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DESIGN/MANUFACTURE

DIRECT CURRENT TORQUER AMPLIFIER'S

PREPARED FOR

NATIONAL AERONAUTICS and SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE,ALABAMA

SUBMITTED BY

ORDNANCE DEPARTMENT
OF THE DEFENSE ELECTRONICS DIVISION
GENERAL ELECTRIC
100 PLASTICS AVENUE, PITTSFIELD, MASSACHUSETTS

Contract NAS 8-11876

FINAL SUMMARY REPORT

DESIGN AND MANUFACTURE OF DIRECT CURRENT TORQUER AMPLIFIERS

Prepared by
D. W. Gilchrest and A. E. Schutz
July 30, 1965

Contract NAS 8-11876

Prepared for:
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

Submitted by:
The General Electric Company
~~Ordnance Department~~
Pittsfield, Massachusetts

FDU 65-8

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Section 1
INTRODUCTION

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Section 1
INTRODUCTION

1-1 OBJECTIVES AND APPROACH

The objective of this program was to design a dc torquer amplifier which uses pulse width modulation (PWM) to obtain a high power efficiency, but allows a continuous dc current to flow through the servo motor to minimize ac losses and heating. This amplifier was to be small enough to be gimbal-mounted and meet the required specifications. To achieve these objectives, integrated circuit differential amplifiers were used for low-level gain, and discrete components were used for the PWM power stage. Commutating diodes are installed in the PWM power stage to provide a path for the motor current during the time between voltage pulses. This path allows the motor current to decay according to the motor's time constant and greatly reduces the ac heating of the motor. All components, including the integrated circuits and discrete components, are mounted on a double-sided printed circuit board. The power transistors are mounted in an aluminum heat sink which provides a good thermal path to the mounting surface. The resulting module is compact and capable of being operated either unpotted or potted in epoxy. While these modules are designed to be hard-wired in a system, a temporary test connector is attached to each module to provide for connecting the modules into various circuits with a minimum of effort.

Design specifications in brief are as follows:

1. Use state-of-the art thin film or integrated circuitry.

2. Symmetry: ±5 percent 0.1-1.7 amp in both directions
   Load = 28.0 ohms + 54 mh

3. Source: 56 ± 2 volt battery supply, with noise rejection such that a 10-volt peak-to-peak square wave on battery produces less effect than 2 mv at input. A minus 28-volt, 50-ma supply is also available.

4. Input impedance: 25 k or greater

5. Frequency response: ±5 percent 0-300 cps

6. Gain adjustable from 10 v/v to 1000 v/v

7. The following accuracies from 15-75 C:

   a. Offset: ±5 mv at input for gain of 250 v/v

   b. Deadband: 3 mv total for gain of 250 v/v

   c. Linearity: ±5% of 0.5 amp gain from 0.05-1.7 amp
      ±10% at maximum current level

8. 4800 and 400 cps voltages are available.

1-2 ACCOMPLISHMENTS

Four objectives of the program have been accomplished as follows:

1. One breadboard and twelve operating modules which meet the intent of all specifications have been constructed and delivered. Detailed graphs of representative data are contained in the appendix.

2. The complete assembly (unpotted) has dimensions of 2.63 by 1.94 by 0.58 inches with all terminals and trim components contained within the envelope.

3. The practical application of a PWM circuit which has continuous current through the motor has been demonstrated. Some of the advantages of this PWM circuit are that the dc gain of the amplifier is independent of load inductance or switching frequency. The maximum ac heating is reduced by a factor greater than four from previous PWM circuits, and the power supply requires less energy absorption capability since it does not receive a power kick-back from the load after each cycle.

4. Torquer amplifier was operated in Huntsville with both an ST124 PIGA loop and an ST124 gimbal servo loop with air bearing gyro and gimbal simulator. Completely acceptable performance was obtained in both servo loops.

1-3 PROJECTIONS

There are two possible directions in which the work could be extended:

1. The modules developed and produced were designed to operate from a 56-volt battery. With a minimum of effort the modules could be converted to operate from a 28-volt supply. It is now understood that this voltage will likely be used.

2. Modules could be built of a new, more efficient design which has subsequently been produced on a General Electric development program. A description of the new circuitry is contained in section 5-1 of this report. While the present module is about 90 percent efficient, the new design would reduce the maximum power consumption to about one-half the present level and result in a reduction in the number of parts required.

Of the above alternatives the latter appears more desirable if additional work is to be done.

1-4 RESULTS

As previously indicated, delivered units met performance specifications. These modules represent a significant improvement in performance over previous PWM circuits in that they provide for a continuous current through the motor even though the voltage is applied in pulses. In addition to the requirements of the contract, a schematic of an improved circuit and a description of its operation is presented which was developed in a continuation of our effort to advance the state of the art.

Section 2
CIRCUIT DESCRIPTION

2-1 BLOCK DIAGRAM

A block diagram of the PWM amplifier is shown in figure 1. An error signal is amplified in the dc amplifier and is added at the summing point to the triangular wave formed in the triangle generator. The summed signal thus consists of a triangle wave whose dc level shifts up and down.

The power amplifier uses pulse width modulation to achieve a high efficiency. Pulse width modulation is obtained by having a high-gain differential amplifier with a precise turn-on voltage so that the amplifier is either cut off or saturated. When the triangle wave goes

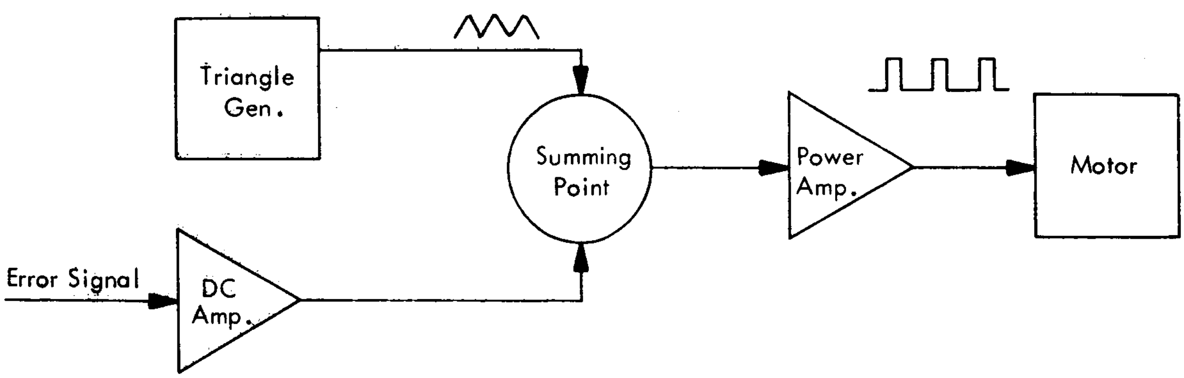


Figure 1. Block Diagram of PWM Circuit

above or below the turn-on voltage, it turns the power stage abruptly on in one direction or the other resulting in a torquing current to the motor.

2-2 TRIANGLE GENERATOR

Figure 2 shows the schematic of the triangle generator. A 10-volt rms sine wave at 4800 cps is fed into the triangle generator and is clipped by Q1 and CR1 into a reasonably square wave. This is amplified by Q1 and is placed across zener diode CR2 to get a regulated, 7-volt square wave. Diodes CR3 and CR4 cut the square wave down to 1.2 volts and are used as a temperature-compensating circuit to balance out changes in the power amplifier. R3 has been adjusted for the proper current through the diodes, thus giving them the desired temperature characteristic. R4 will discharge feed-through capacitor C1 so the square wave will be flat. R40 is an externally mounted resistor used to get the desired output amplitude.

Feedback capacitor C2 causes the amplifier to act as an integrator. An integrated square wave is a triangle. For reasons explained in section 2-4, it was desirable to have output capacitor C14 as small as possible. Because of this, even if a well-shaped triangle appeared at the output of the amplifier, it would get rounded by the small output capacitor. This was circumvented by connecting C2 to the outside of C14 so that the good triangle appeared at the output of C14 instead of at the output of the differential amplifier.

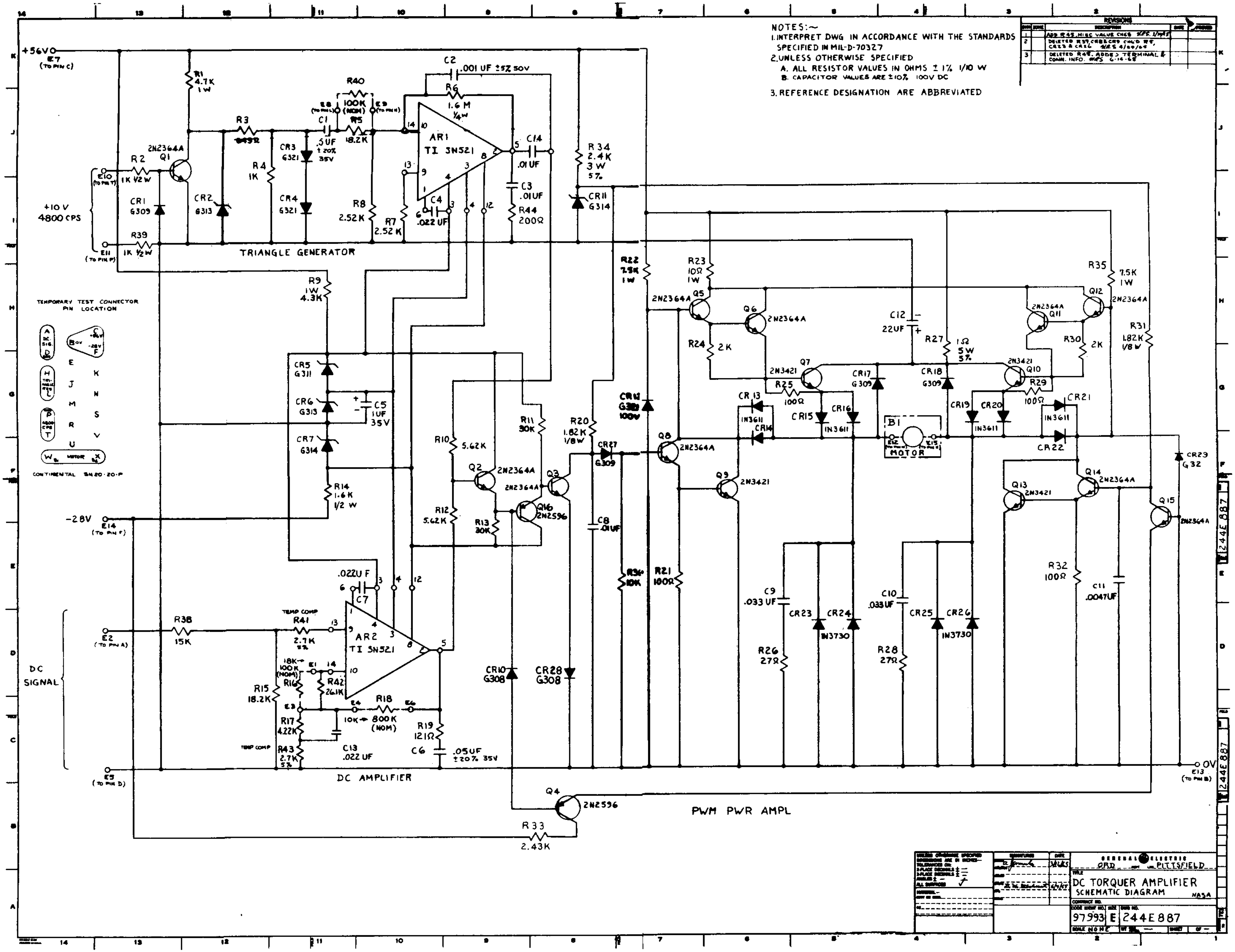


Figure 2. Detailed Schematic of PWM Circuit.

Resistor R6 forces the output of the amplifier to work about 0-volts. R44, C3 and C4 are used to stabilize the amplifier (see figure 3 for Bode Plot).

2-3 DC AMPLIFIER

The dc amplifier has an adjustable gain to give the whole system an overall gain of from 10 v/v to 1000 v/v. The input resistor (R38) and R15 form a voltage divider with a factor of 0.55. Resistor R18 is an externally mounted feedback resistor to vary the gain of the dc amplifier. R18 and the network of R17, R43, and C13 form a voltage divider that places a varying amount of negative feedback on the input. C13 is used to give a phase lead to compensate for the phase lag at the summing point (see section 2-4). The phase lead is shown in figure 4. R43 is a silicon resistor whose resistance increases with temperature, thus increasing the feedback and decreasing the gain of the amplifier. An identical resistor (R41) is placed at the other input so that the amplifier will not become unbalanced as temperature changes. R16 is an externally mounted resistor to balance the amplifier so that 0 volt in gives 0 volt out.

C6, C7, and R19 are used to stabilize the open loop gain of the dc amplifier (see figure 5 for Bode Plot).

2-4 SUMMING POINT OPERATION

Resistors R10 and R12 sum together the output of the triangle generator and the dc amplifier at the base of emitter follower Q2. If the summing point gets below 1.2 volts negative, then the negative supply will cause Q4 and Q15 to turn on. If it goes above 1.2 volts positive, then Q16 will turn off, causing Q3 to turn on. For an explanation of operation beyond these points, see section 2-6.

The triangle output capacitor C14, as well as capacitor C2, causes a loading of the dc amplifier at higher frequencies that gives a phase shift across the dc summing resistor (R12). The phase shift is compensated for by C13 as described previously (see section 2-3).

2-5 LOW LEVEL POWER SUPPLY

The voltages necessary for operation of the low level circuits, -10, +7, and +10 volts, are supplied by zener diodes for stability. C5 is placed across zener CR6 to cushion the effect of current surges.

2-6 SIMPLIFIED POWER OUTPUT STAGE

A simplified schematic of the power stage is shown in figure 6. This circuit develops a pulse-width modulated square wave of voltage across the load.

The dc signal e_1 and the triangle wave e_2 are summed to obtain e_3, which is a triangle with a dc bias. As explained in section 2-4, if the summing point goes above +1.2 volts, Q3 will be turned on; if it goes below -1.2 volts, Q4 will be turned on.

The amplitude of the triangle is adjusted so that when it is centered about 0 volt (dc error signal), neither Q3 nor Q4 is turned on. This will cause the collectors of Q3 and Q15 to be at +10 volts. These positive voltages turn on the two lower Darlingtons formed by Q8, Q9, Q13, and Q14. When these transistors are on, their collectors are down near ground potential, and thus the bases of Q5 and Q12 will be near ground, turning them off. This will cause all six of the upper transistors to be turned off, and thus there will be no current through the motor.

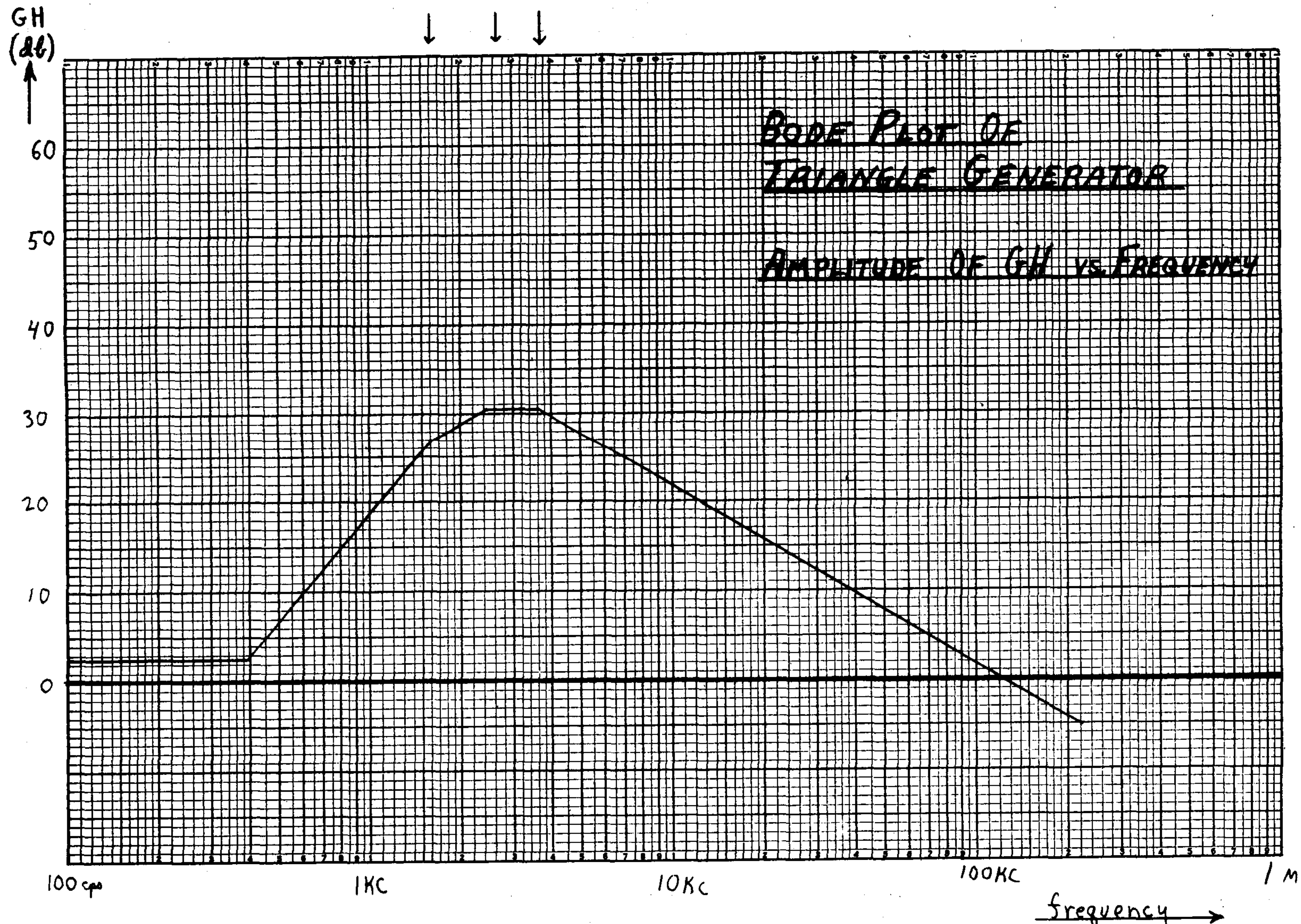


Figure 3. Bode Plot of Triangle Generator.

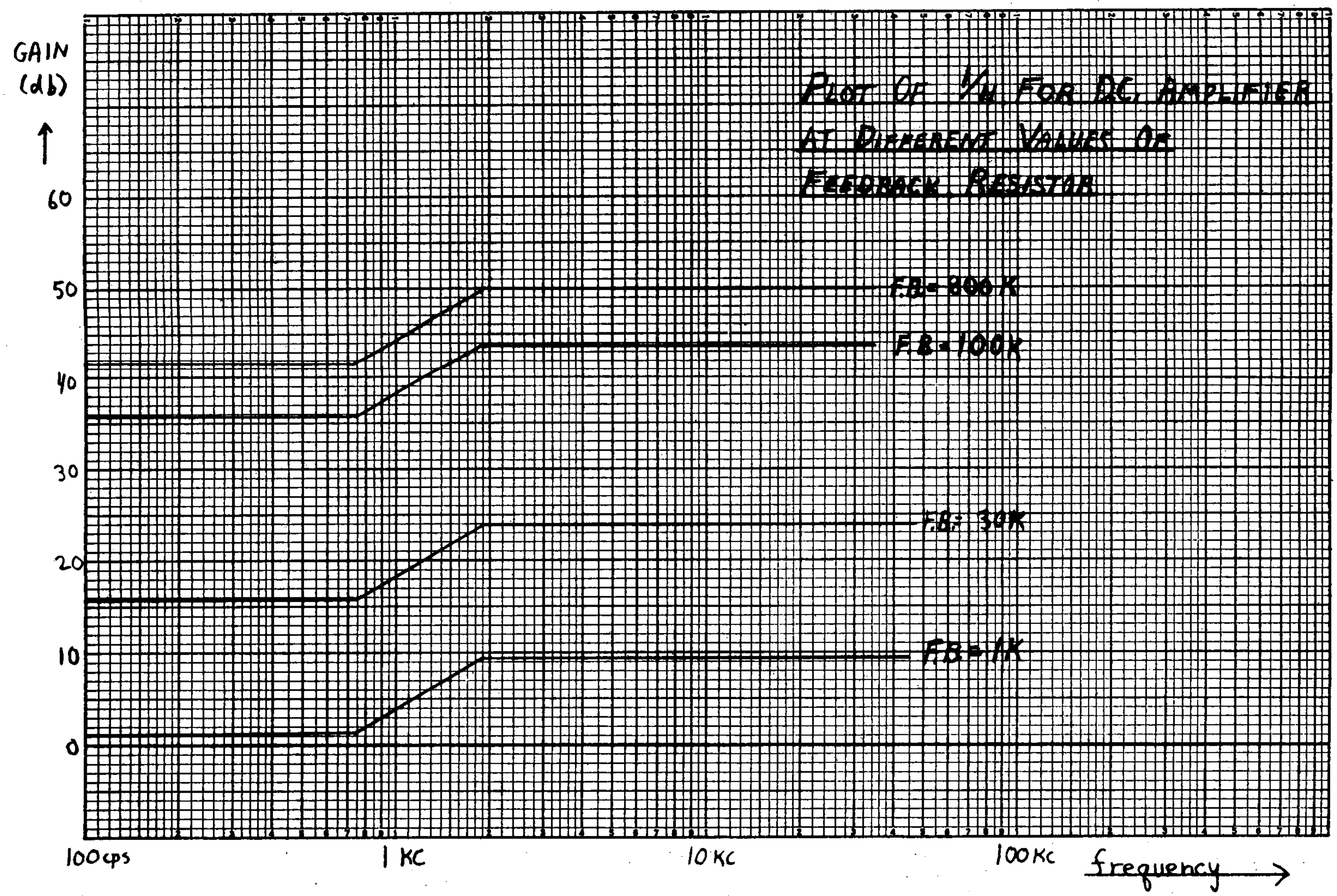


Figure 4. Plot of 1/H for DC Amplifier.

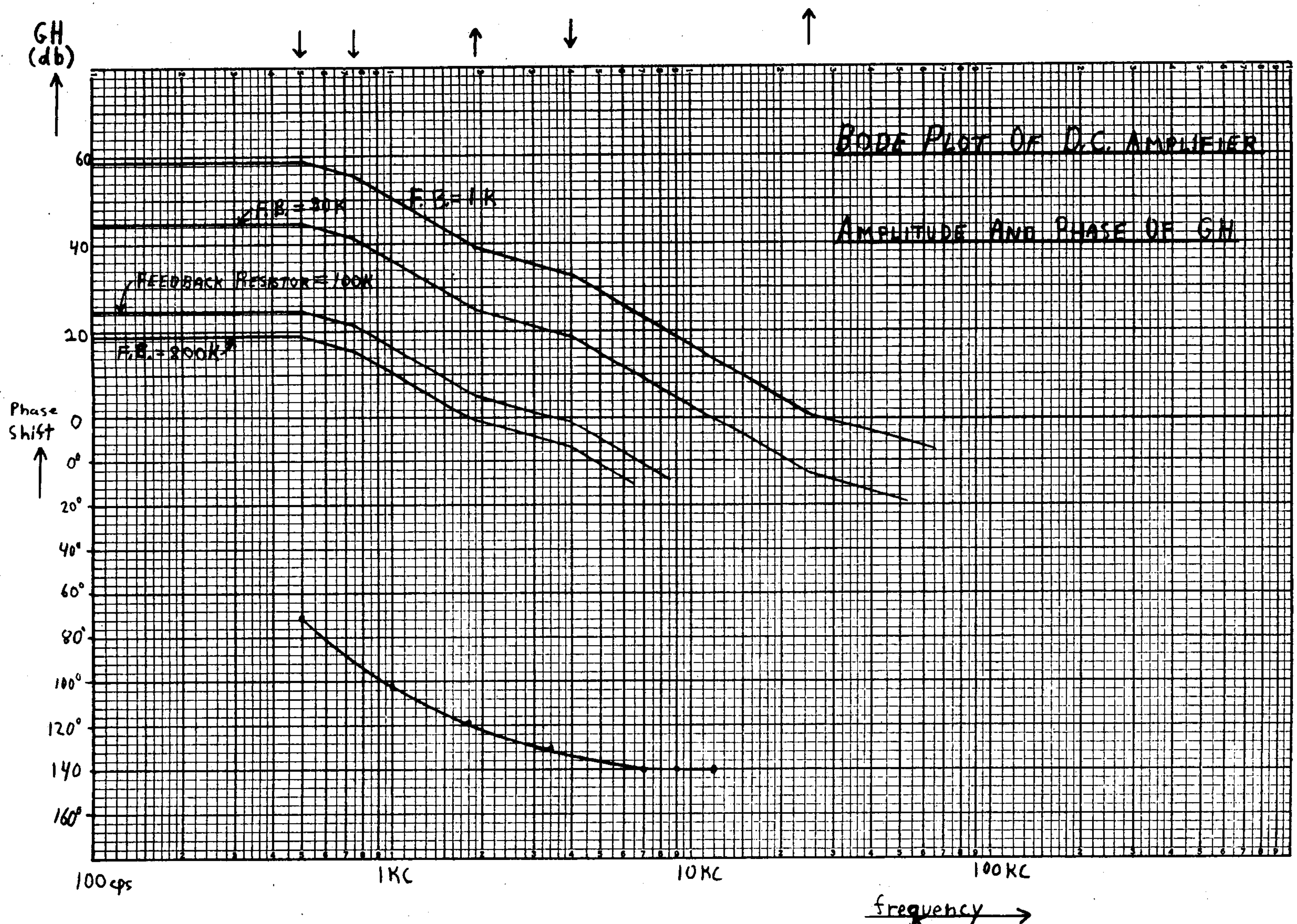


Figure 5. Bode Plot of DC Amplifier.

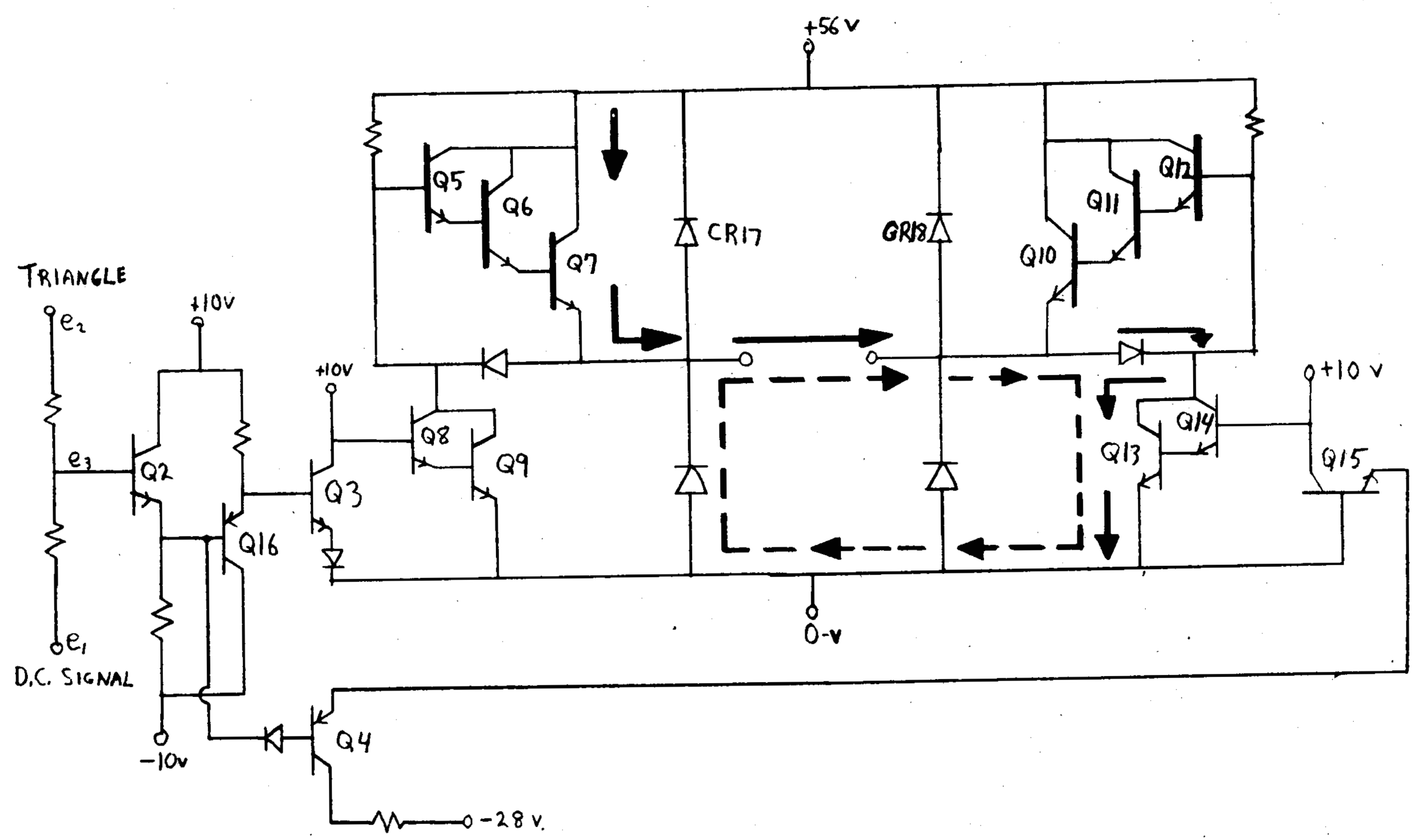


Figure 6. Simplified Schematic of Power Output Stage.

A condition requiring motor current will now be examined. When any portion of the triangle wave is above +1.2 volts, Q3 turns on, turning off Q8 and Q9. This causes a positive voltage to appear on the base of Q5, turning it on. This will turn on Q6 and Q7. Current will then flow through the motor, following the path of the solid arrows, figure 6.

When the triangular signal drops below 1.2 volts, the lower Darlington is switched back on and the upper Darlington is turned off, interrupting the flow of current from the +56-volt line. During the off time, a path is provided for the continuous flow of motor current through a commutating diode as shown by the dashed arrow. This allows the motor current to decay according to the motor time constant and greatly reduces ac heating in the windings.

Similar operation occurs when e_3 goes below -1.2 volts. The current then flows through the motor in the opposite direction.

Diodes CR17 and CR18 are installed to provide a path for the inductive discharge of the motor when the voltage applied to the motor is suddenly reversed. During the reversal, the lower power transistor, through which the motor current had been flowing, is suddenly switched off. At this time CR17 and CR18 provide a path for the inductive surge to be pumped back into the 56-volt line.

Refer to figure 7 for pictures of the output voltage and current. The amplitude of the current waveform is expanded so the ripple is visible.

2-7 COMPLETE POWER OUTPUT STAGE

A schematic of the complete power output stage is shown in figure 2. The general operation has been described in the previous section.

Diodes CR12 and CR29 keep transient negative spikes from appearing at the bases of Q5 and Q12. These spikes would appear at the output. Capacitors C8 and C11 ground noise that appears at the input, and C9 and C10 ground noise at the output. R27, a 1-ohm resistor, keeps the voltage across power transistors Q7 and Q10 at a minimum. Diodes CR15 and CR16 give a larger voltage drop from the base of Q5 to the motor so that, when Q5 is off, it will be turned off hard.

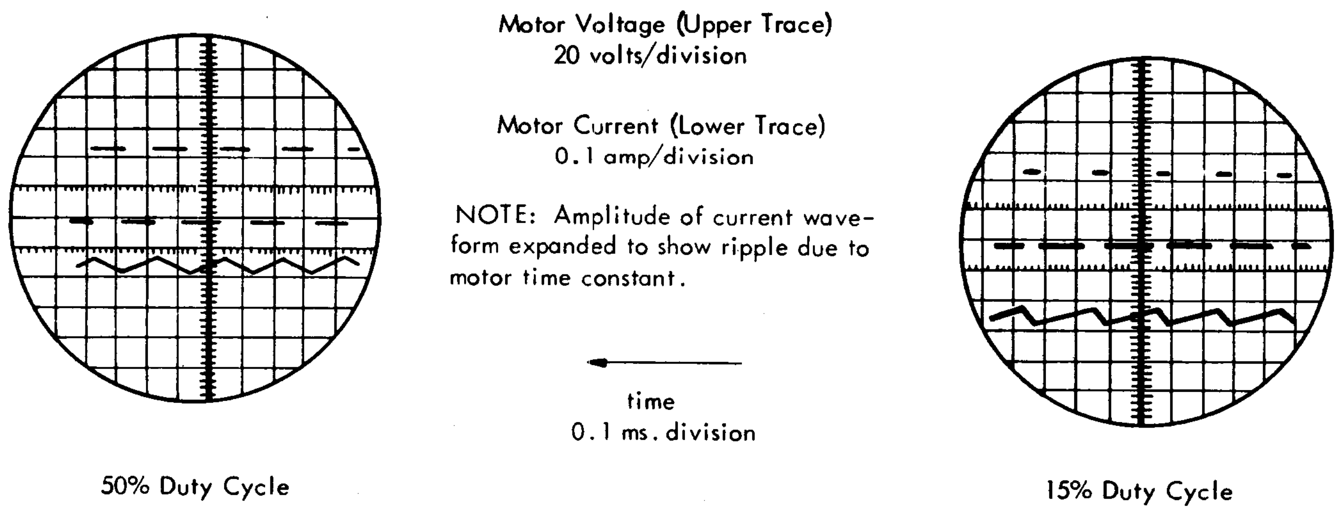


Figure 7. Motor Voltage and Current Waveforms

Section 3
PACKAGING

3-1 MODULE PACKAGING

Each module is constructed of two double-sided printed circuit boards with all components except the integrated circuits mounted between the boards. Figures 8 through 12 follow and contain a mechanical layout, printed board detail and photos of both a complete and opened module. The power transistors are mounted in an aluminum heat sink with the power diodes and resistors touching the heat sink. The module is constructed so that it is capable of being operated unpotted or potted in epoxy. During operation the module should always be mounted to a heat sink. Flight or environmental test modules would also require potting in a good heat-conducting epoxy to obtain optimum thermal conduction and resistance to mechanical shock.

Each module was shipped with a temporary test connector to aid in connecting and disconnecting from test setups. If installed in a system. the test connector and harness would be discarded and the module hard-wired in place. When potting the module it would only be filled up to the level indicated on figure 8. The remaining space around the terminals provides for the installation of trim components and terminal connections within the envelope of the module.

3-2 BREADBOARD

Figure 13 is a photo of the breadboard of the torquer amplifier. It is laid out in a neat manner and has proved helpful in analyzing the operation of the modules. It should also be of use in evaluating possible changes which might be considered in the future.

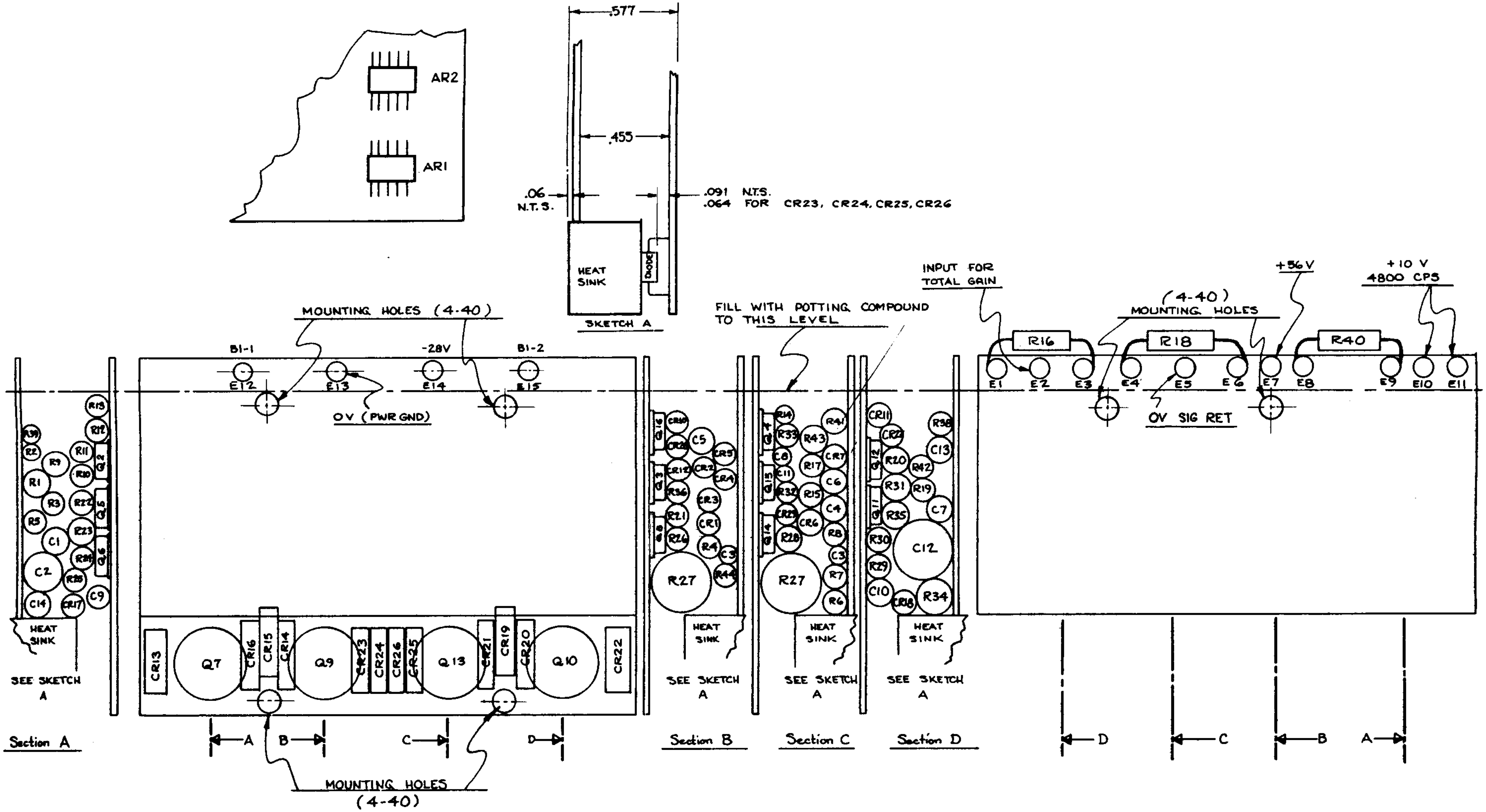
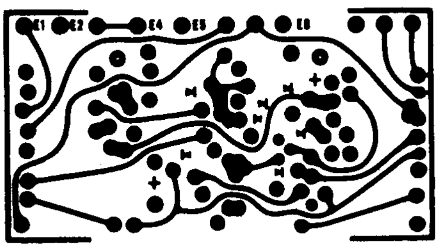
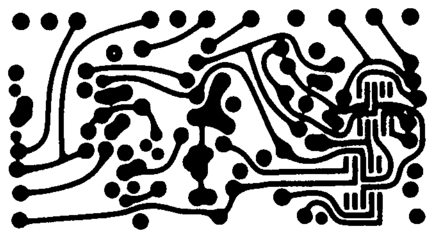


Figure 8. Mechanical Layout of Module.



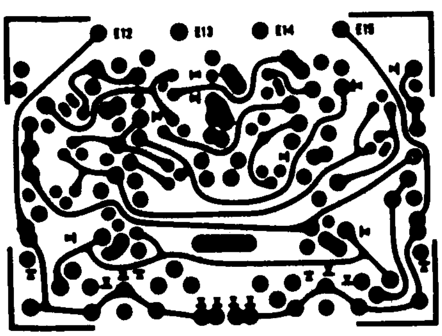
FRONT

(Component Side)



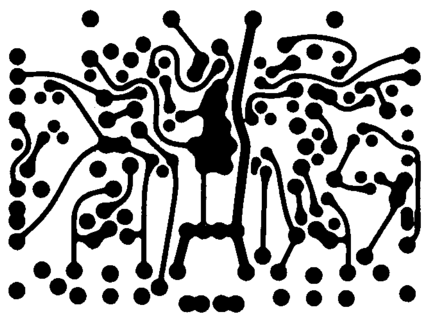
BACK

NOTE: All views show the boards as viewed directly -- not looking through the boards



FRONT

(Component Side)



BACK

Figure 9. Printed Board Detail.

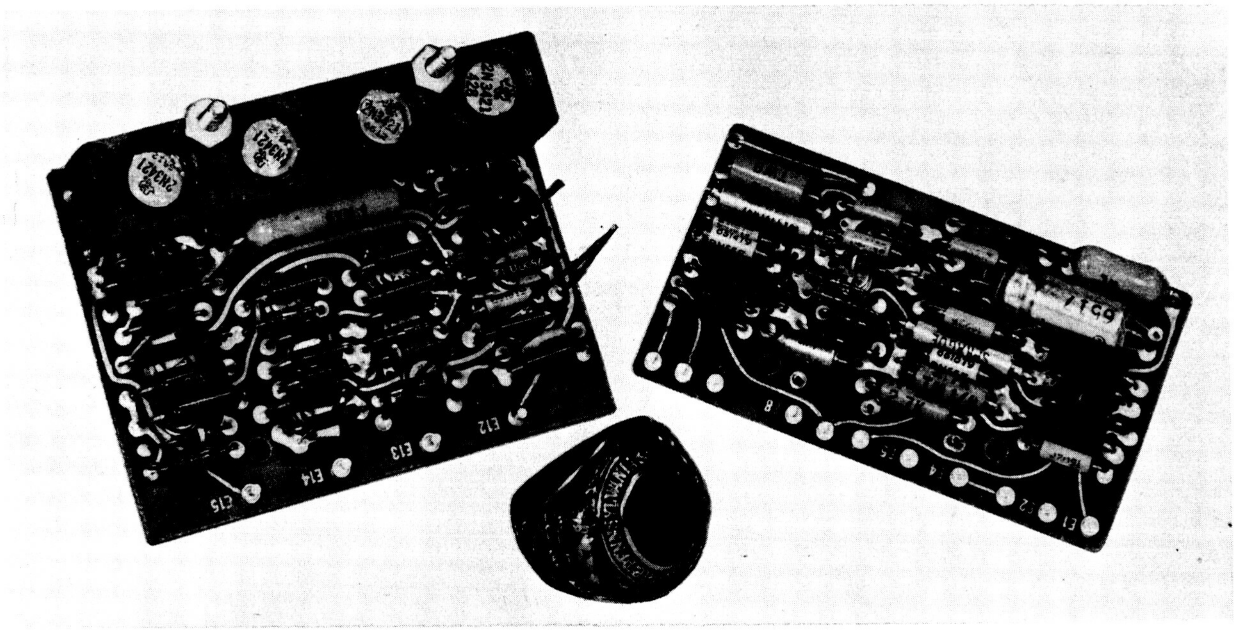


Figure 10. View of Open Module.

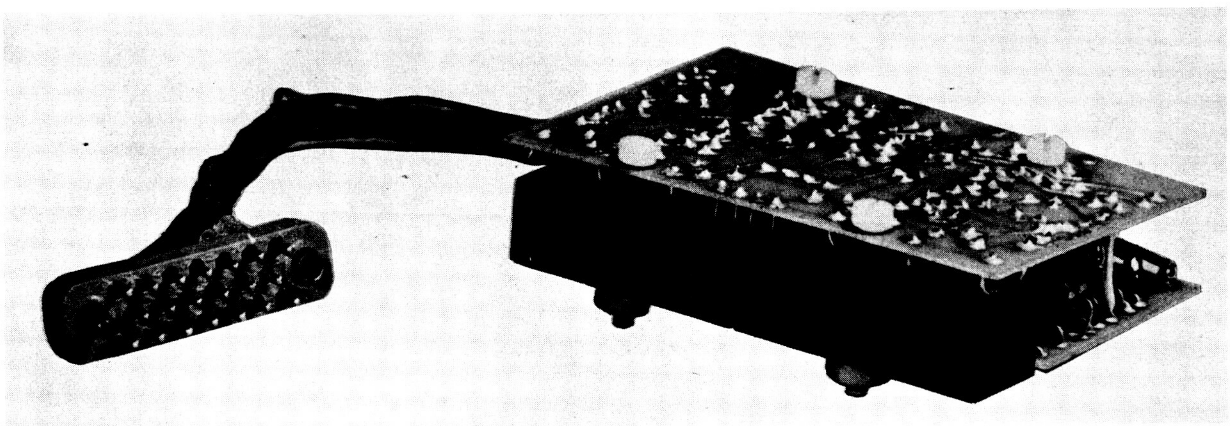


Figure 11. Side View of Module.

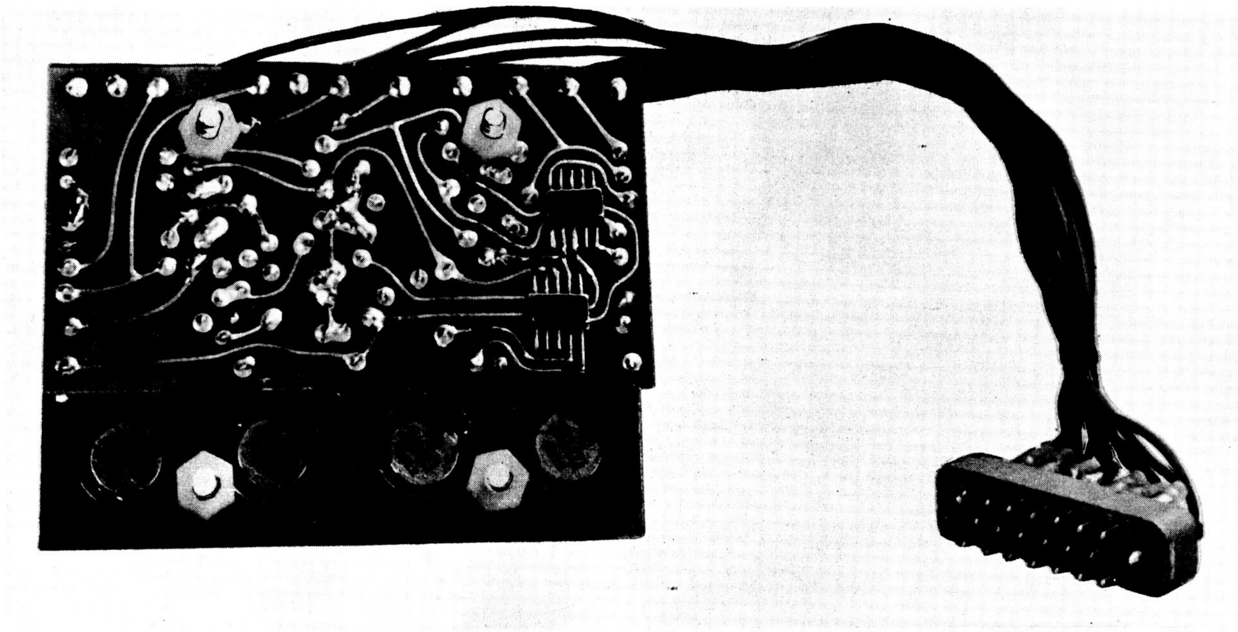


Figure 12. Bottom View of Module.

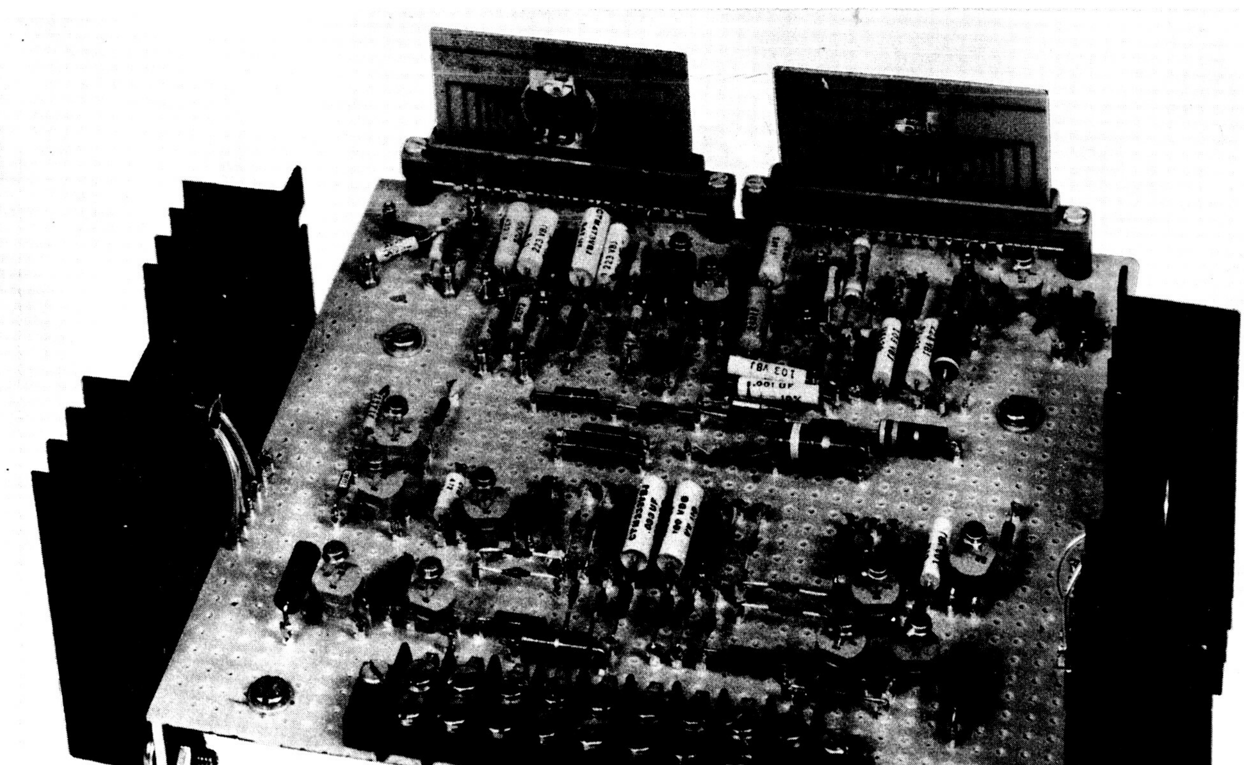


Figure 13. Breadboard.

Section 4
ANALYSIS OF MODULE PERFORMANCE

4-1 TEST SET UP

Each of the modules was tested to check it against the performance specifications. The test set up is shown in figure 14. The input and output signals from the module are filtered through a double resistor-capacitor network before measuring to eliminate the square wave from the measurements. The 30-k resistor in series with the signal source is to simulate the 30-K source impedance which the module will operate with. To operate from other source impedances would only require selecting a different balance resistor, which is connected externally to the module.

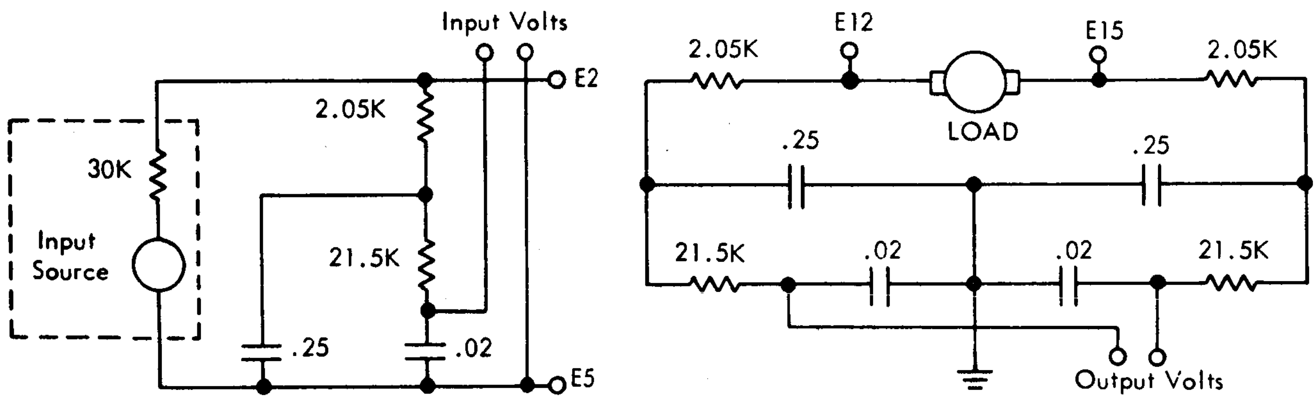


Figure 14. Test Set Up

4-2 MODULE PERFORMANCE

As mentioned previously, the modules and breadboard which were delivered met the intent of the specifications. Detailed graphs of a representative module are contained in the appendix. A summary of module performance is as follows:

1. Linearity - While all modules did not meet the design goal of a 5-percent linearity over the entire range, the outputs were quite linear and would be more than satisfactory for servo performance.

2. Frequency Response - The frequency response was not flat as specified out to 300 cps, but had a gradual rise of as much as 18 percent from 40 cps out to this frequency. This rise was not a 20-db slope as might be expected in a normal linear amplifier, but was a very slight rise due to the nonlinearities of the circuit.

3. Phase shift - Eight of the 13 modules had a phase shift of less than 5 degrees at 300 cps. The remaining five modules had less than 7 degrees phase shift at 300 cps. (While the phase shift of each module could have been brought to less than 1 degree at 300 cps, it was found that the linearity of the amplifier would have been reduced.) All modules did have less than 1 degree phase shift at 100 cps.

4. Deadband and Offset - All modules met the design goals.

5. Noise Rejection - All modules met the design goal.

Section 5
PROJECTED IMPROVEMENTS

5-1 NEW APPROACH

A new PWM circuit was designed recently, under a General Electric development program, that embodies several basic innovations over the present circuit. A schematic is shown in figure 15.

The first change is the use of PNP drivers for the upper power transistors. This allows the power transistors to be easily saturated without the use of dropping resistors and extra diodes. The new configuration eliminates all the load-carrying diodes and the 1-ohm power resistor.

The power amplifier is driven by a square wave which is obtained by the use of two very-high-gain saturating amplifiers, one for the negative side and one for the positive side.

The second basic improvement is applying the triangle to the emitters of the input transistors instead of summing with the dc signal at the bases. This method decouples the dc amplifier from any blocking capacitor in the triangle generator and thus eliminates the possibility of phase shift. The use of a triangle generator with a very low output impedance (4-5 ohms), allows true voltage summing, which is impossible in a parallel summing circuit.

This circuit was designed for a 1-ampere load and a 2400-cps triangle, but worked normally at 2 amperes and would not operate differently at 4800 cps. The square wave is very clean with a rise and fall time of 1.5 to 2 microseconds.

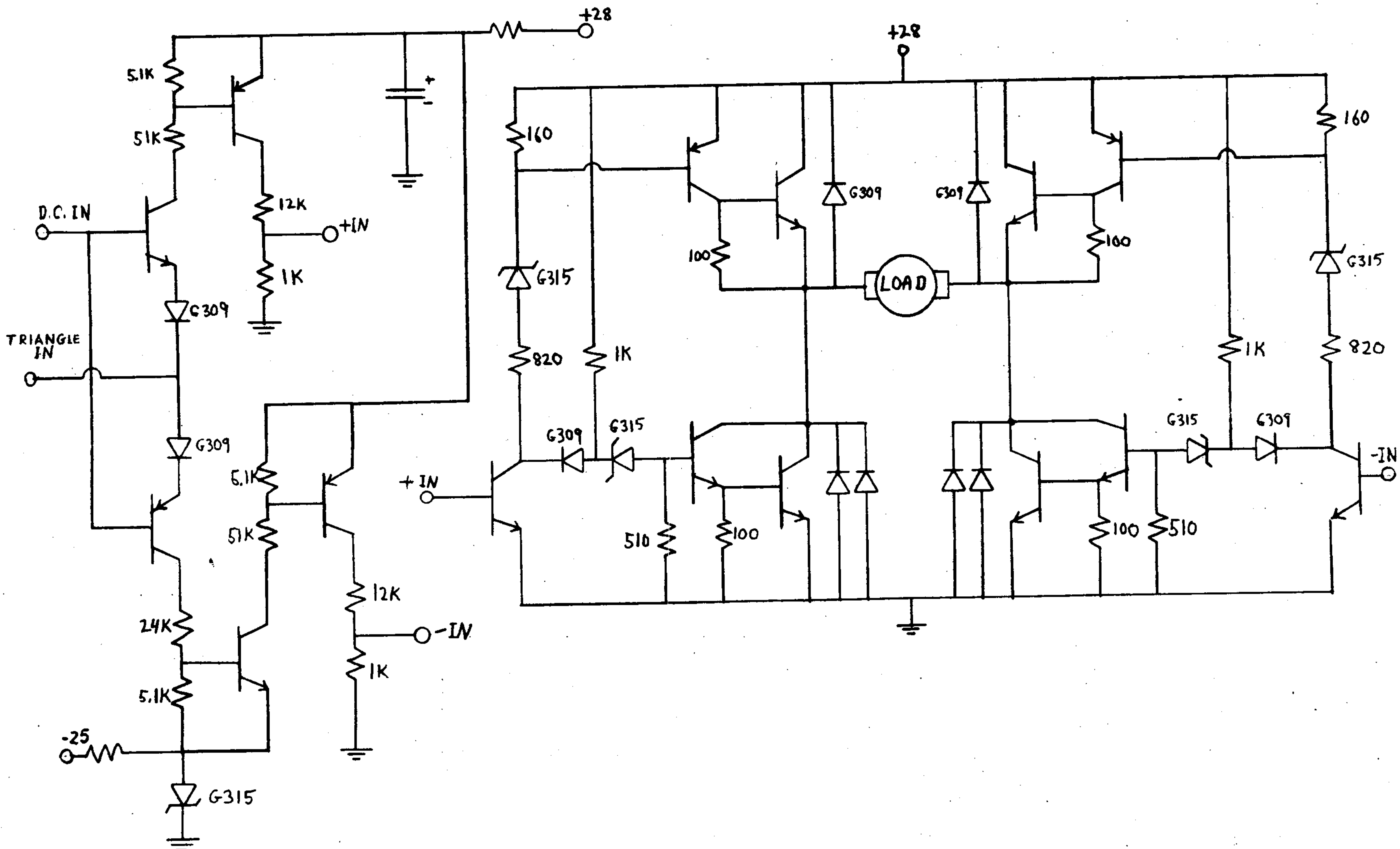


Figure 15. Schematic of Proposed New PWM Circuit.

Section 6
CONCLUSIONS

6-1 CONCLUSIONS AND RECOMMENDATIONS

The amplifier designed for this program is a useful device which meets the performance specifications. Its ability to operate either the ST124 PIGA loop or ST124 gimbal servo loop has been demonstrated at the NASA center in Huntsville. The design represents a significant improvement over previous PWM circuits. In addition to the requirements of the contract, a schematic of an improved circuit and a description of its operation is presented which was developed in our continuing effort for progress. It is recommended that, if additional modules are built, they incorporate the improved circuit design.

A logical continuation of this effort would be to construct a new much smaller ST124 type platform and related equipment. This equipment would not only be smaller and lighter in weight but would use substantially less power and should be more reliable. The Ordnance Department is currently building stable platforms and reentry attitude control systems that are being used in several space applications. These platforms feature not only micro-miniature servo modules but square-wave power supplies to operate the gyro wheels. By installing the servo modules directly on the stable platform, cable runs and interconnections are kept to a minimum. The result is a decrease in weight and volume and an increase in reliability. The Ordnance Department is ready to perform a continuation of refinement in this area or related equipment where we could be of help.

APPENDIX
PERFORMANCE DATA FOR A TYPICAL MODULE

Following is a set of data taken from Module 7.

A-1 Conditions of the tests were as follows:

1. Feedback resistor = 162 k
2. Triangle resistor = 48.7 k
3. Balance resistor = 38.3 k
4. Load = 28 ohms in series with 54 mh.

A-2 Figure 16 shows the gain linearity. This was one of the better modules in this respect. The deadband seen at the center can be reduced merely by decreasing the external triangle resistor.

A-3 Figure 17 is a repeat of the gain curve, but the positive and negative sides are superimposed to show symmetry.

A-4 The frequency response for two values of input amplitude is shown in figure 18.

A-5 Figure 19 is a graph of deadband referred to the input vs temperature.

A-6 Figure 20 shows the offset referred to the input vs temperature.

A-7 When set at null, the output of this (and every other) module did not change at all when a 10-volt peak-to-peak square wave was superimposed on the 56-volt supply. The ends of the deadband measured at the input changed by only 1 mv.

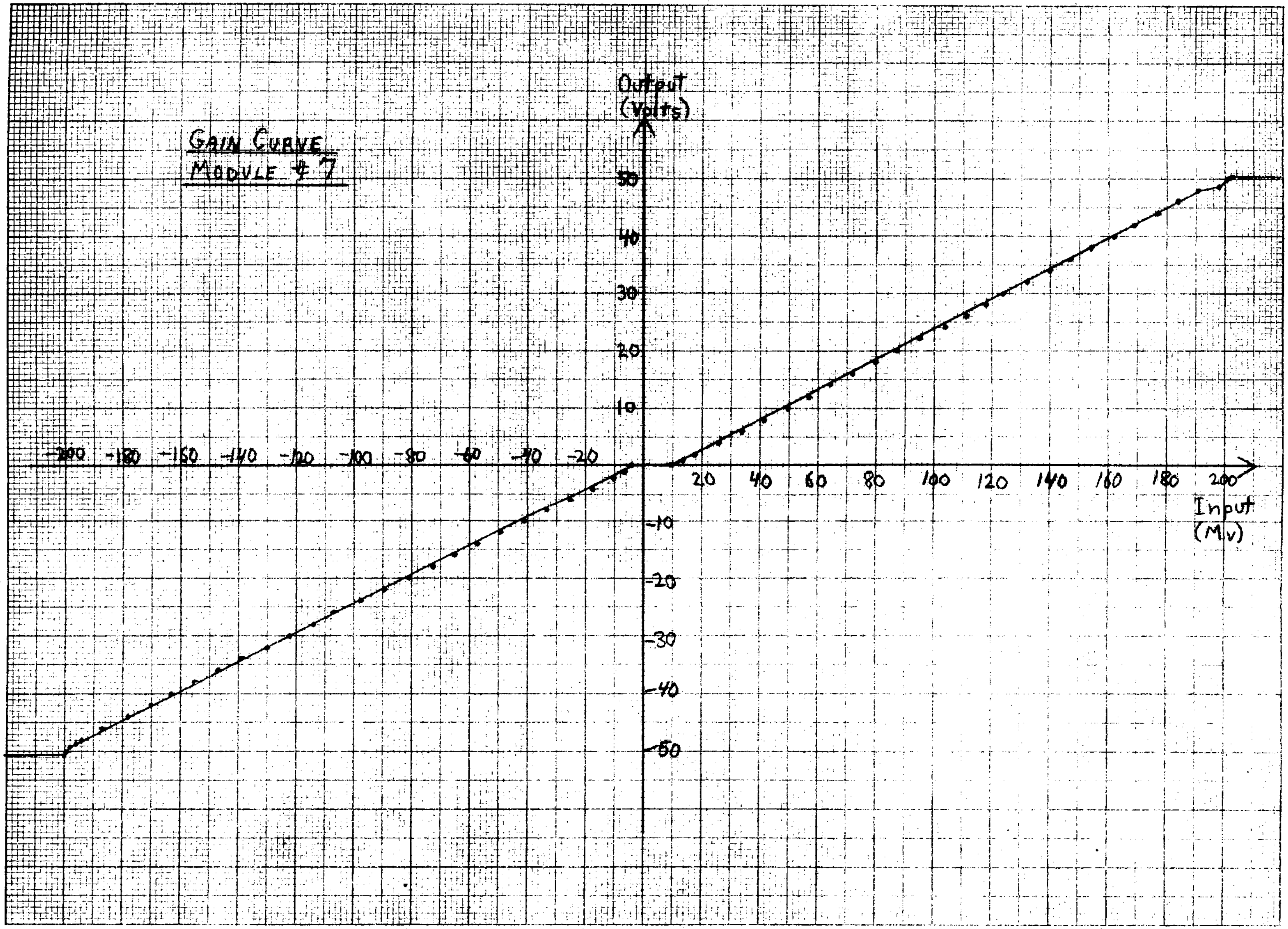


Figure 16. Gain Curve of Module 7.

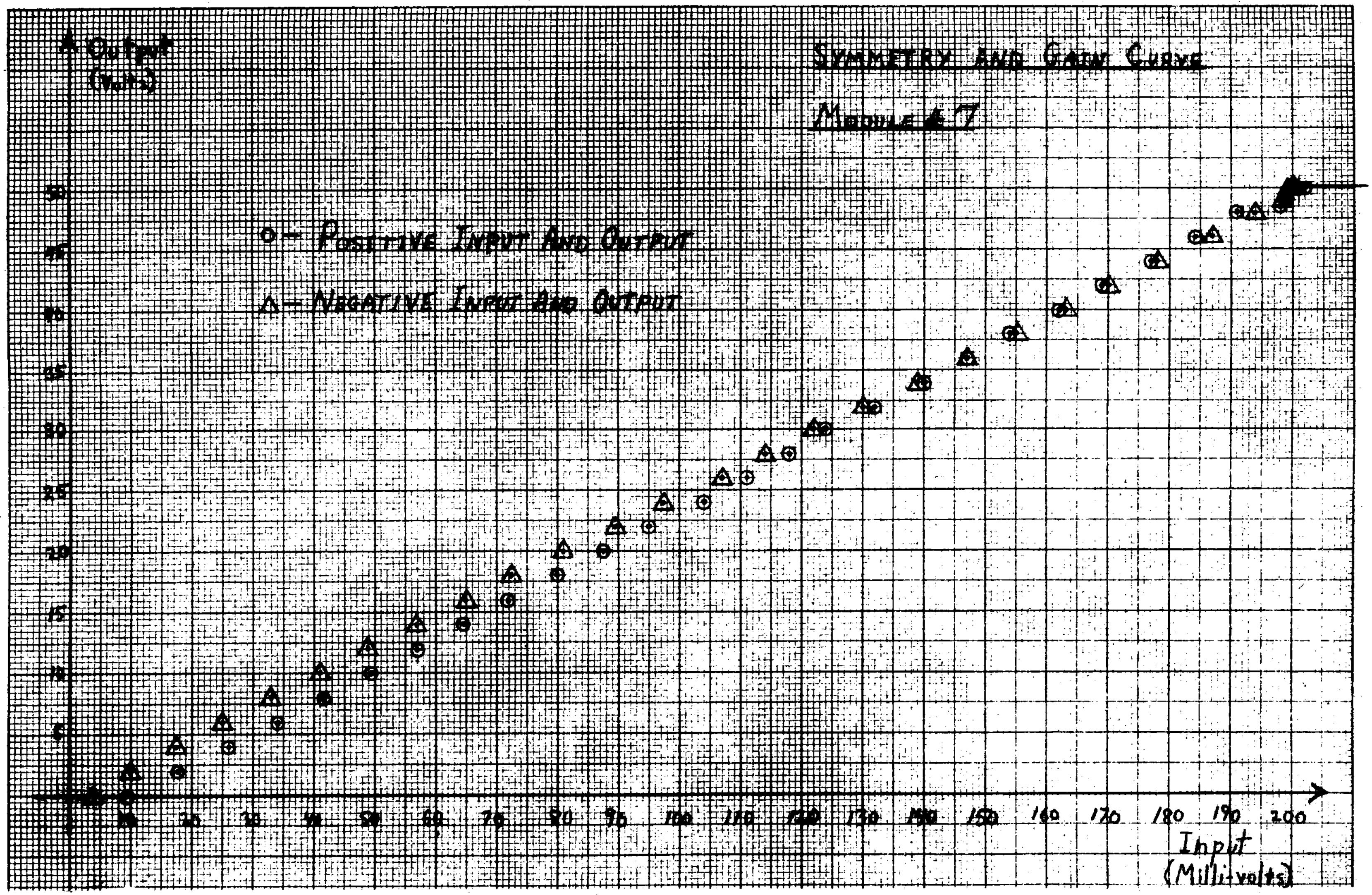


Figure 17. Symmetry Curve of Module 7.

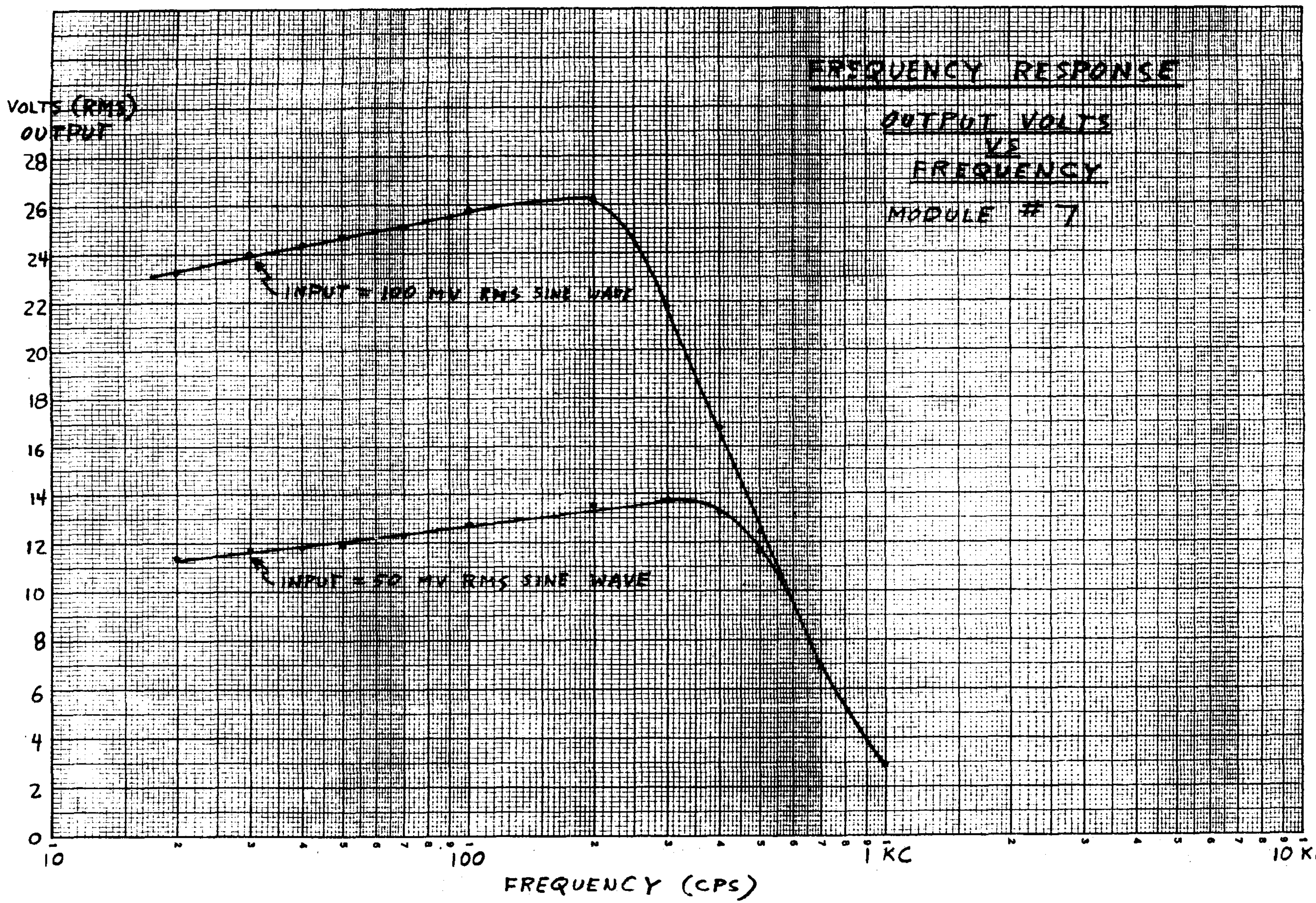


Figure 18. Frequency Response of Module 7.

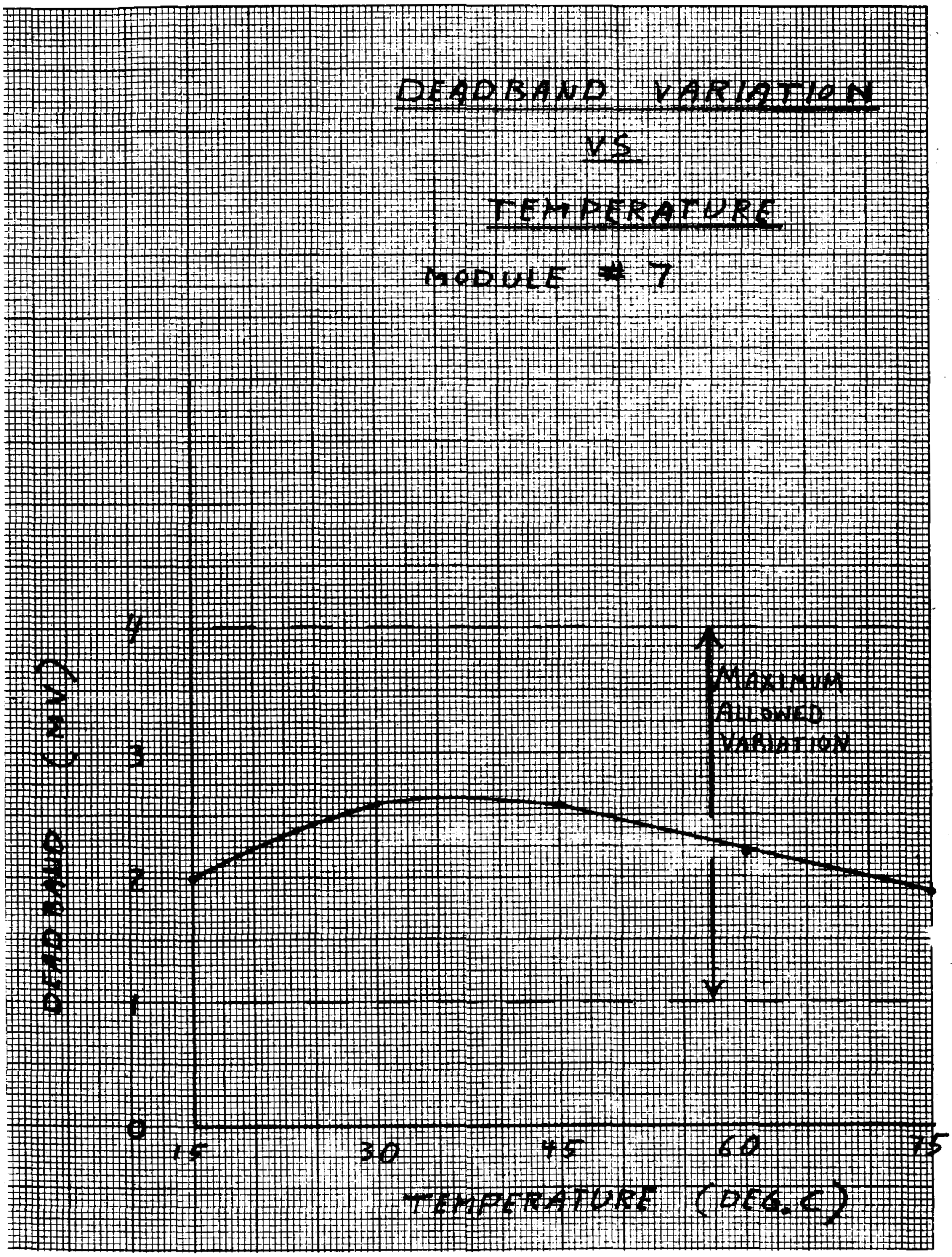


Figure 19. Deadband Variation vs Temperature - Module 7.

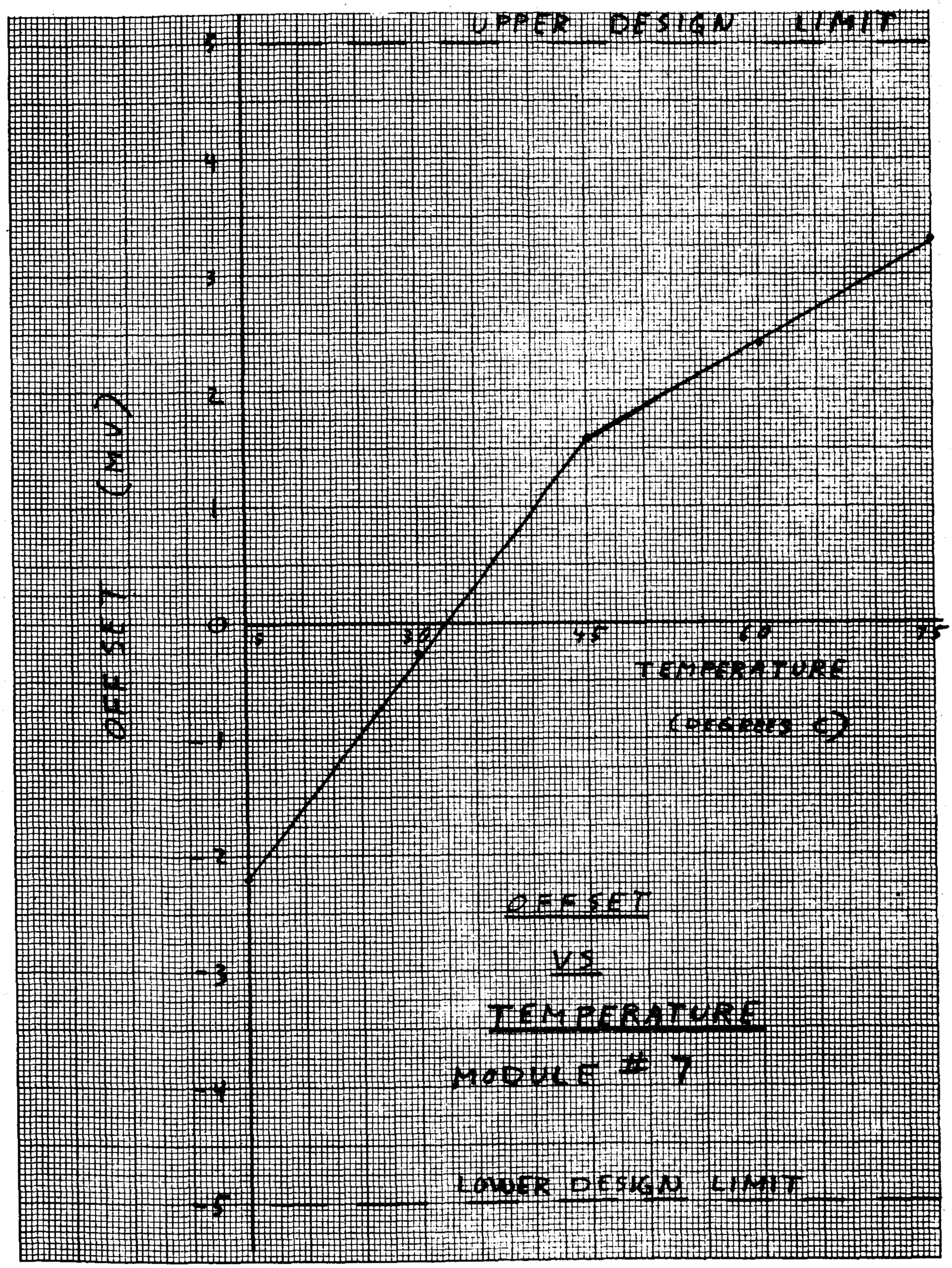


Figure 20. Offset vs Temperature - Module 7.