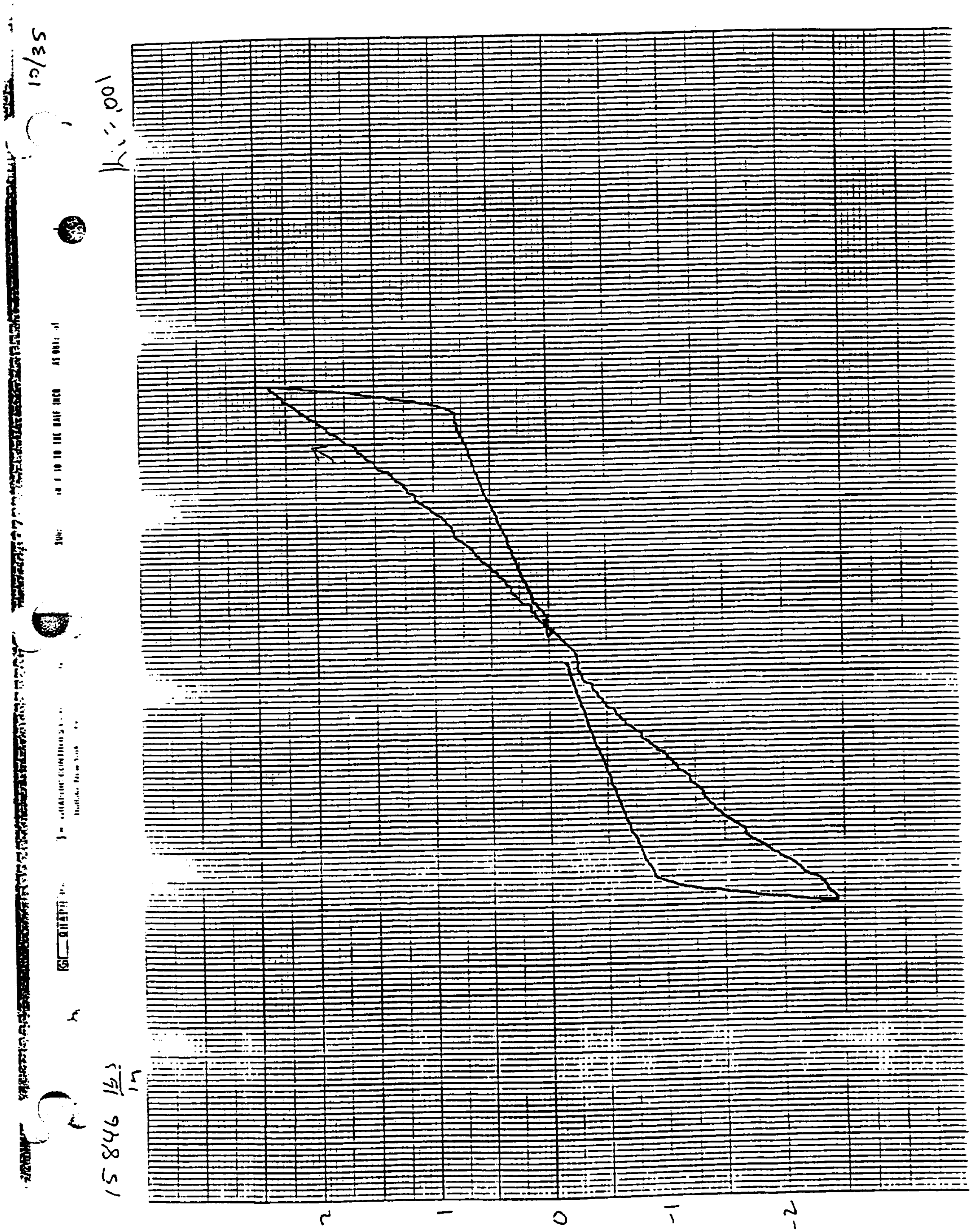
0
1
2


2
1
0
-1
-2

APPENDIX H

Worst Case Error Analysis

Reproduced from 40 HP Electro-Mechanical Actuator Test Report
NASA Contract: NAS325799 - August 1993

Section	Subject
1	Core Loss and Magnetizing Inductance Error; 730 Hz & 55 A/Phase
2	Core Loss and Magnetizing Inductance Error; 150 Hz & 28 A/Phase
3	Rotor Resistance and Leakage Inductance; 730 Hz & 75 A/Phase
4	System Efficiency Error 13,800 rpm & 70 A/Phase
5	Power Stage Efficiency Error 13,800 rpm & 70 A/Phase
6	Motor Efficiency Error 13,800 rpm & 72 A/Phase

Worst Case Error Analysis

Motor Parameters

1) Determine errors in Core Loss (R_m) and Magnetizing Inductance (L_m)

Data Point: Frequency = 730 Hz No Load motor Test

Harmonic Voltage per ϕ = 92.2 V ± 2V

Fundamental Voltage per ϕ = 85.1 V ± 5%

Current per phase = 54.9 A ± 3.1 A

Error in power measurement = ± 310 VA

Error in P.F. measurement = ± 4% PF = 0.14

) Core Loss

$$R_m = \frac{V^2}{P_{real}} \qquad R_{m\,max} = \frac{(92.2+2)^2}{(92.2 \times 54.9 - 310)(0.14 \times 0.96)}$$

where P_{real} = $P_{apparent} \times$ P.F.

$$R_{M\,max} = 13.9\,\Omega$$

$$R_{M\,min} = \frac{(90.2)^2}{(5063 + 310)(.14 \times 1.04)} = 10.4\,\Omega$$

So: Rm (12.2 Ω) Core loss → 13.9 Ω max (+13.9%); → 10.4 Ω min (−14.8%)

Power Accuracy measured = 695 W → 782 W (+12.6%); → 639 W (−8.1%)

1)

3) Magnetizing Inductance

$$Z_{nl} = \frac{V_{fund.}}{I} \qquad Z_{nl\,max} = \frac{89.4}{51.8} = 1.73\ \Omega$$

$$Z_{nl\,min} = \frac{80.8}{58.0} = 1.39\ \Omega$$

$$X_m = \left[\frac{1}{Z_{nl}} - \frac{1}{R_m}\right]^{-1}$$

$X_{m\,max} = 2.06$

$X_{m\,min} = 1.54$

$$L_m = \frac{X_m}{2\pi f} \qquad L_{m\,max} = 4.50 \times 10^{-4}$$

$$L_{m\,min} = 3.37 \times 10^{-4}$$

L_m (3.87E-4)	4.50E-4 max (+16.3%)
	3.37E-4 min (-12.9%)

(2) Determine R_m and L_m at low frequency and low Voltage (High error data point)

Data Point:

Frequency = 150 Hz No Load Motor Test

Harmonic Voltage per ϕ = 23 V ± 0.6 V

Fundamental Voltage per ϕ = 9.6 V ± 5%

Current per ϕ = 28 A ± 3.1 A

Error in power measurement = 93 VA

Error in P.F. measurement = ± 4% PF = 0.15

; Core Loss

$$R_m \max = \frac{(23.6)^2}{(644-93)(0.15 \times 0.96)} = 7.0\,\Omega$$

$$R_m \min = \frac{(22.4)^2}{(644+93)(0.15 \times 1.04)} = 4.4\,\Omega$$

R_m (5.34)	→ 7.0 Ω max (+31.1%)
	→ 4.4 Ω min (−17.6%)

power accuracy P_{real} = 99 W → 115 W max (+16.2%)
→ 79.3 W min (−19.9%)

B) magnetizing Inductance

$$Z_{nl} = \frac{V_{fund}}{I} \qquad Z_{nl\,max} = \frac{(9.6)(1.05)}{(28-3.1)}$$

$$Z_{nl\,max} = 0.40\,\Omega$$

$$Z_{nl\,min} = \frac{(9.6)(0.95)}{(28+3.1)} = 0.29\,\Omega$$

$$X_{m\,max} = \left[\frac{1}{0.29} - \frac{1}{4.4}\right]^{-1} = 0.31$$

$$X_{m\,min} = \left[\frac{1}{0.40} - \frac{1}{4.4}\right]^{-1} = 0.44$$

L_m (3.89 E-4) → 4.67 E -4 max (+20.1%)

L_m (3.89 E-4) → 3.29 E -4 min (-15.4%)

③ Rotor Resistance (R_r) and Leakage Inductance (L_{eq})

Data Point:

Frequency = 730 Hz $\qquad R_s = 0.051 \pm 0.002\ \Omega$

Harmonic Voltage per ϕ = 55.8 V ± 1.2 V

Fundamental Voltage per ϕ = 19 V ± 5%

Current per ϕ = 75.3 A ± 3.1

Error in power measurement = ±186 VA

Error in power factor = ± 4% $\qquad PF = 0.11$

) Rotor Resistance

$$R_{eq} = \frac{\text{Real Power}}{I^2}$$

$$R_{eq\,max} = \frac{[(55.8 \times 75.3) + 186][0.11 \times 1.04]}{(75.3 - 3.1)^2}$$

$R_{eq\,max}$ = 9.63 E-2

$$R_{eq\,min} = \frac{[55.8 \times 75.3 - 186][0.11 \times 0.96]}{(75.3 + 3.1)^2}$$

$R_{eq\,min}$ = 6.9 E-2

$R_r = R_{eq} - R_s$

R_r (3.08 E-2) → 4.53 E-2 max (+47%); → 1.8 E-2 min (−42%)

Power 464 W → 502 max (+8.2%); → 424 min (−8.6%)

(3)

(B) Leakage Inductance

$Z_{br} = \frac{V_{fundamental}}{I}$

$Z_{br}\ max = \frac{19.95}{72.2} = 0.28\ \Omega\ max$

$Z_{br}\ min = \frac{18.05}{78.4} = 0.23\ \Omega\ min$

$X_L = \sqrt{Z_{br}^2 - R_{eq}^2}$

$X_{L\ max} = \sqrt{(0.28)^2 - (6.9\ E{-2})^2} = 0.27$

$X_{L}\ min = \sqrt{(0.23)^2 - (9.63\ E{-2})^2} = 0.21$

$L_{eq} = \frac{X_L}{2\pi f}$

$L_{eq\ max} = 5.89\ E{-5}$ Henries

$L_{eq}\ min = 4.58\ E{-5}$ Henries

$L_{eq}\ (5.21\ E{-5})$ → $5.89\ E{-5}\ (+13.1\%)$; → $4.58\ E{-5}\ (-12.1\%)$

④ System Efficiency Error

Determine error in system efficiency calculation

Data Point:

Frequency = 700 Hz

Dyno Speed = 3450 RPM

Current per phase = 68.9A ± 3.1 A

DC Input Voltage = 178V

$\pm (0.0002 \times 178) + (0.00008 \times 2000)$

$= \pm 0.20V$

DC current = 41 mV

(mv reading across shunt resistor)

$\pm (0.0002 \times 41mv) + (0.00008 \times 200mV)$

$= \pm 0.024 mV$

motor Torque = 53.75 in-lbs ± 3 in lbs

$$\text{System eff \%} = \frac{\text{power out}}{\text{power in}} \times 100$$

$$\text{DC Power In} = V_{DC} \cdot I_{DC}$$

$$\text{DC Power}_{max} = \frac{(178.2) \cdot (41.024)}{0.0004949 \text{ (shunt value)}}$$

$$\text{DC Power}_{max} = 14771 \text{ W}$$

4) (continued)

$$\text{DC power min} = \frac{(177.8)(40.98)}{0.0004949} = 14723\ W$$

$$\underset{(HP)}{\text{motor Power}} = \frac{(\text{motor Torque})(\text{motor RPM})}{5250 \cdot 12} \leftarrow \text{conversion constants}$$

$$\underset{(HP)}{\text{motor Power max}} = \frac{(53.75 \text{ in-lbs} + 3 \text{ in-lbs})(3450 \cdot 4)}{5252 \cdot 12}$$

$$\text{motor } HP_{max} = 12.43$$

$$\text{motor } HP_{min} = \frac{(53.75 \text{ in-lbs} - 3 \text{ in-lbs})(3450 \cdot 4)}{5252 \cdot 12}$$

$$\text{motor } HP_{min} = 11.11$$

$$\text{System eff. max} = \frac{(12.43\ HP)(746\ W/HP)}{14723 (W)} \times 100$$

$$= 63\%$$

$$\text{System eff. min} = \frac{(11.11\ HP)(746\ W/HP)}{14771 (W)}$$

$$= 56\%$$

system eff 59% ↗ 63% max ↘ 56% min

5) Power Stage Efficiency Error

Determine Error in Power Stage Efficiency Error

Data Point :

Frequency = 700 HZ   Motor PF = 0.63 ± 0.5%

Dyno Speed = 3450 RPM

Current per phase = 68.9A ± 3.1A
Voltage per phase = 87.6V ± 2.0V
} Apparent Power = 6036VA ± 310VA

Real Power Out (inverter) = 11930 W ± (1860VA × PF)

Powe Factor out (inverter) = 0.54 ± 0.5%

20KHz Voltage = 350V ± 1.9V

Apparent Power out (inverter) = 21770 VA ± 1860VA

20KHz current out (inverter) = 62.2A ± 3.1 A

Real Power (inverter MAX) = (Apparent power + 1860VA)(PF + 0.5%)
= (21770 + 1860)(.54 × 1.005)
= 12 824 W (+7.5%)

Real Power (inverter min) = (Apparent Power − 1860)(PF − 0.5%)
= 10 698 W (−10.3%)

5) (continued)

Power Stage Out (Per phase) = (Apparent Power ± error)(PF ± error)

Power Stage Out (per phase) max = (6036 + 310)(0.63 x 1.005)

= 4018 W/phase (+6.3%)

Power Stage Out (per phase) min = (6036 − 310)(0.63 x 0.995)

= 3589 W/phase (−5.1%)

Power Stage Eff. % = $\frac{\text{Power Out Motor}}{\text{Power in P.S.}}$ x 100

Power Stage Eff max = $\frac{4018 \times 3}{10698}$ x 100 (← 3 phases)

= 113 %

Power Stage Eff min = $\frac{3589 \times 3}{12824}$ x 100

= 84 %

Power Stage Eff. (87%) → 100% max; → 84% min

(6) Motor Efficiency Errors

Determine the Error in the motor Efficiency calculations

Data Point:

Frequency = 700 Hz

Dyno speed = 3460 RPM ; motor speed = 13,600 RPM

Apparent Power (per phase) = 4895 VA ± 310 VA

Power Factor = 0.61 ± 0.5%

Motor Torque = 44.5 in-lbs ± 3 in-lbs

Single Phase Motor Input Power = [Apparent Power ± Error] [PF ± error]

$$\text{Motor Power}_{max} = (4895 + 310)(0.61 \times 1.005)$$

$$= 3191 \text{ W}/\phi$$

$$\text{motor Power}_{min} = (4895 - 310)(0.61 \times 0.995)$$

$$= 2783 \text{ W}/\phi$$

$$\text{Motor Power Output} = \frac{(\text{motor torque} \pm \text{torque error})(\text{RPM})}{(12)(5252)}$$

motor power max = 10.25 HP

motor power min = 8.96 HP

(6) (continued)

$$\text{maximum efficiency motor} = \frac{\text{motor power out}_{max}}{\text{motor power in}_{min}} \times 100$$

$$= \frac{(10.25\ HP)(746\ W/HP)}{2783\ W/\phi \times 3\phi}$$

$$= 92\%$$

$$\text{minimum efficiency motor} = \frac{(8.96\ HP)(746\ W/HP)}{(3191\ W/\phi)(3\phi)}$$

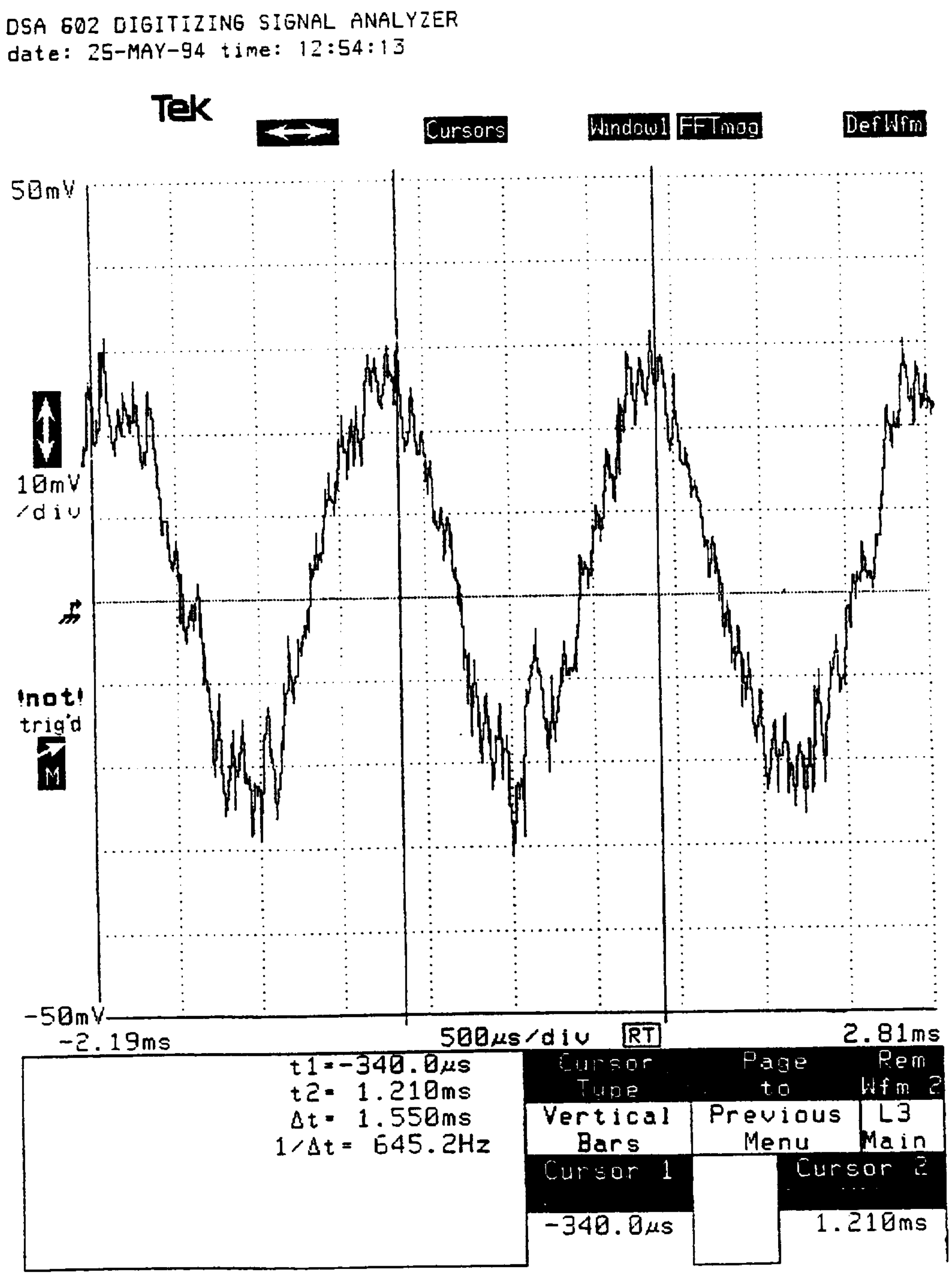
$$= 70\%$$

motor efficiency (80%) — 92% max; 70% min

APPENDIX I

PHASE CURRENT WAVEFORMS

Ia 100A/div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trig'd
M
-50mV
-2.19ms
500µs/div
RT
2.81ms
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t2= 1.210ms
Δt= 1.550ms
1/Δt= 645.2Hz
Cursor Type
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Rem Wfm 2
Vertical Bars
Previous Menu
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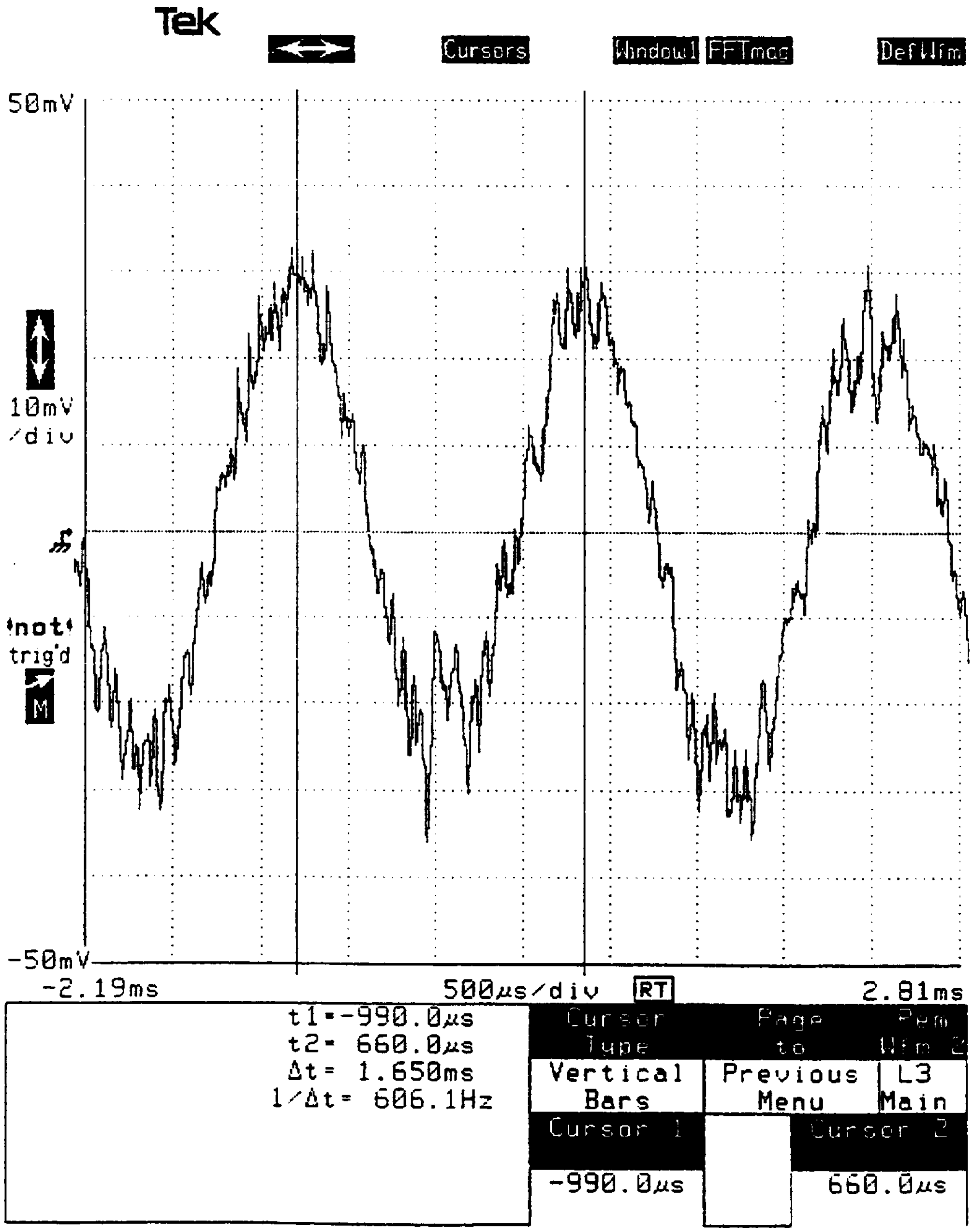

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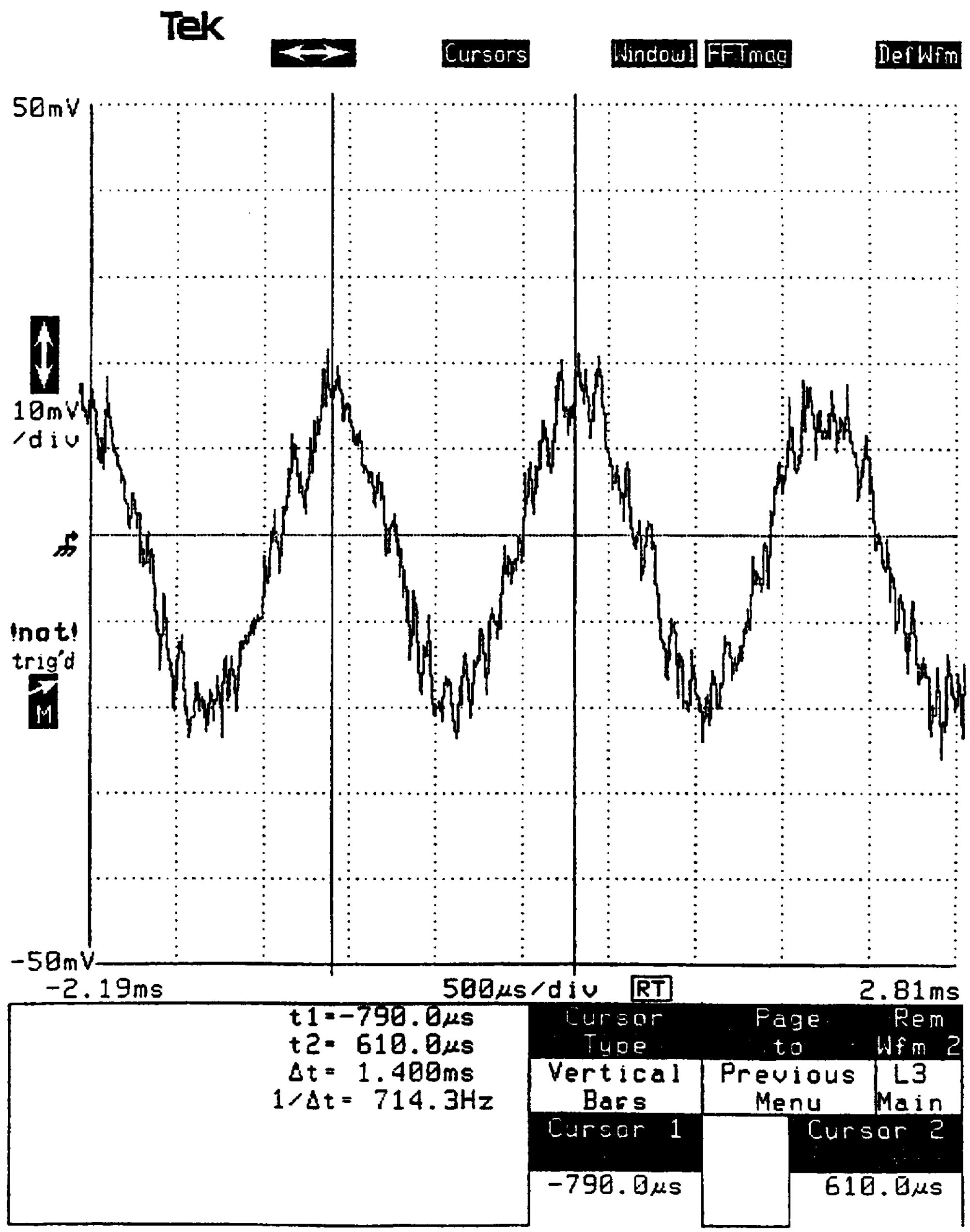

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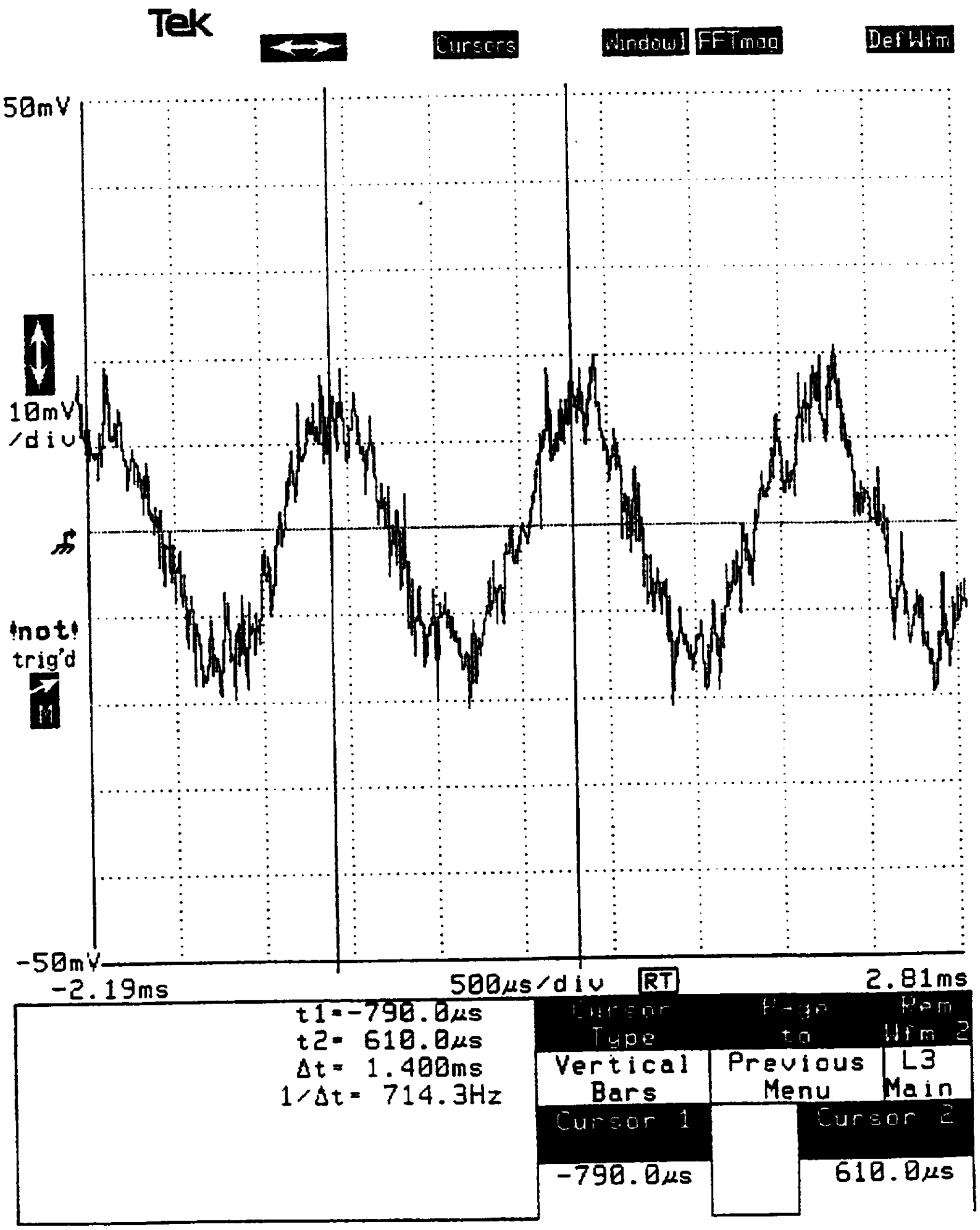

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the work performed on the 68 HP electro-mechanical actuator (EMA) system developed on NASA contract NAS3–25799 for the Electrical Actuation (ELA) Technology Bridging Program. The system was designed to demonstrate the capability of large, high power linear ELAs for applications such as Thrust Vector Control (TVC) on rocket engines. It consists of a motor controller, drive electronics and a linear actuator capable of up to 32,000 lbs loading at 7.4 inches/second. The drive electronics are based on the Resonant DC link concept and operate at a nominal frequency of 55 kHz. The induction motor is a specially designed high speed, low inertia motor capable of a 68 peak HP. The actuator was originally designed by MOOG Aerospace under an internal R & D program to meet Space Shuttle Main Engine (SSME) TVC requirements. The design was modified to meet this programs linear rate specification of 7.4 inches/second. The motor and driver were tested on a dynamometer at the Martin Marietta Space Systems facility. System frequency response, step response and force-velocity tests were conducted at the MOOG Aerospace facility. A complete description of the system and all test results can be found in the body of the report.

14. SUBJECT TERMS

Electromechanical actuator; Resonant converter; Induction motor; Pulse population modulation; Launch vehicles; Thrust vector control

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