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A Joint Report
on the Development of

GUN FIRE CONTROL SYSTEM MARK 61 MOD. 0-2

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VOLUME I

(of Two Volumes)

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Gun Fire Control System
Mark 61 Mod 0-2

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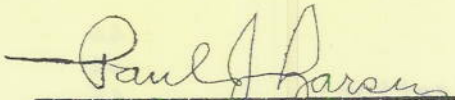
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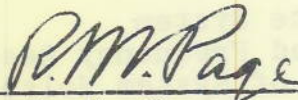
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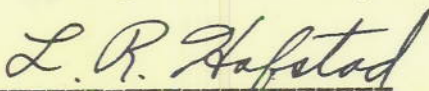
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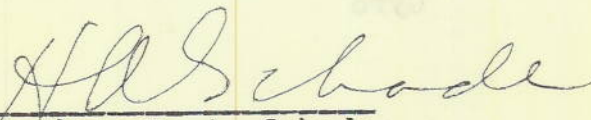
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Reference should be made also to the following reports:

"Calibration of Gun Fire Control Systems Mark 57 and Mark 61", by R. Kogge, issued separately as APL/JHU Technical Monograph No. 134.

"Tests of Computers Mark 16 and Mark 33"; Interim Report, Naval Research Laboratory, C-1100-420/46, by William N. Shaddix; November 18, 1946.

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THE MARK 61 GUN FIRE CONTROL DIRECTOR

PART I GENERAL

A history of the development of the Gun Director Mark 61 up to December, 1944, was given in a report by Paul J. Larsen* to Applied Physics Laboratory, The Johns Hopkins University, dated November 28, 1944. The report gives an account of the development from the initiation of the project in September, 1943, including early work on stabilization, the fundamental design of the Director, and the various changes in design requested by the Navy from time to time. For purposes of completeness and convenience for reference, the original performance Objectives are restated here.

1. Estimated Weight: 5670 lbs above deck, 3465 lbs below deck.
2. Space Requirements: 74 inch diameter working circle, 143 inch height overall.
3. Computers: Designed to carry the necessary components of the Mark 57 Gun Fire Control System.
4. Drive: power, either hydraulic or amplidyne type with control of motion at the Director itself or from a remote station.
5. Operators: Space for the Pointer only. (This was later modified by Navy to provide space for the Control Officer as well.)
6. Control: Both train and elevation from a single joystick or handlebars, whose displacement from a

* Appendix A (Vol. II)

"normal" position determines the angular velocity.

7. Tracking: Optical and blind radar.
8. Train Motion: 720 degrees to allow use of a cable twist for electrical supply.
9. Elevation Motion: -20 degrees to +90 degrees from the deck plane. (This was later changed to -25 degrees to +85 degrees).
10. Tracking Rates: 1 mil per second to 20 degrees per second in train and elevation.
11. Slew Rate: 45 degrees per second in train and elevation.
12. Angular Acceleration: 30 degrees per second per second in train and elevation (original specification).
13. Stabilization: Stabilization of the line of sight against ship roll and pitch, except no cross level compensation; residual roll and pitch amplitudes not to exceed 2 mils under the following conditions:
Roll--25 degree amplitude, 9 second period
Pitch--5 degrees amplitude, 5 second period.
14. Tracking Error: On a normal straight line course with roll and pitch as in paragraph 13 tracking half circle not to exceed 2 mils.
15. Maximum Range of Computation: 6000 yds.
16. Radar: Mark 28
17. Maximum Radar Range: 20,000 yds.
18. Power Supply: Operation from ship's 440V and 115V,

- 60 cycle supply, with power consumption not exceeding 5 kw.
19. Power Supply Variations: Performance not to be affected appreciably with voltage variations of ± 15 percent from normal and frequency variations of ± 8 percent from the normal 60 cps.
 20. Ambient Temperature: Performance to be substantially independent of temperature from -10°F to $+120^{\circ}\text{F}$.
 21. Mounting and Alignment: To be in accordance with established Navy practice and procedure.
 22. Accessibility of Components: All components to be arranged and mounted to facilitate servicing and maintenance.
 23. Structural Requirements: All components and assemblies to be designed to withstand 50 g acceleration and otherwise to conform to Navy structural standards. Components and finished structure to pass all standard Navy structural tests, such as vibration, blast, corrosion, etc.
 24. Servicing Personnel: Design to take into consideration the fact that the equipment is to be operated, serviced and maintained by Navy personnel after a short training period.

The following changes have been made in these objectives to date (in the same order):

1. Weight: 7125 lbs above deck, 3800 lbs (estimated) below deck.

2. Space Requirements: 74.5 inch diameter working circle, 138 5/8 inch height overall with 30 inch Radar Dish.
4. Drive: Hydraulic power drive, with control both local and remote.
5. Operators: Control Officer and Director Pointer in the Director.
7. Tracking: Optical, blind radar, automatic radar.
9. Elevation Motion: -25 degrees to +85 degrees from the deck plane.
10. Tracking Rates: 1 mil per sec to 43 degrees per sec in train and elevation.
11. Slew Rate: 43 degrees per sec in train and elevation.
12. Angular Acceleration: 150 degrees per sec per sec in train and elevation.
15. Range of Computation: 800 to 8000 yds.
16. Radar and Target Acquisition Equipment: MK 47.
17. Maximum Radar Range: 30000 yds.
24. Slew Sight: Means by which the Control Officer can take instant control of the Director in acquiring new targets, and means for automatically aligning the Director with the new line of sight. Instant transfer of control from slew sight to Pointer's Control at discretion of Control Officer.

During the period from November, 1944, to March, 1945, three pre-production models designed in accordance with JHU/APL specifications and recommendations, were delivered by the Norge Division of the Borg-Warner Corporation and underwent various structural

and performance tests. Following is a general description of the servo system in the pre-production model at that time:

1. The power drive consisted of two Vickers variable displacement hydraulic pumps* powered by a double ended, constant speed, 1.5 hp, 440 volt, 3 phase electric motor and connected through high pressure copper tubing to 30°, 3600, rpm Vickers hydraulic motors.** One pump and hydraulic motor drove the Director in train, while the other powered the elevation drive. In order to produce a fine control of speed the rubber seal on the pilot valve of the pump was removed and replaced by a close fitting but free metal seal with approximately 0.0002 inch clearance. The resulting oil leakage was collected and returned to the oil sump by means of an auxiliary electric pump. A spur gear transmission in train and elevation gave a reduction of 492.8 between hydraulic motor and Director motion. The general scheme of gearing, except in some details, was the same as that for the final design as shown in Plate 13.

2. The hydraulic pump stroke control+ was an adaptation and modification of the M2 stroke control as used on the Army 90 mm gun. The stroke motor was a Diehl 2 pole, 2 phase, 20 volt, motor, driving an Elinco D.C.

* Photo Vickers 20400 Pump - See Appendix A (Vol. II)

** Photo of Vickers 30° 3600 r.p.m. hydraulic motor - See Appendix A (Vol. II)

+ Photo of Apex second stroke control - See Appendix A (Vol. II)

stroke generator at one third the motor speed and actuating the hydraulic pump pilot valve through a gear reduction of 240 to 1. Train and elevation limit stops were provided by means of flexible shafts from the drive gear systems, which actuated segments to return the hydraulic valves to the neutral position at the limit of motion. The hydraulic pilot valve was arranged for adjustable dither amplitude at 1600 vibrations per minute.

3. The amplifier for actuating the stroke control consisted of three stages, the first of which was operated as a balanced amplifier with alternating potential applied to the plates. The second and third stages were conventional push - pull stages. This arrangement supplied a phase and polarity sensitive AC output voltage proportional to AC input and to DC input. AC control potentials and the DC stroke generator signal after being fed through an RC network were both applied to the amplifier input.

4. Control of the Director was accomplished by a joystick which actuated rotatable transformers in train and elevation for angular rate control and tachometer generators for position control. Motion of the joystick generated two control signals, one of which produced Director angular velocity proportional to the joystick deflection while the other produced angular velocity proportional to the rate of joystick

deflection. To give the Pointer a sense of solidity about the joystick, viscous dampers were attached to each axis of the joystick gimbal system.

5. The gyros were of the type used in the Computer Mark 17 except that the damping was reduced to critical at the fixed range wire setting employed, which gave just full gyro deflection at the maximum desired tracking rate of 25 degrees per second. The range wire orifice was clamped permanently in this position. Wheel speed was approximately 5000 rpm.

Director Serial No. 1 was shipped to the University of Virginia (U of V) where it was placed on a roll and pitch platform for stabilization and tracking tests. These tests were carried out both with optical and automatic radar tracking by University of Virginia personnel. Director Serial No. 2 was shipped to the Navy Bureau of Ordnance Test Unit at Dam Neck, Virginia, (DN) for firing tests with a dual 40 mm gun on a rolling platform. Director Serial No. 3 went first to the U. S. Naval Gun Factory, Washington, D. C. for temperature performance tests and then to the Chesapeake Beach Annex of the Naval Research Laboratory (CBA) for precision tracking runs on stationary and rolling platform. A description of these tests and their results will be of interest in connection with later developmental changes in the Director.

At the University of Virginia difficulties were immediately encountered with violent hunting in train. This was traced in part to torsional compliance of the roll and pitch table and in

part to compliance in the high pressure oil lines in the Director drive system. The former was reduced to unimportance when stiffeners were welded to the table. A computation showed that the remaining compliance could be accounted for by compressibility of the oil in the high pressure lines and elastic expansion of the copper oil lines themselves.

The following project was set up to perform tests and measurements on these effects and to determine the conditions for their adequate reduction. Means were devised quickly to return the hydraulic pump pilot valve to a position near the neutral from any given displacement. The pump was connected by copper tubing to a hydraulic motor upon the shaft of which was mounted a disc whose moment of inertia was equivalent to that of the Director in train. Various lengths and wall gauges of copper tubing could be used between pump and hydraulic motor. Also attached to the hydraulic motor shaft was an induction generator, by means of which instantaneous angular velocities could be recorded on a Brush recorder.

Following are a few of the experiments which were performed in an attempt to locate the factors influencing this effect.

1. Various methods of bleeding the system of air were tried with both long and short tubing and a transparent window was inserted in the pump housing to determine when the bleeding was complete. The tests indicated that operation of the system while the hydraulic pump pilot valve was stroked periodically bled the system as effectively as any other method.

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2. Pressure gauges were inserted in the high pressure lines to determine whether the transient pressure was rising high enough to operate the internal relief valves in the pump. Within the time constant of the dial gauges the indicated pressure was no more at any time than approximately one sixth that for which the relief valves were set (1250 psi).
3. The pump was driven from a very low impedance power source (a 25 hp hydraulic motor) to determine whether the vibrations were caused by compliance of the pump drive system. The oscillation was substantially unchanged.
4. In addition to O.S. 2943 hydraulic oil the aircraft oil AN-VV-0-366-B designed for use to very low temperatures was tried. No improvement resulted.
5. Plate 70 shows the angular velocity of the hydraulic motor as a function of time (a) with five-foot lines of light gauge copper tubing (0.032 inch wall) and (b) with lines of heavy gauge copper tubing (0.062 inch wall) shortened to approximately fifteen inches each. In the latter case the oscillation has practically disappeared.

It was concluded from these experiments that shorter and heavier lines would provide the best remedy for the oscillation. Shortening of the lines was accomplished in the Director by a

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minor rearrangement of the tubing and proved very effective in reducing the torsional compliance of the system.

The system was used at the University of Virginia for tracking tests on a cub plane both with optical and automatic radar tracking, with the platform stationary and with the platform in motion with a 15 degree amplitude roll and 5 degree pitch. The automatic radar tracking unit was one developed at the University of Virginia. All the pertinent reports in the JHU files from the University of Virginia are included in the present report.*

Director Serial No. 2 was received at JHU in March 1945 where the vibration test was made on the assembled Director.** The complete Gun Fire Control System, consisting of the Director Mk 61, Computer Mk 17, Computer Mk 16, Radar Mk 29 and attendant power supplies, was set up and placed in working order. The Director System was then sent to Dam Neck where it was received on April 4, 1945, for firing run tests. After some preliminary difficulties, mostly with the Computer Mk 17 and the stabilizer, the system was placed in operating condition by the middle of April. The Director and a 40 mm dual gun were mounted on a roll and pitch table from which firing run tests were made during the last two weeks of April. The tests were carried out both with the platform stationary and rolling and with optical tracking, radar spot scope tracking and automatic radar tracking

* Appendix B (Vol. II)

** Appendix C (Vol. II)

using the U of V automatic tracking unit. The latter was installed and adjusted by U of V personnel. The targets consisted of both sleeves and TBD-8 drones for firing tests and of SBD, F6F and F4N piloted aircraft for photographic runs at high tracking rates. Results of these tests are given in the Appendix to this report.*

Director Serial No. 3 arrived at the U.S. Naval Gun Factory in Washington, D.C., on April 17, 1945, for hot and cold operating tests. This test was under the official direction of the Naval Research Laboratory. Arrangements were made for operating signals to be supplied to the Director while in the temperature room. The Director was placed in operation and the temperature reduced to -10°F on April 24, 1945. All components were found to be in operating order except the hydraulic oil, O.S. 1113, which was too stiff to flow through the lines at this temperature. No further trouble with oil was experienced after it was changed to O.S. 2943. However, the slewing rate was reduced to 25 degrees per second and the exposed gear lubricant became too stiff for proper operation. This lubricant (cardium compound No. 10) was replaced with Lubriplate O.S. 1385, which remained soft and provided the correct lubrication. Power consumption was measured by means of a Weston Industrial Analyzer with the results shown in Table 1. The Director ran in train and elevation without further casualty at -10°F for approximately 24 hours. The temperature was raised to 95°F and the Director again cycled for 24 hours. There were no casualties.

* Appendix D (Vol. II)

TABLE 1

Tracking Rate

	<u>Zero°/Sec.</u>	<u>Slew - 25°/Sec.</u>
Volts	442.	442.
Amperes	---	5.0
KW	1.4	3.0
PF	0.60	0.80

Director Serial No. 3 was then shipped to CBA of the Naval Research Laboratory for precision photographic tracking tests by the NRL Group. Several troubles showed up when the system was reassembled at CBA, some of which probably occurred during the cold tests at NGF. The drive from the synchro box to the telescope had a considerable backlash of about 10 mils and the radar worm transmission had worn in such a way that motion occurred in steps and caused excessive vibration. It has since been necessary to redesign the telescope drive as well as to make changes in the design of the worm gear transmission.

Tests were made on a stationary platform on piloted aircraft with optical tracking and automatic radar tracking. For the latter tests, an automatic tracking unit was designed and constructed at NRL which later was adopted as an integral part of the Gun Fire Control System Mk 61. The University of Virginia automatic tracking unit was not tested at this time.

The following points which adversely affected the quality of the tracking were noted and recommendations made for their

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correction.

1. The joystick viscous dampers were designed with Sylphon bellows and were not rugged enough to prevent residual motion of the joystick at the neutral position. The lost motion between joystick and damper made the joystick feel "loose" in the normal position.
2. The position control tachometer potential was too low to give position control of the Director.
3. Linear rate control as provided by the rotatable transformer made tracking at low angular rates very critical.
4. The phases of the various potentials in the control circuit were not well matched. The result was a considerable input to the amplifier which was in quadrature with the actual control signals. This quadrature signal was large enough to saturate the amplifier at tracking rates above about 15 degrees per second.
5. Noise and harmonics in the control circuit were large enough that the amplifier was about half saturated even with zero input signal.
6. The stability of the drive system had a time variable, i.e., the adjustments of the system for stability were not the same at all times. This indicated that

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sensitivities and circuit characteristics were not independent of such factors as line voltage, temperature, ageing of components, such as tubes, and so on. This unpredictable variation in stability was probably connected with that of the amplifier, for the balance adjustment on the latter was also erratic.

7. Lost motion and windup in the telescope drive made good tracking impossible, even when the target image was kept accurately on the telescope cross-hairs.
8. The slew-sight-controlled linear potentiometers introduced control potentials in the amplifier circuit when the operator closed the slew sight switch. It was found in practice that the linear characteristic resulted under some conditions of acceleration in an unstable system when the slew sight servo loop was closed through the operator.
9. Stability of the Director drive system could be obtained only at a fairly low servo loop gain. This was because, as shown later, the gain crossover frequency of the system was much too low, so that the loop gain was necessarily limited to low values if the system was to be stable.
10. Because of dry friction in the system the low servo loop gain meant that the action of the Director was not a unique function of joystick position and rate. Thus

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the tracker had to compensate continually for spurious and unpredictable Director motions, which resulted in quick operator fatigue.

11. The control loop frequency response curves of the Director as shown in Figs. 1, 2, and 3, are very instructive. The first two characteristic curves were obtained with the control signals supplied by a side band frequency generator connected as in Fig. 4. The rotatable transformer (RT) in this unit, which is driven at an adjustable speed by the drive motor, is connected in phase opposition to the Control Transformer (CT), whose shaft is driven by the Director itself. The voltage difference is amplified and actuates the Director power drive system to reduce the differential to zero. If the drive system response is independent of frequency, the amplitude of Director motion as the RT rotates depends only on the voltage amplitude of the RT. Because the system is a physical one this condition is not realized in practice; the amplitude falling off at high frequencies from a corner frequency which depends upon the inertia and torque characteristics of the system. The results of the closed loop frequency response test are shown in Figs. 1 and 2.

In Fig. 1 the two curves marked "elev. = 0"

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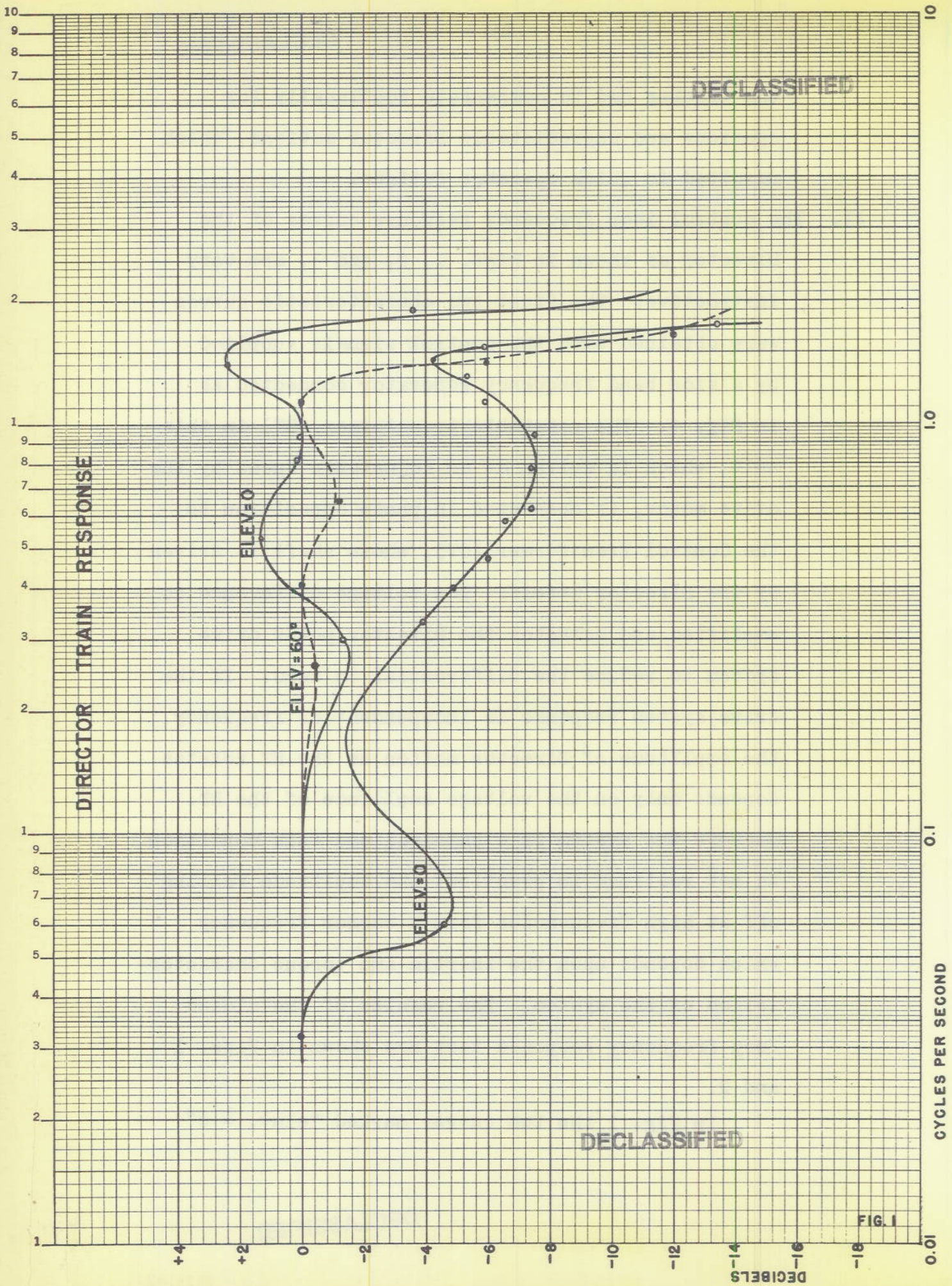
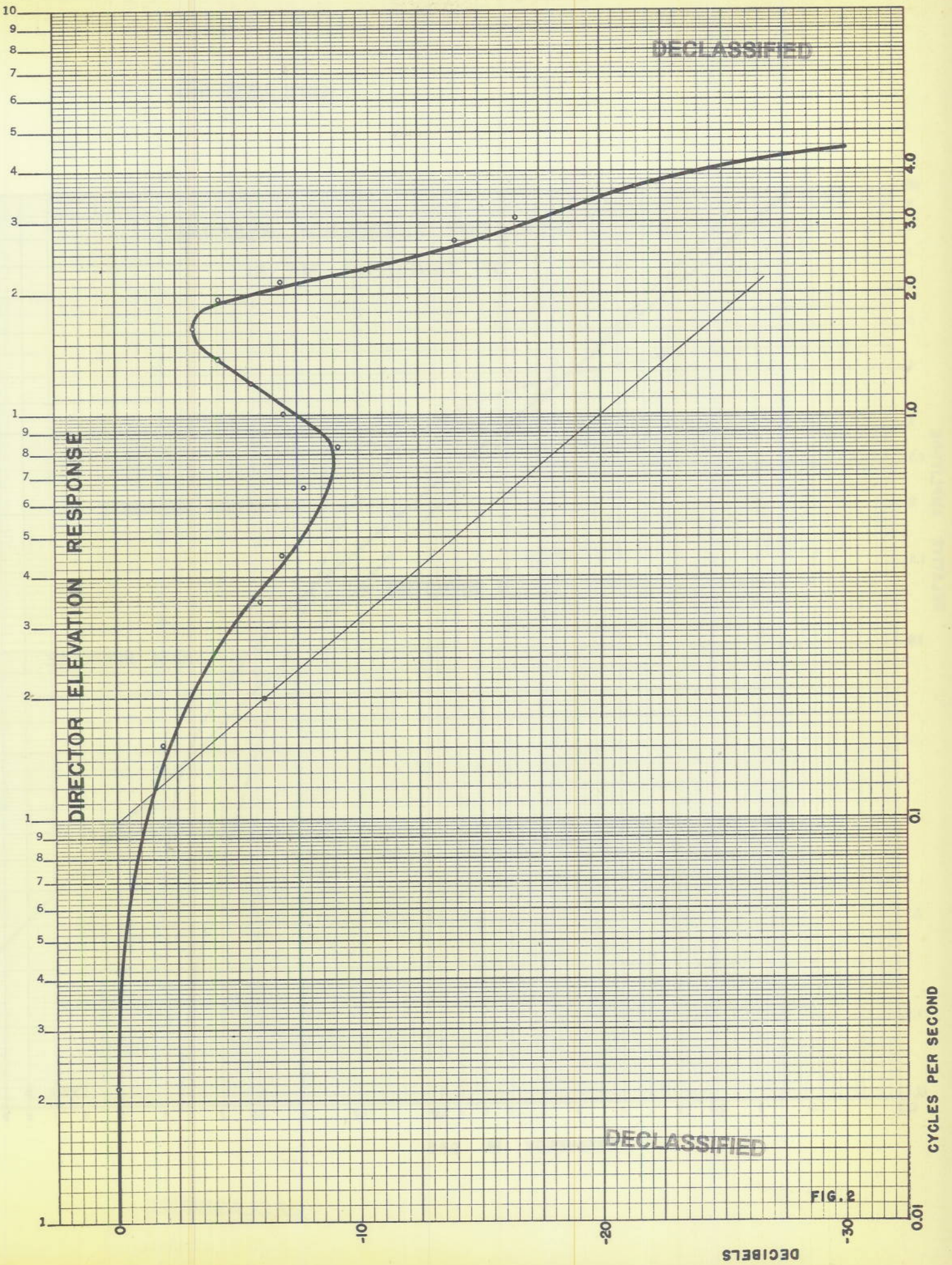


FIG. 1



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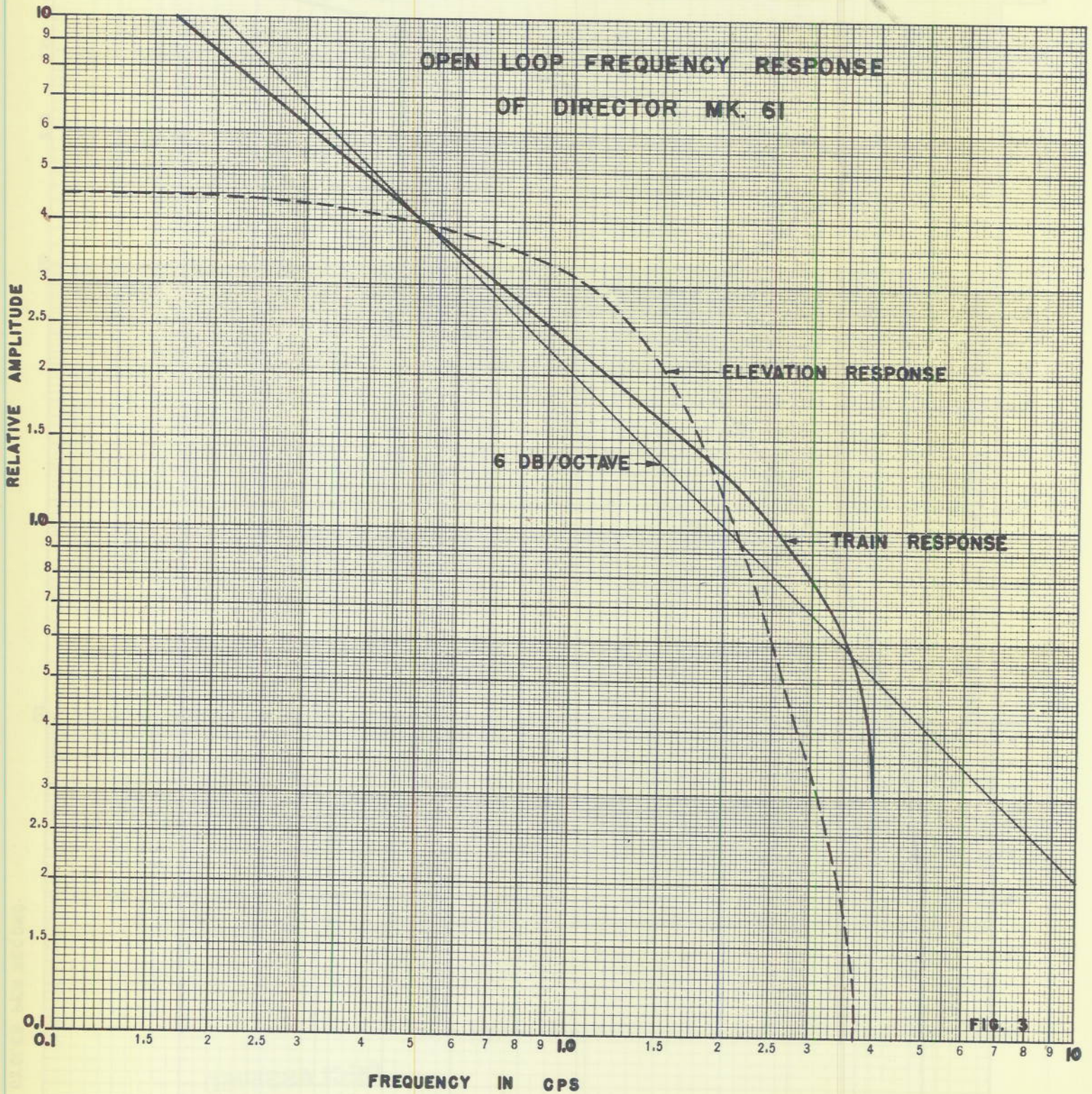
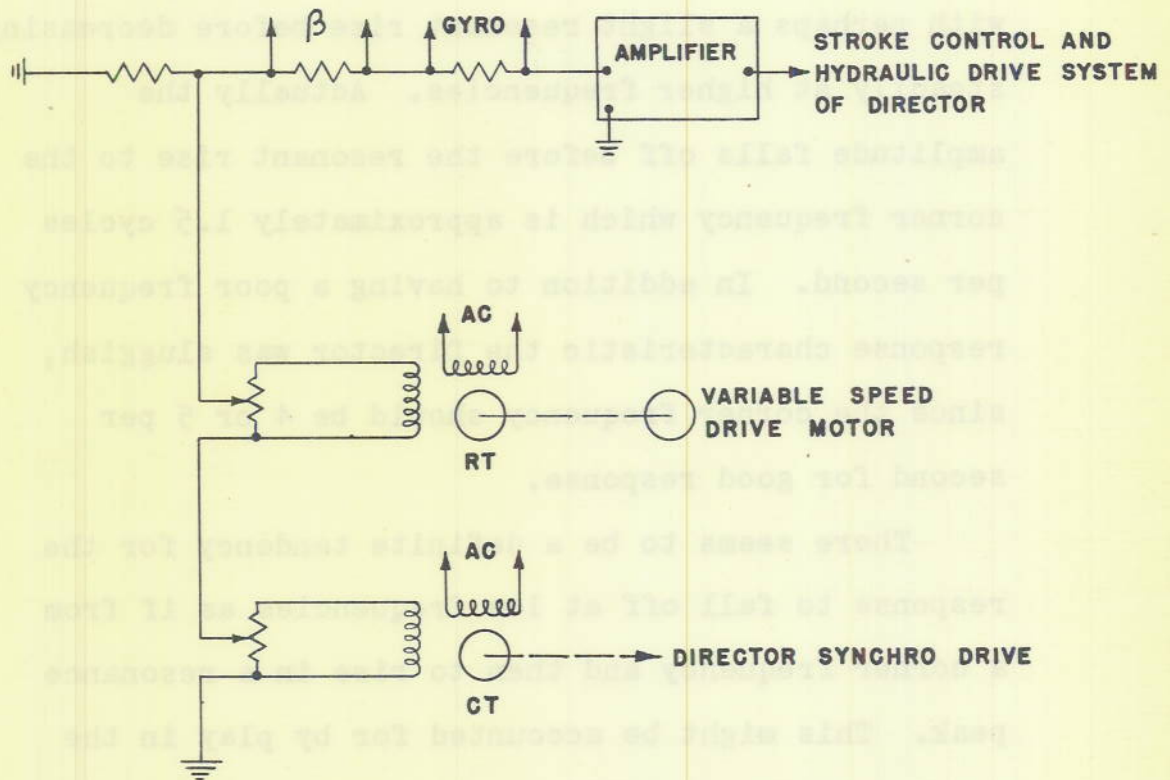


FIG. 3

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DUMMY DIRECTOR CIRCUIT FOR FREQUENCY RESPONSE TESTS OF DIRECTOR MK 61

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were taken about a half hour apart with no adjustments having been made during that interval. This illustrates the variation of system response referred to in paragraph 6 above. The curve marked "elev. = 60°" was taken with the Director elevation angle 60° above the deck plane. The curves should be straight, horizontal lines to the corner frequency, with perhaps a slight resonant rise before decreasing steadily at higher frequencies. Actually the amplitude falls off before the resonant rise to the corner frequency which is approximately 1.5 cycles per second. In addition to having a poor frequency response characteristic the Director was sluggish, since the corner frequency should be 4 or 5 per second for good response.

There seems to be a definite tendency for the response to fall off at low frequencies as if from a corner frequency and then to rise in a resonance peak. This might be accounted for by play in the gearing to the stabilizer cradle or compliance in the stabilizer mounting, which in fact was quite appreciable at the time and has since been reduced considerably. Such a condition would reduce feedback at the higher frequencies and result in a motion of increased amplitude.

Fig. 3 shows the frequency characteristic when

the Director is driven by a cycling signal with no feedback from the synchro system of the Director. As shown later the slope from zero frequency should be -1 to the corner frequency and more rapid thereafter. These tests indicate two deficiencies of the system: (1) The servo loop gain should be increased for a "tighter" servo system and (2) The system design should be modified to give a uniform frequency response at low frequencies.

12. Tests on automatic radar tracking were surprisingly good, considering the above test results, as shown in the NRL reports. However, two things are worth mentioning. The velocity lag became objectionably large at high angular rates and the Director had a tendency to hunt when moving in one direction. The first is reduced when the servo loop gain is increased and the second indicates excessive phase or amplitude asymmetry in the circuits, which probably was in the amplifier.

At this time a joint project was undertaken for the redesign of the Director drive system by the JHU/APL group and the Fire Control Section of the Naval Research Laboratory to reduce or eliminate the above difficulties. The remainder of the report is concerned with the redesigned system, its principles, the revised system with ideal components, the system with real components, the components themselves, test equipment and recommendations for further improvements.

PART 11

THE IDEAL SERVO SYSTEM AND THE REAL SYSTEM

For purposes of illustration, the complete Fire Control System Mk 61 is shown in Plate 1. It is a "line of sight" system in which the Director and radar point to present position, while the gun points to future position, corrected for ballistic quantities. Radar target ranging and gun laying are both provided for.

A photograph of the Director is shown in Plate 2 together with a rear view in Plate 3 and views of the basket through the open access door in Plates 4, 5 and 6. Views from the front, back and sides of the basket which rotates in train, are shown in Plates 7 to 10 inclusive. The various components are shown mounted upon the sides of the basket for maximum accessibility. Plate 11 shows the shell with the main bearing spider and mounting at the bottom and the bull-ring spur gear and roller pad for guiding of the basket at top. The gear faces are vertical - a feature which allows expansion of the shell vertically without affecting the gear mesh. Plate 12 shows the main controls in the Director basket accessible to the Control Officer and the pointer. The Main Switch and Stop and Start control is so located that both operators can reach it instantly and the True Bearing Dial and Cable Twist Dial can be read by both operators.

The Director gear system is illustrated in Plate 13. All main power drive gears except the Radar Worm Drive are spur gears, to reduce the dry friction in the drive system to a low

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value. All drive gears are of steel, precision made and shaved, with teeth properly shaped for low friction and long life. Bearings are either ball or roller bearings properly sealed against weather where exposed. All gears and bearings are lubricated with Standard Navy approved oils and greases. Plate 13(a) is a lubrication chart of the Gun Director. The couplings indicated in yellow in Plate 13 are micrometer couplings by which angular adjustments of shafts can be made easily and accurately without danger of future misalignment by slippage. Plate 13(b) is an axis alignment chart of the Gun Director based upon alignment checks as given in Ordnance Specification O.S. 3932.

Plate 14 is a photo of the power drive system components, while Plate 15 gives the complete Train and Elevation Hydraulic Power Drive System in diagrammatic form. The 1.5 hp electric motor drives both train and elevation pumps as well as the sump pump, which returns oil collected from the pilot valve leakage to the filler tank. By-pass valves in the high pressure lines allow relative motion between the hydraulic system and the Director. High pressure hydraulic lines are of heavy gauge copper tubing (0.062 inch wall) and are as short as possible. Hydraulic lines are zinc plated. Rubber seals have been eliminated from the hydraulic pump pilot valves and close fitting but free (0.0002 inch clearance) metal seals substituted. The dry friction of the pilot valve is less than 0.5 oz, which compares with 12 to 16 ozs for the neoprene seal. The oil used in the system is Navy O.S. 2943.

The AC and DC Power System schematic is shown in Plate 16. The entire system was designed for supply limits in accordance with the Objectives. Power circuits are arranged for maximum

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safety to operating personnel without introducing chances of mis-function under emotional stress. To place the Director in operation the Train Lock Plunger must be disengaged, the Main Switch must be "on" and the "start" switch must be pushed before Director Drive will start. It is not possible to damage any equipment by a difference in sequence of the operations in starting the Director. When using the Power Drive the Manual Crank drive must, of course, be disengaged. A spring keeps the latter normally in the disengaged position. It is not necessary to wait for warm-up time, since immediate operation is possible before gyros are up to speed, although there will be no control until the amplifier tubes are warm, which requires about 15 seconds.

Plate 17 is a simplified schematic of the Electrical Control System. The control potentials are supplied by three main sources in the system: (a) The control signal proper, which may be furnished by the Pointer's Control Unit (Manual Rate) Mk 31 Mod 0, the Automatic Tracking Radar Unit in the Radar Console Mk 6, the Target Acquisition Control Unit (Joystick), or the Slew Sight, Mk 6 Mod 0; (b) the external servo loop feedback potential furnished either by the Stabilizer Mk 1 Mod 0 or a feedback tachometer provided for the purpose; and (c) the internal servo loop feedback potential, furnished by a tachometer provided for the purpose in the Hydraulic Pump Stroke Control as described presently. The control potentials appear across resistances connected in series in the control

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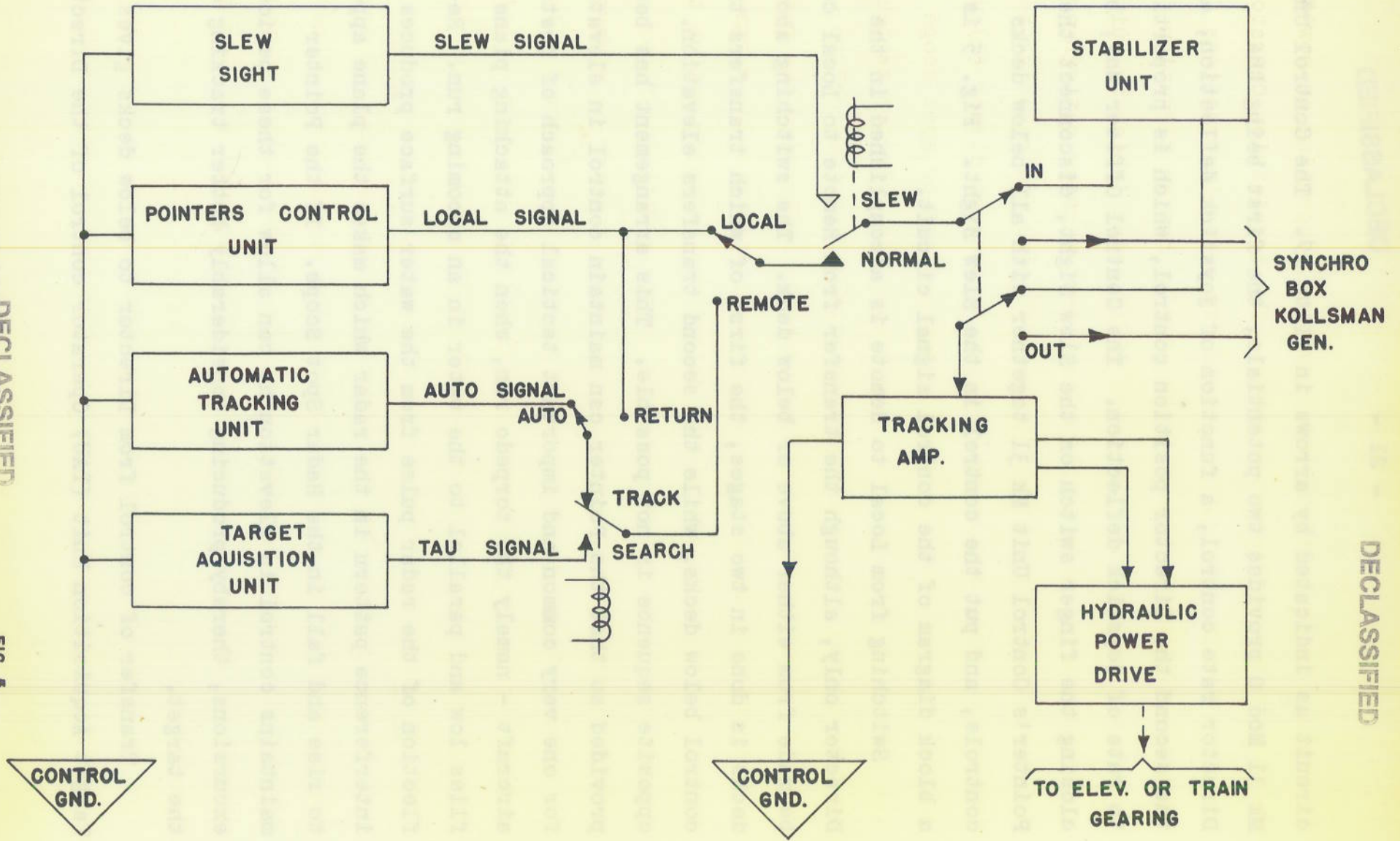
circuit as indicated by arrows in Plate 17. The Control Unit Mk 31 Mod 0 provides two potentials, the first being the Director rate control, a function of joystick deflection, and the second the Director position control, which is proportional to rate of joystick deflection. The Control Officer may, by closing the finger switch on the Slew Sight, disconnect the Pointer's Control Unit Mk 31 together with all below decks controls, and put the control in the Slew Sight. Fig. 5 is a block diagram of the control signal circuit.

Switching from Local to Remote is accomplished in the Director only, although the transfer from Remote to Local can be made from either above or below deck. The switching above decks is done in two stages, the first of which transfers train control below decks, while the second transfers elevation. The opposite sequence is not possible. This arrangement has been provided so that the Pointer can maintain control in elevation for one very common and important tactical approach of hostile aircraft - namely the torpedo run, when the attacking plane flies low and parallel to the water in an oncoming run. Reflection of the radar pulse from the water surface produces an interference pattern in the radar which makes the plane appear to rise and fall in the Radar Spot Scope. If the Pointer maintains control in elevation he can allow for these periodic excursions, thereby producing considerably better tracking of the target.

Transfer of control from Director to below decks gives the Target Acquisition Unit (TAU) Operator control of the Director

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SIGNAL FLOW DIAGRAM
OF
GUN DIRECTOR MK. 61



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FIG. 5

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in train only or in train and elevation, depending on how the shift is made, as described above. The Acquisition Operator may look for targets either on his own or on instructions from Control Information Center (CIC), for he has an Elevation (E) scope, a Plan Position Indicator (PPI) scope (which by suitable switching may be made to show the Director radar pattern or Ship's Search radar pattern), and both true and relative bearing dials. Upon acquiring a target he decides either (1) upon automatic radar tracking or (2) upon optical or spot scope tracking. In the former case he places his selector switch on "Radar" and depresses the foot switch from "Search" to "Track", pilot lights on the TAU console indicating the position of the switches at all times. In the latter case he warns the Director Pointer by telephone, shifts the selector switch to "Director" and depresses the foot switch. With the foot switch on the "Search" position the radar nutator is always in elliptical scan. In the "Track" position it is normally in conical scan. If the operator wishes to search with conical scan he places the selector switch on "Conical", leaving the foot switch on "Search."

Plate 18 shows the Gun Director Cable Diagram. The reader is referred to the Director Instruction and Maintenance Manual OP 1562 for schematic wiring diagrams of the various component assemblies and terminal cabinets. The Component List for the Gun Director is given in Plates 19 and 20. The Cable Diagram for the complete Gun Fire Control System Mk 61 is given in Plate 21, while the component list for the overall Gun Fire

Control System is given in Plate 22. Plate 23 is a Gun Fire Control System Flow Diagram of signals.

The servo system is composed of the elements indicated in the simplified block diagram of the system. (Fig. 6) The power level from the Error Measuring element and the Control Signal is very low as compared to that required to control the Power Drive, so the Control Device contains amplifiers (both electrical and hydraulic) as well as the mechanical means for controlling the Power Drive. The problem is reduced to one of determining the properties of actual elements (in contradistinction to ideal elements) that will make the final performance of Director and Operator compatible with the Objectives as set down at the beginning of this report.

In the design of any servo system whatever, no matter what its configuration might be, the following points are of prime importance if the actuated body is to obey the command supplied by the signal source both accurately and rapidly.

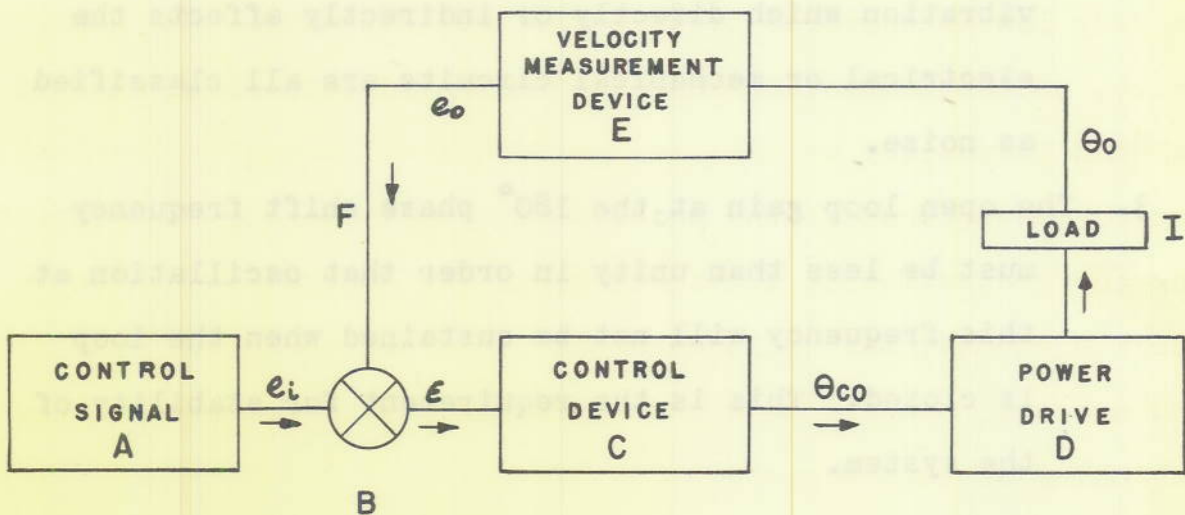
1. The overall gain of the open servo loop must be large.

With the correct type of feedback this results in a high primary stiffness or what is generally called a "tight" servo. The meaning of the term "Gain of the open servo loop" is discussed presently.

2. The signal to noise ratio must be high, otherwise excessive random motion of the system about the equilibrium position will result. Actually this is one of

SIMPLIFIED BLOCK DIAGRAM
OF
THE POWER DRIVE SYSTEM
IN
THE MK. 61 DIRECTOR

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- A - CONTROL JOYSTICK SIGNAL
- B - MIXER
- C - AMPLIFIER AND HYDRAULIC DRIVE STROKE CONTROL
- D - VICKERS VARIABLE DISPLACEMENT HYDRAULIC POWER DRIVE
- E - RATE GYRO
- I - INERTIA LOAD OF DIRECTOR
- e_i - CONTROL SIGNAL AS OBTAINED FROM JOYSTICK, AUTOMATIC TRACKING UNIT OR SLEW SIGHT
- e_o - FEEDBACK VOLTAGE FROM RATE GYRO
- E - ERROR SIGNAL (DIFFERENCE BETWEEN e_i AND e_o)
- θ_{c0} - CONTROL DEVICE ANGULAR POSITION FROM THE NORMAL POSITION WHICH DETERMINES THE POWER DRIVE OUTPUT VELOCITY
- θ_0 - OUTPUT ANGULAR POSITION OF DIRECTOR WITH RESPECT TO A FIDUCIAL POSITION

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the factors which determine the maximum practicable gain for the servo loop. For this purpose everything which obscures the desired result is considered to be noise. Dry friction in bearings or gears, play in gear teeth, spurious electrical signals, and external vibration which directly or indirectly affects the electrical or mechanical circuits are all classified as noise.

3. The open loop gain at the 180° phase shift frequency must be less than unity in order that oscillation at this frequency will not be sustained when the loop is closed. This is the requirement for stability of the system.

The Ideal System

For the reasons enumerated above the frequency range of interest extends considerably higher than frequencies represented by ship roll or than those supplied by the Pointer as he tracks the target. This is because the maximum permissible gain at low frequencies (say less than 2 cps., which is the region used for stabilization and tracking) is directly dependent on the properties of the system at higher frequencies. Let us consider first one example of an "ideal" system, i.e., one which has perfect components. These components would contribute no noise and would have uniform response characteristics over all frequencies.

The gain of the open servo loop is a very useful concept and

is defined in the following way. Let the circuit be interrupted at the point F in Fig. 6. If a signal e_i is applied to cause the system to move in sinusoidal motion at frequency f , a signal e_o will be generated by the rate gyro E. The open loop gain is defined as

$$\mu = \frac{e_o}{e_i} \quad (1)$$

where all quantities are in general complex.

The gain μ is a function of the frequency f . To make the manner of dependence clear consider the type of the elements used in the Mark 61 Director. The Control Device is a hydraulic stroke control consisting of an electrical amplifier, a stroke motor, and necessary gearing and auxiliary equipment. The ideal device would be one in which the instantaneous output angular velocity under all conditions would be proportional to the input signal to the amplifier. This is just the condition to be satisfied by an integrator, for the total angular distance in any time interval is given by

$$\phi_{co} = \int \dot{\phi}_{co} dt = k_1 \int e dt = k_2 \int e_i dt$$

and if $e_i = k_2 e^{j\omega t}$ where $\omega = 2\pi f$ and f is the frequency of the applied signal,

$$\phi_{co} = - \frac{k_1}{\omega} e^{j\omega t} \quad (2)$$

The displacement, then, is a sinusoidal function of time with amplitude inversely proportional to the frequency and with a phase lag of 90° . Thus the gain μ is infinite for zero frequency and the system output would build up to infinity with a steady

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signal input.

For use later in the discussion the following is a more explicit statement of the ideal transmission characteristic. Consider first a ball integrator in which the output angular velocity $\dot{\phi}_o$ is proportional to the input angular deflection ϕ_i . If the input shaft is made to follow an angular sinusoidal motion of amplitude ϕ , there results

$$\phi_i = \phi e^{j\omega t}$$

$$\dot{\phi}_o = k \phi_i, \text{ where } k \text{ is a constant of proportionality.}$$

Then

$$\phi_o = \int \dot{\phi}_o dt = k \int \phi_i dt = k \phi \int e^{j\omega t} dt = \frac{k \phi_i}{j\omega}$$

or

$$\frac{\phi_o}{\phi_i} = \frac{k}{j\omega}$$

The angular frequency ω_c , at which $|\phi_o| = |\phi_i|$, is called the gain crossover frequency or unity gain frequency of the unit. Since ϕ_o and ϕ_i differ in phase by 90 degrees, $\phi_o/\phi_i = -j$ at the gain crossover frequency, and the above equation becomes

$$\frac{\phi_o}{\phi_i} = \mu = \frac{\omega_c}{j\omega} = \frac{\omega_c}{p} \quad (3)$$

where μ is the frequency transmission characteristic of the unit, and $p = j\omega$.

In many devices used in fire control work the input quantity may be an applied potential to which the output angular velocity is proportional, or vice versa.

Let the output angular velocity be $\dot{\phi}_o$ and the input voltage

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be e . We may think of a fictitious input angle θ_i which is proportional to e . Then

$$\dot{\theta}_o = k \theta_i = k k_1 e$$

where k and k_1 are constants. As before

$$\theta_o = \int \dot{\theta}_o dt = k \int k_1 e dt = k \int k_1 e_o e^{j\omega t} dt = \frac{k k_1 e}{j\omega}$$

where the applied potential is sinusoidal.

Rearranging

$$\frac{\theta_o}{k_1 e} = \frac{k}{j\omega}$$

when

$$|k_1 e| = |\theta_o|$$

we have

$$k = \omega_c$$

and

$$\mu = \frac{\omega_c}{j\omega} = \frac{\omega_c}{p} \quad (4)$$

where $p = j\omega = \frac{d}{dt}$ and is the conventional operator.

A similar argument gives μ for a differential element:

$$\mu = \frac{p}{\omega_c} \quad (5)$$

The angular velocity of the Power Drive element is proportional to the pilot valve displacement. The same analysis shows this element to be an integrator with properties similar to those of the Control Device.

The Velocity Measuring element is a gyro so arranged that

the output electrical signal is proportional to the input angular velocity. In the ideal case this relationship would be independent of the input frequency. Then if the input amplitude θ_m is kept constant the output signal is given by

$$e_o = k_1 \frac{d\theta_o}{dt} = k_1 \frac{d}{dt} (\theta_m e^{i\omega t}) = k_1 \omega \theta_m e^{i\omega t} \quad (6)$$

Thus the output signal is sinusoidal with amplitude proportional to the frequency and with a phase lead of 90° . If these relationships are plotted on log log paper as in Fig. 7, the results for these ideal elements are straight lines of unit slope, positive for the differential type elements and negative for the integral type elements. From the definition of the decibel it follows that the curve for the former rises 20 db per decade or approximately 6 db per octave of frequency change while that of the latter decreases at the same rate.

If, now, the three elements are connected in series as in Fig. 6, but with F still open, and if a sinusoidal signal e_i is applied, the combination frequency characteristic will show a decrease of 20 db per decade and a phase lag of 90° (Fig. 8). The open servo loop gain μ at any frequency is defined as the ratio of the peak output voltage e_o at that frequency to the peak input voltage e_i . The gain crossover frequency f_c is defined as that frequency at which the magnitude of e_o is equal to e_i .

The ideal system described above is one which would remain

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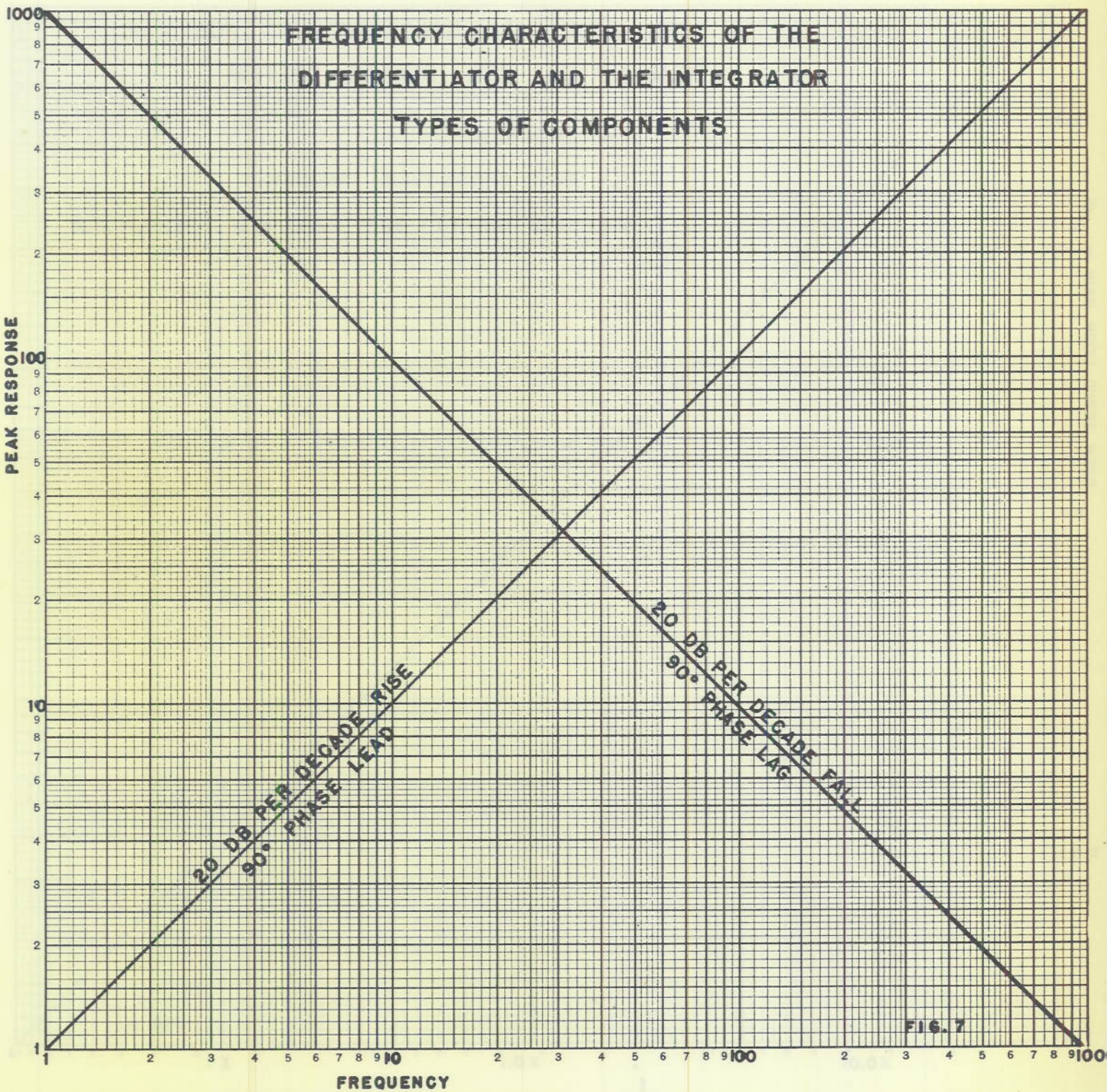


FIG. 7

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OPEN LOOP GAIN CHARACTERISTIC FOR THE
IDEAL 20 DB PER DECADE SYSTEM.

f - FREQUENCY

f_c - GAIN CROSSOVER FREQUENCY

ϕ (PHASE SHIFT) = 90° FOR ALL FREQUENCIES

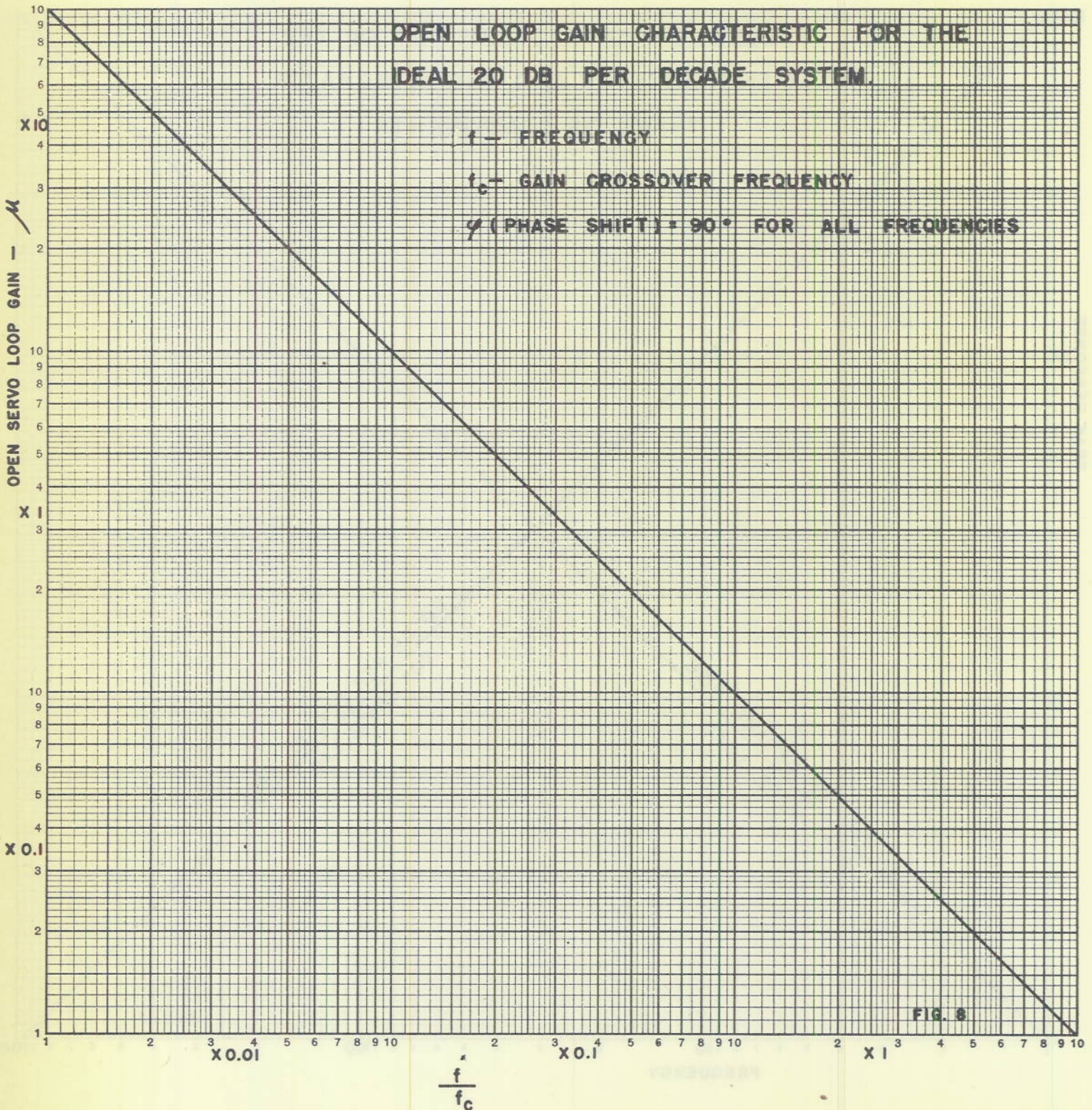


FIG. 8

stable at all frequencies when the servo loop is closed, i.e., when the circuit at F is completed. This is evidently true because at no frequency are the necessary and sufficient conditions for sustained oscillation satisfied, namely, that there be a frequency for which the phase shift is 180° and that at this frequency the open loop gain be greater than unity.

This can be shown quantitatively by applying the well known feed-back amplifier relationship:

$$A = \frac{\mu}{1 - \beta\mu} \quad (7)$$

where in general all terms are complex, and

A = External transmission characteristic

μ = Open servo loop gain

β = Feedback factor (fraction of output returned to input.)

However, $\beta = -1$ since the total output of the gyro is fed back into the amplifier input. Eq. (7) then becomes simply

$$A = \frac{\mu}{1 + \mu} \quad (8)$$

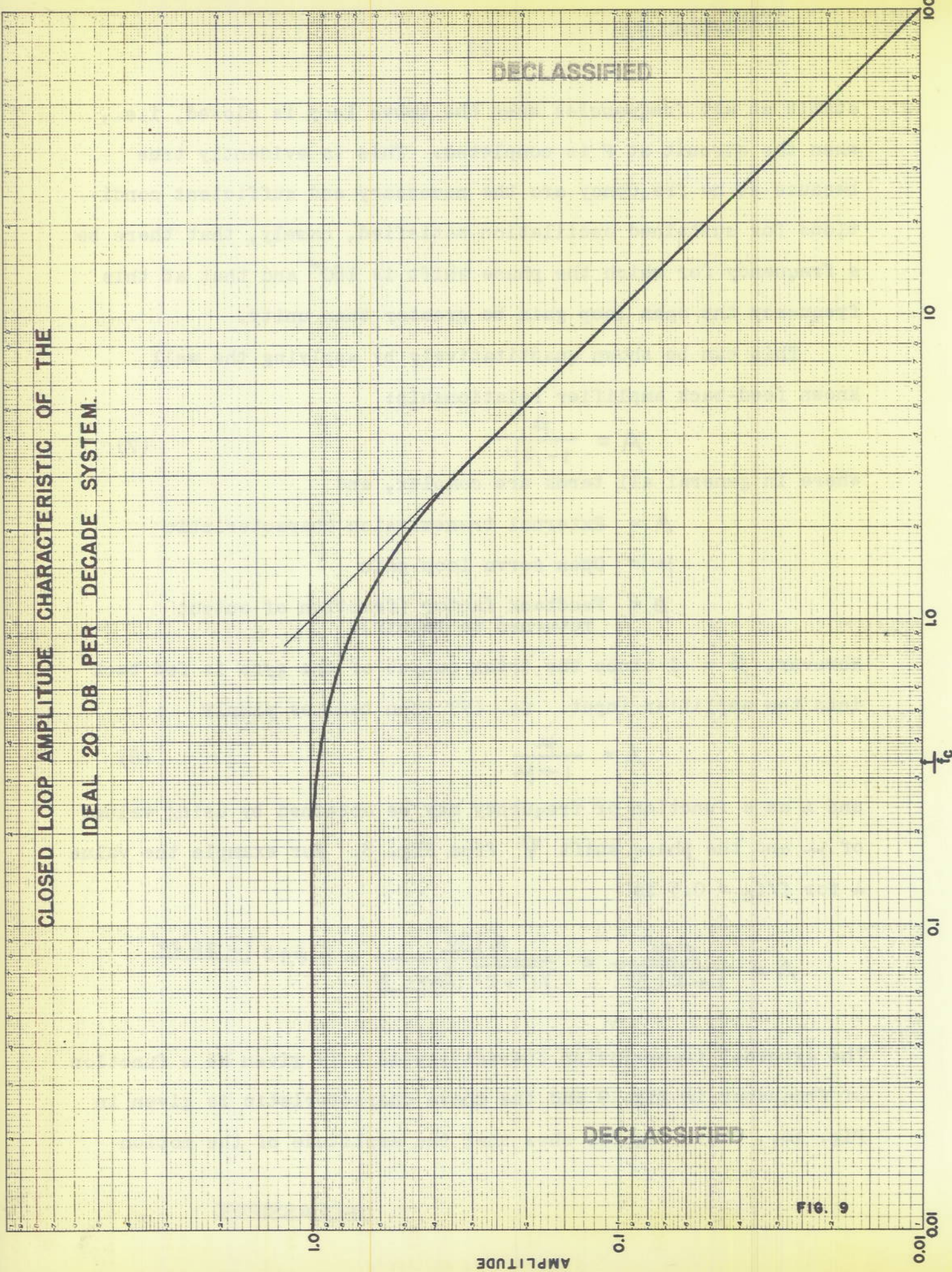
and A as a function of frequency may be obtained by using values of μ and the phase shift ψ from Fig. 8. For example the value A for $f/f_c = 0.5$ is

$$A = \frac{2 \angle 90^\circ}{1 + 2 \angle 90^\circ} = \frac{2 \angle 90^\circ}{\sqrt{1^2 + 2^2} \angle \tan^{-1} 2} = 0.893 \angle -26^\circ 30'$$

The external transmission characteristic A is given as a function of frequency in Fig. 9 and the phase characteristic is given in Fig. 10. These figures show that the amplitude of the motion

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CLOSED LOOP AMPLITUDE CHARACTERISTIC OF THE
IDEAL 20 DB PER DECADE SYSTEM.



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FIG. 9

AMPLITUDE

0.01

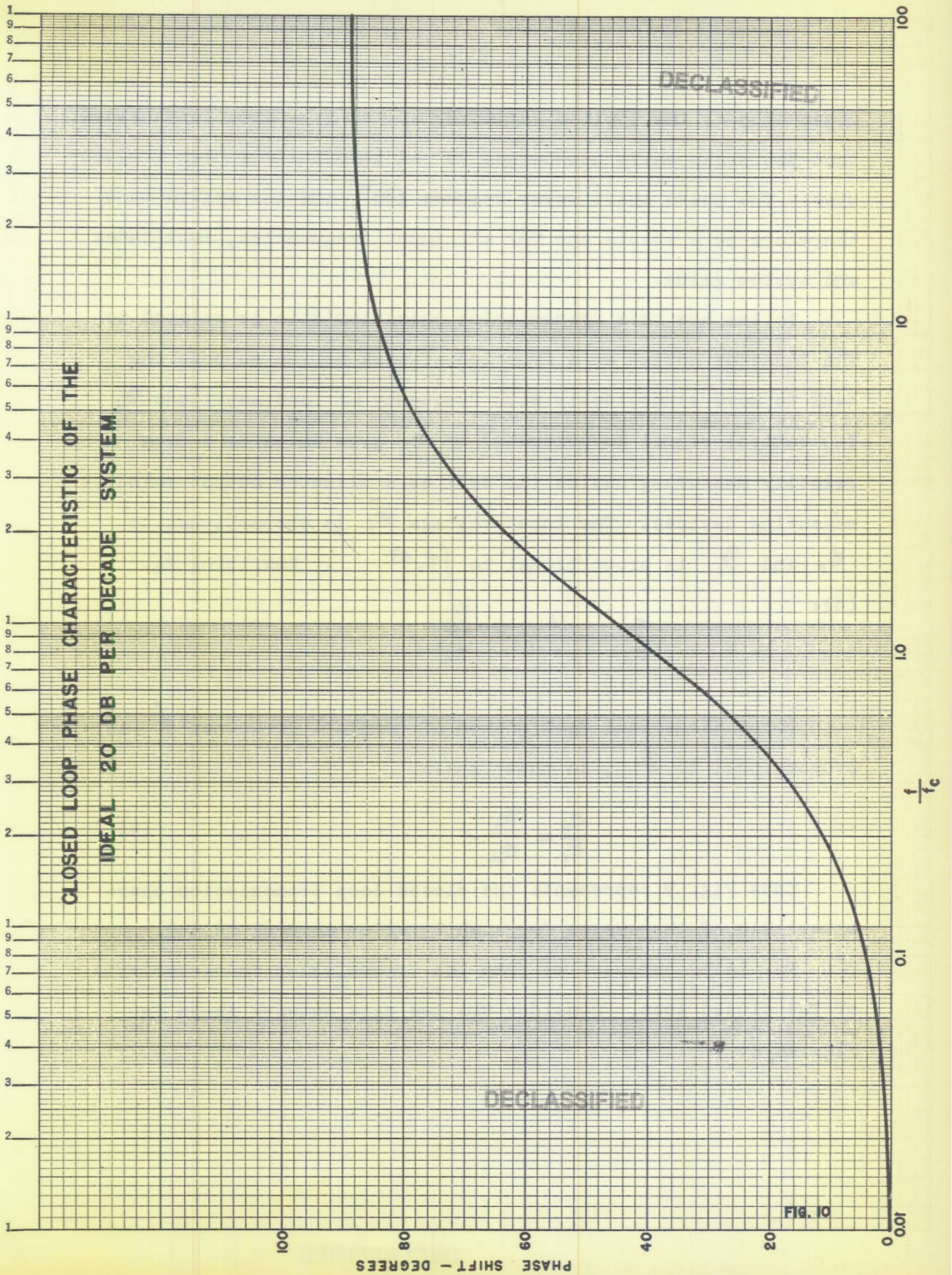
0.1

1.0

10

100

CLOSED LOOP PHASE CHARACTERISTIC OF THE
IDEAL 20 DB PER DECADE SYSTEM.



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FIG. 10

never exceeds the applied amplitude of the gyro and, furthermore, that the phase shift approaches 90° at indefinitely high frequencies. The phase shift never reaches 180° , and the system must therefore be a stable one for all input frequencies, amplitudes and system gains.

To see how this transmission characteristic is related to the Director motion as a function of deck motion suppose the deck to move sinusoidally with frequency ω and amplitude ϕ_d . The control signal is generated by the gyro which is a deck velocity measuring device (as well as a Director output velocity measuring device). The input voltage e_i is proportional to $\dot{\phi}_d$ and e_o is proportional to $\int e_o dt$. Rewriting Eq.

(8):

$$\frac{e_o}{e_i} = \frac{\mu}{1+\mu} = \frac{\dot{\phi}_o}{\dot{\phi}_d}$$

For a sinusoidal deck motion of constant frequency ω is proportional to ϕ , so that finally

$$\frac{e_o}{e_i} = \frac{\phi_o}{\phi_d} \quad (9)$$

Thus Fig. 9 represents the closed loop transmission characteristic of the system for stabilization to deck motion.

For later purposes we find the transmission characteristic of the closed loop. Consider the low pass network shown in Fig. 10 A:

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$$i = \frac{e_i}{R + \frac{1}{pC}}$$

Then

$$e_o = i \frac{1}{pC} = \frac{e_i \left(\frac{1}{pC}\right)}{R + \frac{1}{pC}}$$

or

$$\frac{e_o}{e_i} = \frac{1}{pRC + 1}$$

The product RC is the time constant of the circuit and its reciprocal 1/RC is the angular frequency ω_c of gain crossover (i.e., the frequency of intersection of the sloping part of the characteristic with the unity gain line) or the corner frequency of the network.

Then

$$A_L = \frac{e_o}{e_i} = \frac{\omega_c}{p + \omega_c} \quad (10)$$

This equation is plotted out in Figs. 9 and 10.

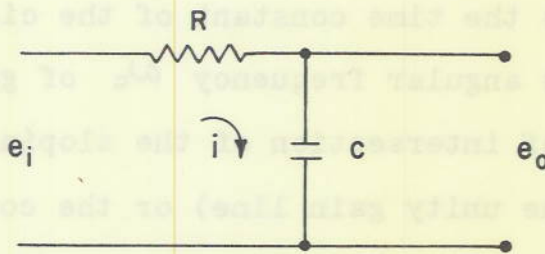
A similar argument shows for a high-pass network:

$$A_H = \frac{p + \omega_c}{\omega_c} \quad (11)$$

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LOW PASS NETWORK

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FIG. 10A

The complex voltage error ϵ is given by

$$\epsilon = e_o - e_i = k(\phi_o - \phi_d) = - \frac{k\phi_d}{1+\mu}$$

from which the complex angular error ϵ_ϕ is

$$\epsilon_\phi = \frac{\phi_d}{1+\mu} \quad (12)$$

To obtain μ for the overall idealized system it is only necessary to take the product of the separate μ characteristics. If the gain crossover frequencies of the Control Device, the Power Drive, and the Rate Gyro are, respectively, $\omega_{M'}$, ω_H , and ω_G , the error expression becomes

$$\epsilon_\phi = \frac{\phi_d}{1 + \left(\frac{\omega_{M'}}{p}\right)\left(\frac{\omega_H}{p}\right)\left(\frac{p}{\omega_G}\right)}$$

If in this particular system ω_H is made approximately to equal ω_G , then

$$\epsilon_\phi = \frac{\phi_d}{1 + \frac{\omega_{M'}}{p}}$$

For angular frequencies of deck motion much less than $\omega_{M'}$,

$$\left| \frac{\omega_{M'}}{p} \right| \gg 1, \text{ and}$$

$$\epsilon_s = \frac{p\theta_d}{\omega_{M'}} = \frac{1}{\omega_{M'}} \frac{d\theta_d}{dt} = \frac{\dot{\theta}_d}{\omega_{M'}} \quad (13)$$

If the maximum roll amplitude and frequency to be expected are known and the maximum allowable stabilization error has been established the minimum acceptable value of $\omega_{M'}$ can be determined. Substituting the requirements in the original Objectives (Paragraph 13):

$$0.12 \text{ degree error} = \frac{17.5 \text{ }^\circ/\text{sec.}}{2\pi f}$$

or $f = 23 \text{ cps.}$

a result agreeing with that obtained by other means (Fig. 21).

In a manner similar to that used previously the Control Device error can be determined for deck motion, i.e., for stabilization against roll.

We saw that the error between the deck motion and Director motion is

$$\epsilon = \frac{\dot{\theta}_d}{\omega_{M'}}$$

The Control Device error, then, is the derivative of this error, since one must go backward through the Power Drive, which is an integrator as used in the system; then

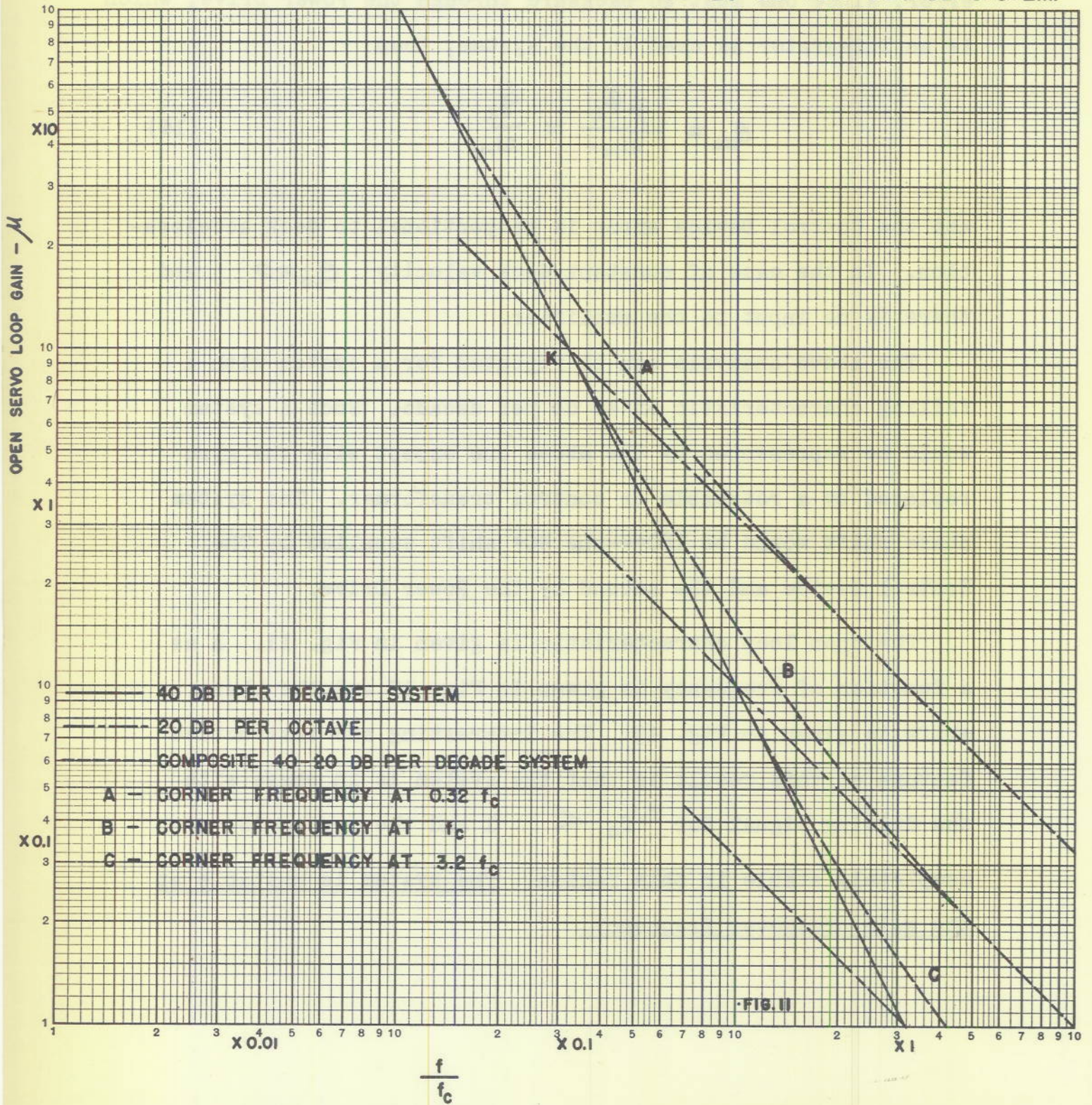
$$E_{sc} = \frac{p \dot{\theta}_d}{\omega_{M'}} = \frac{\ddot{\theta}_d}{\omega_{M'}} \quad (14)$$

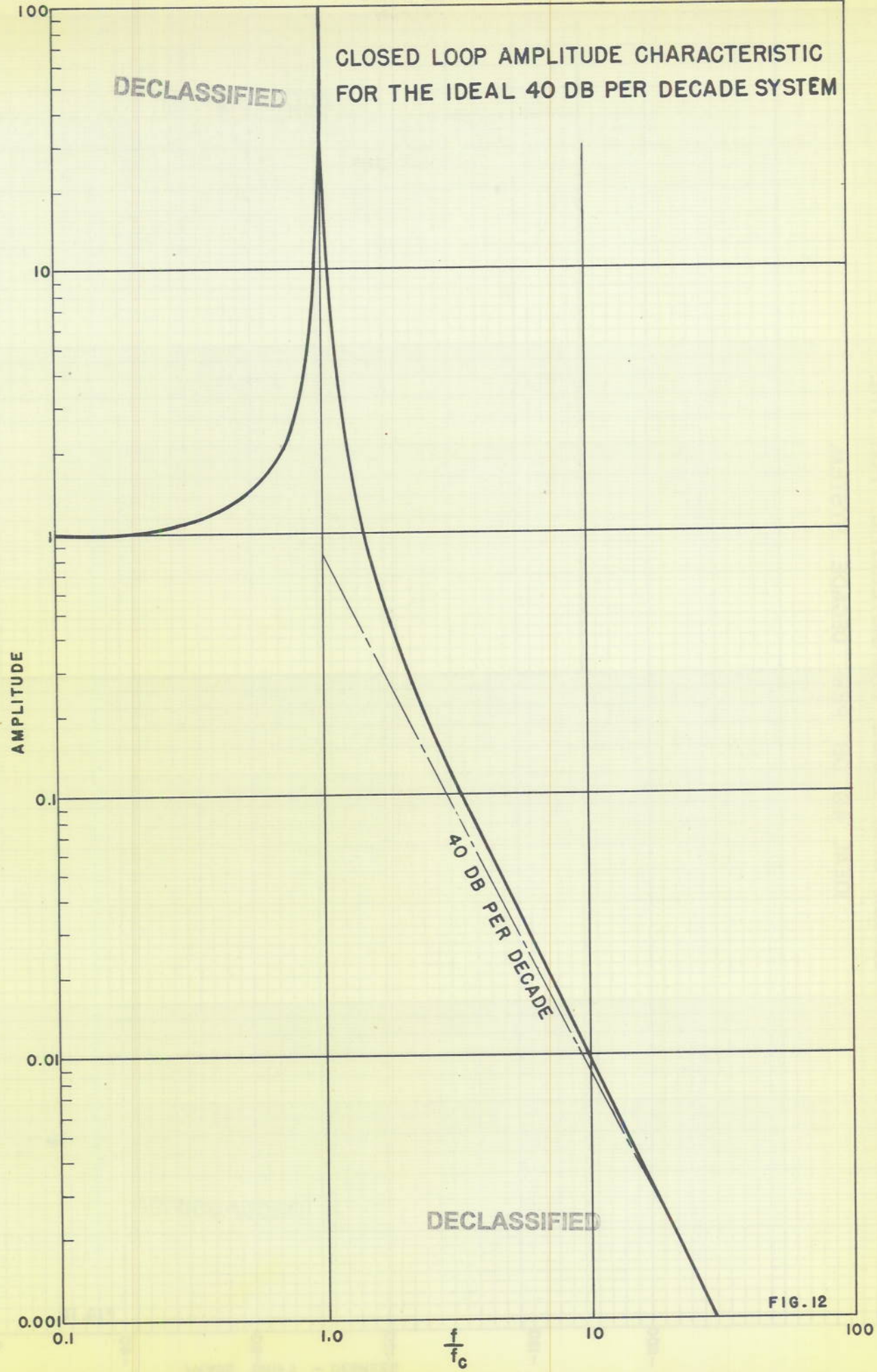
and the Control Device error is proportional to deck acceleration. In the case of constant deck velocity $E_{sc} = 0$ and there is no input to the amplifier.

The above analysis can be repeated for a system with a falling characteristic of 40 db per decade. Such a system would be represented by the above one except with the gyro replaced by a rotatable or control transformer. The system phase shift would be 180°--one 90° shift supplied by The Control Device and the second by the Power Drive.

The open loop characteristic is given in Fig. 11. A as a function of frequency is given in Fig. 12 and the phase shift is given in Fig. 13. The interesting and instructive feature of this result is that the system is in phase with the driving signal for $f/f_c < 1$ and the system is completely stable in this region. The system is unstable at the gain crossover frequency.

OPEN LOOP GAIN CHARACTERISTICS FOR THE IDEAL 40 DB PER DECADE SYSTEM AND FOR THE IDEAL COMPOSITE 40-20 DB PER DECADE SYSTEM.





CLOSED LOOP PHASE CHARACTERISTIC FOR THE
IDEAL 40 DB PER DECADE SYSTEM.

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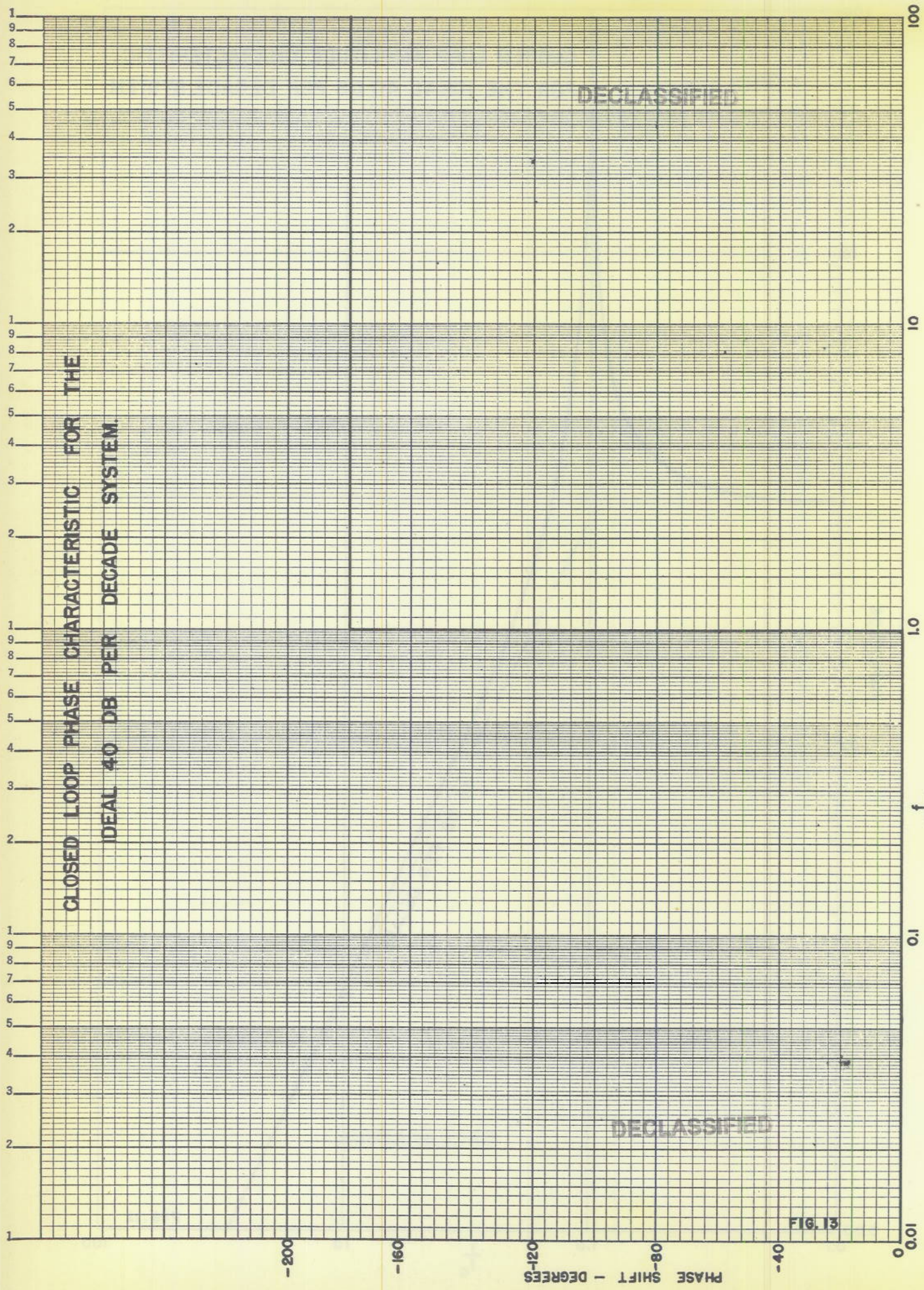


FIG. 13

This gives a clue as to how the 40 db per decade system may be modified or equalized to produce a stable system. If at some point such as K in Fig. 11 the slope of the line were changed so that the slope at gain crossover is 20 db per decade the phase reversal at gain crossover will be replaced by a 90° phase shift--a condition which we have seen is a stable one. As a matter of fact it is not necessary that the phase shift be reduced as much as 90° at gain crossover frequency to produce a stable system. This may be seen by calculating the closed loop characteristics of the ideal 40-20 db per decade system with the corner frequency placed at various positions with respect to the gain crossover frequency of the 40 db per decade system. Fig. 14 gives the open loop phase relationship between input and output as a function of frequency for three positions of the corner frequency as indicated in Fig. 11. The closed loop amplitude and phase characteristic is calculated from Eq. (8), the following being a sample solution:

Calculate the amplitude and phase at $f/f_c = 1$ for curve A, Fig. 11. From this curve $\mu = 3.4$ and from Fig. 14 the open loop phase shift $\psi = 108^\circ$. Then

$$A = \frac{\mu \angle \psi}{1 + \mu \angle \psi} = \frac{3.4 \angle -108^\circ}{1 + 3.4 \angle -108^\circ} = \frac{3.4 \angle -108^\circ}{3.26 \angle -91^\circ} = 1.04 \angle -17^\circ$$

The amplitude and phase characteristics so calculated are given for the three cases in Fig. 15 and Fig. 16, respectively.

The system is stable for all three cases, but with resonance peaks at which the amplitude of the system exceeds the input amplitude.

OPEN LOOP PHASE CHARACTERISTIC OF THE IDEAL
COMPOSITE 40-20 DB PER DECADE SYSTEM.

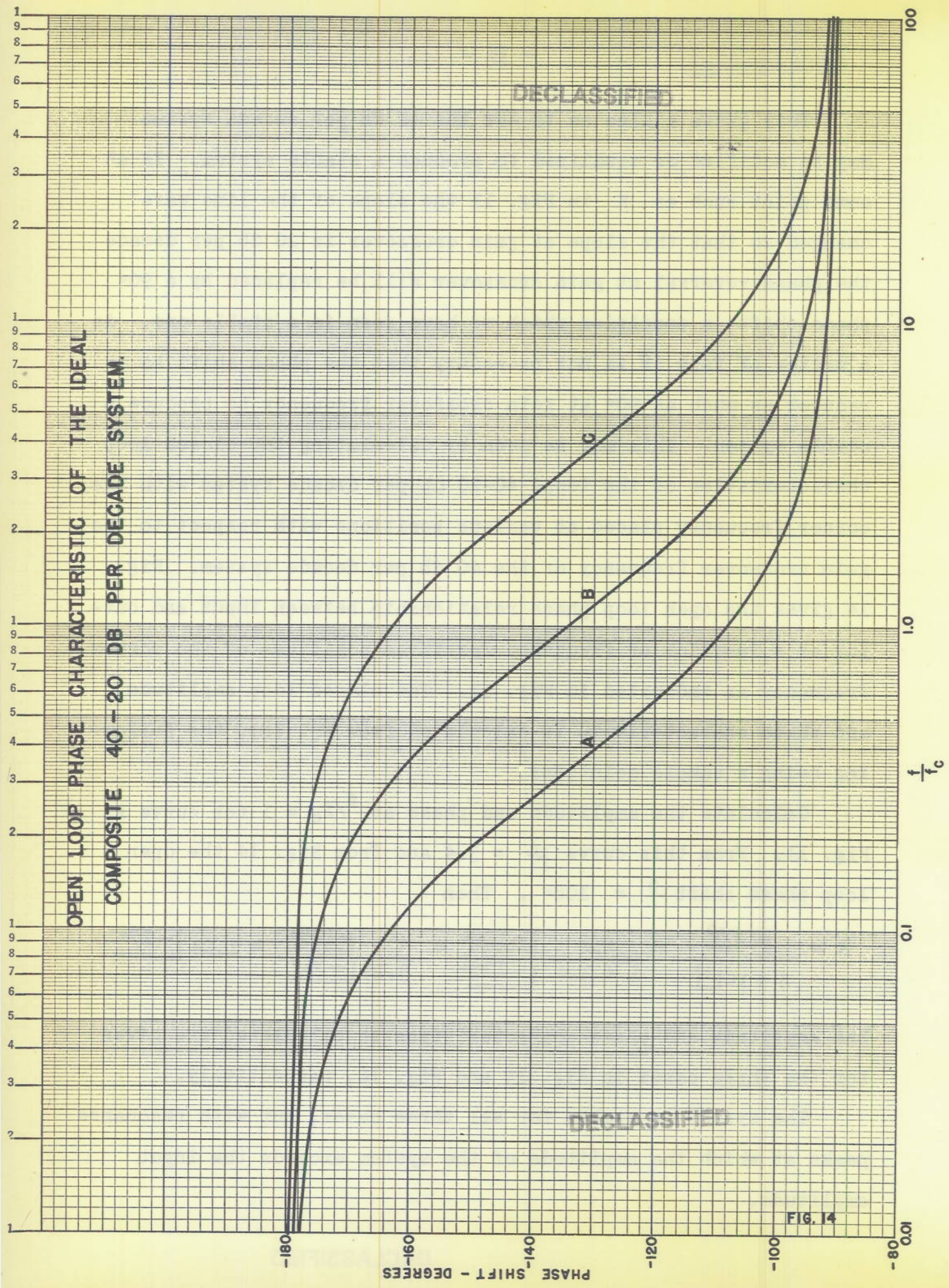
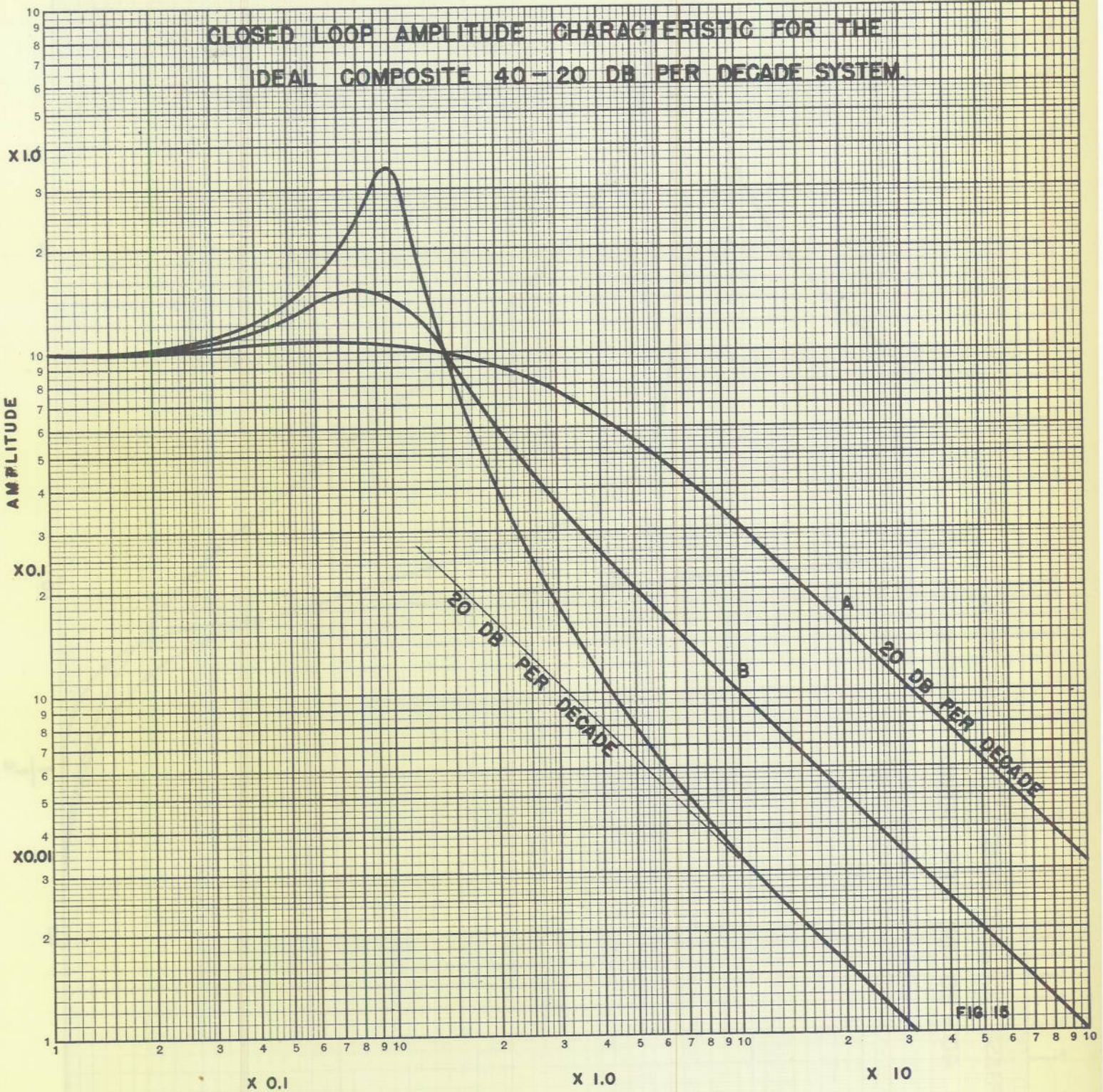


FIG. 14

CLOSED LOOP AMPLITUDE CHARACTERISTIC FOR THE
IDEAL COMPOSITE 40-20 DB PER DECADE SYSTEM.



$$\frac{f}{f_c}$$

OPEN LOOP PHASE CHARACTERISTIC FOR THE IDEAL
COMPOSITE 40 - 20 DB PER DECADE SYSTEM.

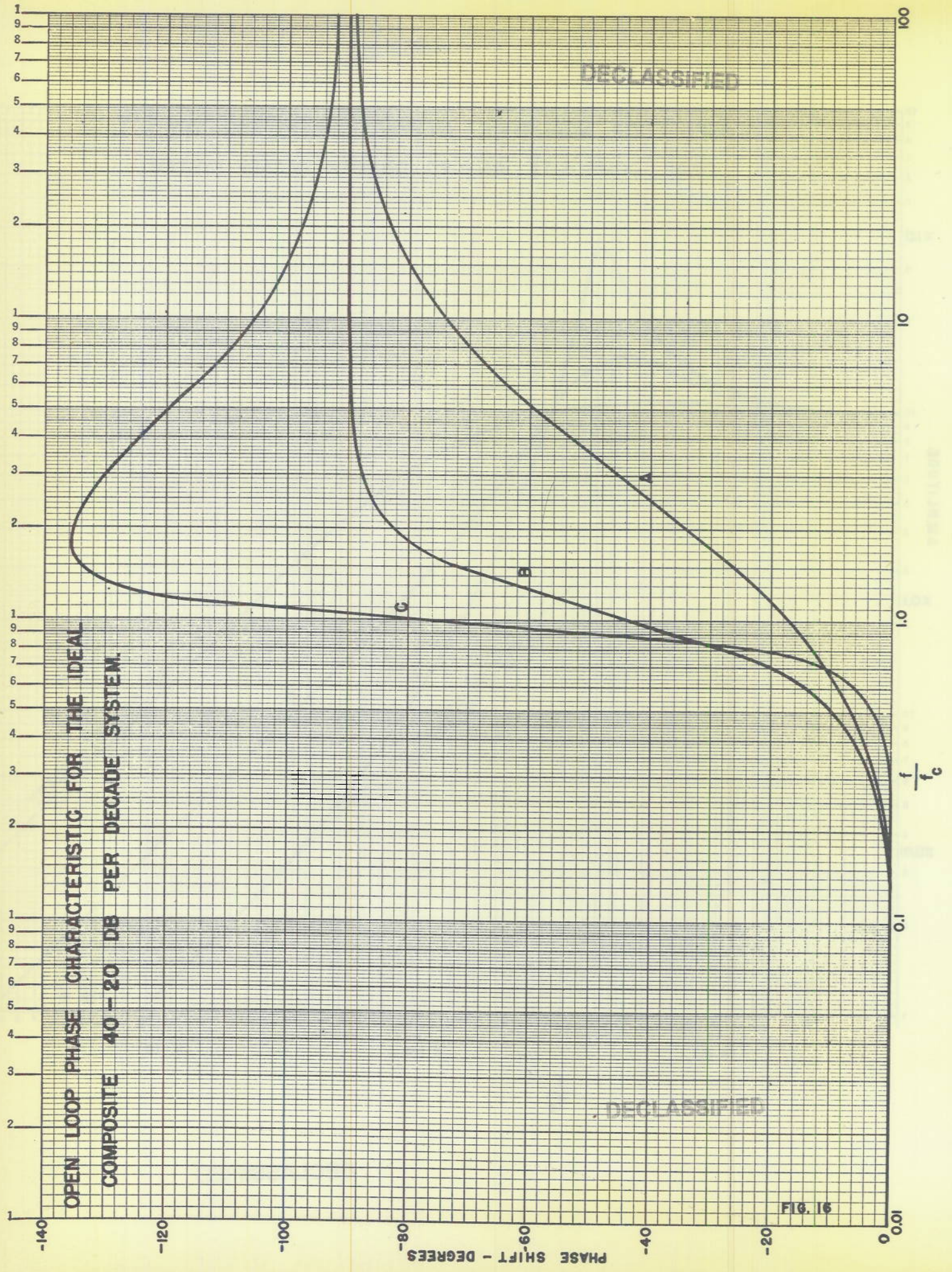


FIG. 16

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The system used in the Mark 61 Director is, as we have seen, a 20 db per decade system, at least at moderate frequencies---not so low that the gyro signal will be obscured by noise or so high that the Control Device or Power Unit will not follow the actuating signal. At a sufficiently high frequency, then, the open loop characteristic will change from 20 db per decade to 40 db per decade. We must inquire into the effects on the stability of the system. The open loop characteristic in this case is shown in Fig. 17, where again three cases are assumed, one with the corner frequency at the 20 db per decade gain crossover frequency, one at $0.1 f_c$ and one at $10 f_c$. The open loop phase characteristic is shown in Fig. 18, the closed loop amplitude characteristic in Fig. 19, and the closed loop phase characteristic in Fig. 20. Thus if the open loop gain crossover frequency is not too high the system will be a stable one. This factor limits the loop gain which may be used and hence the overall performance of the servo system. Any method of extending the 20 db per decade region would allow higher gain with stability and therefore a "tighter" servo loop.

It is of interest to inquire what the gain crossover frequency of an ideal system must be if it is to satisfy the requirements for stabilization of the Director as listed in the Objectives. A 2-mil amplitude residual roll with a 25° amplitude deck roll implies an open loop servo gain μ of approximately 220. The gain μ slopes off at 20 db per decade from 0.111 cps, and as shown in Fig. 21 reaches gain crossover at approximately 24 cps. The objective in the the design of a Director is to approach this ideal

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OPEN LOOP GAIN CHARACTERISTIC FOR THE IDEAL
COMPOSITE 20 - 40 DB PER DECADE SYSTEM.

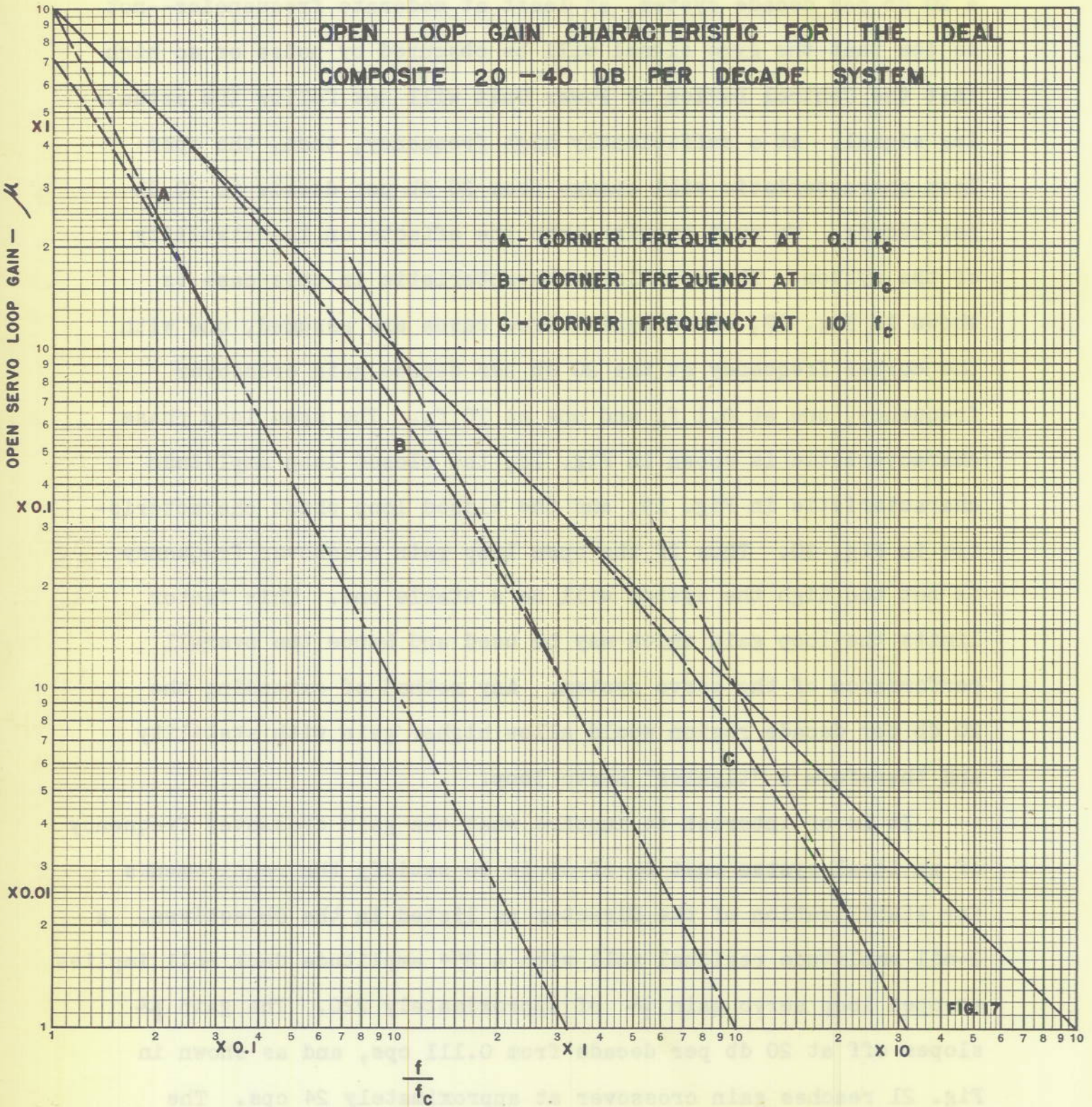
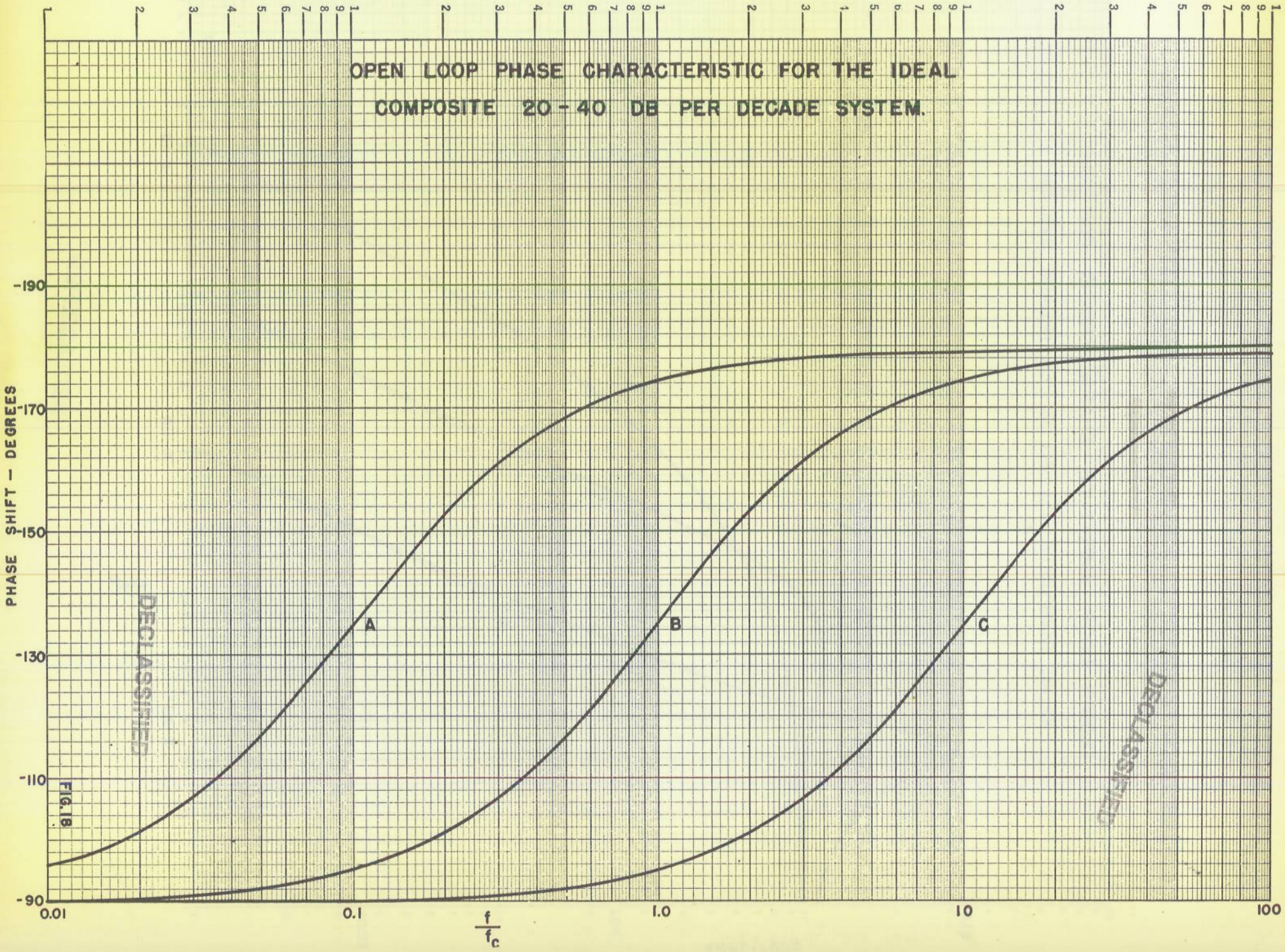


FIG. 17

OPEN LOOP PHASE CHARACTERISTIC FOR THE IDEAL
COMPOSITE 20 - 40 DB PER DECADE SYSTEM.



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CLOSED LOOP AMPLITUDE CHARACTERISTIC FOR THE
IDEAL COMPOSITE 20-40 DB PER DECADE SYSTEM.

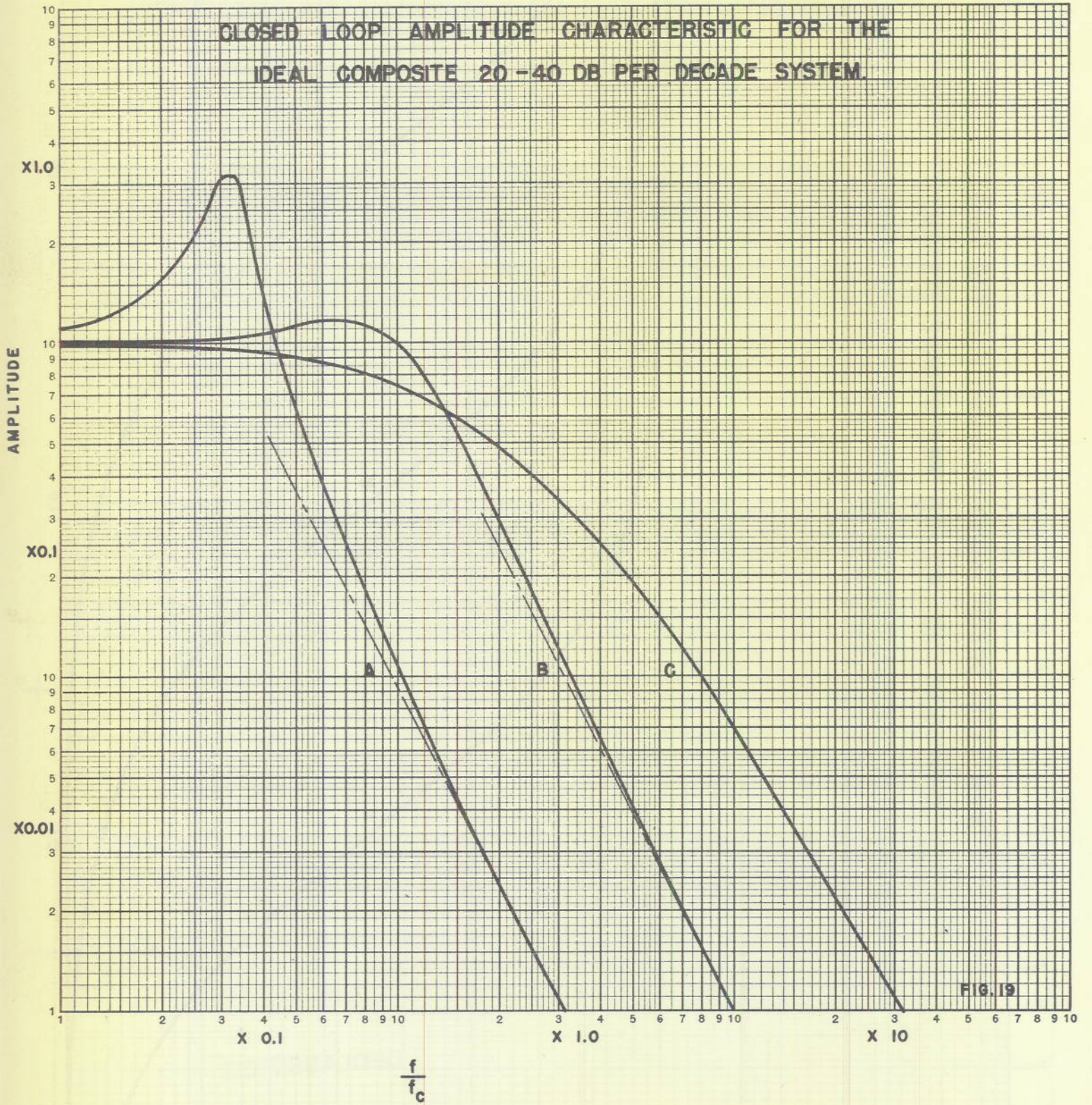
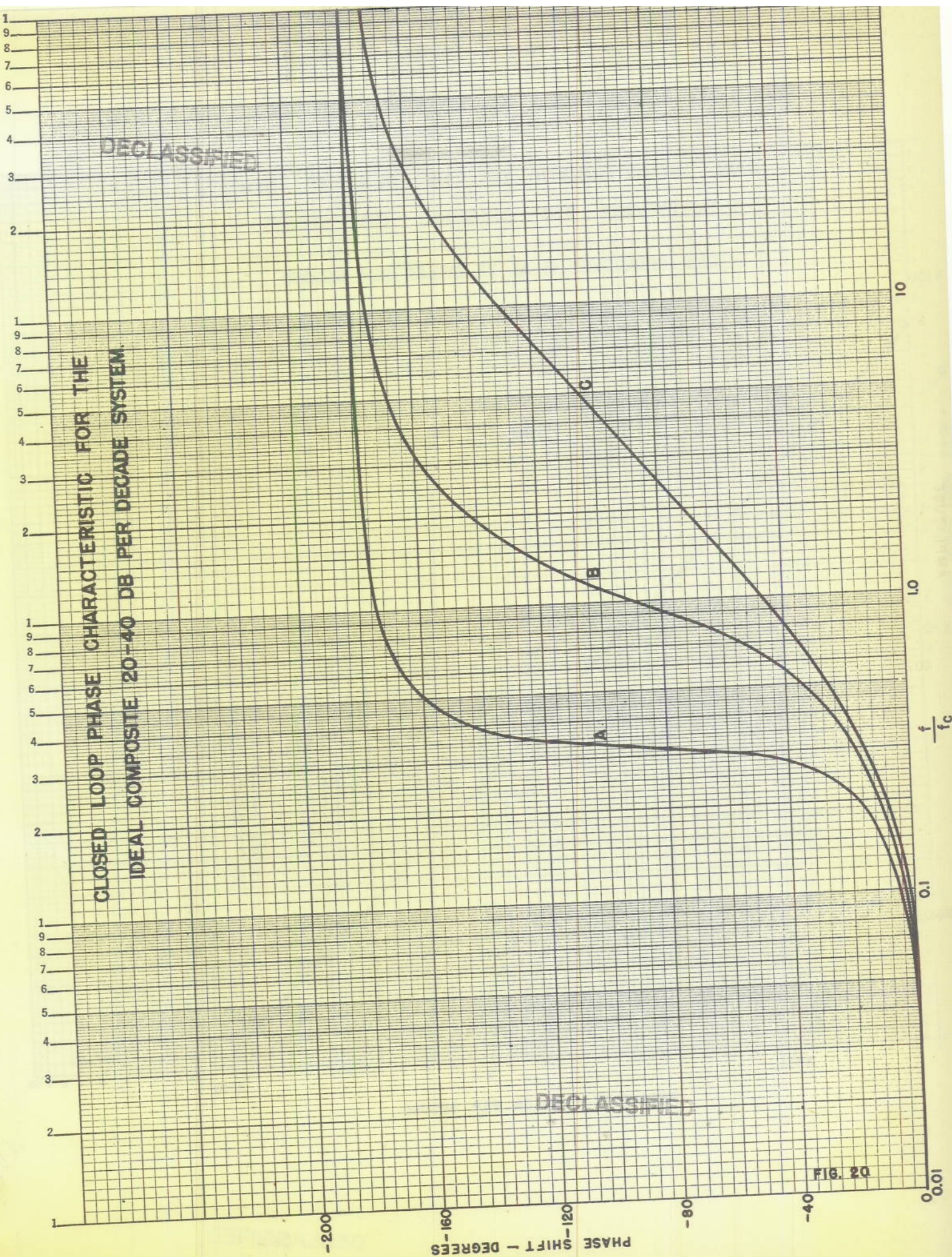


FIG. 19

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CLOSED LOOP PHASE CHARACTERISTIC FOR THE
IDEAL COMPOSITE 20-40 DB PER DECADE SYSTEM.



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FIG. 20

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GAIN CHARACTERISTIC OF THE PERFECT SYSTEM

SATISFYING THE ORIGINAL OBJECTIVES.

GAIN Crossover IS AT 24 CYCLES PER SECOND.

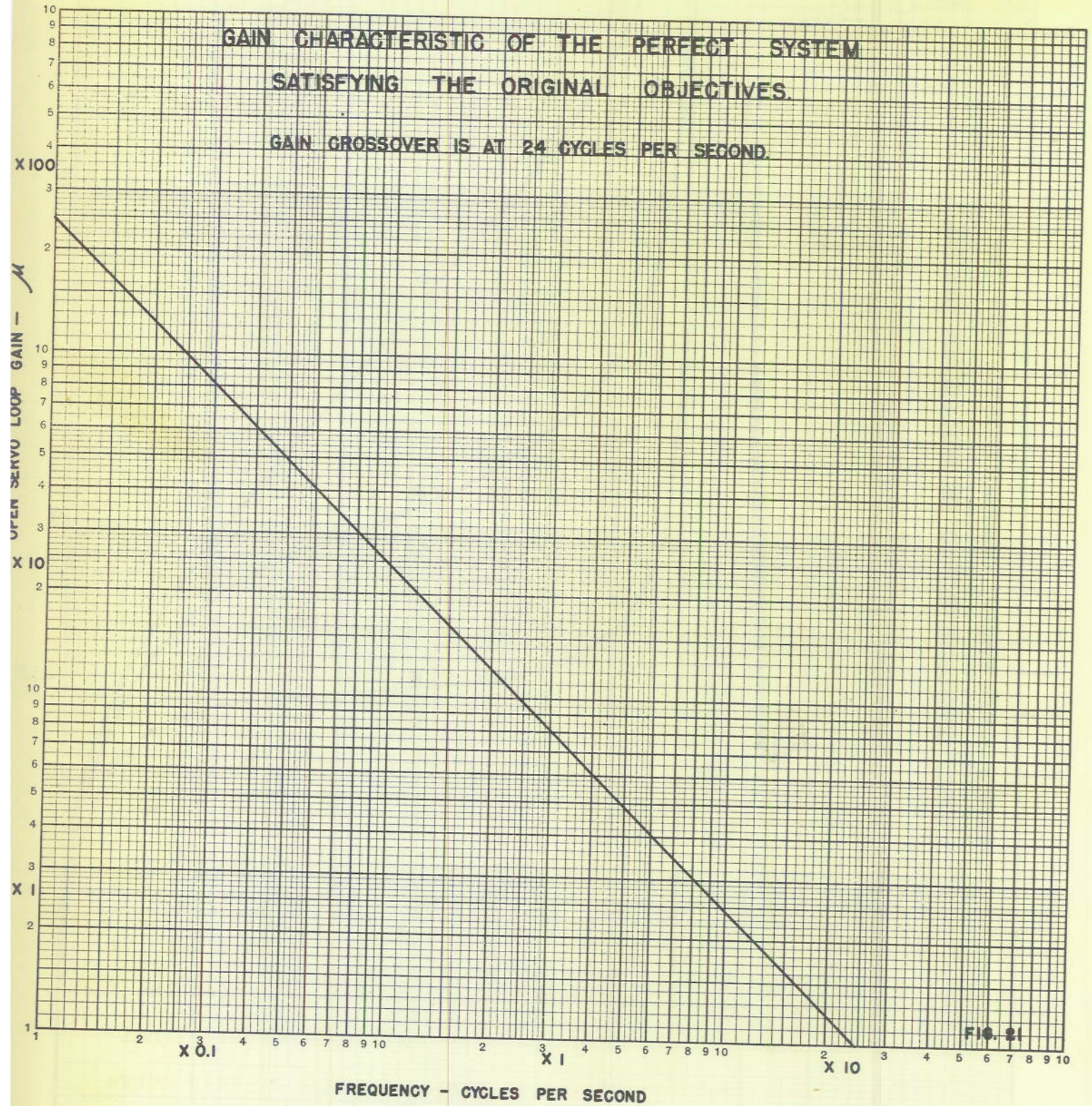


FIG. 21

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close enough to give the performance desired, together with stability of the system.

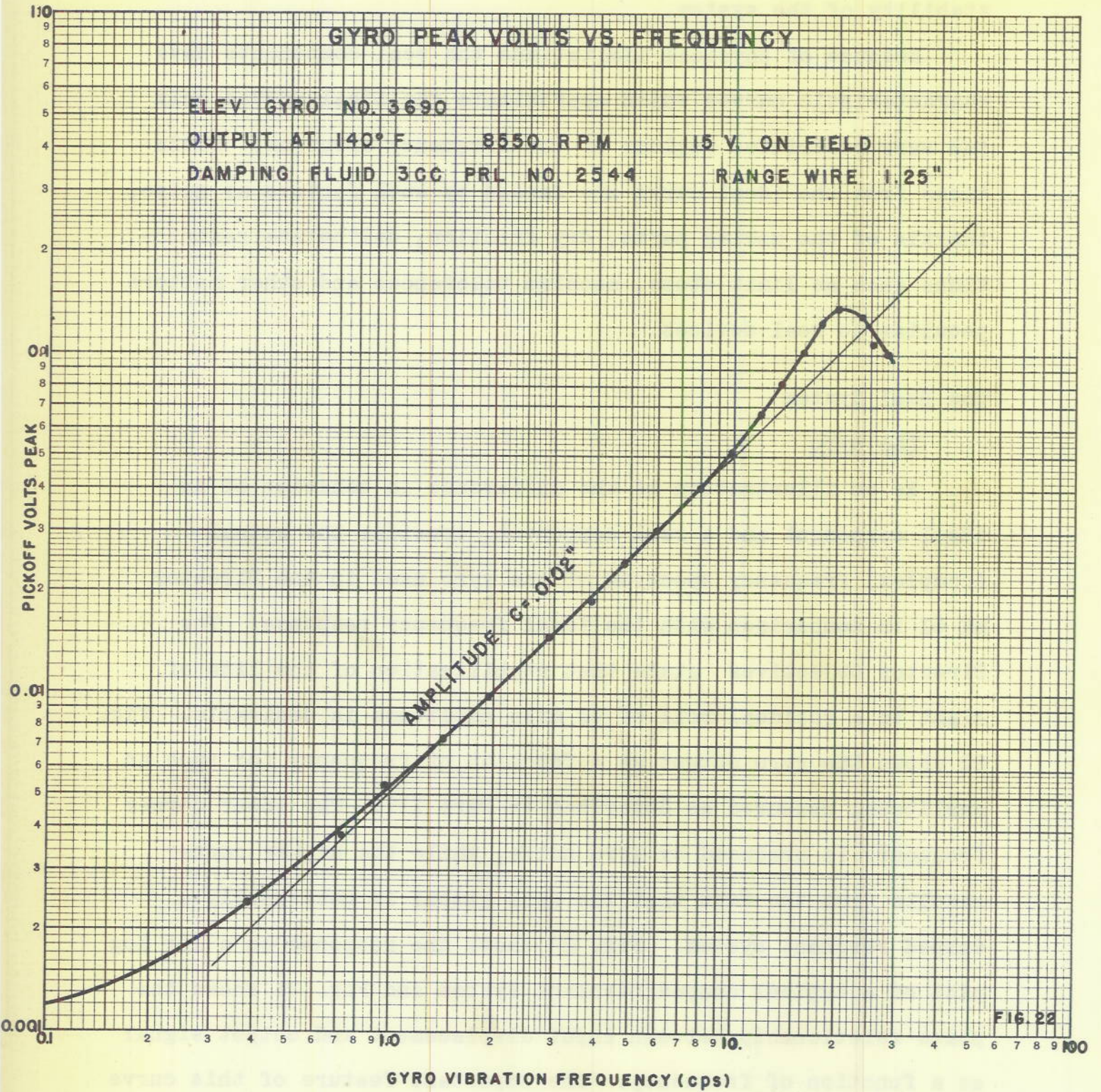
Because of physical limitations the real components have characteristic curves which approximate the ideal curves only for very restricted regions of the frequency spectrum. Deviations from the ideal curve are caused by such factors as noise, inertia of the moving parts, dry friction, deliberate restrictions such as limit stops, machine tolerances and other matters peculiar to real devices.

The Real System

The Gyro

As an illustration of the difference in behavior of an ideal component and a real component, consider the actual (complex) frequency spectrum of the gyro used in the Director MK 61 in comparison with the ideal frequency response. The Director Objectives state that stabilization of the line of sight to a residual roll of ± 2 mils amplitude is desirable. Fig. 22 shows the gyro output as a function of frequency for such an amplitude, measured as described in Part III. The lower corner frequency is produced by gyro noise, while the higher corner results from the fact that the gyro gimbal is necessarily a damped resonant system. Fig. 23 shows the response on a log log plot of a typical damped resonant system and Fig. 24 shows the phase relationship between input displacement and output signal as a function of frequency. The important feature of this curve is that it departs practically linearly with frequency from the

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RESPONSE OF A RESONANT SYSTEM
TO SINUSOIDAL EXCITATION.

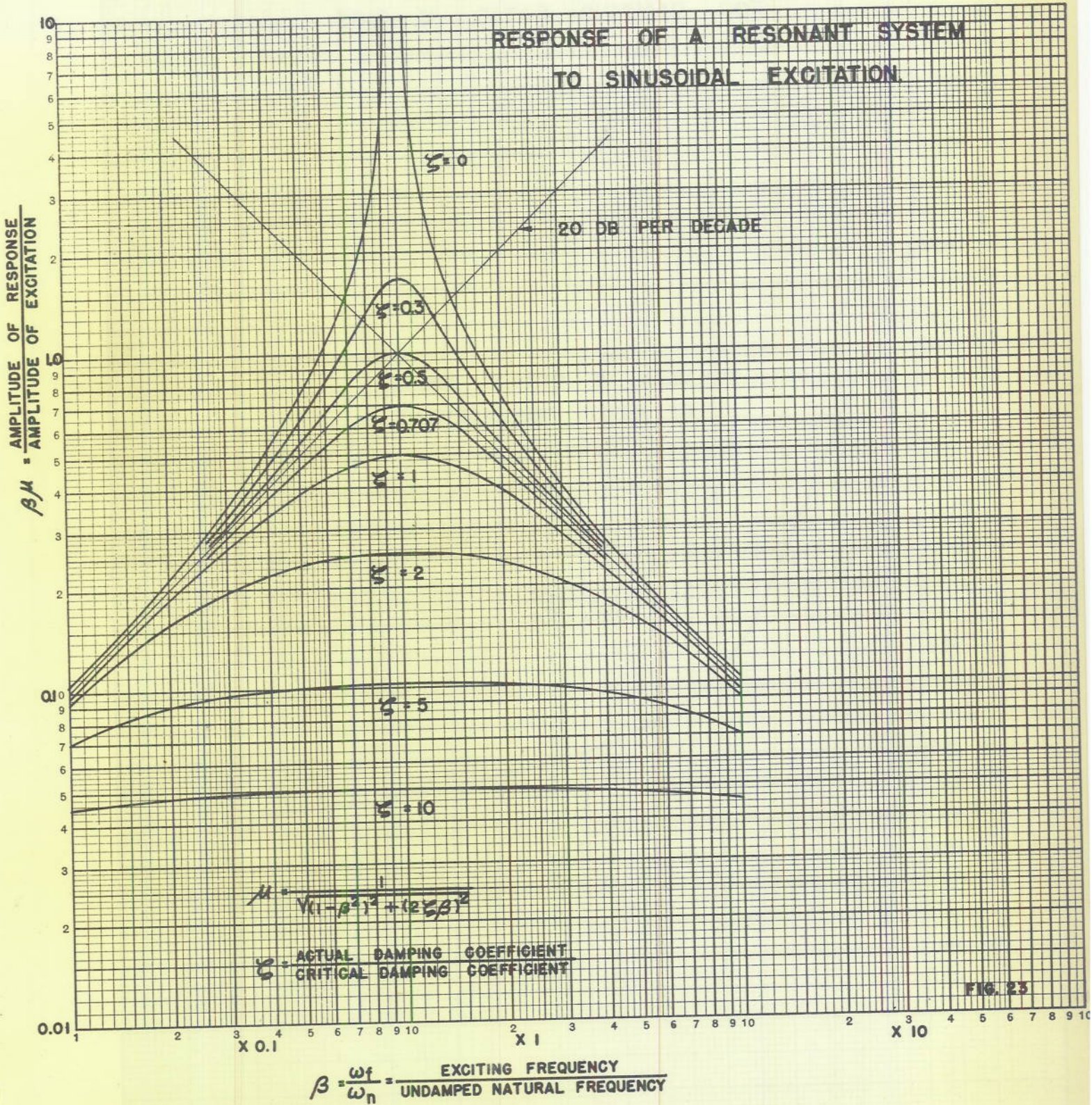
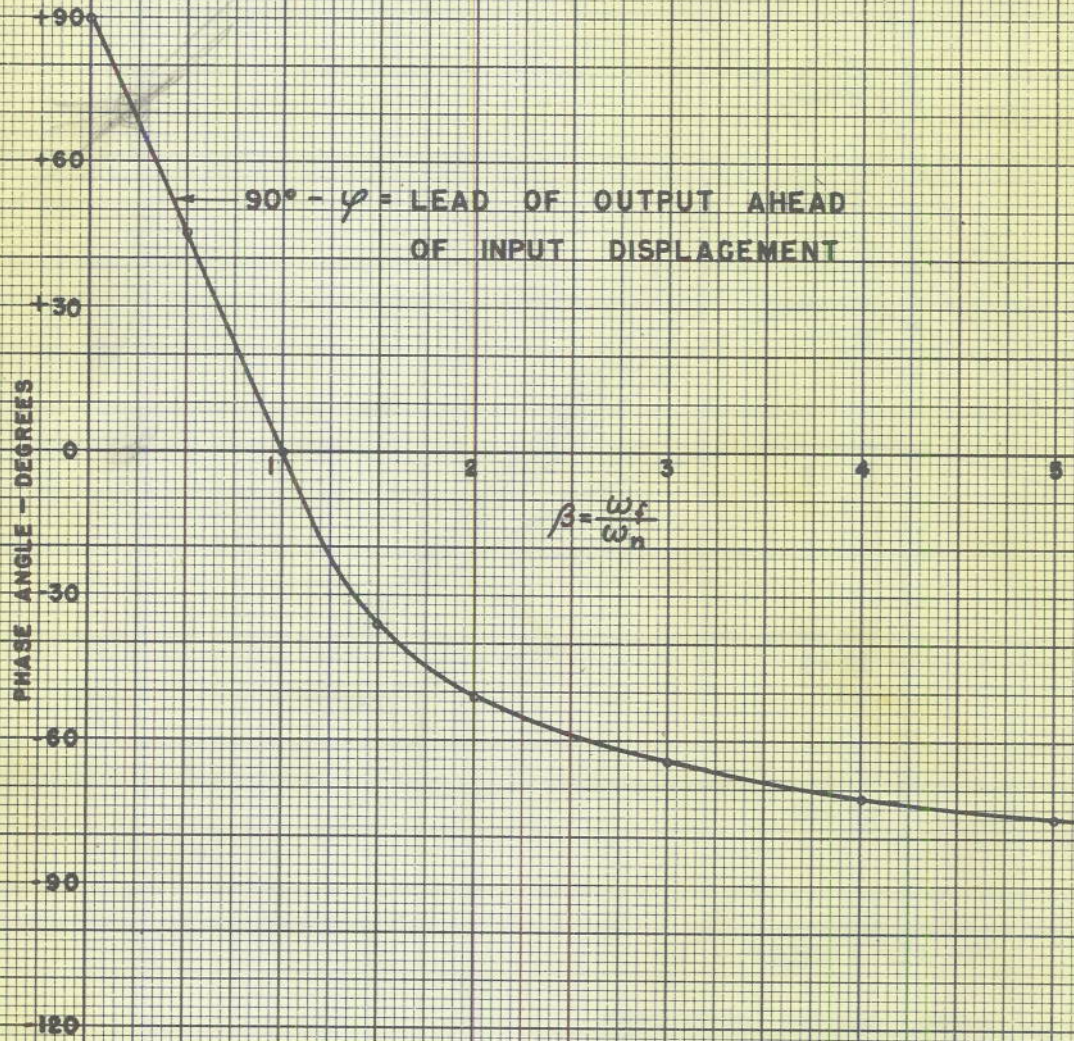


FIG. 23

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PHASE ANGLE OF GYRO OUTPUT MOTION
V.S. INPUT FREQUENCY
FOR DAMPING RATIO $\zeta = 0.65$



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FIG. 24

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ideal $+90^\circ$ phase shift line. Therefore, to keep the phase shift near the desirable $+90^\circ$ throughout the working frequency range, it is essential that the high frequency corner of the gyro be far removed from the open servo loop gain crossover frequency of the system--much farther than one would assume necessary from the amplitude characteristic alone. The existence of a high frequency corner is a feature common to all components.

The Control Device

The control device is composed of an amplifier with equalizing network, a stroke motor with necessary gearing and dither arrangement to control the Power Drive and a feedback generator driven by the stroke motor, as shown schematically in Fig. 25. The amplifier is merely a power amplifying device whose gain and phase properties should be independent of frequency, over the range of side band frequencies to be transmitted by the system. Care has to be taken to realize these conditions, as described in some detail elsewhere in this report.

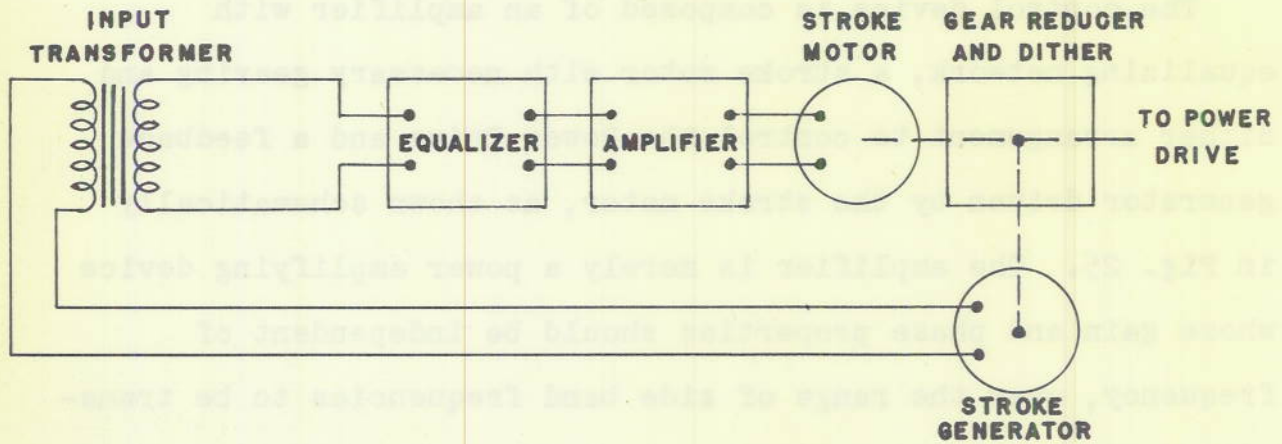
After careful experimental examination it becomes apparent that the stroke motor is the element most seriously limiting the performance of the system. This may be seen when the characteristic curve (Fig. 26) is compared to the ideal characteristic as in Fig. 7. The curve of the real device as determined by experiment, drops off at 20 db per decade to a corner frequency of 5.5 cps. and then decreases at the rate of 40 db per decade.* This of course involves a change of phase shift from -90° to -180° in the limits.

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* For a fuller description of the stroke motor see Part III.

**SCHEMATIC BLOCK DIAGRAM OF CONTROL DEVICE
USED TO STROKE THE HYDRAULIC POWER DRIVE SYSTEM**

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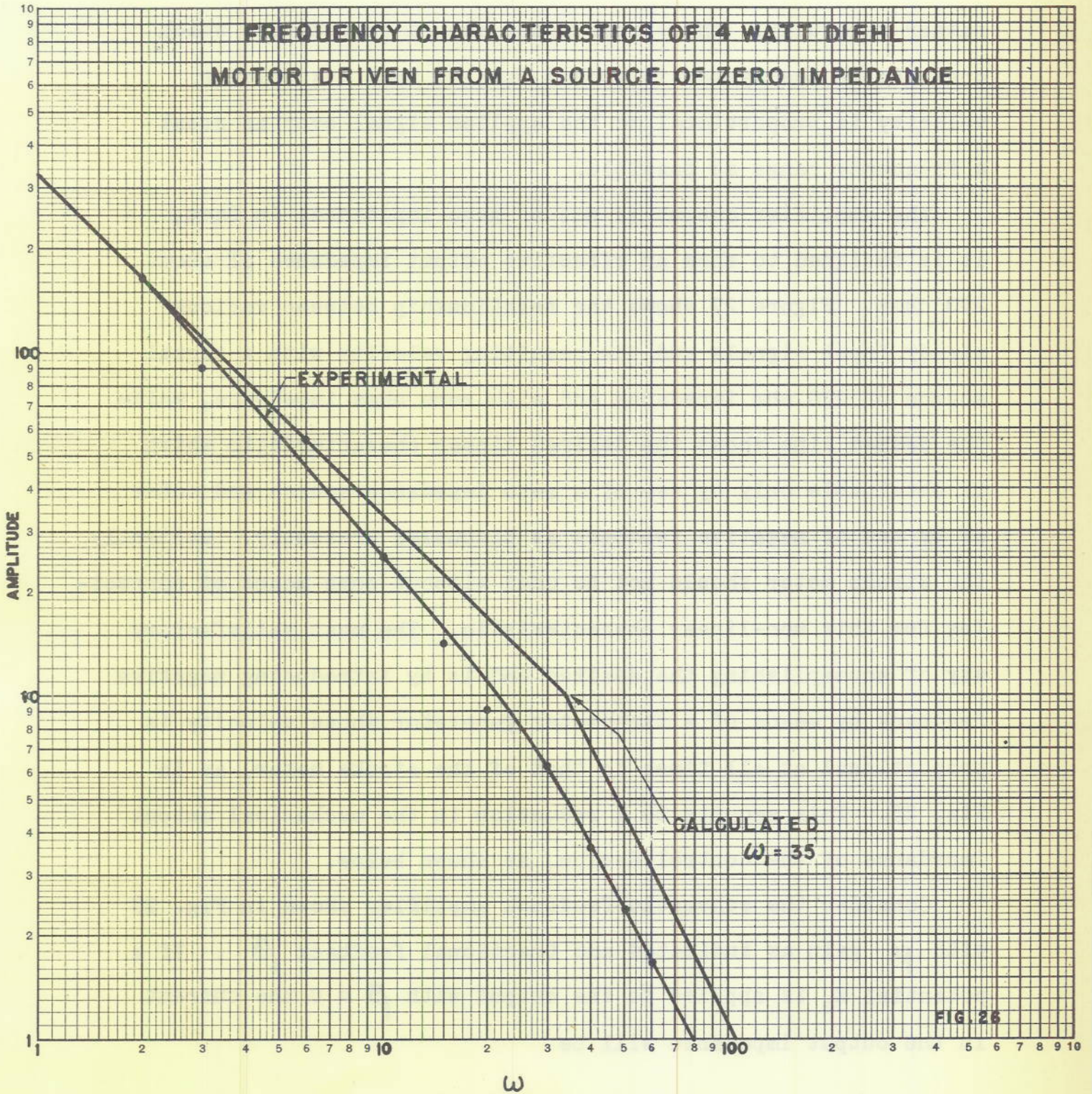


FIG. 26

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The properties of the stroke motor and its role in the system are of considerable interest, so we shall examine them rather carefully. The stroke motor should be a device which operates in the system in such a fashion that its angular velocity is proportional to the applied signal over as great a frequency range as possible.

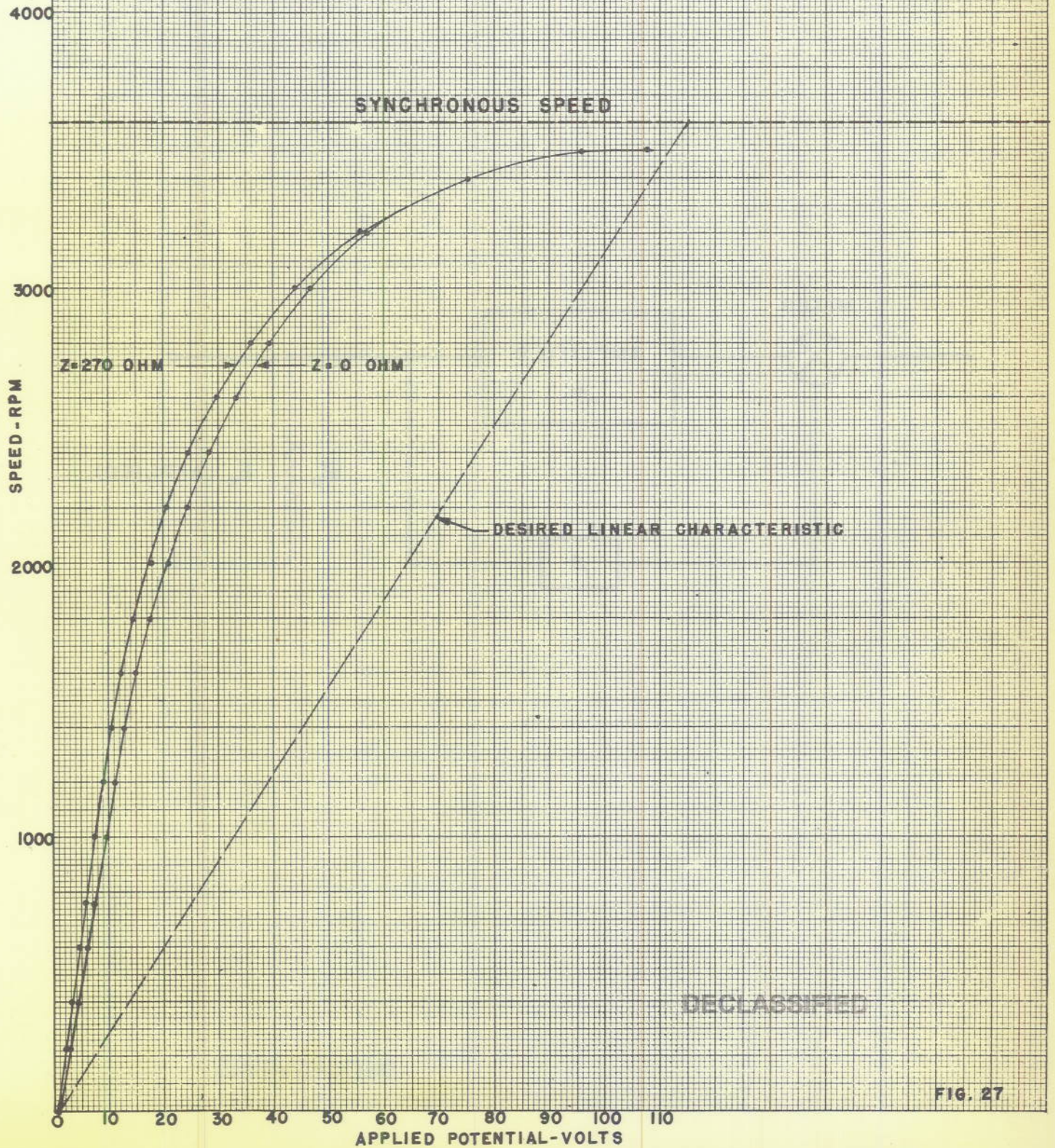
The amplifier output is not of zero impedance; in fact, it is designed to show an effective output impedance of about 270 ohms. Figure 27 shows the relationship between various steady input signals and the resulting velocity with a signal source of 270 ohm impedance and with zero ohms impedance, while the dashed line shows the desired linear characteristic which is obtainable only by use of a zero impedance source and motor or by use of negative feedback as discussed presently. Evidently the stroke motor should not be used without some means of correcting for this non-linear characteristic. The most satisfactory way of accomplishing the desired end is by introducing negative feedback by means of a tachometer generator whose velocity is proportional at all times to that of the stroke motor, as in Fig. 25. This amounts to a reduction in the mechanical output impedance of the control device, as shown below.

Consider the schematic feedback amplifier shown in Fig. 28 with μ gain as indicated and fractional feedback β . If a potential E_o is applied to the output with $\beta = 0$ the current in the output impedance will be

$$I_o = \frac{E_o}{Z_o}$$

SPEED-VOLTAGE CHARACTERISTIC FOR DIEHL 4 WATT MOTOR
WITH 270 OHM IMPEDANCE SOURCE AND ZERO IMPEDANCE SOURCE

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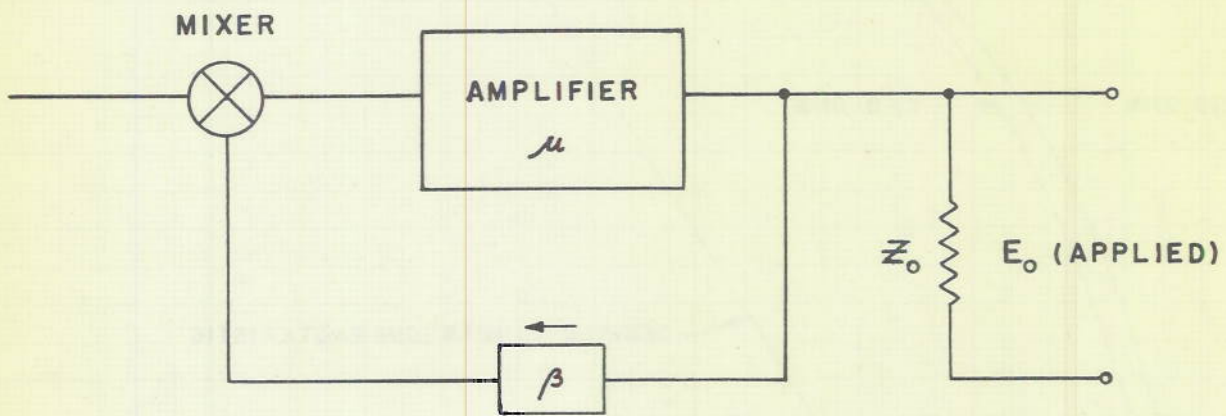


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FIG. 27

FEEDBACK AMPLIFIER

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If, now, the β path is completed the new current I' in the output impedance is:

$$I' = I_0 - \mu\beta I_0 = \frac{E_0}{Z_0} (1 - \mu\beta)$$

The new impedance is, then

$$Z' = \frac{Z_0}{1 - \mu\beta} \quad (15)$$

and, since β is a negative quantity, Z' is less than Z_0 . A decrease in electrical impedance means a decrease in the effective mechanical impedance of the motor which is being driven by the amplifier. The reduction in impedance improves the load regulation of the motor, thereby reducing the effects of temperature changes and changes of friction with time upon the performance of the stroke control system.

The effectiveness in reducing the impedance by feedback means can be seen by considering the Control Device used in the MK 61. The μ gain is approximately 5500 and the feedback factor about 0.04. The impedance Z_0 of motor and output transformer is 960 ohms.

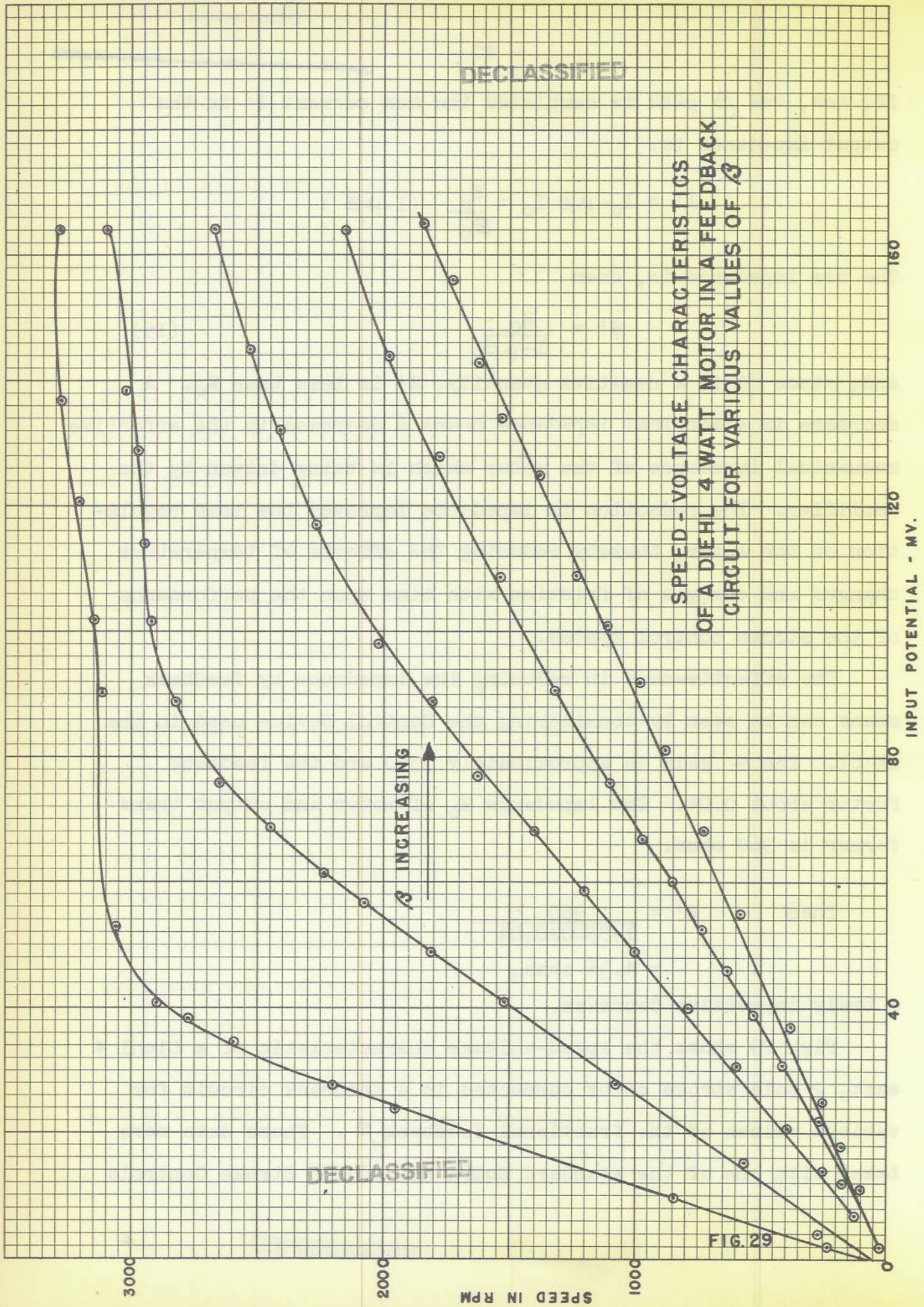
$$\begin{aligned} \text{Then } Z' &= \frac{960}{1 + 5500 \times 0.04} \\ &= 4.36 \text{ ohms,} \end{aligned}$$

a truly impressive decrease.

Fig. 29 shows the speed-voltage characteristic of a Diehl 4 watt, 2 pole stroke motor connected in a feedback circuit for various values of the fractional feedback β . These data were taken with one of the standard BuOrd No. 903255 Stroke Controls

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SPEED - VOLTAGE CHARACTERISTICS
OF A DIEHL 4 WATT MOTOR IN A FEEDBACK
CIRCUIT FOR VARIOUS VALUES OF β



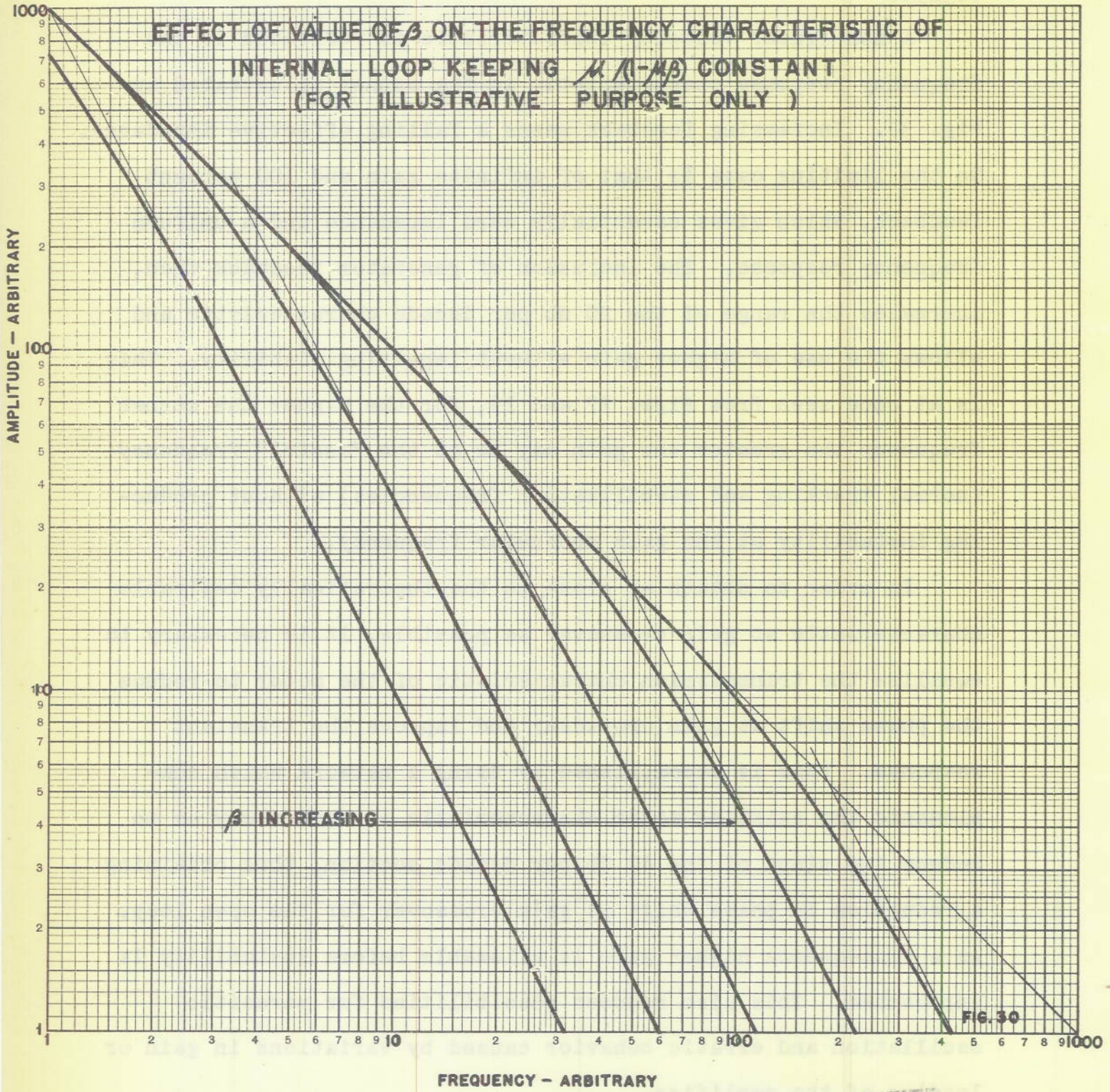
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FIG. 29

as used in the Director and the Tracking Amplifier BuOrd No. 903259.

A non-linear velocity characteristic is reflected in the frequency response characteristic in the manner illustrated in Fig. 30. Increasing feedback means a falling effective impedance. So the limiting case is that of infinite gain and 100 percent feedback, which gives essentially zero impedance and a uniform frequency response. The inclusion of generator feedback then, increases the range of the 20 db per decade characteristic and allows the use of higher gain without impairing stability. This is at once seen from Figs. 17 and 19, for the higher the corner frequency the greater the gain may be at the "useful" frequency (normal tracking and stabilization frequencies) without producing instability at the gain crossover frequency.

In order to obtain as close to the theoretically desirable characteristic at gain crossover as possible, it is necessary to equalize the transmission characteristic of the motor to reduce the phase shift at gain crossover and improve the transient response. This is accomplished by using a network which complements the existing motor characteristic in such a way as to reduce the slope of the 40 db per decade section, thus obtaining a reduction in phase shift at gain crossover for the open loop. As a consequence higher gain is allowable before instability is approached. This also reduces possibilities for parasitic oscillation and erratic behavior caused by variations in gain or loading of the amplifier.



Such a network is the Bridged Parallel T Pad (Fig. 31) described in more detail elsewhere in this report. Fig. 32 shows the side band transmission of this circuit element, indicating the rising frequency characteristic from a lower corner frequency of approximately 9 cps. Because of the upper corner the characteristic never rises faster than 15 db per decade. Hence, when the composite open loop characteristic for the Control Device is obtained by adding (on a logarithmic scale) the curve for the T pad to that for the Diehl motor the curve decreases not 40 db per decade but about 24 db per decade. (Fig. 33) The resulting phase shift, then, is approximately -110° instead of -180° . The appearance of the phase shift characteristic is sketched in Fig. 34, which gives an approximate idea of the curve and was not plotted from calculations.

Because the carrier frequency is 60 cps. the actual amplitudes and phase shifts higher than about 30 cps. are not truly represented by these figures. However, the use of them is validated by the fact that the frequencies to be transmitted through the system are less than 30 cps. The slope intercepts with the unity gain axis and the phase shift at the point of gain crossover are significant because they establish the error in following an input signal as well as the band pass of the system.

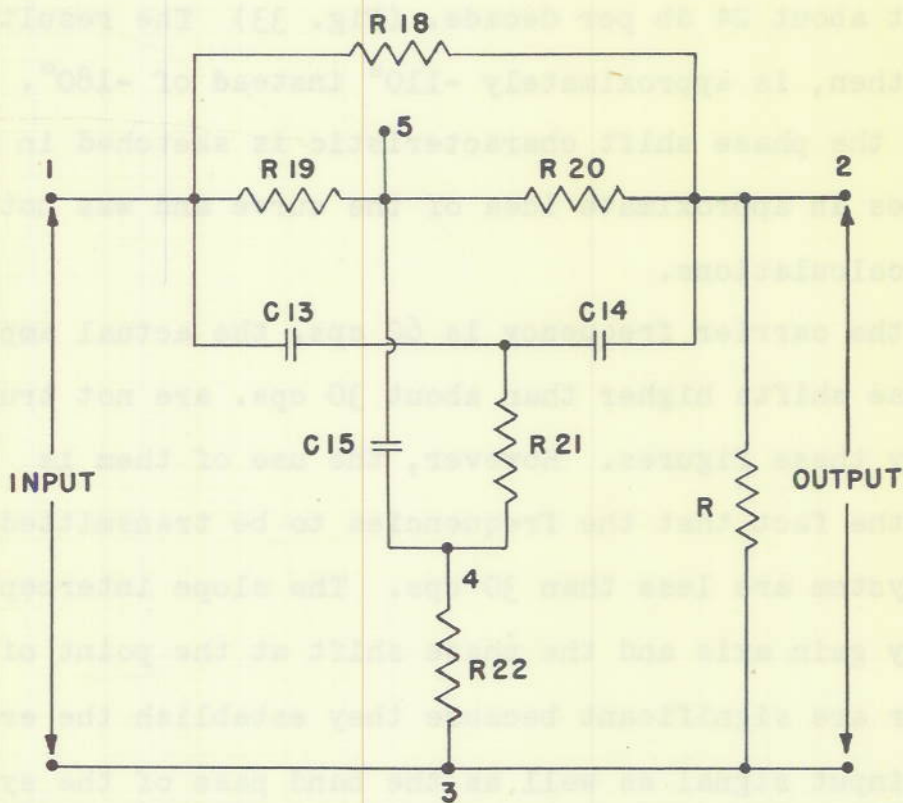
The transmission characteristic of the Control Device can be calculated analytically by applying principles discussed above. The transmission characteristic of the Parallel T sidebands can be approximated by

BRIDGED PARALLEL T PAD

WIRING DIAGRAM

(BUORD. DWG. NO. 903184)

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SIDE BAND TRANSMISSION OF BRIDGED
PARALLEL T PAD.
(BUORD. DWG. NO. 903184)

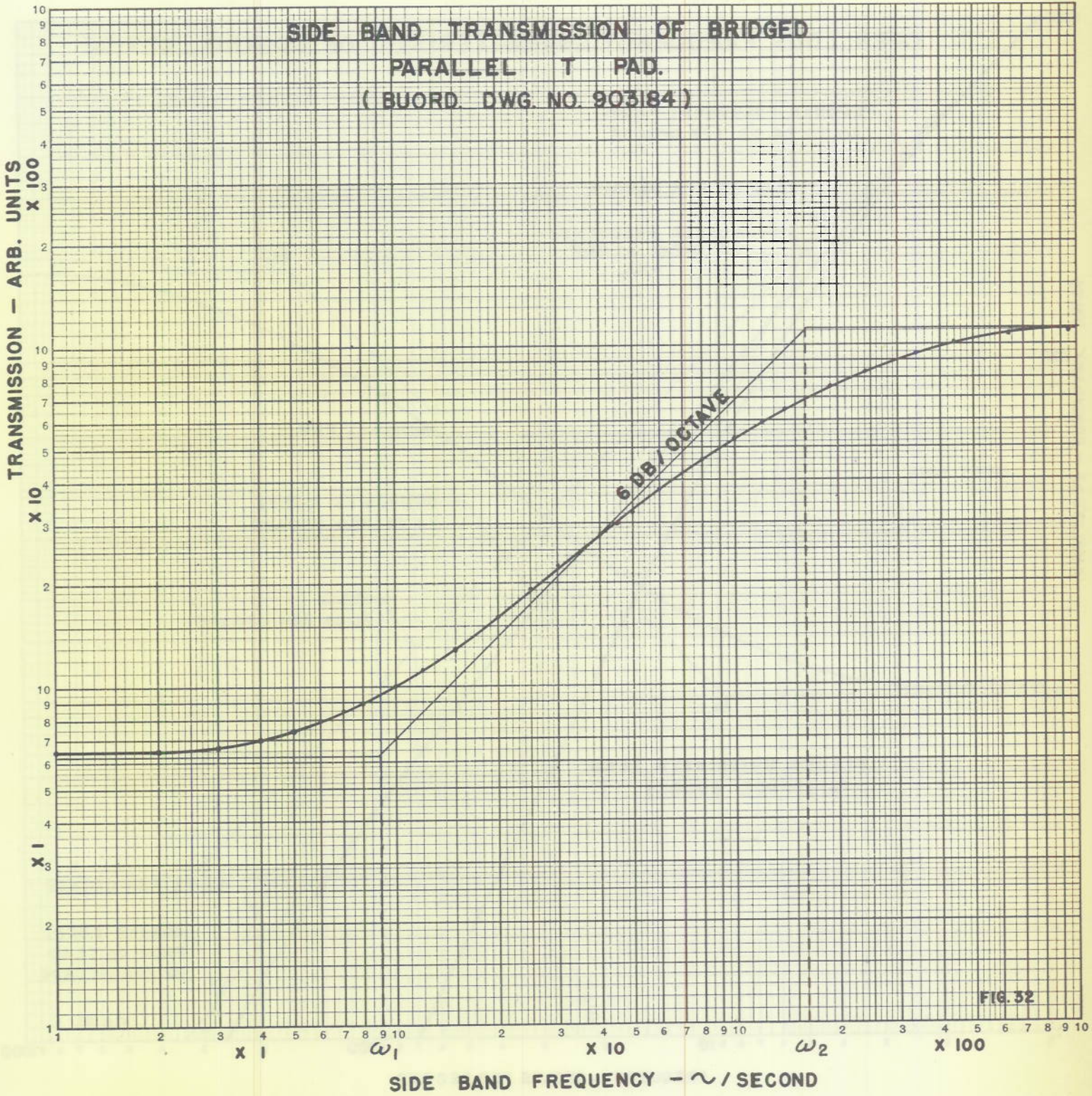
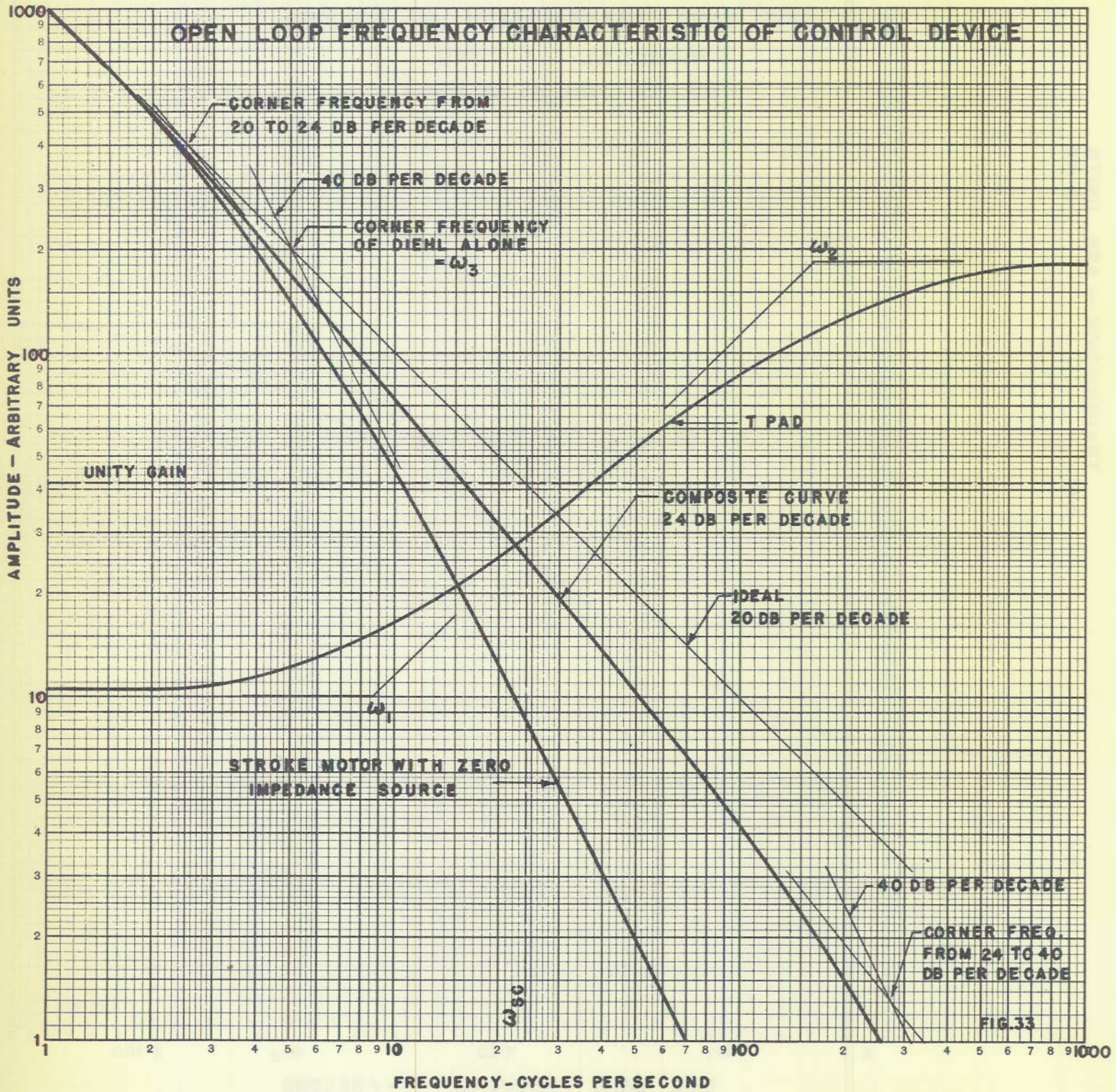
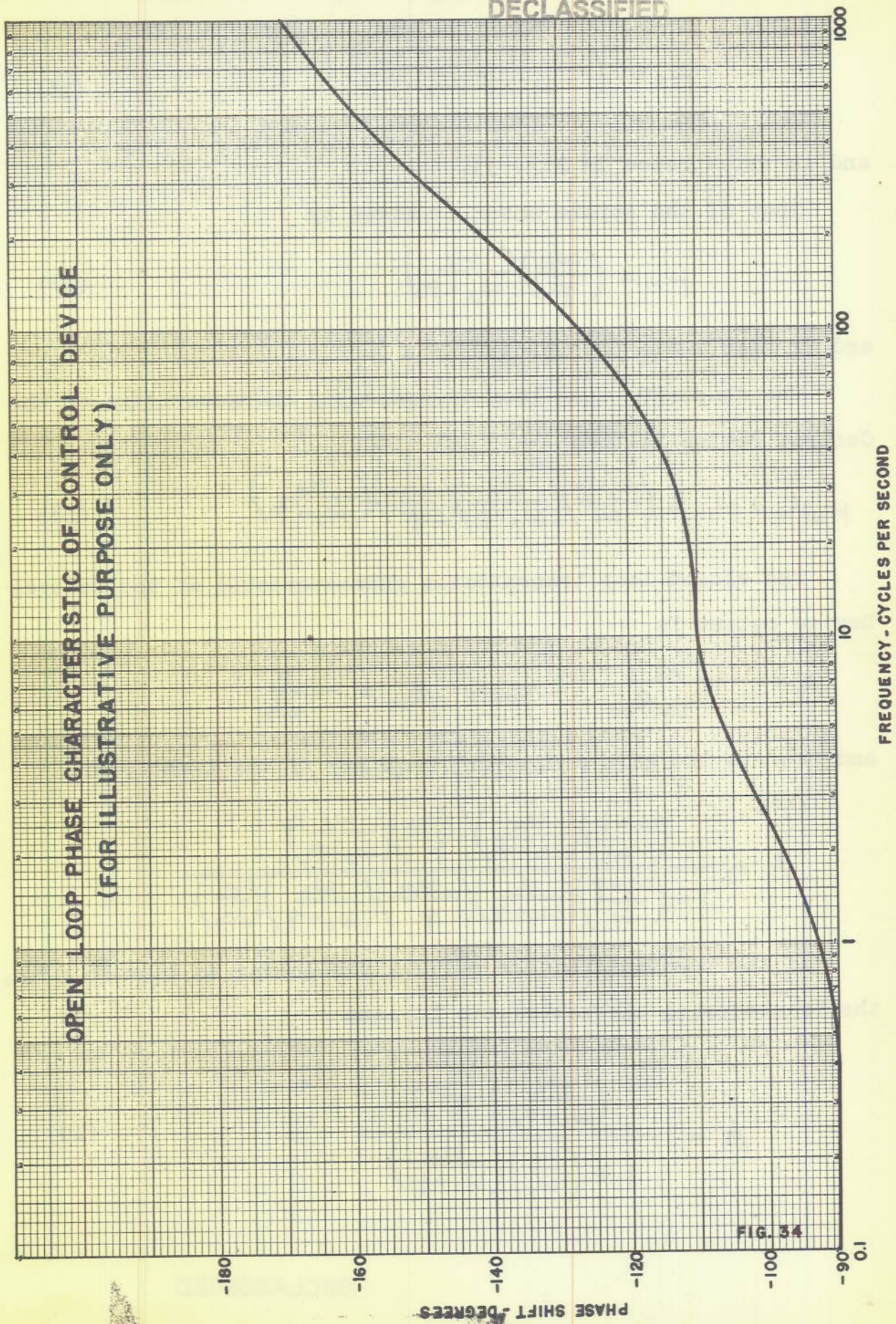


FIG. 32



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OPEN LOOP PHASE CHARACTERISTIC OF CONTROL DEVICE
(FOR ILLUSTRATIVE PURPOSE ONLY)

FIG. 34

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$$\mu_N = \left(\frac{\omega_1 + p}{\omega_1} \right) \left(\frac{\omega_2}{\omega_2 + p} \right) \quad (16)$$

and is illustrated in Fig. 33.

That of the stroke motor is given by

$$\mu_M = \left(\frac{\omega_{sc}}{p} \right) \left(\frac{\omega_3}{\omega_3 + p} \right) \quad (17)$$

and is also shown in Fig. 33.

The composite open loop transmission characteristic of the Control Device is then

$$\mu_N \mu_M = \mu_{sc} = \left(\frac{\omega_1 + p}{\omega_1} \right) \left(\frac{\omega_2}{\omega_2 + p} \right) \left(\frac{\omega_{sc}}{p} \right) \left(\frac{\omega_3}{\omega_3 + p} \right) \quad (18)$$

The closed loop transmission characteristic of the Control Device output is

$$A = \frac{\mu_{sc}}{1 - \mu_{sc} \beta_{sc}} \quad \text{where } \beta_{sc} = - \frac{p}{\omega_T}$$

and ω_T is the gain crossover frequency of the tachometer.

Then

$$A = \frac{\left(\frac{\omega_1 + p}{\omega_1} \right) \left(\frac{\omega_2}{\omega_2 + p} \right) \left(\frac{\omega_{sc}}{p} \right) \left(\frac{\omega_3}{\omega_3 + p} \right)}{1 + \left(\frac{\omega_1 + p}{\omega_1} \right) \left(\frac{\omega_2}{\omega_2 + p} \right) \left(\frac{\omega_{sc}}{p} \right) \left(\frac{\omega_3}{\omega_3 + p} \right) \left(\frac{p}{\omega_T} \right)}$$

If the constants of the network are chosen so that $\omega_1 = \omega_3$, the transmission characteristic becomes

$$A = \frac{\left(\frac{\omega_2}{\omega_2 + p} \right) \left(\frac{\omega_{sc}}{p} \right)}{1 + \left(\frac{\omega_2}{\omega_T} \right) \left(\frac{\omega_{sc}}{\omega_2 + p} \right)} \quad (19)$$

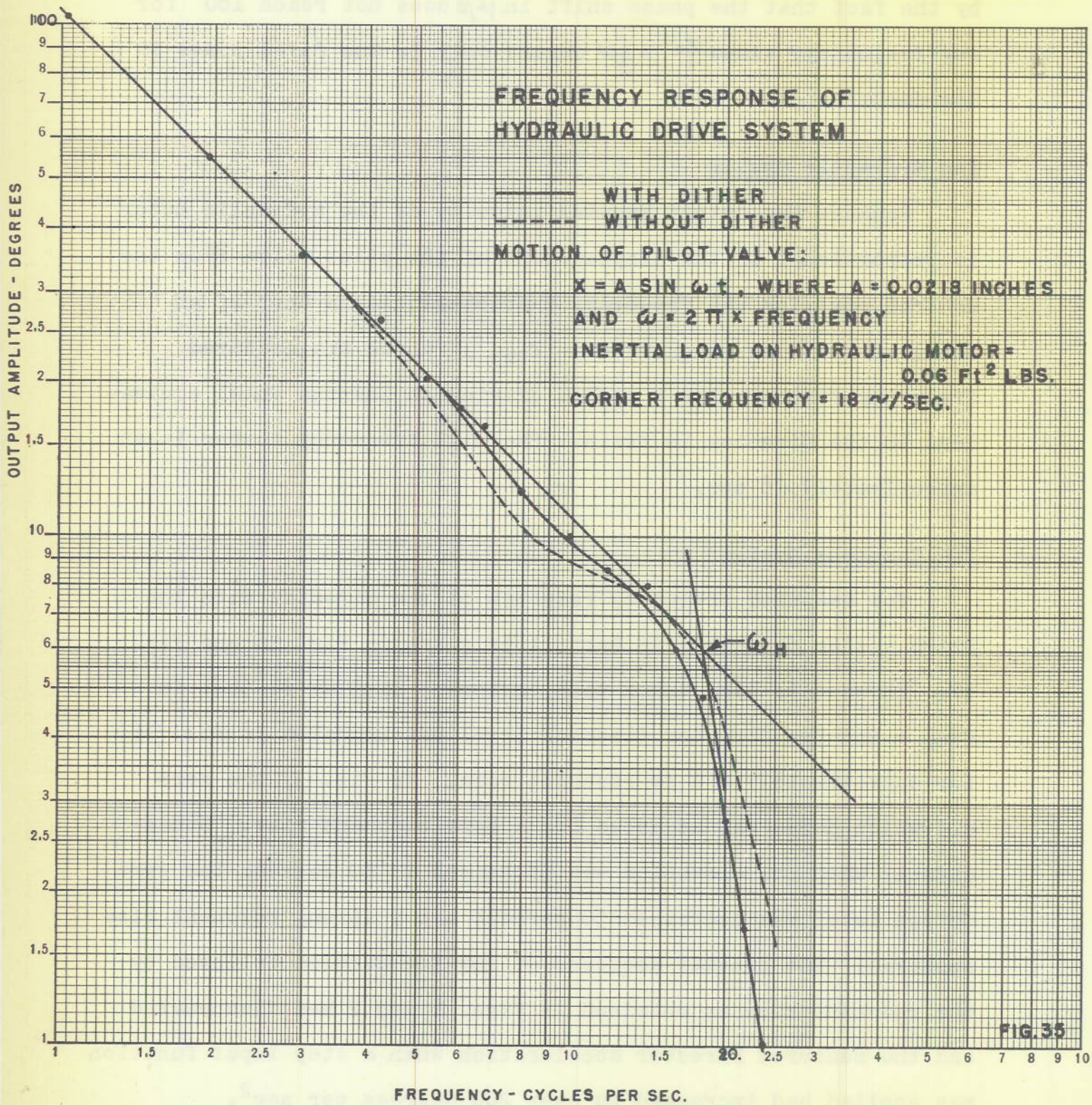
That the closed loop is stable at all frequencies is assured by the fact that the phase shift in μ/β does not reach 180° for any frequency, since $p = j\omega$ occurs only to the first power in the denominator.

The Hydraulic System

Because the output angular velocity of the hydraulic motor is proportional to the displacement of the pilot valve from the neutral position the frequency characteristic is that of an integrator at low frequencies. Fig. 35 shows the measured frequency response for a system driving an inertia wheel equivalent to the Director in train. The high frequency corner is at approximately 18 cps.

The Complete System

The measured frequency response of the Director with the Drive system described in Part II is given in Fig. 36 and Fig. 37. These data were taken with equipment similar to that in Fig. 4 and the Director feedback level was adjusted in Fig. 36 for approximately a 2 db resonant rise. In Fig. 37 the zero elevation curve was adjusted for a zero resonant rise. Consequently when the elevation was increased to 60 degrees the gyro output level was decreased 50 percent and a strong resonant rise appeared. The initial decrease at low frequencies followed by the resonant rise as obtained in Figs. 1 and 2 had disappeared, and the measured Director acceleration when a step input function was applied had increased to over 200 degrees per sec².



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FREQUENCY RESPONSE OF DIRECTOR IN TRAIN (ZERO ELEV.)

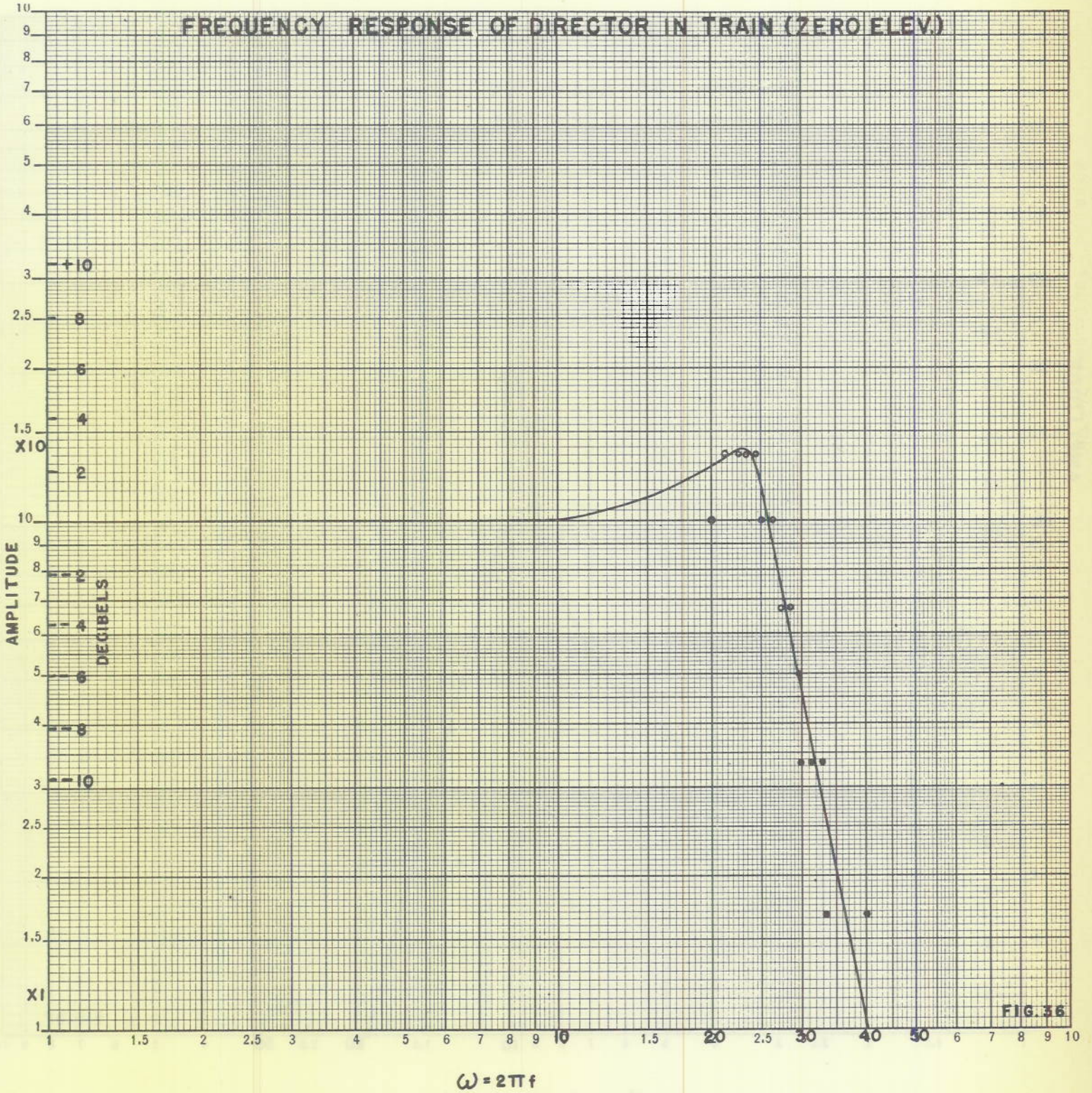


FIG. 36

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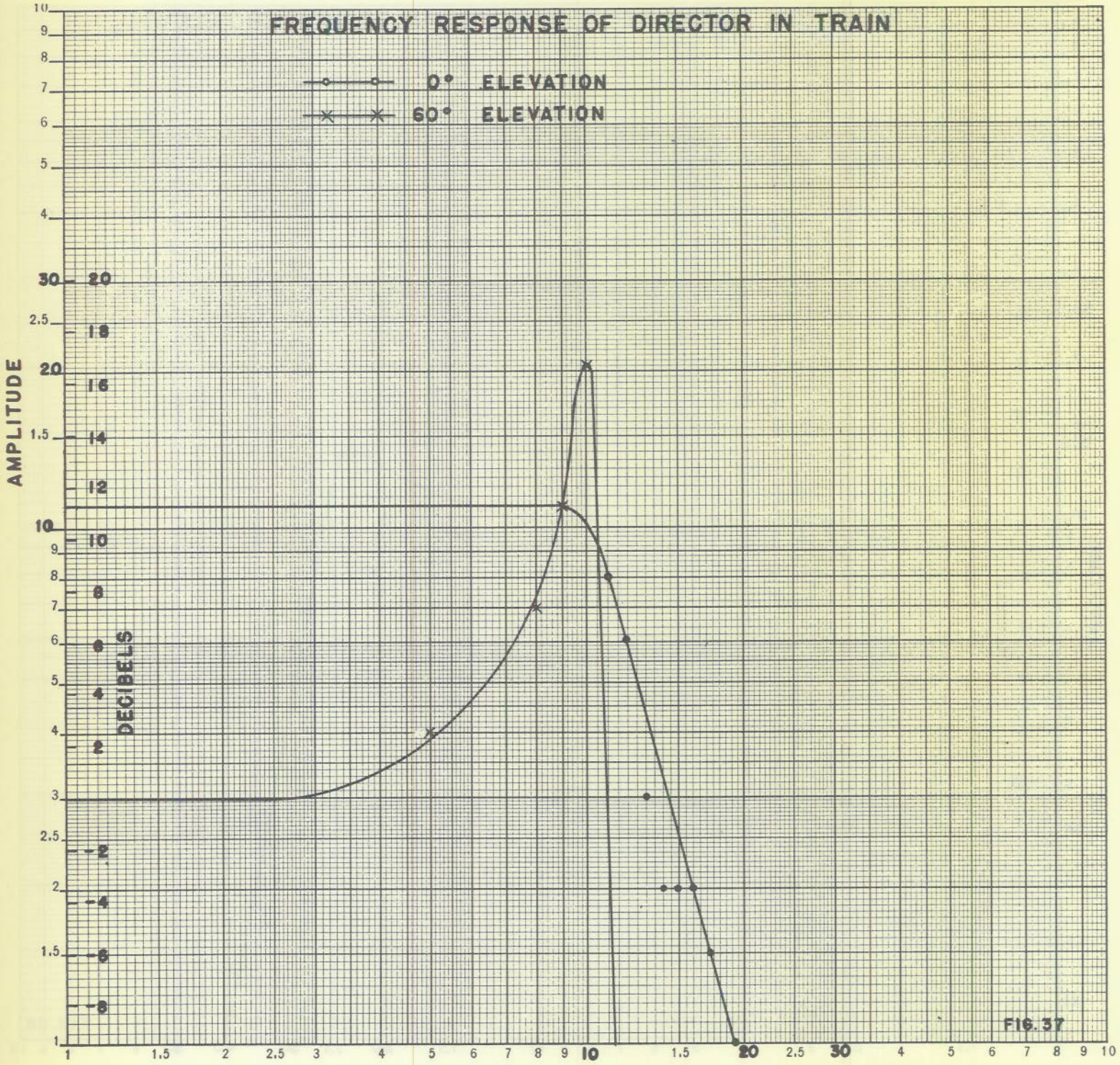


FIG. 37

$\omega = 2\pi f$

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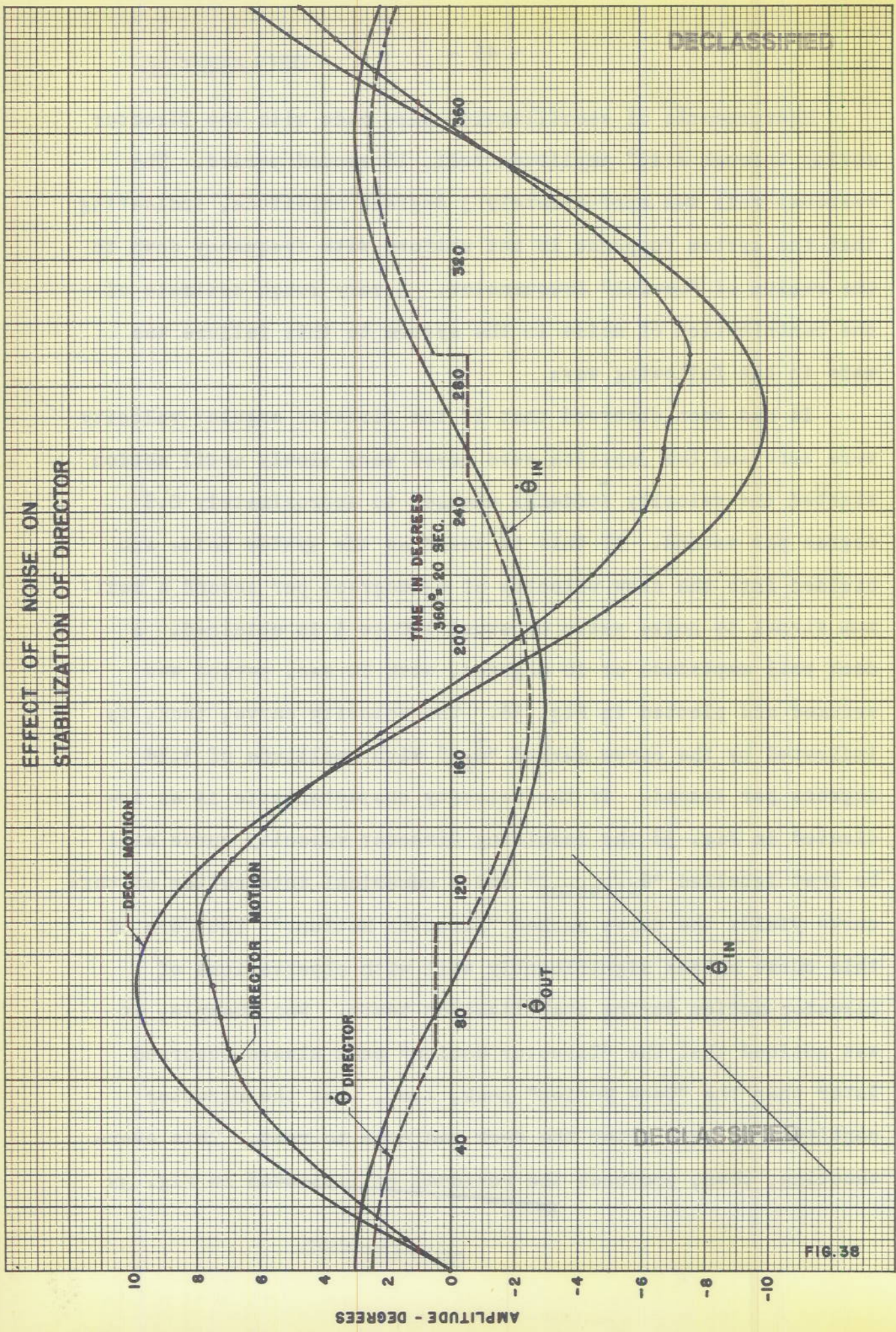
Measurements of stabilization were made with the Director moving through a 15° amplitude roll, 15 second period. The residual roll was approximately 3 degrees amplitude, indicating that the system response is not uniform with frequency down to the region of "useful" frequencies. A very rough estimate of the contribution of noise in the system to this failure was made in the following way:

It had been observed that if the Director angular velocity were zero and the joystick were moved very slowly until motion started the velocity suddenly changed to approximately 0.5 degree per second. If this is taken as the system noise and divided into the slew velocity of 43 degrees per second a maximum signal to noise ratio of about 100 to 1 is obtained. A deck roll amplitude of 10 degrees, with 20 sec. period was assumed and plotted in Fig. 38. The velocity curve, then, is indicated by the curve marked " $\dot{\theta}_{in}$ " with amplitude of 3.14 degrees per second. If the velocity characteristic is as indicated in Fig. 38 the resulting Director velocity curve will be that labelled " $\theta_{Director}$ " and a numerical integration of this curve yields the curve marked "Director Motion." The form of this curve agrees significantly well with observations of Director motion during stabilization tests. For example, it was noticed that the "Director Motion" peak always occurred later than the "Deck Motion" peak, i.e., that the Director continued to move after the deck had come to rest. This overshooting, then, produces the residual roll plotted in Fig. 39

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EFFECT OF NOISE ON STABILIZATION OF DIRECTOR



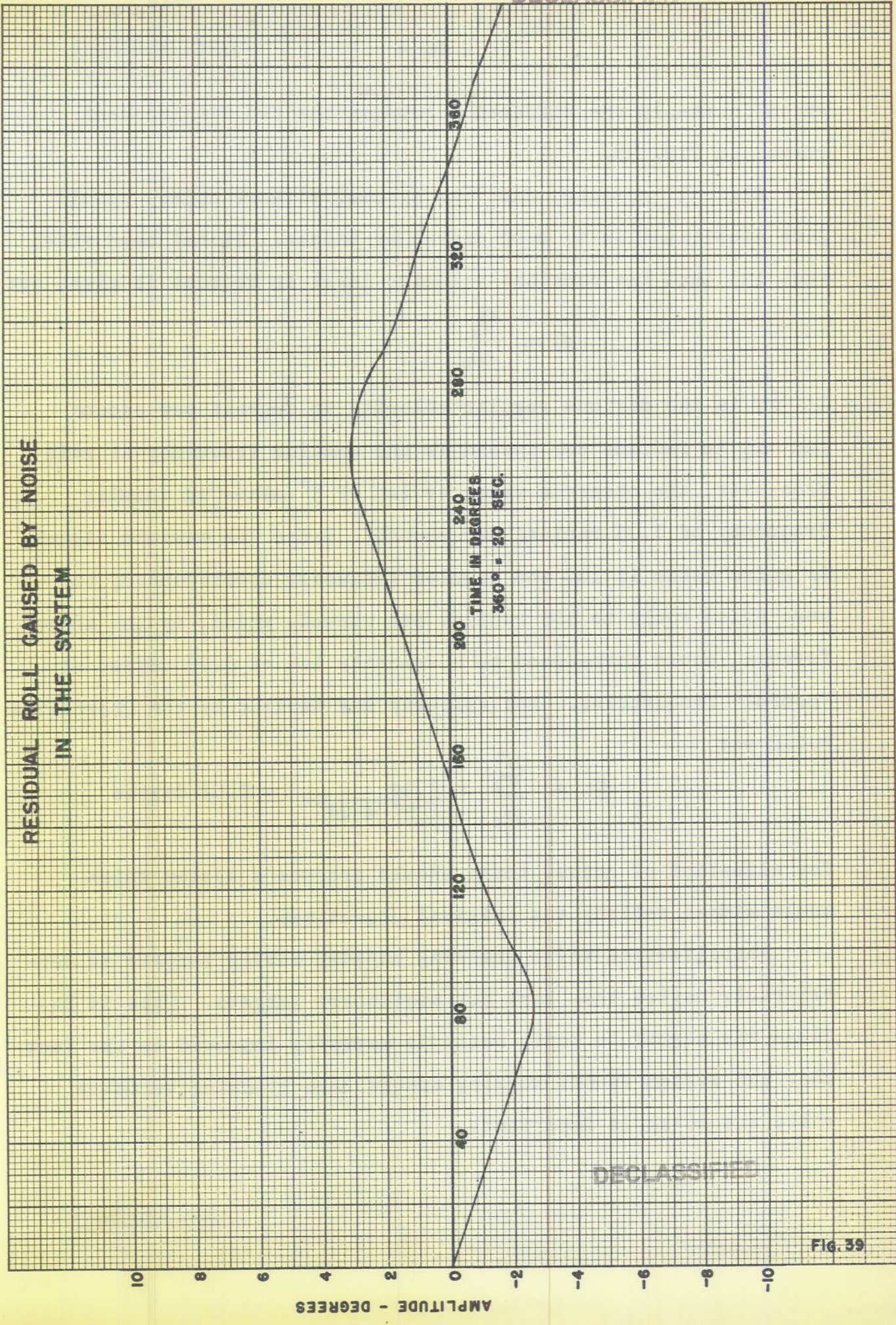
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FIG. 38

AMPLITUDE - DEGREES

TIME IN DEGREES
360° = 20 SEC.

RESIDUAL ROLL CAUSED BY NOISE
IN THE SYSTEM



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FIG. 39

AMPLITUDE - DEGREES

which is simply the difference between the two displacement curves in Fig. 38.

Fig. 33 indicates that the system, without noise, should give stabilization to 0.02 degree or better. It has been shown (Eq. 13) that the constant velocity lag ϵ in degrees is given by:

$$\epsilon = \frac{\dot{\phi}_i}{\omega_c}$$

if $\dot{\phi}_i$ is the maximum angular velocity in degrees per second and ω_c in radians per second is the angular frequency at gain crossover, the observed velocity lag of 3° means an angular frequency of 1.05 radians per second. Since the maximum signal to noise ratio is 100 the angular frequency corresponding to zero noise would be 105 radians per second, which, by the above formula, would correspond to a velocity lag of 0.03 degree at "useful" frequencies. The velocity lag implied by the Objectives would be:

$$\epsilon = \frac{\dot{\phi}_i}{\omega_c} = \frac{3.14}{2 \pi \times 24} = 0.02 \text{ degree}$$

The elimination of noise, then, should produce a system which would almost satisfy the original objectives.

Stabilization while tracking rapidly moving targets is considerably better than that for stationary targets. This is because the signal to noise ratio is markedly improved by the fact that the system is not working around zero tracking velocity where the noise is important.

Analysis of the Entire System

The Control Device.

Fig. 40 is a schematic diagram of the Control Device. The various (complex) characteristics are, according to the derivations previously performed:

Equalizer:
$$\mu_E = \frac{\omega_1 + p}{\omega_1} \cdot \frac{\omega_2}{\omega_2 + p} \quad (20)$$

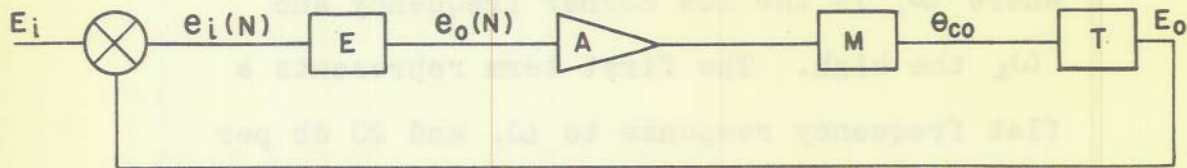
where ω_1 is the low corner frequency and ω_2 the high. The first term represents a flat frequency response to ω_1 and 20 db per decade rise thereafter, while the second represents a flat response to ω_2 and 20 db per decade decrease thereafter.

Amplifier:
$$\mu_A = \text{const.} \quad (21)$$

Motor:
$$\mu_M = \frac{\omega_{M'}}{p} \cdot \frac{\omega_M}{\omega_M + p} \quad (22)$$

where $\omega_{M'}$ is the unity gain angular frequency of the 20 db per decade characteristic and ω_M is the motor corner frequency. Two terms are required here, the first representing the ideal 20 db per decade decrease of the integrating device and the second the corner frequency introduced by inertia of the motor.

SCHEMATIC CIRCUIT OF CONTROL DEVICE



E_i = INPUT SIGNAL OF CONSTANT AMPLITUDE, VARIABLE FREQUENCY.

ω = ANGULAR FREQUENCY OF INPUT SIGNAL.

$e_i(N)$ = INPUT POTENTIAL TO EQUALIZER NETWORK E.

$e_o(N)$ = OUTPUT POTENTIAL OF EQUALIZER NETWORK E.

θ_{co} = STROKE CONTROL (M) OUTPUT ANGLE FROM CENTRAL POSITION.

E_o = POTENTIAL GENERATED BY TACHOMETER T.

Tachometer: $\mu_T = \frac{p}{\omega_T}$ (23)

where ω_T is the unity gain angular frequency.

The overall μ characteristic is the product of the individual characteristics, or

$$\mu = \left(\frac{\omega_1 + p}{\omega_1} \right) \left(\frac{\omega_2}{\omega_2 + p} \right) \left(\frac{\omega_{M'}}{p} \right) \left(\frac{\omega_M}{\omega_M + p} \right) \quad (24)$$

and the feedback factor β is

$$\beta = \frac{p}{\omega_T} \quad (25)$$

If ω_1 is made equal to $\omega_{M'}$ and if ω is assumed to be limited to values small compared to ω_2 the μ characteristic (Eq. 24) is reduced to

$$\mu = \frac{\omega_{M'}}{p} \quad (26)$$

The closed loop response becomes

$$A = \frac{\frac{\omega_{M'}}{p}}{1 + \left(\frac{\omega_{M'}}{p} \right) \frac{p}{\omega_T}} = \frac{\frac{\omega_{M'}}{p}}{1 + \frac{\omega_{M'}}{\omega_T}} \quad (27)$$

To a good approximation we may assume $\omega_T \gg \omega_{M'}$,
so that

$$A = \frac{\omega_{M'}}{p} \quad (28)$$

and it is seen that the gain characteristic of the Control Device

is limited by the stroke motor.

Hydraulic Pump and Motor Loaded with Inertia of Director.

If the corner frequency of the Power Drive with inertia load is assumed high enough that the unity gain frequency lies in the 20 db per decade region

$$\mu_H = \frac{\omega_H}{p} \tag{29}$$

Gyro

Here the characteristic rises 20 db per decade to unity gain and then falls 20 db per decade (See Fig. 23).

The complex gain characteristic μ_g is, accordingly

$$\mu_g = \frac{p}{\omega_g} \left(\frac{\omega_g}{\omega_g + p} \right)^2$$

and, again if $\omega \ll \omega_g$ the characteristic becomes

$$\mu_g = \frac{p}{\omega_g} \tag{30}$$

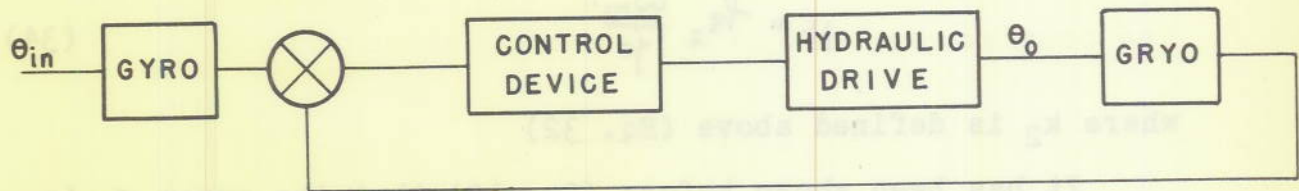
Closed Loop Response to Deck Motion

For purposes of analysis the system can be considered to be that shown in Fig. 41. Then from the inverse feedback relationship

$$\frac{\phi_o}{\phi_{IN} \left(\frac{p}{\omega_g} \right)} = \frac{\left(\frac{\omega_{M'}}{p} \right) \left(\frac{\omega_H}{p} \right)}{1 + \left(\frac{\omega_{M'}}{p} \right) \left(\frac{\omega_H}{p} \right) \left(\frac{p}{\omega_g} \right)} = \frac{\frac{\omega_{M'} \omega_H}{p^2}}{1 + \frac{\omega_{M'}}{p} R_2} \tag{31}$$

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SCHEMATIC CIRCUIT OF EXTERNAL LOOP



θ_{in} = DECK MOTION

θ_o = DIRECTOR MOTION

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FIG. 41

where

$$k_2 = \frac{\omega_H}{\omega_g} \tag{32}$$

then

$$\frac{\phi_o}{\phi_{IN}} = \frac{\frac{\omega_M \omega_H}{p \omega_g}}{1 + \frac{\omega_M \omega_H}{p \omega_g}} \tag{33}$$

The closed loop then is equivalent to a simple feedback loop (Fig. 42 (a)) whose open loop μ characteristic is

$$\mu = k_2 \frac{\omega_M}{p} \tag{34}$$

where k_2 is defined above (Eq. 32)

It has been shown before (Eq. 12) that the error ϵ is given by

$$\epsilon = \frac{\phi_{IN}}{1 + \mu} = \frac{\phi_{IN}}{1 + k_2 \left(\frac{\omega_M}{p} \right)}$$

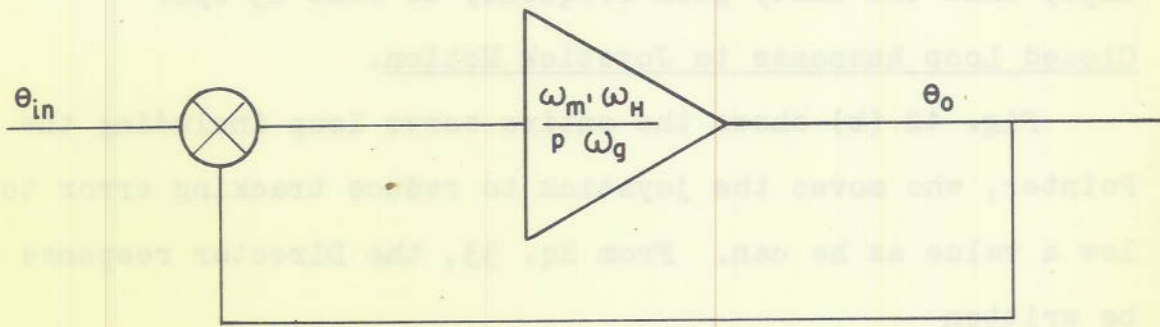
If the input angular frequency (i.e., the deck roll frequency) is low, $\mu \gg 1$, and

$$\epsilon = \frac{\phi_{IN}}{k_2 \frac{\omega_M}{p}} = \frac{\dot{\phi}_{IN}}{k_2 \omega_M} \tag{35}$$

If the gyro unity gain frequency is the same as the hydraulic drive corner frequency, $k_2 = 1$ and the equation

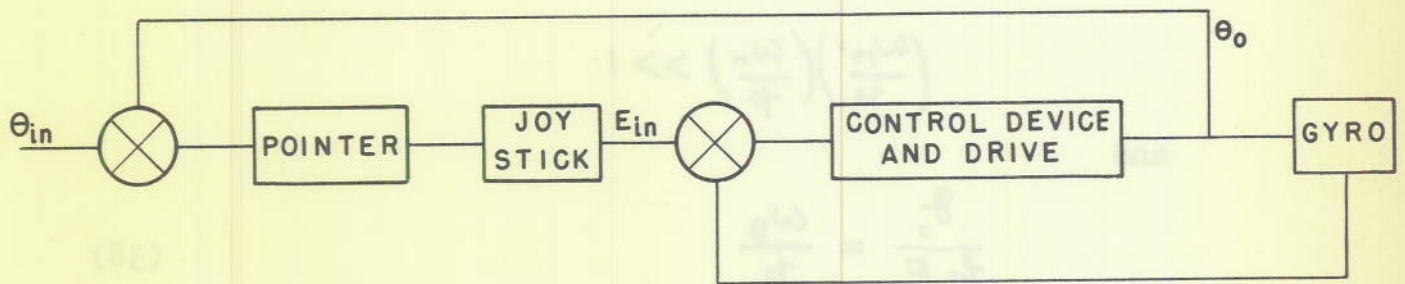
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EQUIVALENT CIRCUIT OF SERVO LOOP



(a)

SERVO SYSTEM INCLUDING POINTER



(b)

θ_{in} = TARGET POSITION

θ_o = DIRECTOR POSITION

E_{in} = CONTROL VOLTAGE FROM JOYSTICK

$K\theta_{in}$ = FICTITIOUS ANGLE REPRESENTED BY INPUT POTENTIAL

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becomes

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$$\epsilon = \frac{\dot{\theta}_{IN}}{\omega_{M'}} \quad (36)$$

As shown before (following Eq. 13) the original Objectives imply that the unity gain frequency is some 23 cps.

Closed Loop Response to Joystick Motion.

Fig. 42 (b) shows the entire servo loop including the Pointer, who moves the joystick to reduce tracking error to as low a value as he can. From Eq. 33, the Director response can be written

$$\frac{\theta_o}{kE_{IN}} = \frac{\left(\frac{\omega_{M'}}{p}\right)\left(\frac{\omega_M}{p}\right)}{1 + \left(\frac{\omega_{M'}}{p}\right)\left(\frac{\omega_M}{p}\right)\left(\frac{p}{\omega_g}\right)} \quad (37)$$

For angular frequencies contained in tracking motions

$$\left(\frac{\omega_{M'}}{p}\right)\left(\frac{\omega_M}{p}\right) \gg 1$$

and

$$\frac{\theta_o}{kE_{IN}} = \frac{\omega_g}{p} \quad (38)$$

If the joystick potentiometer shaping is ignored, the frequency characteristic of the joystick unit, including the position tachometer, becomes (See Eq. 11):

$$\mu_j = \frac{\omega_j + p}{\omega_j} \quad (39)$$

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Tests, as yet incomplete, at the Naval Research Laboratory indicate that, within limits, a man responds as a simple integrator, i.e., that the frequency characteristic μ_p of the Pointer may be represented by

$$\mu_p = \frac{\omega_p}{p} \quad (40)$$

The combined μ characteristic is the product of Eqs. 38, 39 and 40, or

$$\mu = \left(\frac{\omega_g}{p}\right) \left(\frac{\omega_j + p}{\omega_j}\right) \left(\frac{\omega_p}{p}\right)$$

and the closed loop response, assuming a uniform response for man over the range of frequencies contained in tracking, is

$$\frac{\phi_o}{\phi_{in}} = \frac{\left(\frac{\omega_p}{p}\right) \left(\frac{\omega_g}{p}\right) \left(\frac{\omega_j + p}{\omega_j}\right)}{1 + \left(\frac{\omega_p}{p}\right) \left(\frac{\omega_g}{p}\right) \left(\frac{\omega_j + p}{\omega_j}\right)} \quad (41)$$

Because p appears to the second power, Eq. 41 implies a system of 40 db per decade breaking into one of 20 db per decade before or at gain crossover, providing $\omega_j < \omega_g$.

The error expression is, from Eq. 12,

$$\epsilon = \frac{\phi_{in}}{1 + \left(\frac{\omega_p}{p}\right) \left(\frac{\omega_g}{p}\right) \left(\frac{\omega_j + p}{\omega_j}\right)}$$

But at very low frequencies $\mu \gg 1$, and $\frac{\omega_j + p}{\omega_j} \rightarrow 1$, so that

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$$\epsilon = \frac{\phi_{IN}}{\frac{\omega_p \omega_g}{p^2}} = \frac{\ddot{\phi}_{IN}}{\omega_p \omega_g} \quad (42)$$

This equation indicates that for low angular frequencies of the target motion, the Pointer will track with negligible velocity error and with an acceleration error inversely proportional to the corner frequency of the Pointer himself, i.e., a quick human reaction will produce better tracking.

At higher frequencies (above 0.5 cps, see Fig. 67), the error is

$$\epsilon = \frac{\phi_{IN}}{\left(\frac{\omega_p \omega_g}{p^2}\right) \left(\frac{\omega_j^2 + p}{\omega_j}\right)} \quad (43)$$

and rapidly becomes a velocity error unless ω_j' is increased. However, tracking frequencies above 0.5 cps are rarely encountered except for aircraft traveling at supersonic speeds.

If "position control" is eliminated by removing the joystick tachometers from the circuit, the μ characteristic becomes

$$\mu = \frac{\omega_p}{p} \cdot \frac{\omega_g}{p} = \frac{\omega_p \omega_g}{p^2} \quad (44)$$

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The closed loop response is

$$\frac{\phi_o}{\phi_{IN}} = \frac{\frac{\omega_p \omega_g}{p^2}}{1 + \frac{\omega_p \omega_g}{p^2}} \quad (45)$$

and the error is

$$\epsilon = \frac{\phi_{IN}}{1 + \frac{\omega_p \omega_g}{p^2}} \quad (46)$$

For values of the applied angular frequency ω approaching $\sqrt{\omega_p \omega_g}$ the error becomes

$$\epsilon = \frac{\phi_{IN}}{1-1} = \infty \quad (47)$$

and the system, which includes the Pointer, becomes unstable at this frequency.

If, on the other hand, the applied frequency is low, $\mu \gg 1$ and the error is

$$\epsilon = \frac{\ddot{\phi}}{\omega_p \omega_g} \quad (48)$$

The system, therefore, is stable for low target frequencies, i.e., long range, but unstable for high target frequencies.

The system with position control is stable for all input frequencies within the capabilities of the Pointer with velocity lag negligible at low frequencies, while the system without position control is unstable except for low input

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and the closed loop response is

$$A = \frac{\left(\frac{\omega_g}{p}\right)\left(\frac{\omega_1}{\omega_1+p}\right)\left(\frac{\omega_2+p}{\omega_2}\right)}{1 + \left(\frac{\omega_g}{p}\right)\left(\frac{\omega_1}{\omega_1+p}\right)\left(\frac{\omega_2+p}{\omega_2}\right)} \quad (51)$$

At low angular frequency

$$\frac{\omega_2+p}{\omega_2} \rightarrow 1 \quad \text{and} \quad \mu \gg 1$$

The error ϵ is

$$\begin{aligned} \epsilon &= \frac{\theta_{IN}}{\left(\frac{\omega_g}{p}\right)\left(\frac{\omega_1}{\omega_1+p}\right)} = \frac{(\omega_1 p + p^2) \theta_{IN}}{\omega_1 \omega_g} \\ &= \frac{\dot{\theta}_{IN}}{\omega_g} + \frac{\ddot{\theta}_{IN}}{\omega_1 \omega_g} \end{aligned} \quad (52)$$

The automatic tracking performance requirements have been established as follows:

1. Steady-state velocity error = 0.1° at $10^\circ/\text{sec}$.
2. Steady-state acceleration error = 0.1° at $1^\circ/\text{sec}^2$.

Substituting these requirements in Eq. 52, there results

$$\omega_g = 100 \text{ rad per sec} \quad (53)$$

$$\omega_1 \omega_g = 10 \text{ (rad per sec)}^2 \quad (54)$$

The resonance frequency of the gyro is adjusted to 20 cps

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(Fig. 22), which gives $\omega_g = 125$, satisfactorily close to the required value. From Eq. 54, $\omega_s = 0.1$. This extremely low corner frequency provides a very desirable feature, namely a long coast period during which the Director continues to track the target even though no signal is received. Thus the target is not lost during moderate periods of radar fading.

$$\text{The angular frequency } \omega_2 = \sqrt{\omega_s \omega_g} = 3.3$$

so that

$$f_2 = 0.5 \text{ cps.}$$

Part III - Components

Stabilizer MK 1 Mod 0

The Stabilizer Mk 1 is shown in Plate 24 and a sectionalized view of one of the gyros in Plate 25. The gyroscope is adapted from those of the Computer Mk 17 with as few changes as possible and is so designed that the output electrical signal is proportional to the rotational rate of the gyro about the input axis. The wheel is air driven from a constant pressure source provided by a diaphragm type air pump. The pressure is maintained constant by means of a regulator valve and an air chamber. The wheel, whose moment of inertia is 7312.92 gm-cm^2 , rotates at 8500 rpm on ball bearing races. The wheel is maintained in a gimbal which is suspended on wires through the gimbal axis and which likewise forms the output axis of the gyro. The input axis is perpendicular both to the output axis and to the wheel axis. The purpose of the wire suspension for the gimbal is to reduce gimbal friction to a minimum. The gimbal axis is maintained in the normal position by means of the range wire, which in the Computer Mk 17 is adjustable in length but in the Stabilizer is clamped at a fixed length. The moment of inertia of the gimbal about the output axis is 5340 gm cm^2 , and together with the range wire forms a resonant system, whose frequency depends upon the stiffness of the range wire. In the gyro stabilizer the resonance frequency is fixed at approximately 20 cps, for with this range wire stiffness, the maximum gyro deflection occurs at slew velocity. In order to avoid undesirable vibration of the gimbal

system, viscous damping is provided in the gyro about the gimbal axis and is so adjusted as to give the proper gyro response characteristic as discussed below.

The above gyro arrangement is one which gives a constant angular displacement of the gimbal system from the normal position for a constant input angular velocity. The sense of the displacement depends upon the direction of rotation of the wheel and the direction of the input angular velocity. If the range wire spring has a linear characteristic, the angular deflection of the gimbal will be proportional to the input angular velocity for constant wheel velocity.

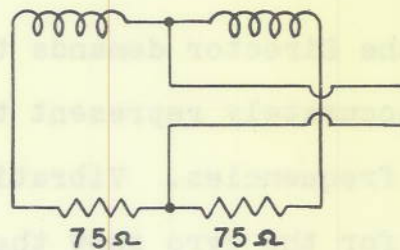
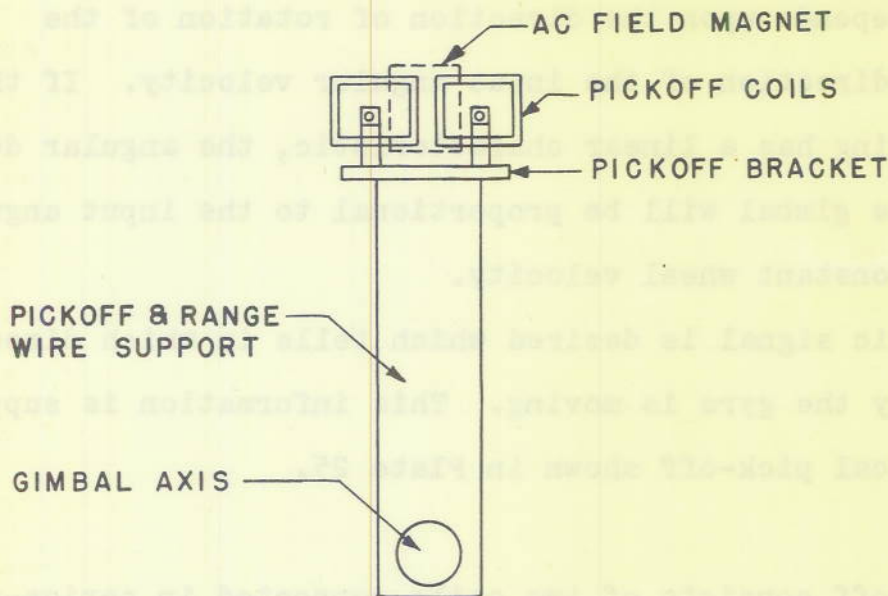
An electric signal is desired which tells in which direction and how rapidly the gyro is moving. This information is supplied by the electrical pick-off shown in Plate 25.

The Pick-Off

The pick-off consists of two coils connected in series-aiding and mounted to move with the gimbal as in Fig. 44. As the gimbal deflects, a voltage is produced whose phase sense depends upon the direction of deflection and whose magnitude is proportional to gimbal deflection.

Proper operation of the Director demands that the electrical signal from the pick-off accurately represent the motion of the gyro gimbal system at all frequencies. Vibration tests with the pick-off bracket designed for the gyro show that the resonance frequency of the pick-off system is 20 cps and that the value of Q for the system is 1.4. An attempt was made to increase

PICKOFF SCHEMATIC AND WIRING DIAGRAM



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the stiffness of the bracket by a slight redesign which added stiffened sections. The redesigned bracket gave no improvement and the project was dropped when further tests indicated that this was not a major source of spurious signals.

A more serious fault with the pick-off is the fact that the induced signal in the coils has a very considerable quadrature component, as shown in Fig. 45. A complete redesign of the pick-off system would be required to eliminate this fault and has not been attempted.

An idea of the linearity of the pick-off system is given in Figs. 46, 47 and 48, the first of which shows the output voltage as a function of deflection, the second the output as a function of torque applied to the gimbal and the third the deflection as a function of torque.

The pick-off output voltage should be either in phase or in phase opposition with the supply line voltage. A simple resistance capacitance network corrects for phase shift in the pick-off field magnet.

Gyro Sensitivity and Noise

The sensitivity of the gyro has been so adjusted that the gimbal deflection is the allowed maximum of 2° from the normal position for an angular input velocity of 43° per second which is the slew velocity of the Director. In the original Objectives for the Director, smooth tracking to 1 mil per second was specified. This would correspond to a signal of $1/750$ the maximum signal. The noise generated in the gyro by vibration and other-

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QUADRATURE AND IN-PHASE OUTPUT VOLTAGE OF PICKOFFS

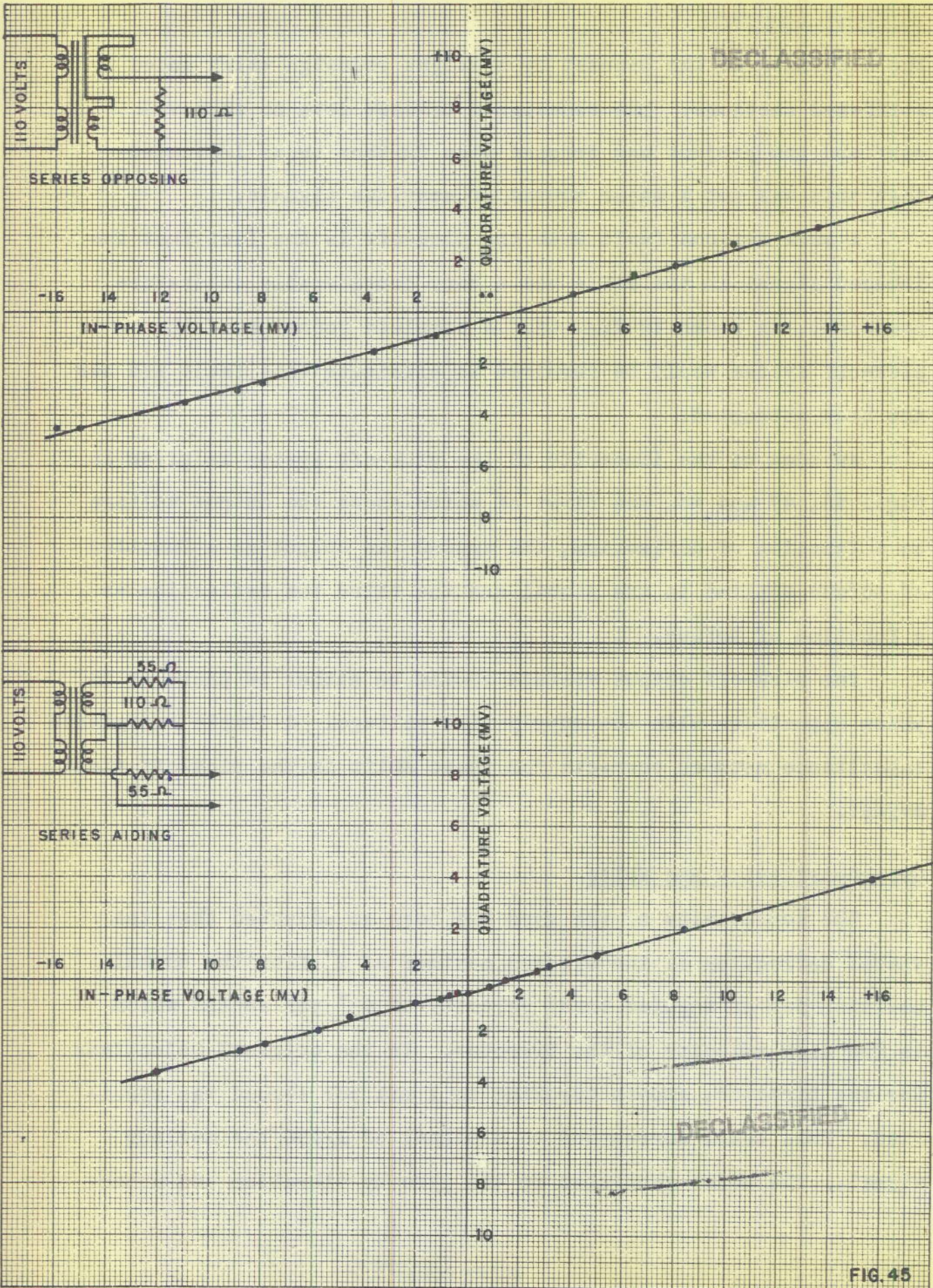
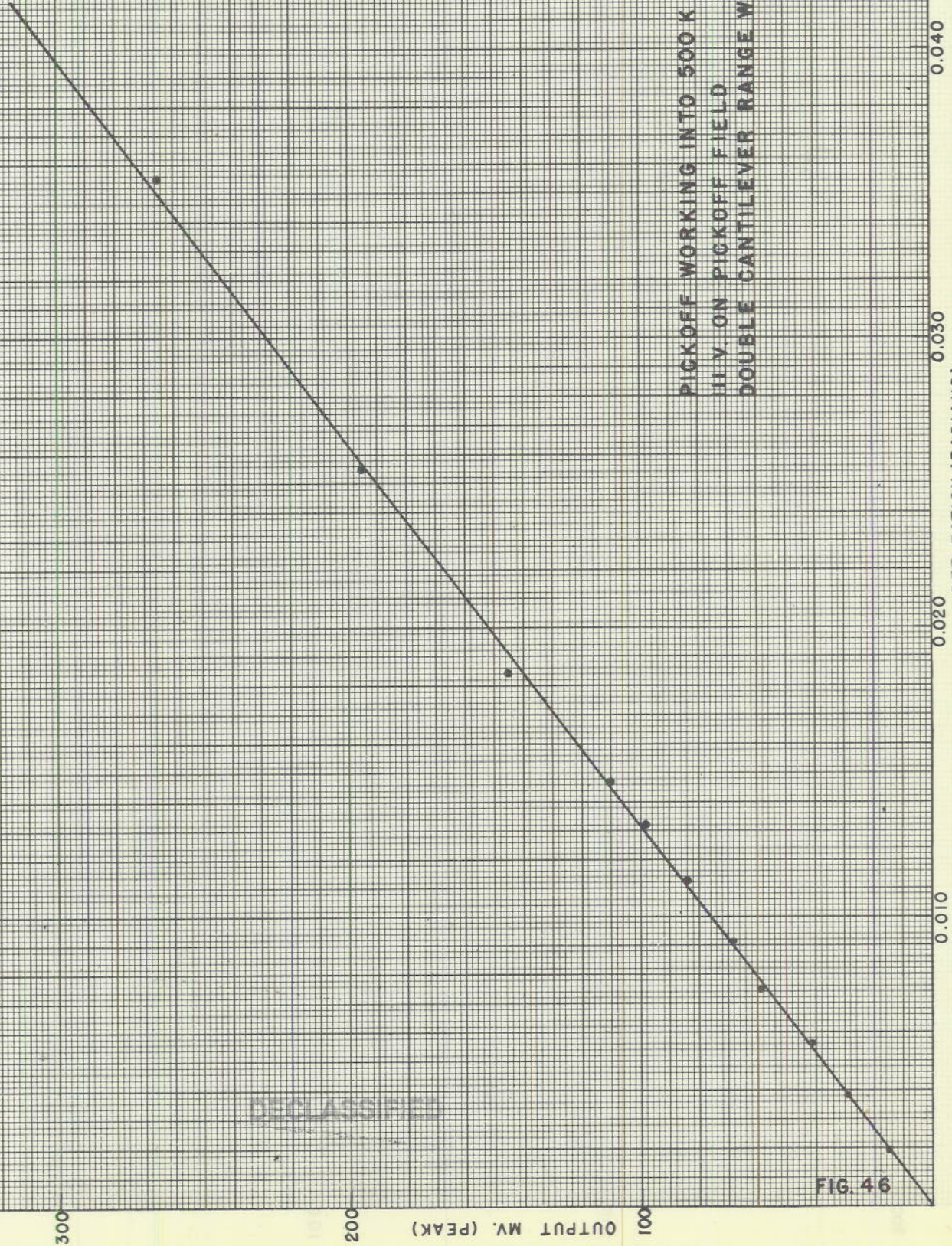


FIG. 45

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VOLTAGE OUTPUT VS GIMBAL DEFLECTION
ELEVATION GYRO (#3690) FROM STABILIZER MK I



PICKOFF WORKING INTO 500 K OHMS
111 V ON PICKOFF FIELD
DOUBLE CANTILEVER RANGE WIRE AT 1.25" LENGTH

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FIG. 46

OUTPUT MV (PEAK)

DEFLECTION (RADIAN)

VOLTAGE OUTPUT VS TORQUE APPLIED TO GIMBAL
ELEVATION GYRO (# 369J) FROM STABILIZER MK I

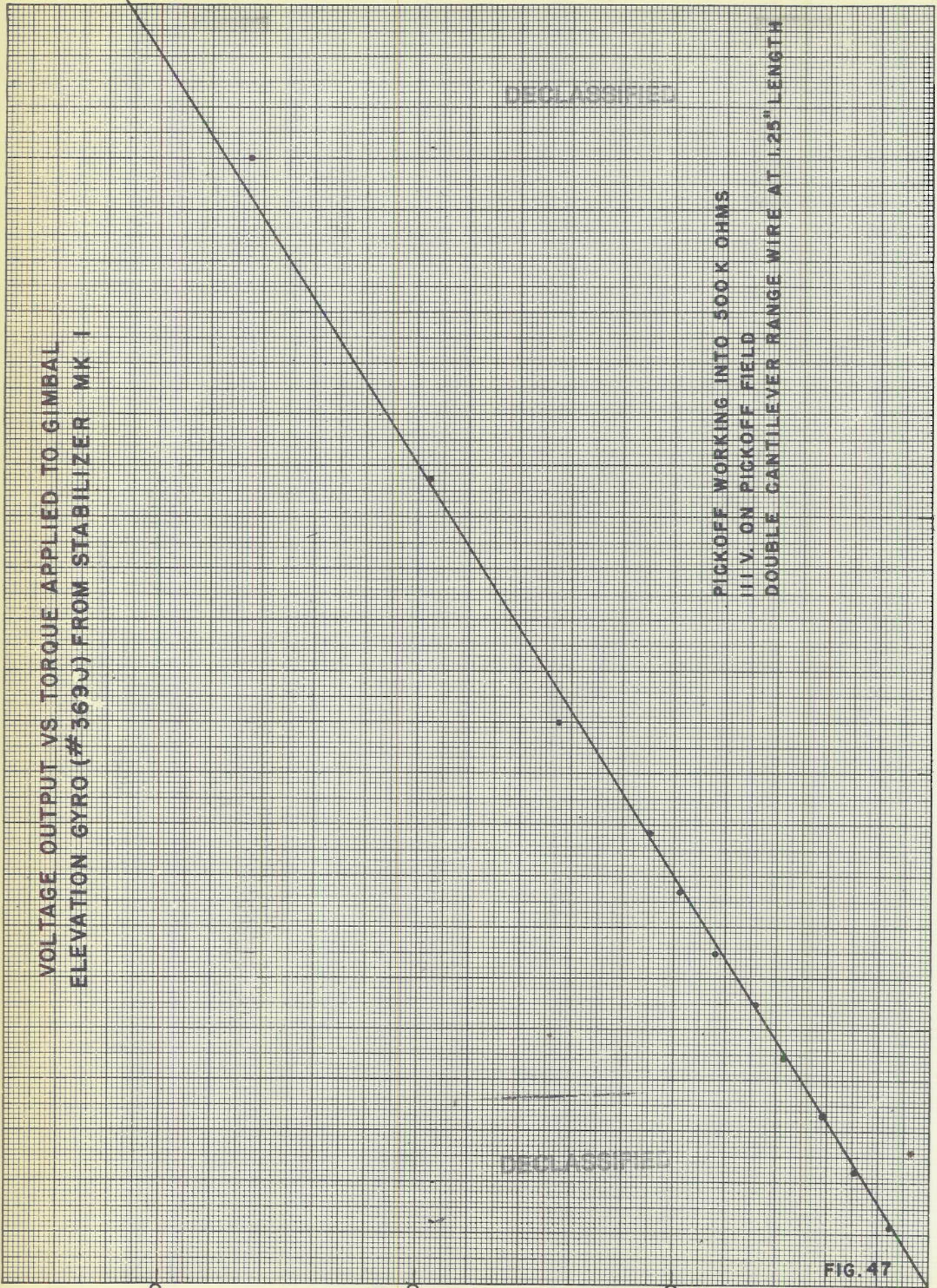
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PICKOFF WORKING INTO 500 K OHMS
111 V. ON PICKOFF FIELD
DOUBLE CANTILEVER RANGE WIRE AT 1.25" LENGTH

OUTPUT MV. (PEAK)

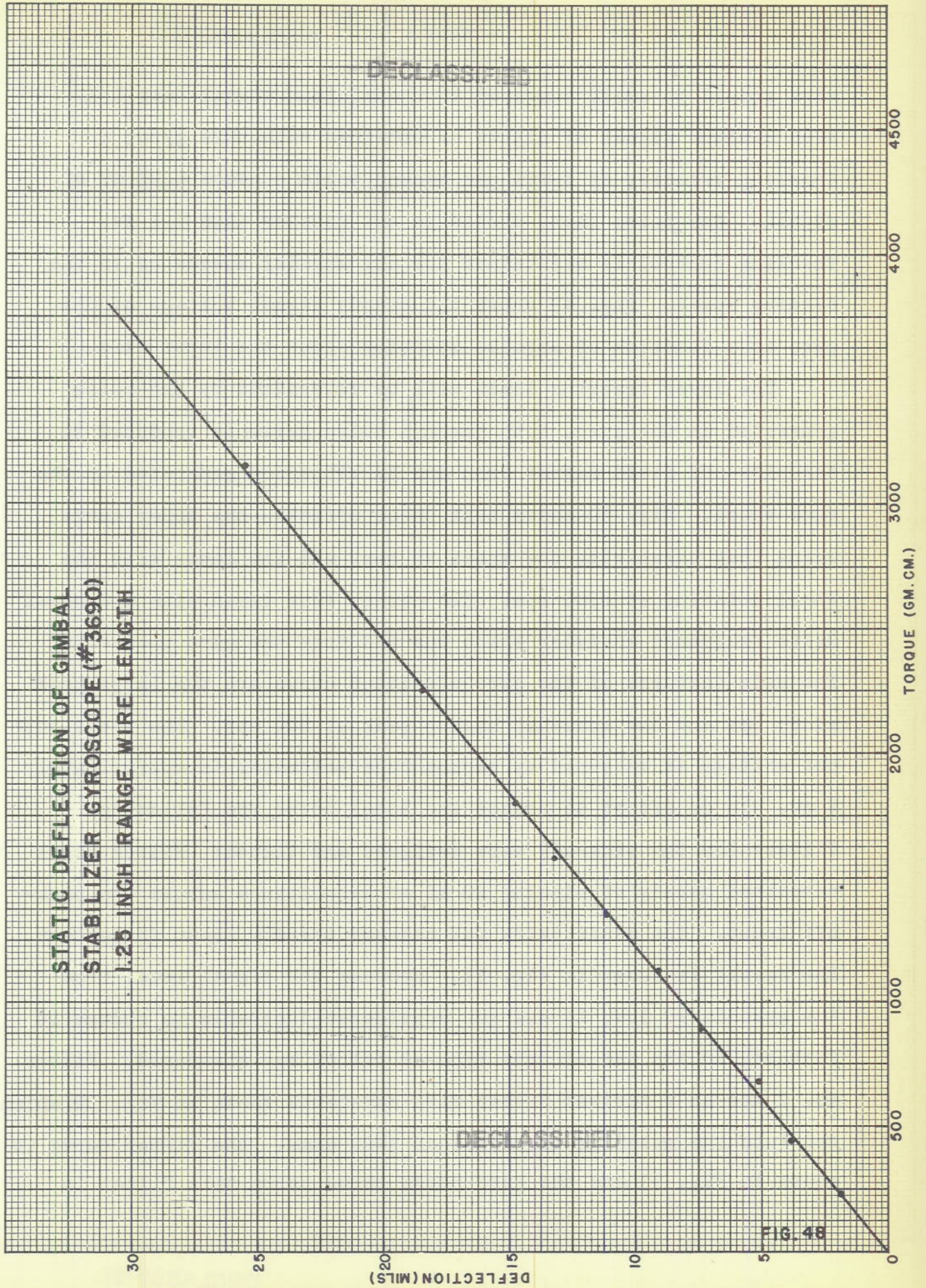
TORQUE DYNE CM. 400×10^4

FIG. 47



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STATIC DEFLECTION OF GIMBAL
STABILIZER GYROSCOPE (#3690)
1.25 INCH RANGE WIRE LENGTH

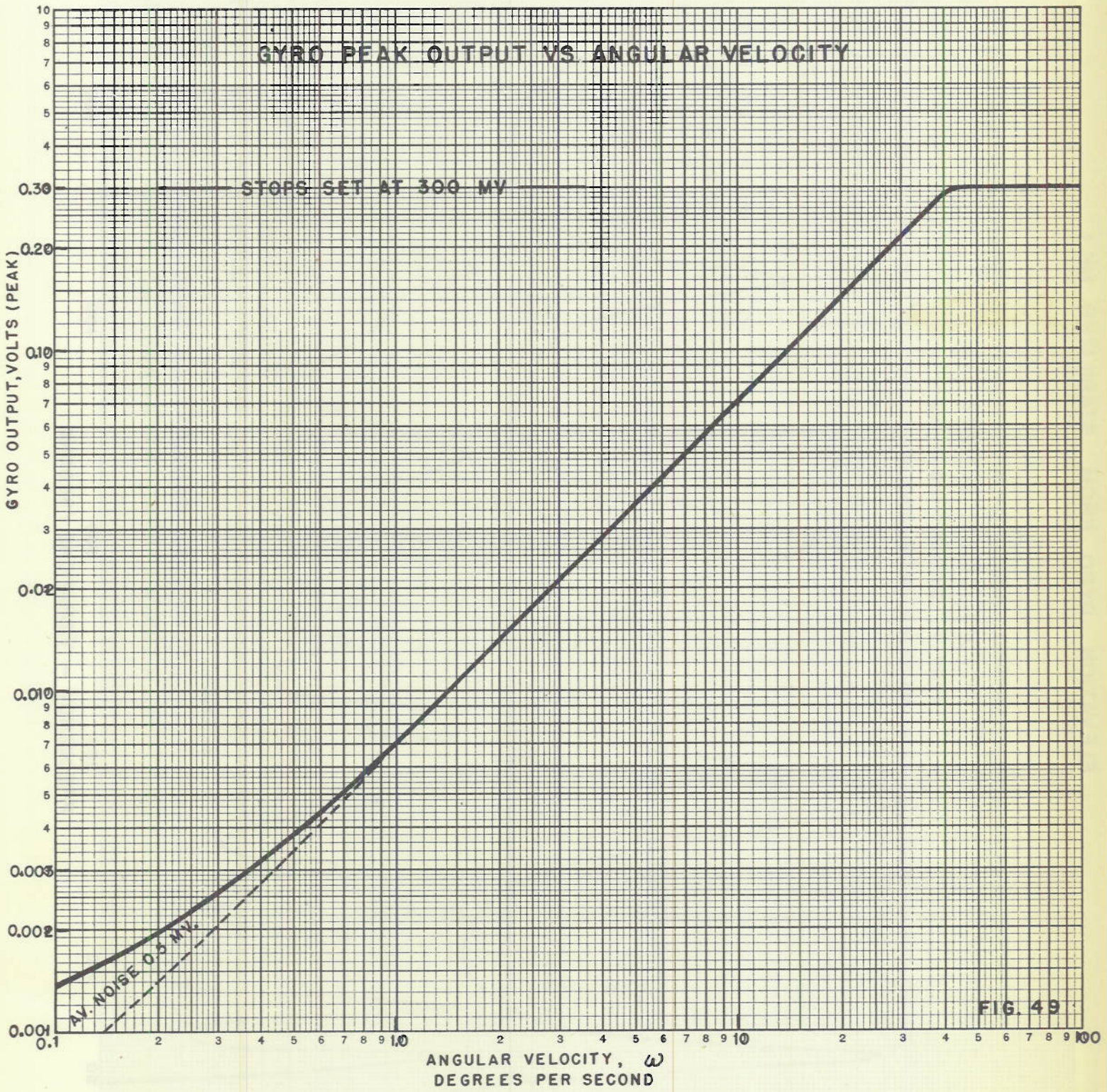


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FIG. 48

wise should be small compared to the minimum signal--say $1/3$. With maximum signal of 213 mv as obtained with this gyro, a tracking velocity of 1 mil per second would produce 0.28 mv of signal. The noise then, should be not greater than 0.1 mv. Tracking control is maintained for all angular speeds up to the slewing speed. Fig. 49 shows the output signal voltage of the gyro as a function of angular velocity about the input axis.

The lower tracking limit will be determined by the noise generated in the gyro, both through third harmonic produced in the pick-off field magnet iron and by vibration generated by the gyro wheel. Fig. 50 shows both these effects--the upper curve being that taken with the wheel at rest and the lower with the wheel rotating at 8500 rpm. The curves were taken with a General Radio frequency analyzer which was fed from the gyro pick-offs. The main features of the gyro vibration curve are the large peak at 85 cps and the somewhat higher peak at 200 cps. The total output voltage as measured by vacuum tube voltmeter is approximately 4 mv. In an effort to reduce the total noise the following filters for the pick-off were designed and tested: Filter No. 1 consisted merely of placing 20 mf of capacitance across the pick-off input. The sensitivity was reduced thereby about 20 percent. The result is shown in Fig. 51. Because the signal level from the gyro is so low, it was not considered desirable to reduce it further, so the use of this type of filter was abandoned. Filter No. 2 was an M-derived filter with constants shown in Fig. 52 which fed into the matching impedance of 3400 ohms. The filter curve is shown in Fig. 53 and the gyro noise curve using this filter in



ELEVATION GYRO FROM STABILIZER MK. I

SPEED 8500 R.P.M.
PICKOFF COILS BUCKING
PICKOFF MAGNET 115 V 60 ~
WORKING INTO 500 K

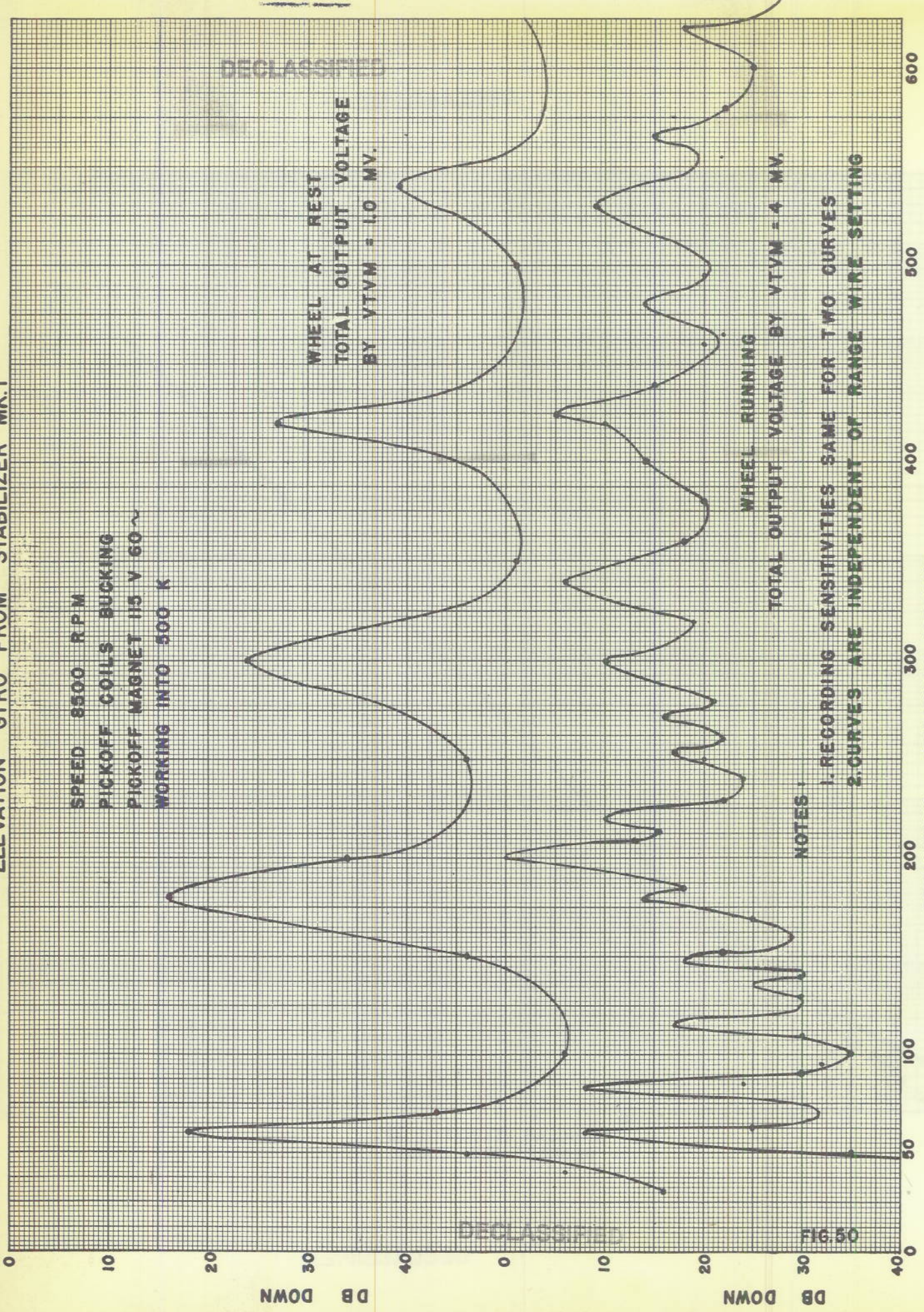
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WHEEL AT REST
TOTAL OUTPUT VOLTAGE
BY VTVM = 1.0 MV.

WHEEL RUNNING
TOTAL OUTPUT VOLTAGE BY VTVM = 4 MV.

NOTES:

- 1. RECORDING SENSITIVITIES SAME FOR TWO CURVES
- 2. CURVES ARE INDEPENDENT OF RANGE WIRE SETTING



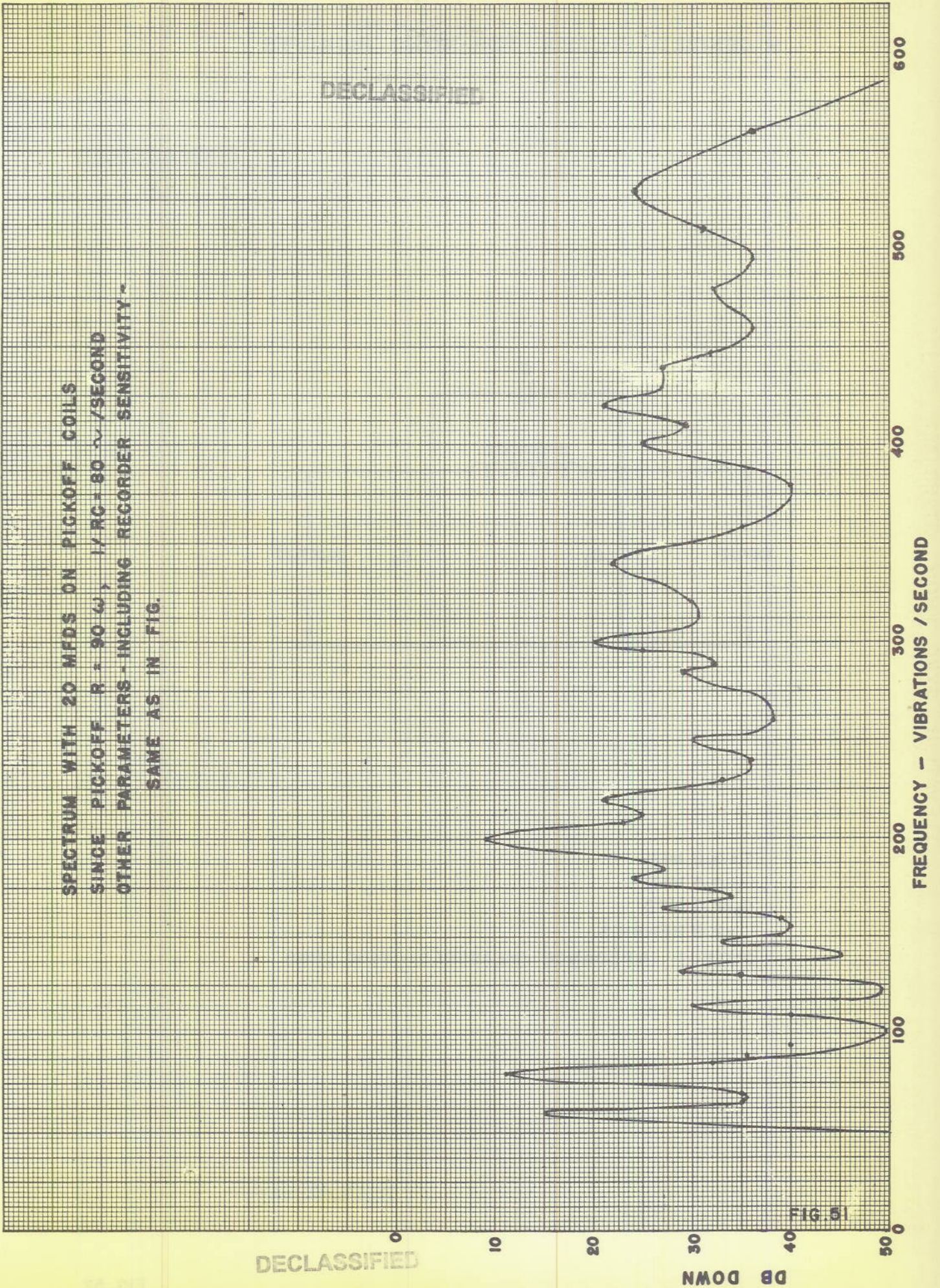
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FIG. 50

ELEVATION GYRO FROM STABILIZER MK. I

SPECTRUM WITH 20 MFDS ON PICKOFF COILS
SINCE PICKOFF $R = 90 \Omega$, $1/RC = 80 \sim / \text{SECOND}$
OTHER PARAMETERS - INCLUDING RECORDER SENSITIVITY -
SAME AS IN FIG.

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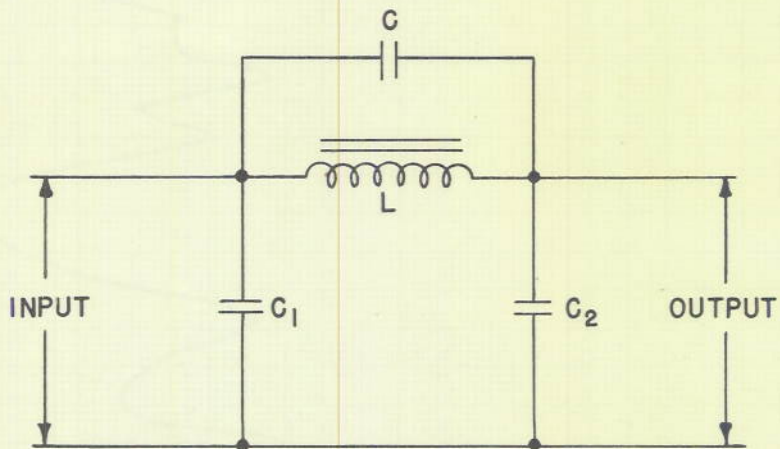
DB DOWN

FIG 51

FREQUENCY - VIBRATIONS / SECOND

M DERIVED FILTER FOR GYRO PICKOFFS

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$C = 0.2$ MFD

$C_1 = 0.5$ MFD

$C_2 = 2.0$ MFD

$L = 2.9$ HENRIES

OUTPUT IMPEDANCE (MEASURED) = 3400 OHMS

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GYRO FILTER
WORKING INTO MATCHING
IMPEDANCE OF 3400 OHMS

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DB DOWN FROM INPUT

FREQUENCY - CYCLES / SECOND

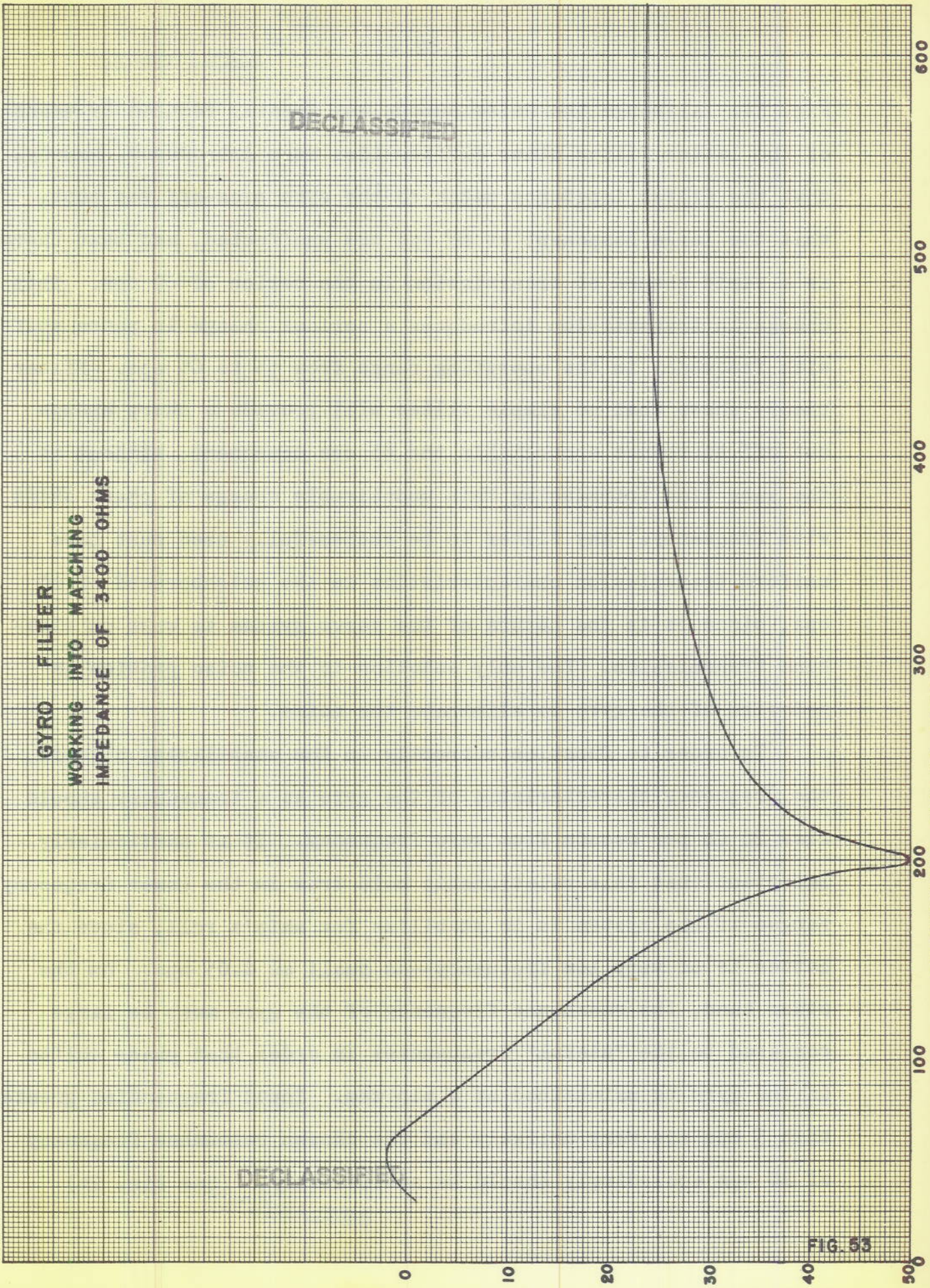


FIG. 53

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Fig. 54. Although the noise output was greatly reduced by means of the latter filter other difficulties were introduced, namely, that the filter impedance match to the gyro pick-off was poor, that the large component at 85 cps was unaffected, and that there is a rapid change of transmission in the region of 60 cps. This change in transmission introduces a serious change in phase shift with frequency in the operating range from 55 to 65 cps. Filter theory shows that no simple filter will provide a sharp enough cut off to reduce appreciably the 85 cps component, without at the same time introducing this undesirable change of phase shift with frequency. Any filter to be successfully used must have uniform transmission characteristics in the neighborhood of 60 cps, since it is the nature of the servo system to work on side-band transmission. The only solution to the noise problem is redesign of the gyro to eliminate the noise.

In order to function correctly in the stabilizing circuit, the frequency characteristic of the gyro as a transducer should rise 20 db per decade from zero frequency. It is particularly important that this relationship hold true in the lower frequency ranges if the system is to stabilize for ship's roll, since the latter is of very low frequency--as small as 0.05 cps. On the other hand, the resonance frequency of the gyro must be large compared to the "useful" frequencies in order that phase shifts in the gyro be maintained at a minimum. Input frequencies greater than 5 cps are very unlikely and the chosen resonance frequency of 20 cps accordingly should be satisfactory. (See Fig. 24)

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ELEVATION GYRO FROM STABILIZER MK. I

NOISE SPECTRUM WITH FILTER NO. 2
RECORDER SENSITIVITY SAME
AS USED IN FIG. 50
FILTER WORKING INTO 3400 OHMS

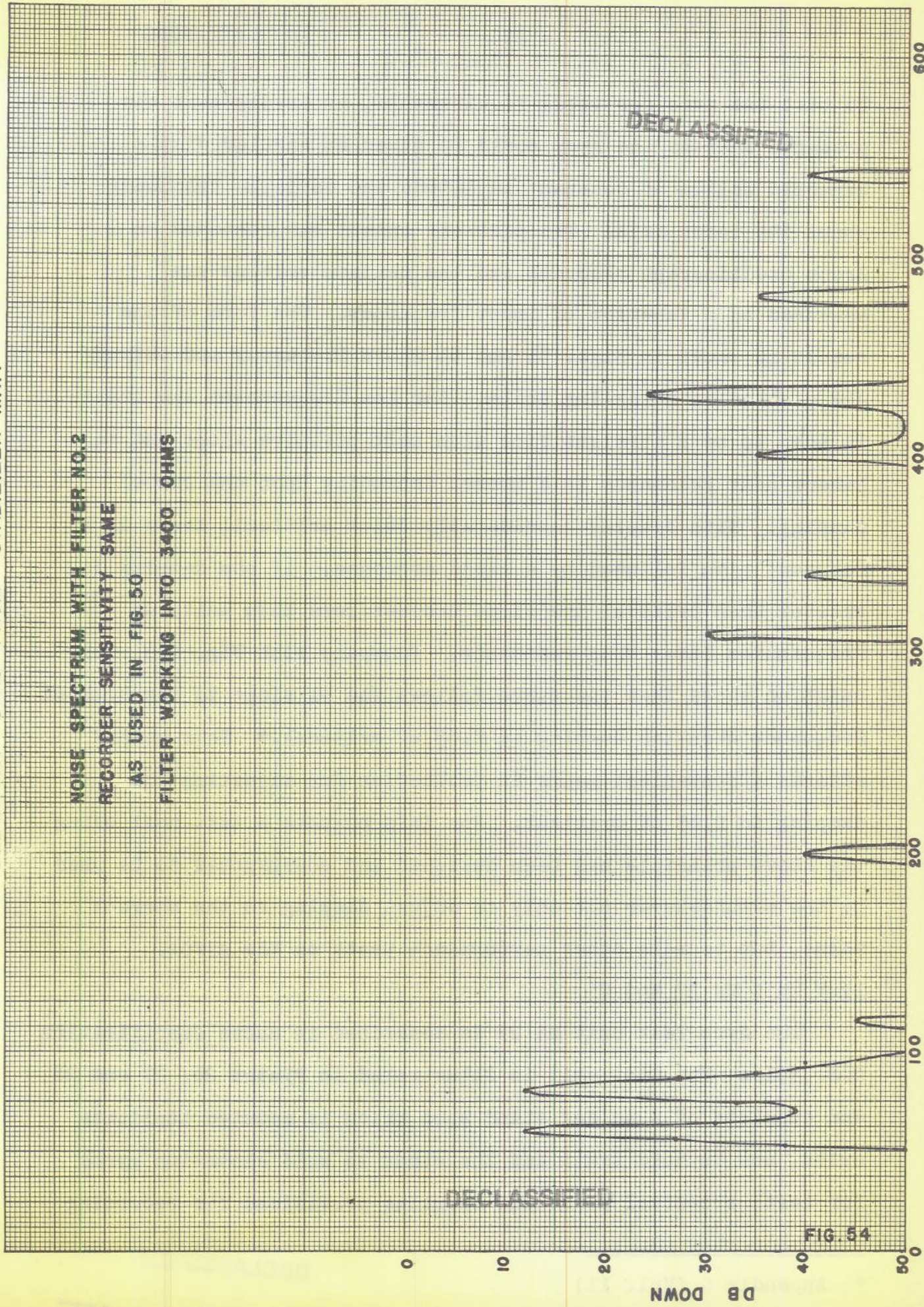


FIG. 54

To test the gyro for these requirements, an arrangement was prepared whereby the gyro could be given an angular simple harmonic motion of constant amplitude and variable frequency about its input axis. The pick-off output was recorded on a Brush Oscillograph recorder and the maximum voltage was measured as a function of input frequency. The form of the result is shown in Figs. 55 and 56 where frequency and output are plotted on a log-log scale. For low frequencies the graph is seen to be a straight line with unit positive slope and to behave near resonance in a manner depending upon the gimbal damping. With damping considerably below critical, there is a resonant rise followed by a rapid decrease. If the damping is greater than critical the slope becomes less than unity at frequencies lower than resonance. (Compare with Fig. 23) Calculation shows that the curve follows the +1 slope to the highest frequency when the damping is 0.65 of critical.* This method affords a convenient means in production for adjusting the damping to 0.65 of critical. For this purpose a test unit using the above principle has been designed and constructed to be used by the manufacturer not only to adjust damping to the correct value, but to make other performance tests on the gyros.

Test Unit MK 27 Mod 0

The gyro Test Unit MK 27 is described in BuOrd Specification O.S. 3916. The test unit is illustrated in Plates 26, 27 and 28 and consists of a welded stand upon which is mounted duplicate units, one to hold train and the other to hold elevation gyros for test, a control panel and mounting provisions for recording

* Appendix G (Vol. 11)

ELEVATION STABILIZER GYRO TESTS

OUTPUT AT 140°F. 8500 RPM AIR 140°F
DAMPING FLUID 5 CC EACH END
ELEV. GYRO NO. 3240

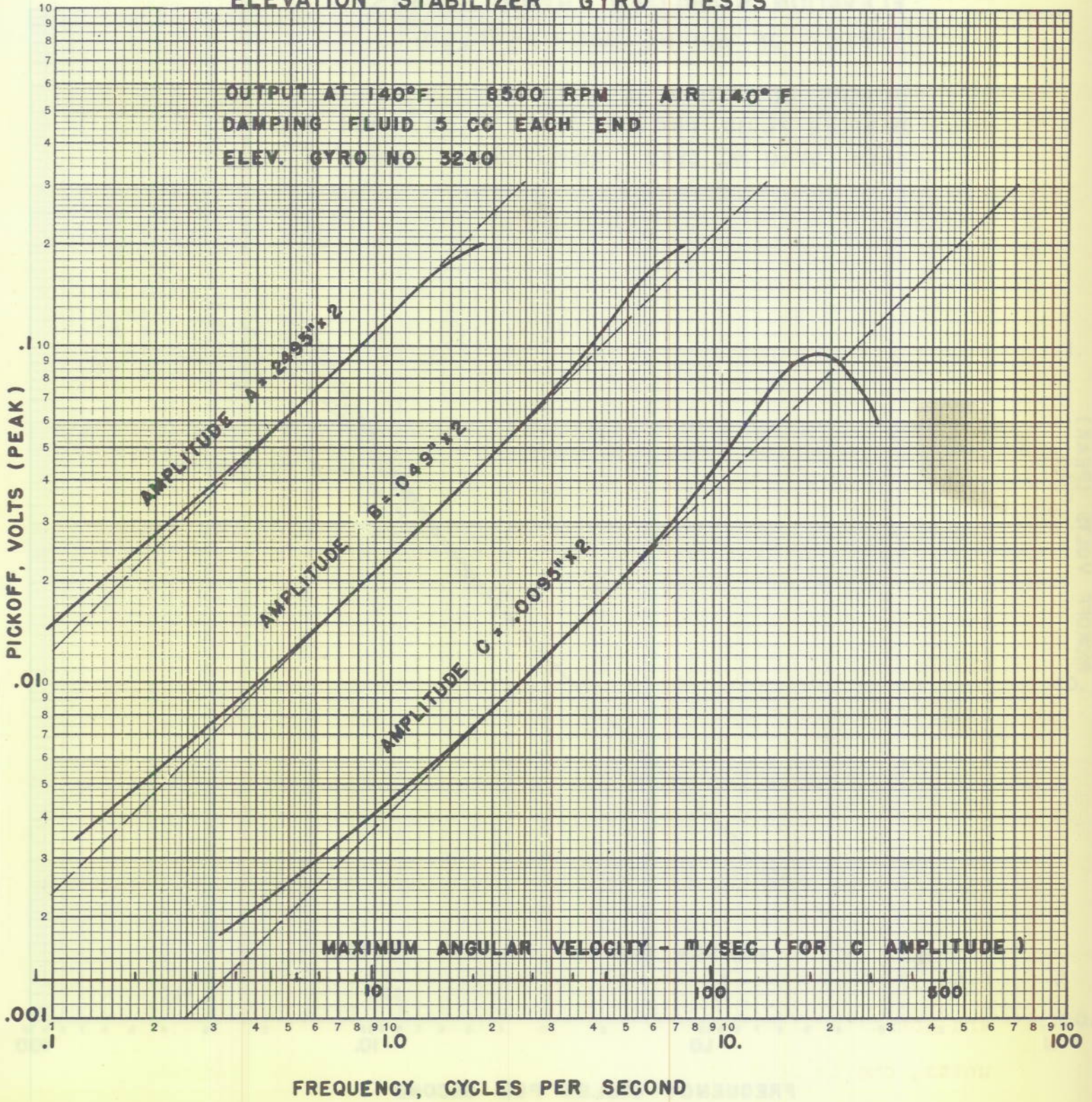


FIG. 55

ELEVATION STABILIZER GYRO TESTS

EFFECT OF ADDING DAMPING FLUID

OUTPUT AT 140° F

DAMPING FLUID FROM 3 CC TO 5 CC, EACH END

ELEV. GYRO NO. 3240 AMPLITUDE C * .0095"X2

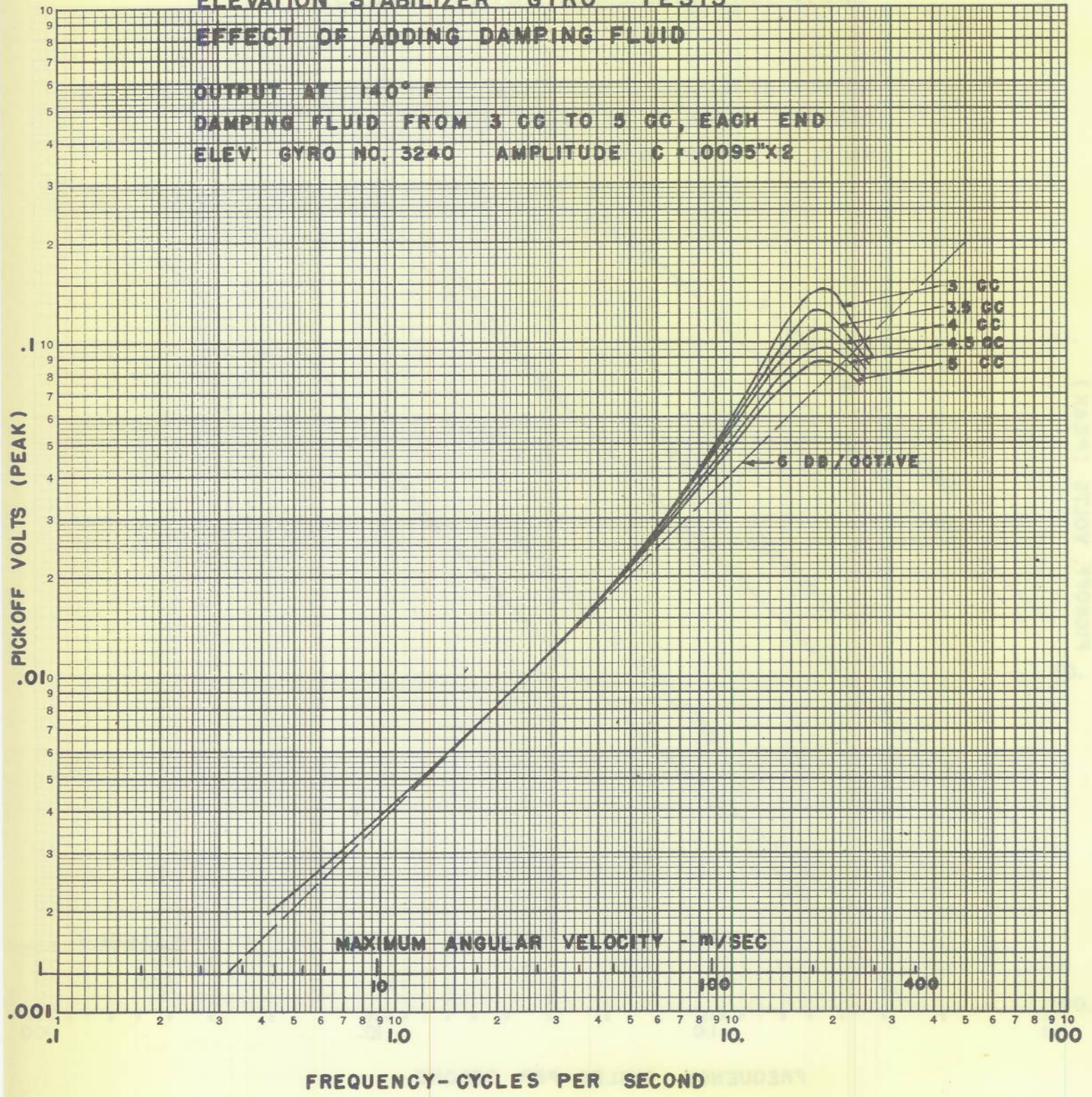


FIG.56

instruments on the top. Each unit is arranged to rock the gyro about its input axis at any of three desired amplitudes and at continuously variable frequencies from 0.1 to 30 oscillations per second. On the lower shelf is mounted the air pump for the gyros together with the variable displacement pump for the hydraulic motors which operate the individual units. Provisions are made for maintaining the gyro under test at the specified ambient temperature.

Plate 29 is the complete circuit for the test unit, while Plate 30 is a typical record for a single frequency. Complete instructions for operation of the test unit and performance of the production test are given in the Specifications.

When peak output voltage as a function of gyro input frequency has been determined the results are plotted on log-log graph paper as in Fig. 57 which shows the test results for a gyro acceptable for use in the Stabilizer Mk 1. Because of machine tolerances in the gyro dampers the result sometimes shows a resonance peak as in Fig. 55. This requires that the quantity of damping fluid be readjusted to give the correct characteristic.

Other Tests

Fig. 58 shows the characteristic for all three amplitudes of motion. For the larger amplitudes A and B the frequency range does not include the resonance frequency because the gimbal amplitude becomes so great before that frequency that the gimbal hits the stops. Also illustrated is the effect of

CALIBRATION DATA - MK. I STABILIZER GYRO

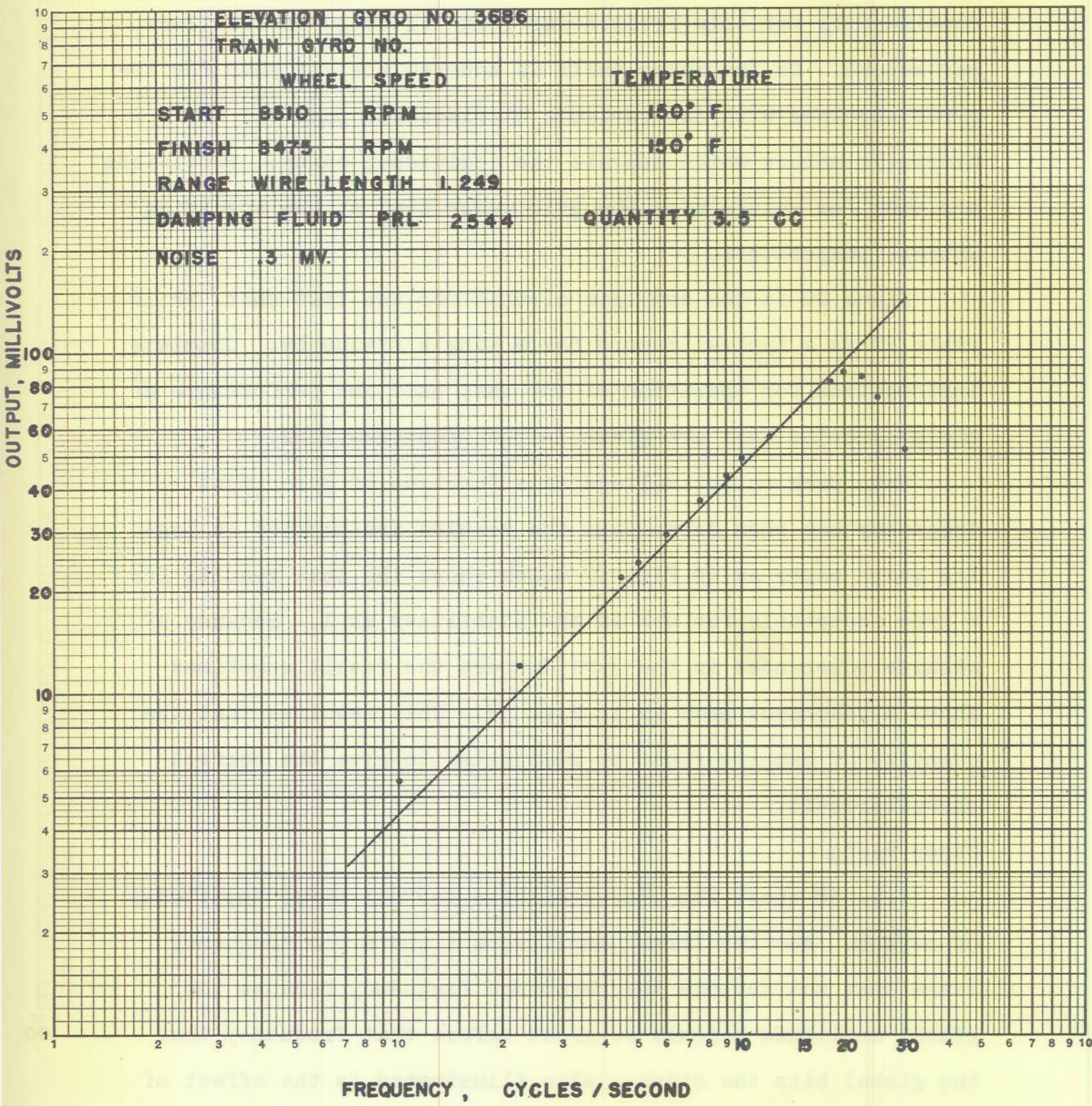


FIG. 57

ELEVATION STABILIZER GYRO TESTS

DAMPING FLUID 4 CC ONE END, 3.5 OTHER END
ELEV. GYRO NO. 3240

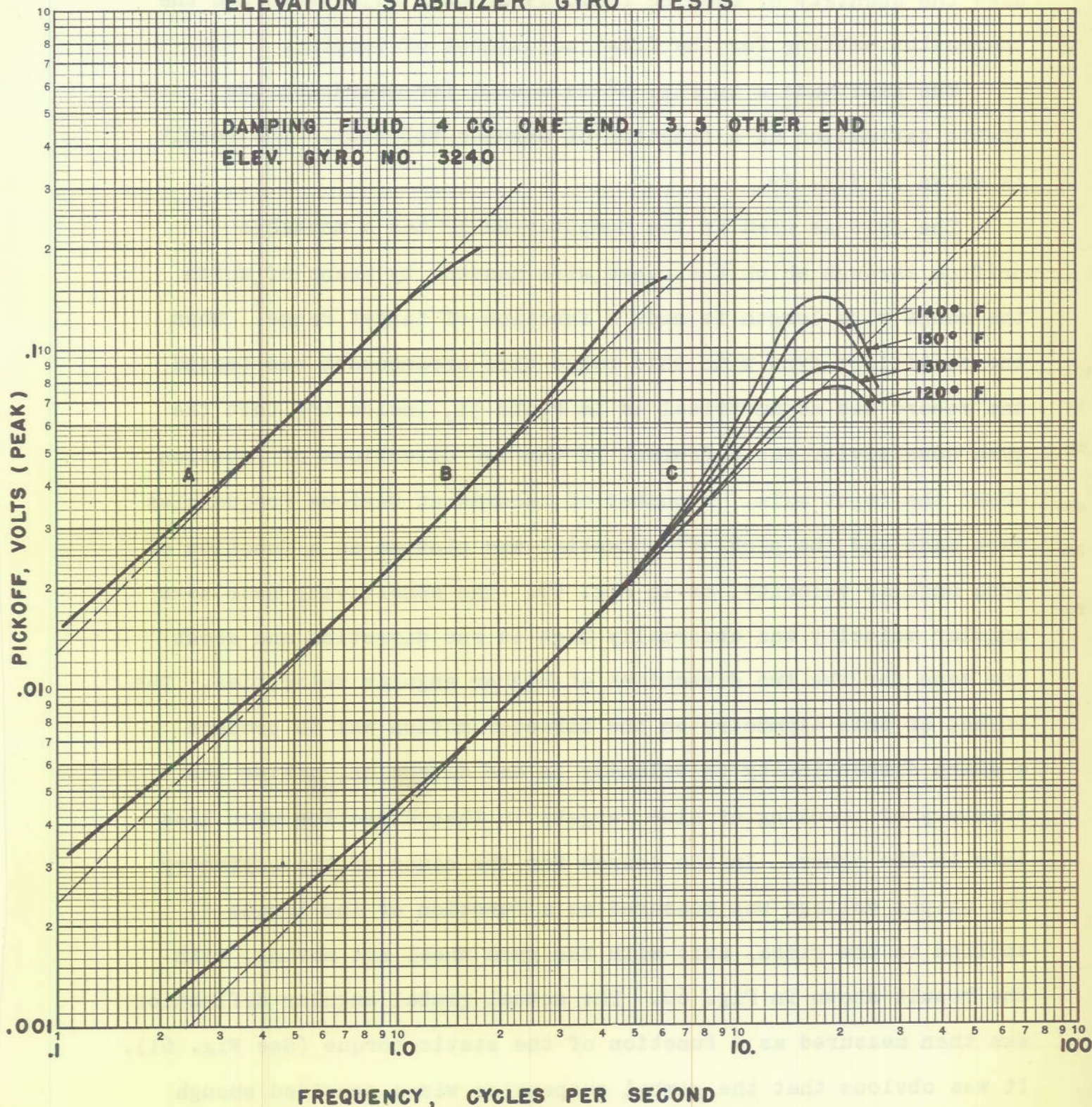


FIG. 58

gyro temperature on the characteristic. The factory adjustment uses the quantity of damping fluid as a rough adjustment and the thermostat setting for the final adjustment of damping.

The amplitude A in Fig. 58 is useful for measuring the static deflection as a function of angular velocity. The result is shown in Fig. 49.

The gyro as used in the Computer Mk 17 has a moveable orifice through which the range wire passes, by means of which the range wire length is made a function of target range. When the stabilizer gyro with this range wire arrangement was tested the record was asymmetrical as in Plate 31, indicating that the gyro sensitivity was different in the two directions of rotation about the input axis. A number of records at various frequencies were made and the pick-off potential was plotted as a function of gyro angular velocity, as in Fig. 59. The sensitivity near zero angular velocity was abnormally high in one direction and about the same for the two directions at higher angular velocities. The effect of this asymmetry on the Director motion was to produce a sharp discontinuity in velocity in one direction, making the accuracy of tracking of slow targets in that direction much less than in the other. In the search for the cause of the asymmetry the output voltage was measured as a function of the torque applied to the gimbal axis with the gyro wheel not moving, with the result shown in Fig. 60. The actual gimbal angular deflection was then measured as a function of the static torque (See Fig. 61). It was obvious that the gimbal suspension wires provided enough torque normally to keep the range wire pressed against one side of

GYRO SER. NO. 2821

OUTPUT SIGNAL VS. INPUT
ANGULAR VELOCITY
CONDITIONS SAME AS IN FIG. 60
EXCEPT WHEEL SPEED 8500 RPM

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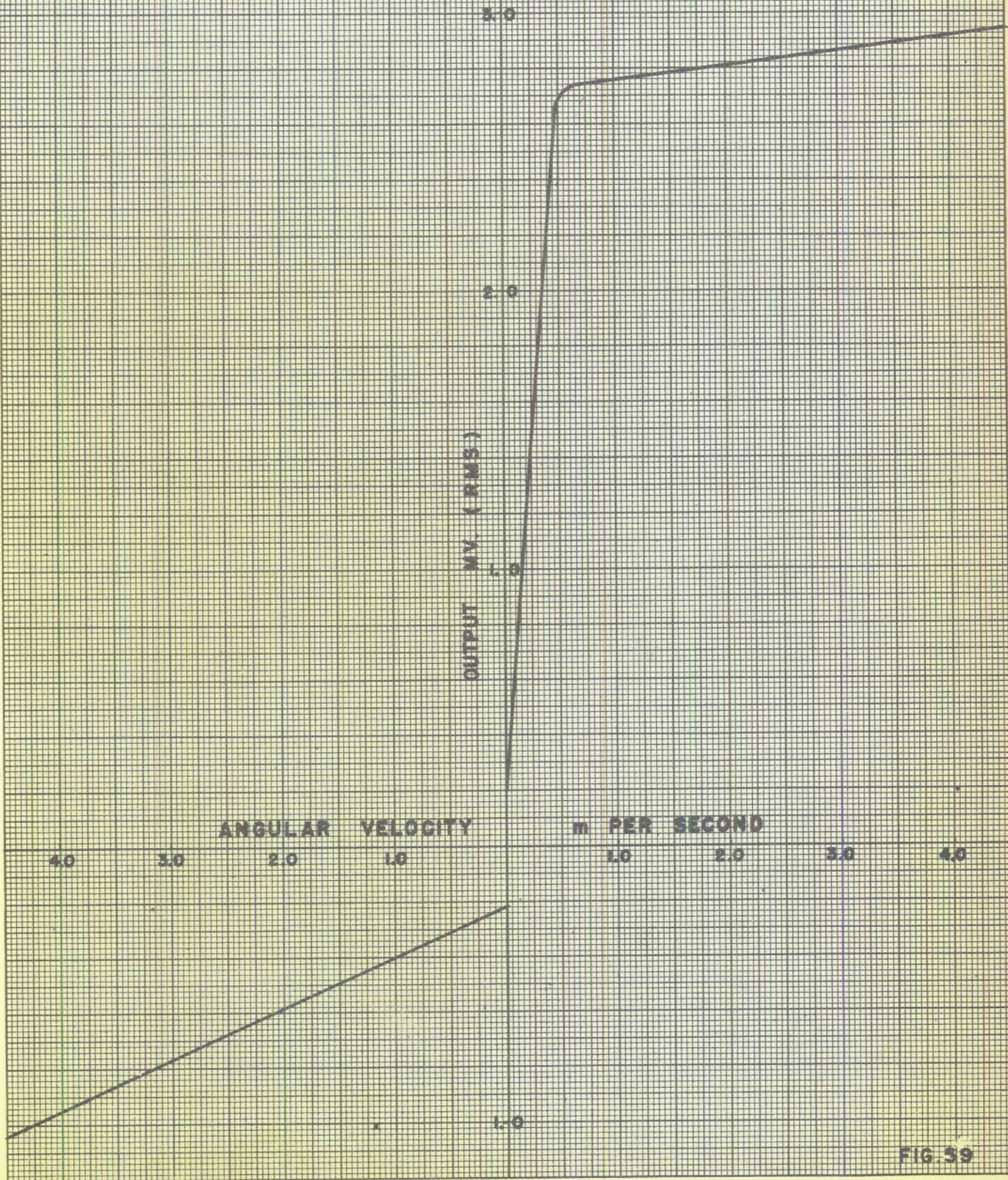


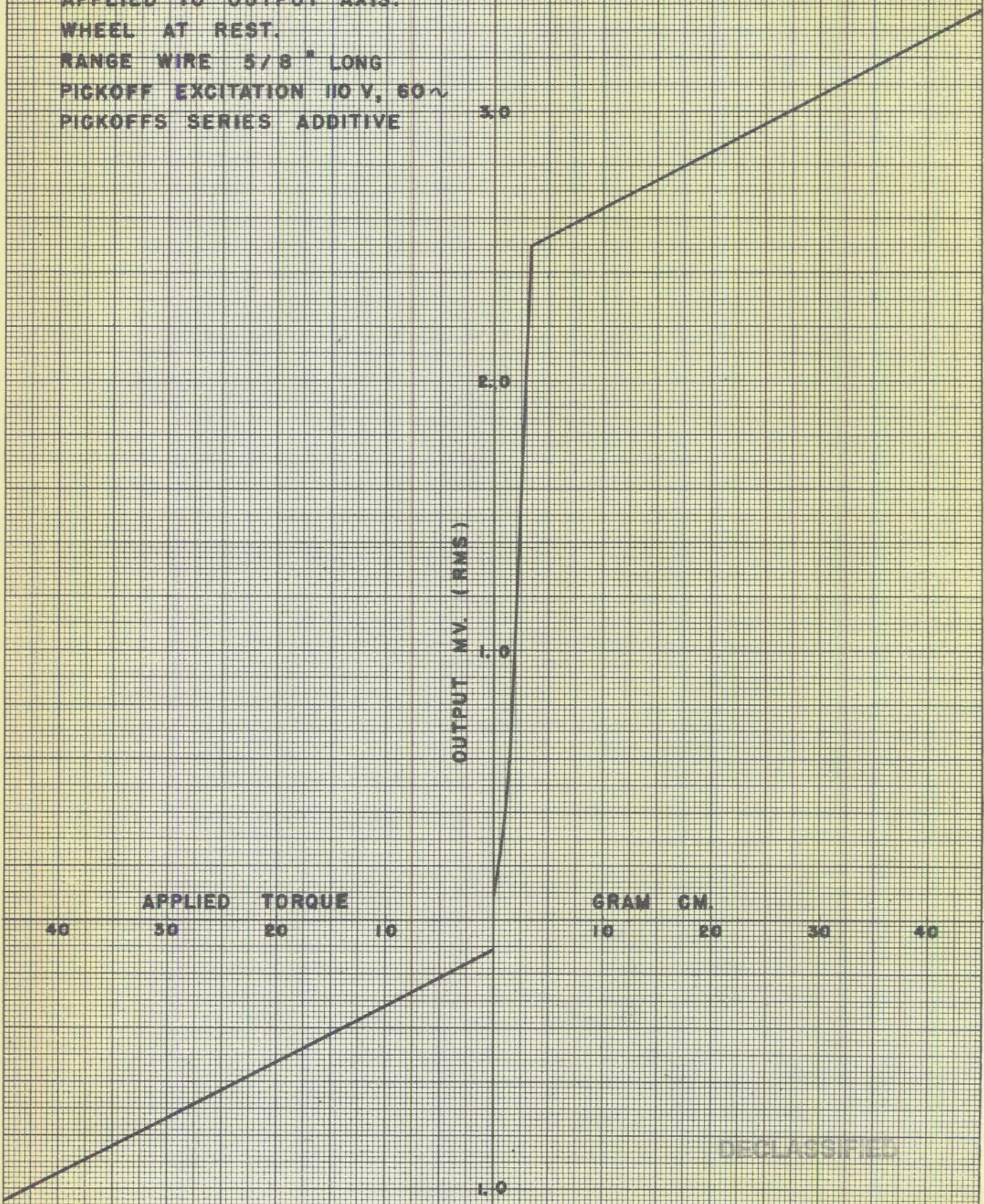
FIG. 59

DECLASSIFIED

GYRO SER. NO. 2821

DECLASSIFIED

OUTPUT SIGNAL VS. TORQUE
APPLIED TO OUTPUT AXIS.
WHEEL AT REST.
RANGE WIRE 5/8" LONG
PICKOFF EXCITATION 110 V, 60~
PICKOFFS SERIES ADDITIVE



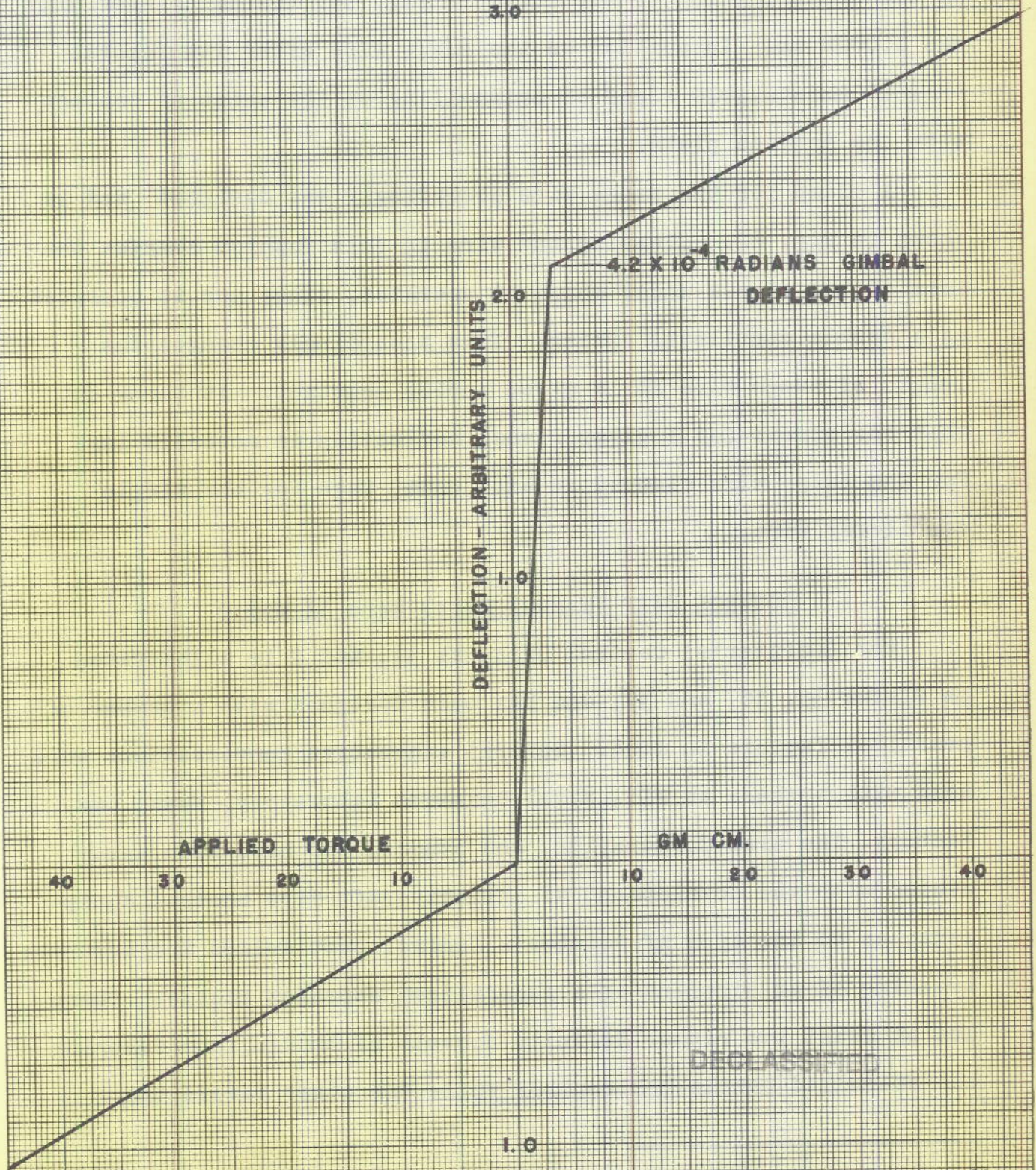
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FIG. 60

GYRO SER. NO. 2821

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GIMBAL DEFLECTION VS.
APPLIED TORQUE



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FIG. 61

the orifice. This finally was verified by a measurement of the resistance between range wire and orifice plate. There was no difficulty in detecting the play by this means. From the width of the steep portion of the curve in Fig. 59, the calculated play was 0.0008 in. Inspection of the range wire after its removal showed unmistakable signs of Brinnelling at the point of contact with the orifice plate.

A clamp for the range wire accordingly was designed* and is shown in Fig. 62. Clamping the wire in this fashion changes the form of the stress under which it operates, since now it operates as a double cantilever spring. This accordingly changes the length of range wire for a given spring constant. It turns out that the stress for a given gimbal deflection is actually less for the range wire clamped at both ends, than for the single cantilever wire.

CONTROL UNIT (Manual Rate) Mark 31 Mod 0

The (Pointer's) Control Unit, Mk 31, Mod 0 is illustrated in Plates 35, 36, and 37, and has been designed with a number of practical factors in mind. Several exhaustive conversations were held with workers at MIT, Naval Research Laboratory, Naval Gun Factory, The Arma Corporation, and others, who have been associated with the development of anti-aircraft fire control equipment, as to the type of Pointer's Control best suited for accurate tracking of an airplane on a generalized approach course. There are at least two rather definite schools of thought, one favoring the so-called handle-bar control while the other favors the

* Appendix G (Vol. II)

STABILIZER GYRO RANGE WIRE CLAMP

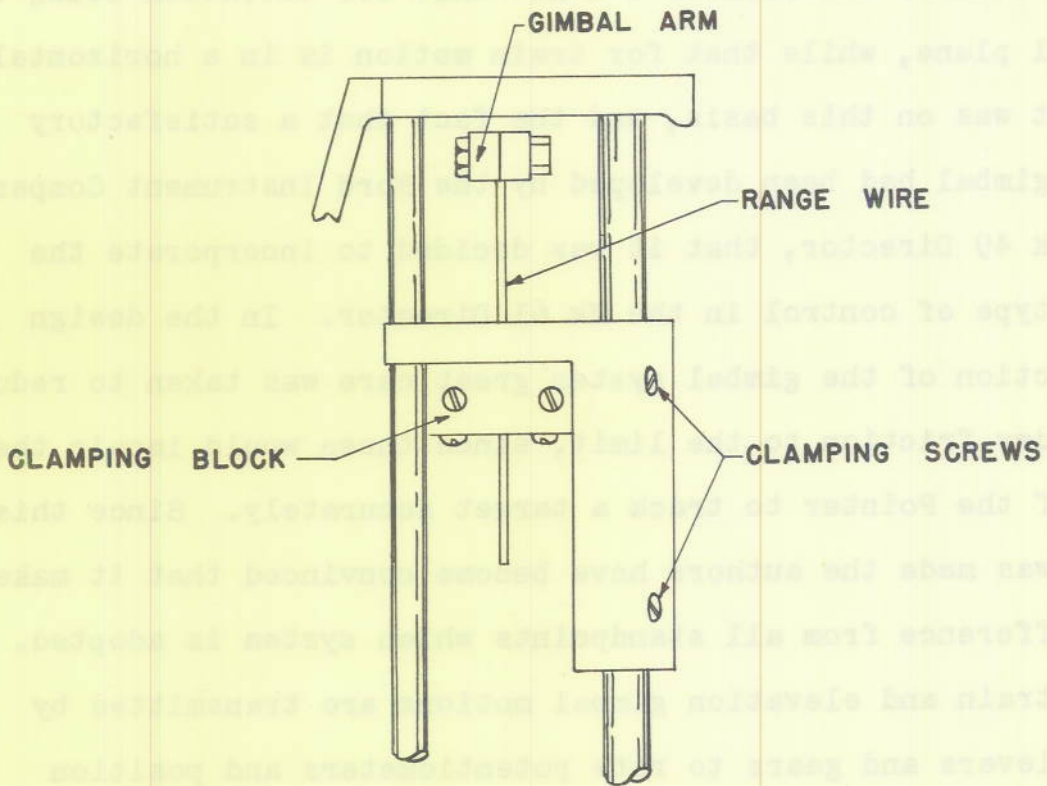


FIG. 62

joystick control. In the handle-bar control, two different types of motion are required to produce Director motion in train and elevation, namely, a rotary motion about a vertical axis, and a rotary motion about a horizontal axis. While the actual motion of the joystick gimbal is identical with that of the handle-bar control, the method of producing this motion is somewhat different, for the Pointer grasps a handle pointing directly forward and away from himself. The motion of his hand forms a kind of polar coordinate system in which the radius vector determines the Director line of sight angular velocity in both direction and magnitude. Thus motion in train and elevation requires the same type of motion of the Pointer's hand--that for elevation being in a vertical plane, while that for train motion is in a horizontal plane. It was on this basis, and the fact that a satisfactory joystick gimbal had been developed by the Ford Instrument Company for the Mk 49 Director, that it was decided to incorporate the joystick type of control in the Mk 61 Director. In the design and production of the gimbal system great care was taken to reduce play and dry friction to the limit, since these would impair the ability of the Pointer to track a target accurately. Since this decision was made the authors have become convinced that it makes little difference from all standpoints which system is adopted.

The train and elevation gimbal motions are transmitted by means of levers and gears to rate potentiometers and position tachometers. (Plate 37) Considerable care has been taken in the design and construction to reduce mechanical play and dry

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friction to a minimum. Play in the system, of course, destroys the linear relationship between joystick deflection and the desired output signal. The objection to dry friction in the system arises from the fact that the frictional drag is independent of velocity so that the force required to track simultaneously in train and elevation is greater than that for train or elevation tracking alone. The effect of this is that when one tries to move the joystick in a circle, the actual motion is more in the form of a square and motion along a diagonal is resolved into step motion along the train and elevation directions.

On the other hand, if dry friction is reduced to the point where it is not noticeable, the joystick feels loose in the hand of the Pointer and he finds some difficulty in keeping it at a constant deflection, the tendency being to overshoot all motions. For this reason, viscous dampers were placed on the train and elevation gimbals (Plate 36), care being taken that here too the dry friction was held to a minimum. The viscous dampers consisted of three discs moving between other stationary discs and separated by approximately 0.005 inch. The construction is shown in Plate 39. The space between was filled with Dow-Corning Silicone fluid of high viscosity, the highest obtainable at the time being 30,000 poises.

Fig. 63 shows the torque versus velocity curve for this damper at the temperatures indicated in the figure. In the Director the dampers are thermostated at approximately 140°F. Silicone fluid has the advantage that the viscosity varies rather slowly

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VISCOUS DAMPER

TYPE DRWG. NO. G-0770

- o- 73°F
- x- 35°C
- + 160°F

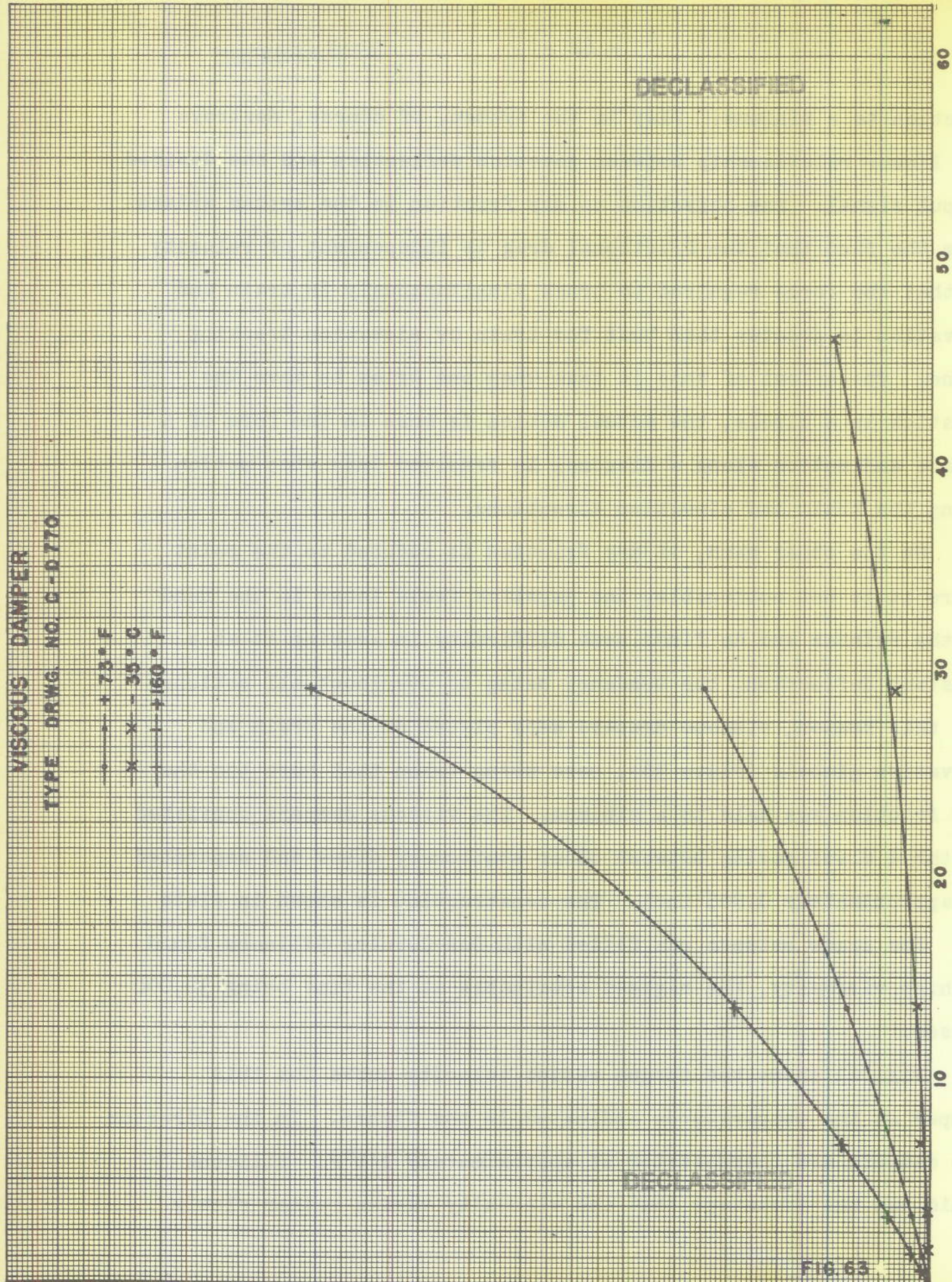
ANG. VEL. - ° / SECOND

TORQUE - IN. LBS.

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DECLASSIFIED

FIG 63



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with temperature and, therefore, does not become so stiff at minus 10°F that the mechanism would be unduly strained when the joystick is operated. The construction and design provide a structure rigid enough that the viscous drag is felt immediately when the joystick is moved.

To give the Director Pointer a sense of the direction of displacement of the joystick from the neutral and to arrange that the Director velocity falls to zero when the joystick is released, springs are provided for returning the gimbal to the normal position with a time constant of about 4 seconds. The dampers and springs are shown in Plate 36.

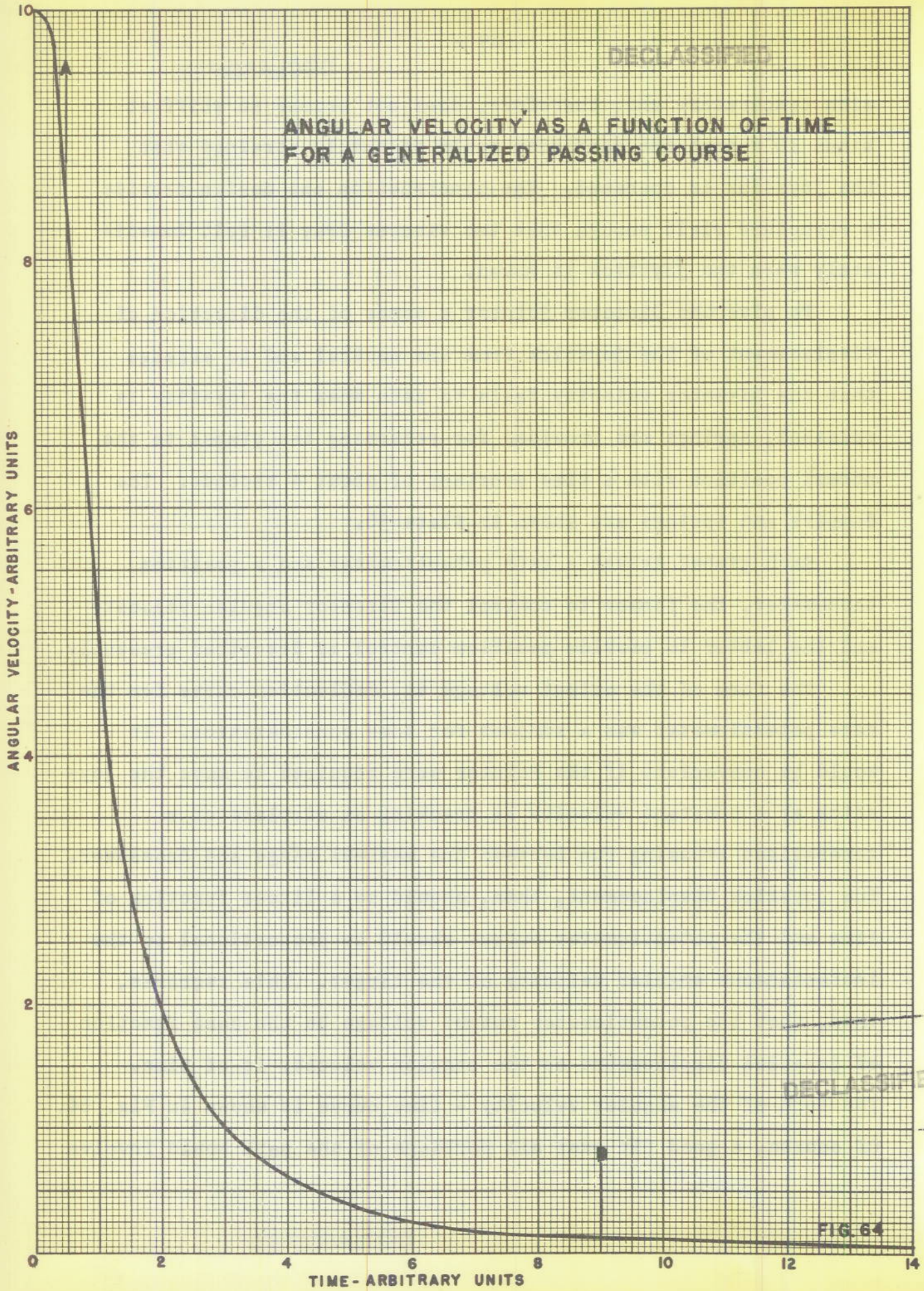
Each gimbal drives a rate potentiometer and a position tachometer, the former to control the Director angular velocity and the latter to provide position control as described presently.

The form of the output voltage vs. deflection curve for the rate potentiometer was a subject for some consideration. It would be convenient if the Pointer were required to move the joystick at a constant velocity in tracking an airplane on a generalized crossing run between the maximum range and crossover. The joystick displacement, then, should be a linear function of time and the potentiometer output should be proportional to the instantaneous angular velocity of the target. This requires, then, that the potentiometer output voltage be the same function of joystick displacement as the angular velocity is of time. The form of the angular velocity - time curve is shown in Fig. 64. Of course, a good fit over all portions of the path would involve

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ANGULAR VELOCITY AS A FUNCTION OF TIME FOR A GENERALIZED PASSING COURSE



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FIG. 64

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a complicated arrangement. Accordingly, the region for which a fit was attempted was that between the more or less arbitrary points A and B (Fig. 64), where the point B was made to occur near the central or normal position of the joystick.

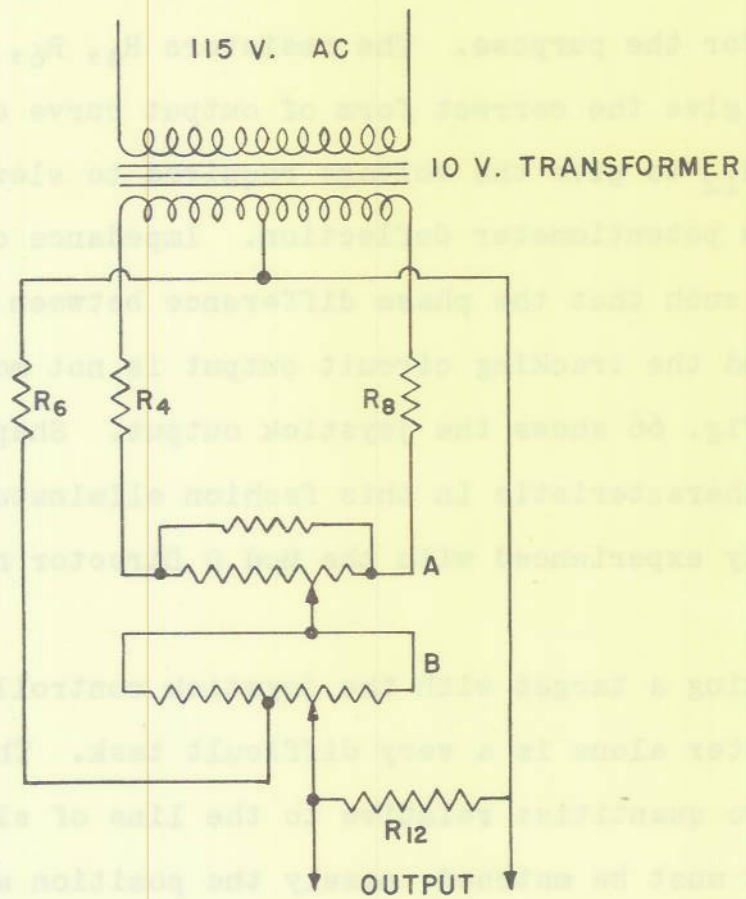
The circuit is shown in Fig. 65 and Plate 38. The dual potentiometer AB is a Leeds and Northrup two inch model constructed for the purpose. The resistors R_4 , R_6 , and R_8 were chosen to give the correct form of output curve and the resistor R_{12} to give the voltage required to slew the Director at maximum potentiometer deflection. Impedance of the transformer is such that the phase difference between the supply voltage and the tracking circuit output is not more than one degree. Fig. 66 shows the joystick output. Shaping of the joystick characteristic in this fashion eliminates the excessive sensitivity experienced with the Mod 0 Director near zero tracking rate.

Tracking a target with the joystick controlling a rate potentiometer alone is a very difficult task. This is true because two quantities relative to the line of sight (LOS) and the target must be matched, namely the position and its first derivative. The tracking potentiometer governs the angular velocity. The Pointer's judgment must supply the position through anticipating as the target approaches the crosshair in the telescope, for he must bring the LOS on the target at the correct angular velocity. To aid his judgment, there is provided a rate integral device or a position control. The

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TRACKING POTENTIOMETER WITH SHAPED OUTPUT

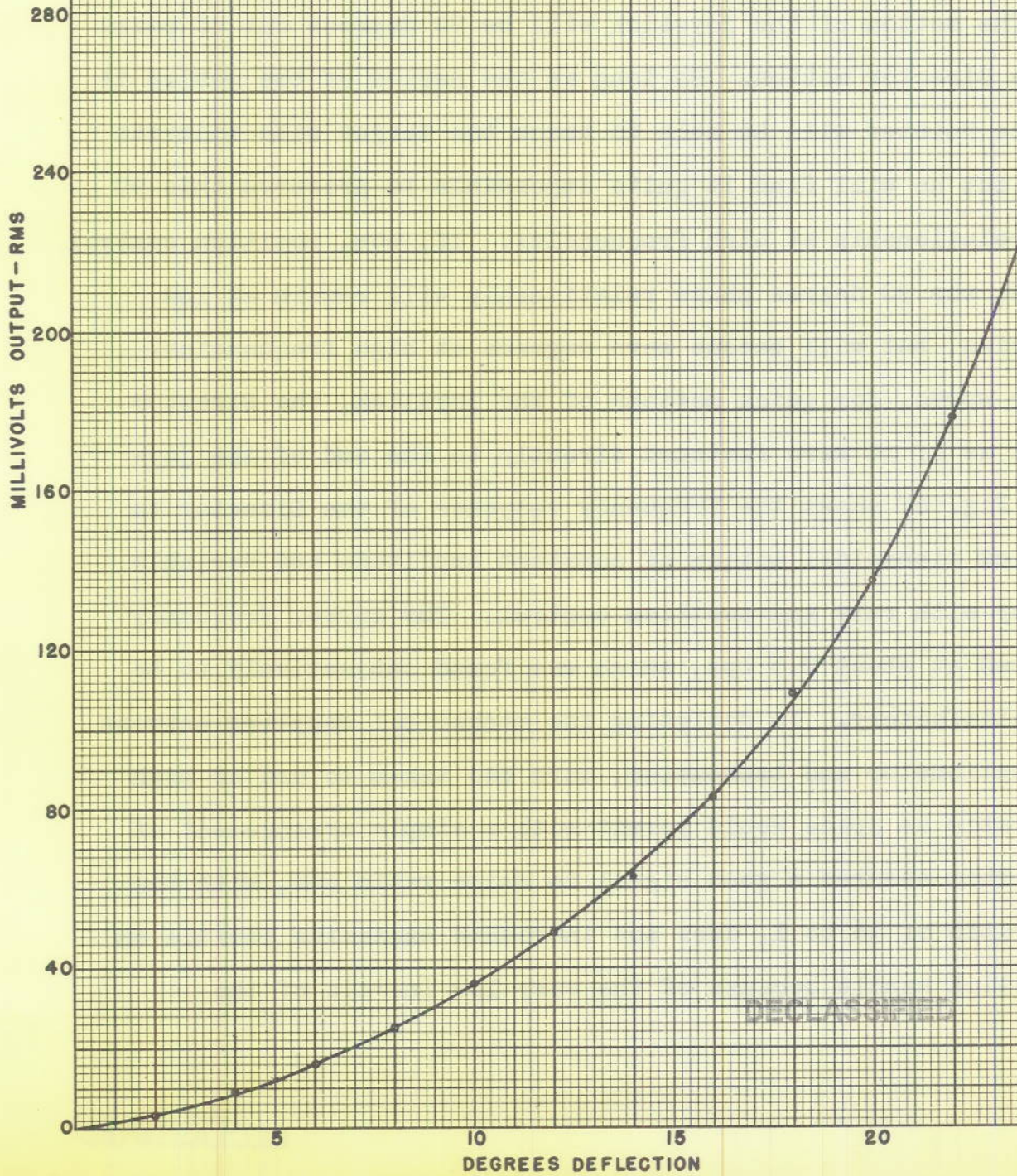
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PCU JOYSTICK DEFLECTION
VS
PCU OUTPUT

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FIG. 66

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position control signal is supplied by a tachometer also driven by the joystick motion. The tachometer output, which appears in series with the potentiometer potential, is proportional to the rate at which the joystick is moved.

The necessity for position control can be seen in another way. Let the target move from side to side in sinusoidal motion and let the Pointer track the target with potentiometer control only. The motion of the joystick will be 90 degrees out of phase with the Director motion. So long as the period of the motion is large the Pointer will be able to track the target with moderate success but he will find it quite impossible to preserve this 90 degree relationship at high frequencies. If, now, position control is added, the 90 degree phase relationship will remain at low frequencies, but will become zero degrees at high frequencies. In other words, for quick motions of the joystick, the Director will act as if it were fastened directly to the end of the joystick. Fig. 67 shows the frequency response of the Director to a joystick sinusoidal motion of constant amplitude and variable frequency with rate and position control. The corner frequency was placed at about 0.5 cps, which was found subjectively to be quite satisfactory. In designing the mechanical coupling between the potentiometer and tachometer, care was taken to use as high a gear ratio as space would permit with a simple arrangement of gears. This assures a good signal to noise ratio and, with the chosen ratio of 36 to 1, does not introduce excessive inertia on the joystick handle because of the very low inertia of the

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EFFECT OF POSITION CONTROL ON FREQUENCY
CHARACTERISTIC OF IDEAL 20DB PER DECADE SYSTEM

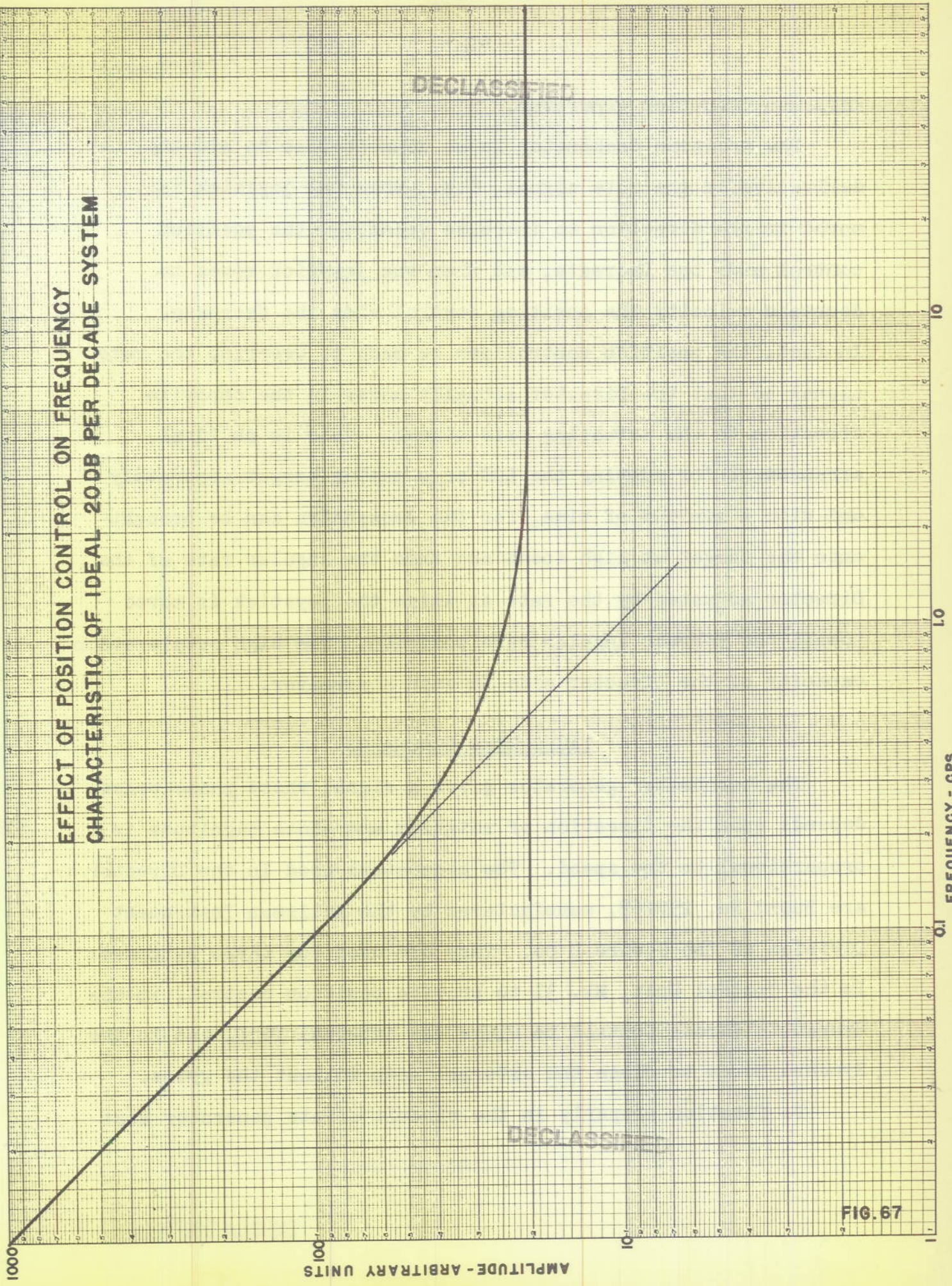


FIG. 67

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Kollsman induction generator.

The position tachometer is so connected as to aid the derivative of the rate signal, i.e., when the joystick is moved in the direction to increase velocity, the position control aids the increase, and when the joystick moves to decrease velocity the position control aids the decrease. In fact, the position control can be made to override the rate signal so that the Director actually moves in the opposite direction to the actuating rate signal. This is an ideal arrangement for putting the LOS on a moving target accurately and with a minimum of time, for the crosshairs can be brought onto the target at high speed and then the angular rate of the Director adjusted by the rate at which the joystick is moved toward the correct angular rate position. The high acceleration capacity of the Director aids in such a maneuver.

TACHOMETER GENERATOR

The tachometer generator gives a signal whose phase sense depends upon the direction of rotation and whose magnitude is proportional to the speed. The generators used in the Director are BuOrd No. 257468, manufactured by the Kollsman Instrument Division of the Square-D Co. They are used for three purposes: In the Control Unit, Mk. 31 to provide position control, in the Hydraulic Stroke Control to close the internal loop, and in the Synchro Boxes to close the external loop without the gyros.

To function properly in the circuit a rate generator must

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have certain properties in addition to those mentioned above. The signal with the rotor at rest in any angular position must be inappreciable, the harmonic content of the induced signal should be low, and the phase shift through the generator should be zero, when feeding into the correct impedance. All these quantities should be independent of speed, temperature and other physical conditions.

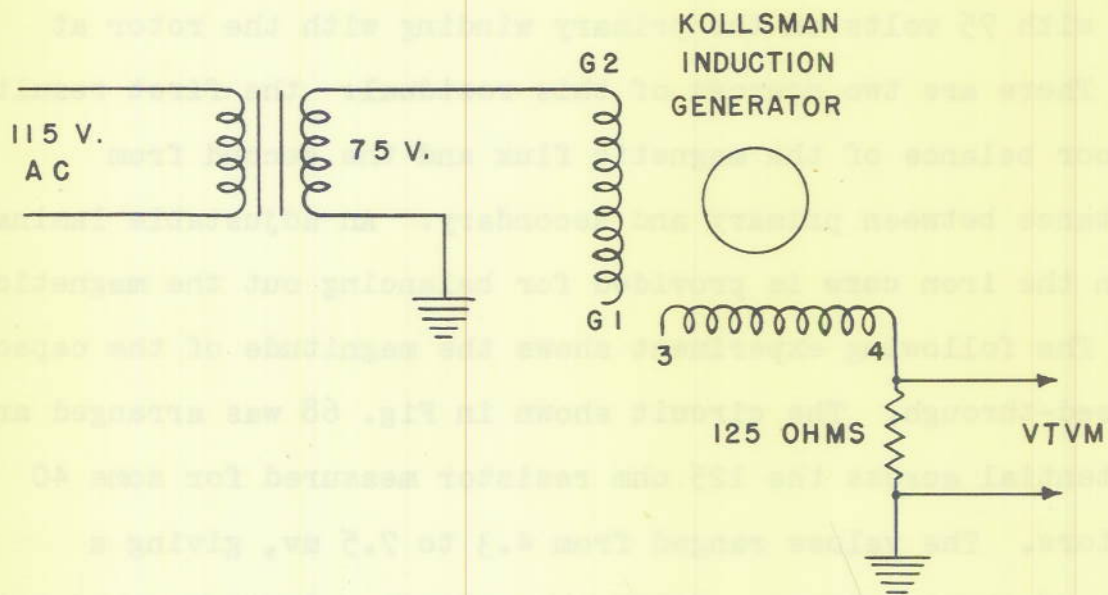
The tachometer generator gives approximately 100 mv residual signal with 75 volts on the primary winding with the rotor at rest. There are two sources of this residual: the first results from poor balance of the magnetic flux and the second from capacitance between primary and secondary. An adjustable lamination in the iron core is provided for balancing out the magnetic flux. The following experiment shows the magnitude of the capacitive feed-through. The circuit shown in Fig. 68 was arranged and the potential across the 125 ohm resistor measured for some 40 generators. The values ranged from 4.3 to 7.5 mv, giving a current of about 0.04 ma. Since the generator is to be used with a resistor of this order of magnitude shunting the secondary this gives about the zero rotation residual--too much for use in the input circuit of the amplifier.

The residual was reduced considerably by introducing into the secondary circuit a potential produced by reactance current in the primary, as shown in Plate 33. The amount of potential introduced is controlled by the potentiometer according to the need of the particular generator. The phasing condenser C1 is

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CIRCUIT FOR MEASURING CAPACITIVE FEEDTHROUGH OF KOLLSMAN RATE GENERATOR

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FIG. 68

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included to provide zero phase shift between supply line and circuit output. The supply voltage was limited to 75 volts, for above this the iron saturates and introduces a considerable third harmonic. By means of this circuit the residual potential is reduced for most generators to less than 1.5 mv and the phase angle between input and output is less than 4° .

Generators were found to vary considerably in their residual and their phase shift. In order to select the generators best suited for use in the Director the Test Unit Mk 29 Mod 0 illustrated in Plate 32 was developed. The circuit of the Test Unit is given in Plate 34. The Test Unit is described in Procurement Specification O.S. 5301 and instructions for the test in O.S. 3923. One chassis contains the supply transformer, the fixture for holding the generator during test, a motor which rotates the generator in either direction at a known rate, and the test circuit proper. Circuit constants have been very carefully matched for all test units. The second chassis contains resonant filters for elimination of harmonics from the generated signals for purposes of accurate measurement. A Ballantine vacuum tube voltmeter, a cathode ray oscillograph, and a General Radio Strobotac complete the required equipment. The quantities checked in the test are: (1) Minimum Residual voltage for several angular positions of the rotor; (2) voltage output at a specified speed in both directions; (3) phase shift at the specified speed in both directions.

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Accepted units are stamped BuOrd No. 257468-5 if they have a smooth shaft and BuOrd No. 257468-6 if they have a pinion shaft.

TRACKING AMPLIFIER

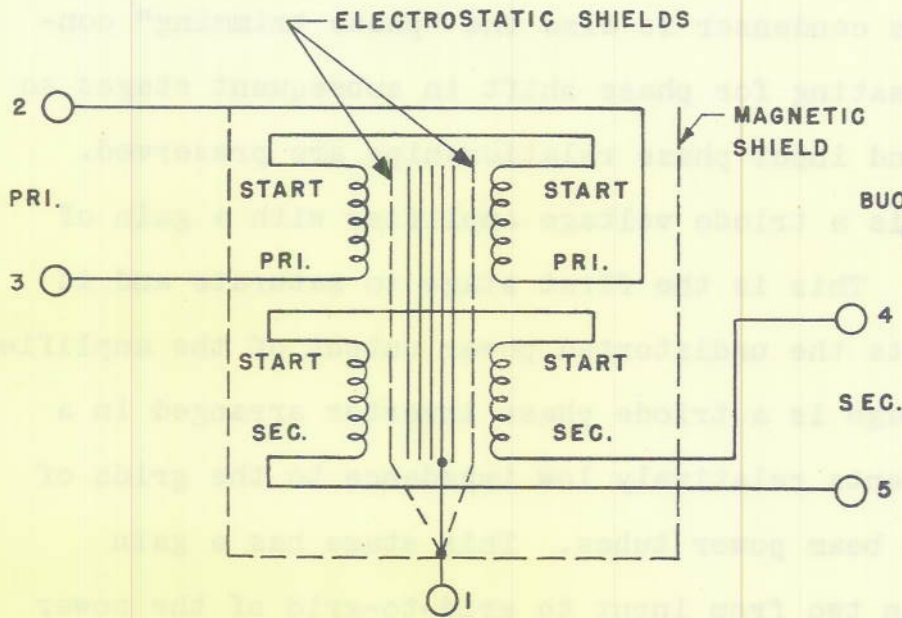
The Tracking Amplifier BuOrd Dwg. No. 903259, circuit BuOrd Dwg No. 903260 is a conventional one except for the equalizing network, which is mounted on the Amplifier chassis. The amplifier is shown in Plate 40 and the circuit in Plate 41.

The input transformer specifications are shown in Fig. 69. Primary impedance at low signals (order of 0.010 volt) is approximately 120 ohms and at high levels (0.25 volt) is about 250 ohms. Secondary impedance is about 80,000 ohms. The use of Electric Metal or Mu Metal for the core is necessary because the transformer is used at such low input levels, since this is the nature of a servo system. It was likewise found necessary to shield the transformer from external fields, principally that from the filament supply transformer by a complete Mu Metal shield inside the transformer can. The hum bucking construction was found to reduce magnetic pickup appreciably. All transformers are hermetically sealed.

The input transformer feeds into the high impedance equalizing network, to be described in a separate section, and then to the grid of the first amplifier tube. The first stage uses a 6AC7 in a conventional circuit to give a voltage gain of approximately 100. The circuit design is such that the gain is relatively

TRACKING AMPLIFIER
INPUT TRANSFORMER SPECIFICATIONS

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BUORD, 903427
O.S. 3928

D.C. RESISTANCE

TERMINALS 2 - 3 : 15 OHMS AT 25°C
TERMINALS 4 - 5 : 740 OHMS AT 25°C

PRIMARY IMPEDANCE

400 OHMS AT 60 ~ (0.2 VOLT)

LEAKAGE RESISTANCE

TERMINALS 2 - 3 TO 4 - 5 : 1500 MEGOHMS AT 500 VOLTS D.C.
TERMINALS 2 - 3 TO 1 : 1500 MEGOHMS AT 500 VOLTS D.C.
TERMINALS 4 - 5 TO 1 : 1500 MEGOHMS AT 500 VOLTS D.C.

VOLTAGE RATIO

2.7 ± 0.3 VOLTS AT TERMINALS 4 - 5 (MEASURED WITH VTVM),
FOR 0.2 VOLT 60 ~ APPLIED TO TERMINALS 2 - 3.

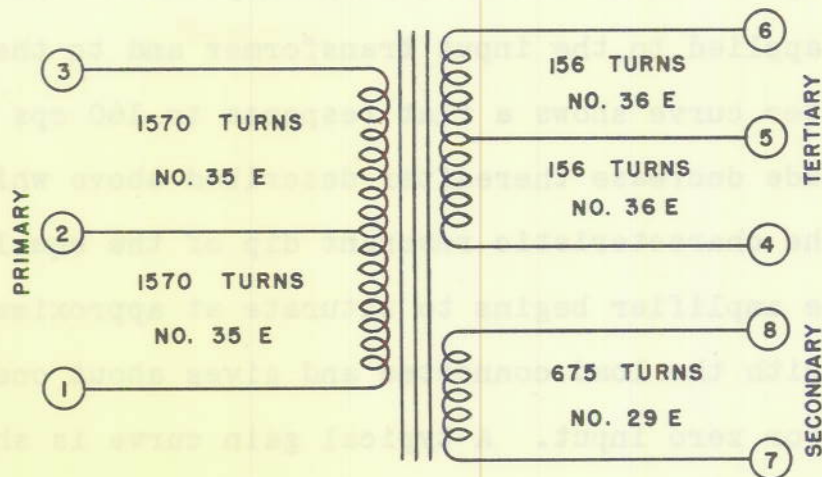
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independent of plate supply potential. As shown in Plate 41 a condenser C3 shunts the plate of the 6AC7 to ground. A flat characteristic to a corner frequency of approximately 160 cps and then a fall-off of 20 db per decade is produced by this arrangement. This condenser is also the "phase trimming" condenser for compensating for phase shift in subsequent stages so that the output and input phase relationships are preserved. The second stage is a triode voltage amplifier with a gain of approximately 32. This is the first stage to saturate and it consequently limits the undistorted power output of the amplifier.

The third stage is a triode phase inverter arranged in a circuit that presents relatively low impedance to the grids of the following 6V6 beam power tubes. This stage has a gain slightly less than two from input to grid-to-grid of the power stage. The self-biased power stage of 6V6 beam power tubes feeds into the output transformer shunted by condensers C11 and C12. The latter are inserted for the purpose of rendering the impedance looking back into the transformer from the output winding a resistive one. The values of the condensers are such that the resonance frequency is considerably different from 60 cps so that time delays and phase shifts with frequency, characteristic of resonant circuits, are avoided. A 10 percent negative feedback signal improves stability of the amplifier. Specifications for the output transformer are shown in Fig. 70.

The output impedance of the output transformer is 500 ohms, but because of the amplifier feedback the effective output impe-

DECLASSIFIED TRACKING AMPLIFIER
 OUTPUT TRANSFORMER SPECIFICATIONS



BUORD. 904087
 O.S. 3928

D.C. RESISTANCE

TERMINALS 1-3: 575 OHMS \pm 10%
 TERMINALS 7-8: 24 OHMS \pm 10%
 TERMINALS 4-6: 65 OHMS \pm 10%

INDUCTANCE

TERMINALS 1-3: 85 H (MINIMUM) AT 230 VOLTS
 TERMINALS 7-8: 4 H (MINIMUM) AT 51 VOLTS
 TERMINALS 4-6: 0.8 H (MINIMUM) AT 23 VOLTS

VOLTAGE RATIO

WITH 115 VOLTS 60 ~ AT TERMINALS 1-3, VOLTAGES
 MEASURED WITH VTVM SHOULD BE AS FOLLOWS:

TERMINALS 1-3 57.5 \pm 1.0 VOLTS
 TERMINALS 2-3 57.5 \pm 1.0 VOLTS
 TERMINALS 4-5 5.75 \pm 0.25 VOLTS
 TERMINALS 5-6 5.75 \pm 0.25 VOLTS
 TERMINALS 7-8 20.0 \pm 2.0 VOLTS

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FIG. 70

dance of the amplifier is reduced to 270 ohms. Since the impedance of the load (one winding of the Diehl stroke motor) is 700 ohms, this gives fairly good load regulation. The overall gain, including the equalizing network, is about 76 db at 60 cps. Fig. 71 shows the frequency response of the amplifier with signal applied to the input transformer and to the first grid. The latter curve shows a flat response to 160 cps and the 20 db per decade decrease thereafter described above while the former shows the characteristic resonant dip of the equalizing network.

The amplifier begins to saturate at approximately 55 volts output with the load connected and gives about one volt noise output for zero input. A typical gain curve is shown in Fig. 72.

EQUALIZING NETWORK

As discussed previously the equalizing network is for the purpose of extending the 20 db per decade frequency range of the Control Device (Fig. 6). This is accomplished by inserting into the circuit a component with a rising frequency characteristic from a corner frequency approximately matching that of the stroke motor. Such a network is the Parallel T pad (Fig. 31 and Plate 54) BuOrd No. 903184).

Analysis of the unbridged parallel T pad shows that the impedance of the parallel path should be one half that of each element in the series path and that the resonance frequency is that frequency for which the capacitive reactance of each condenser is equal to the corresponding resistor in the circuit. If the attenuation at resonance is to be high the resistors and

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FREQUENCY RESPONSE OF TRACKING AMPLIFIER

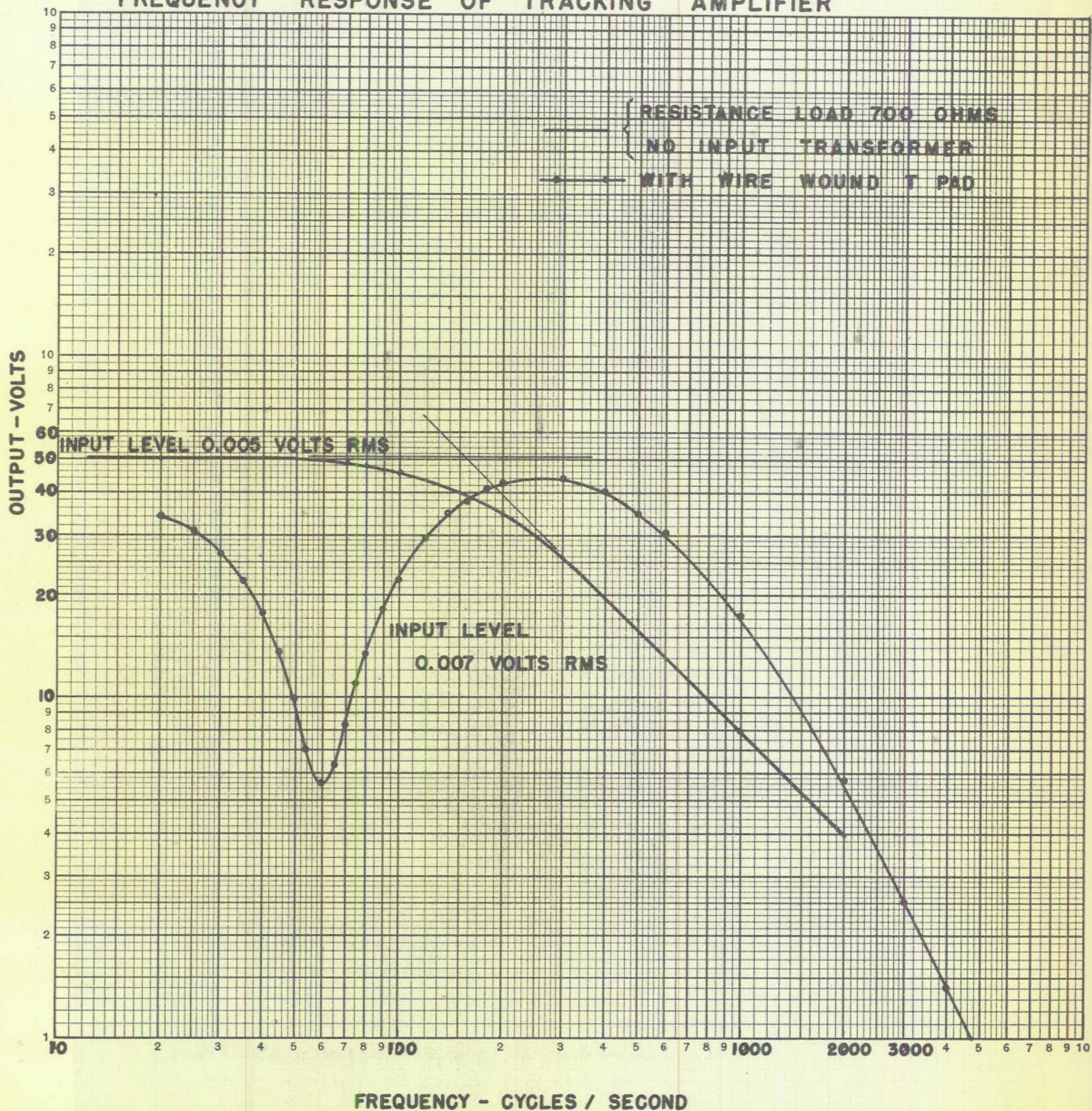
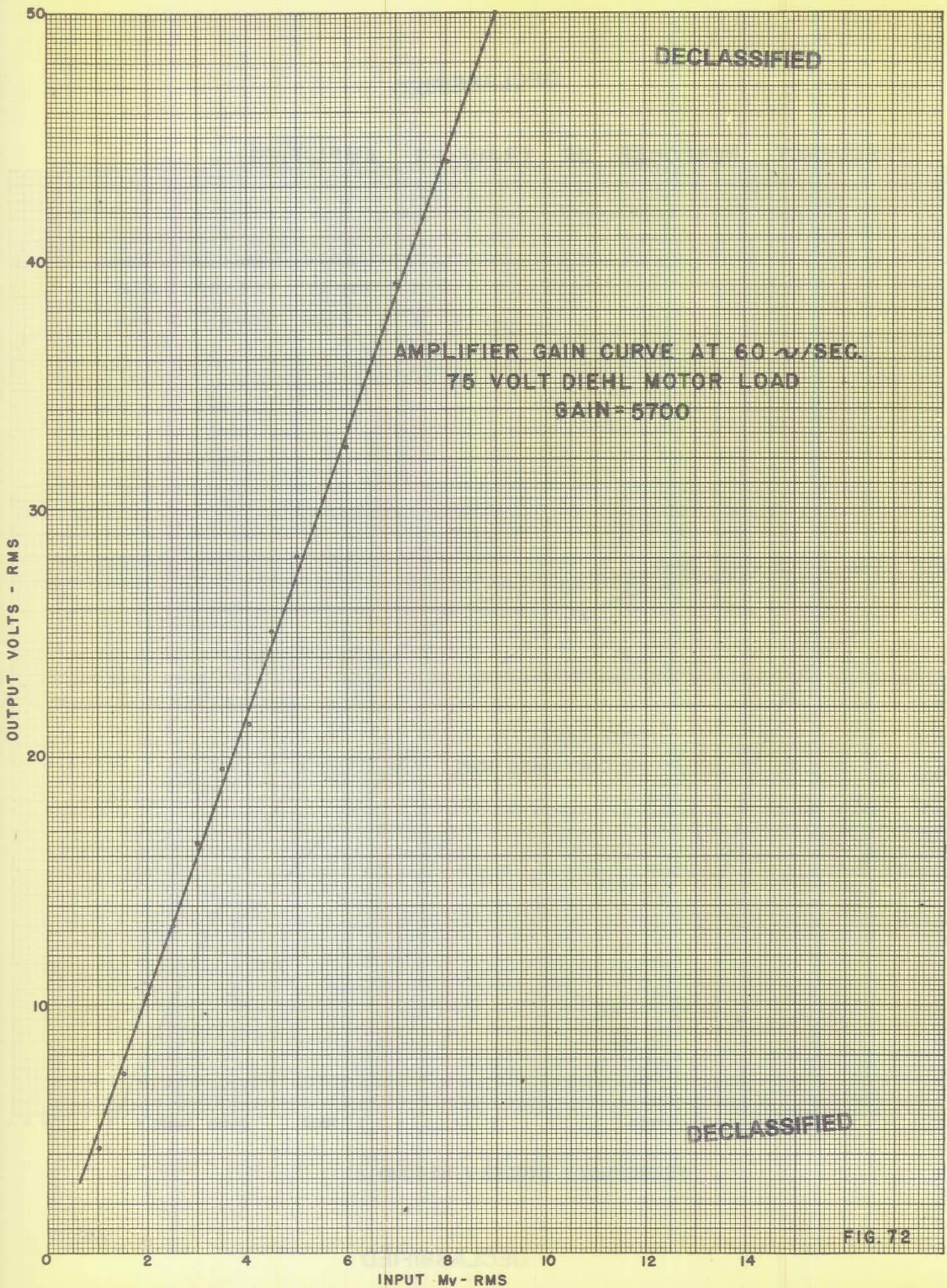


FIG. 71

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FIG. 72

capacitors must be well matched and if the resonance frequency is to be 60 cps the values must be close to nominal.

The first units to be made had carbon resistors, but it was soon found that time and temperature variations were considerable. So wire wound resistors were substituted with a nominal tolerance of 0.1 percent with silvered mica condensers of 0.5 percent tolerance. These units are now considered satisfactory for use in the Director.

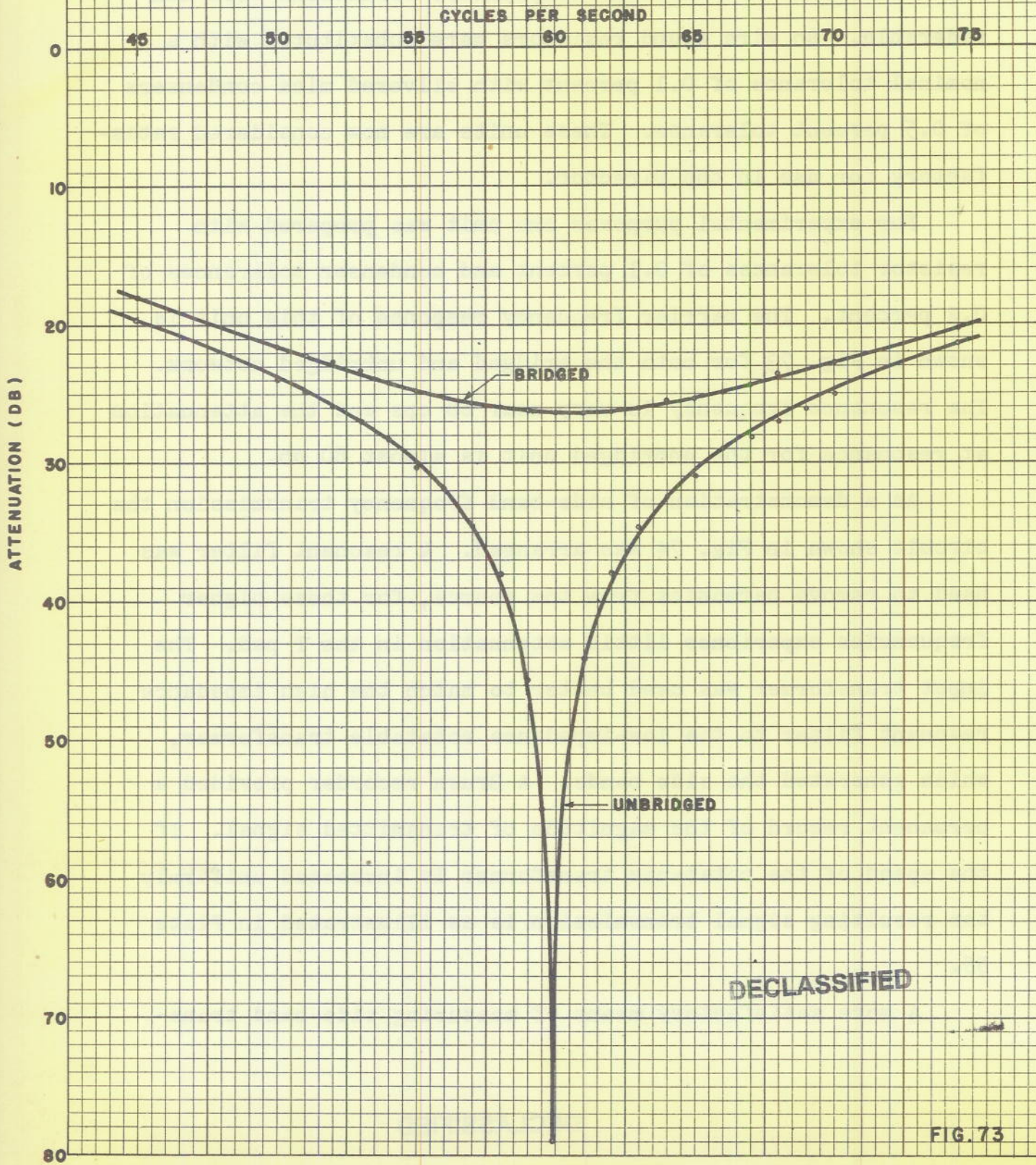
For experimental purposes one unit was prepared with resistor tolerances of 0.1 percent and condenser tolerances of 0.2 percent. The carrier frequency response of this unit is shown in Fig. 73 for both the bridged and unbridged network. The resonance frequency is very near 60 cps and the attenuation at resonance for the unbridged unit is almost 80 db.

As a demonstration of side-band frequency transmission the circuit shown in Fig. 74 was arranged. A resonant filter was used to remove harmonics from the source, for these higher frequencies experience little attenuation in the T pad. The input transformer was used better to match the high impedance resonant filter to the low-impedance rotatable transformer, which generated the side bands. A Brush recorder provided a permanent record of the magnitude of transmitted signal. If the speed of the rotatable transformer is increased uniformly the resulting signal transmission is as illustrated in Plate 55.

A more satisfactory means of measuring side-band trans-

PARALLEL T NETWORK
FREQUENCY RESPONSE

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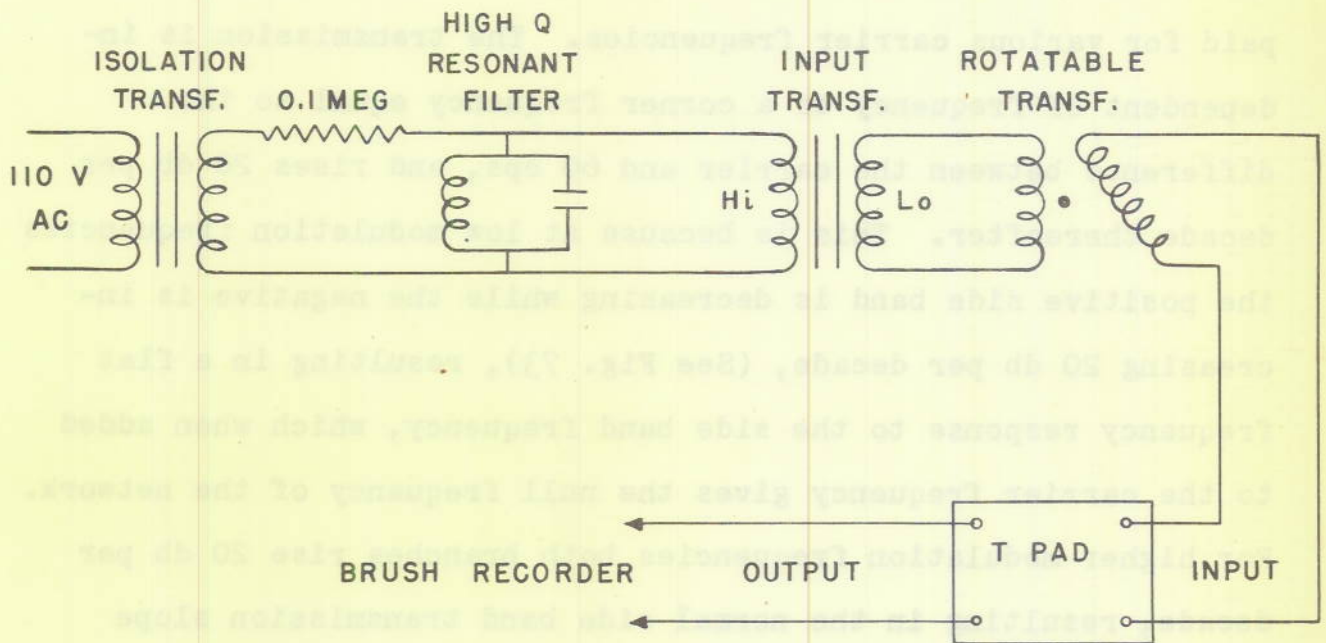


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FIG. 73

CIRCUIT FOR MEASUREMENT OF SIDE BAND
TRANSMISSION OF PARALLEL T PAD

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FIG. 74

mission is from plots such as those in Fig. 73 from which transmission against frequency difference from resonance may be obtained. The side-band transmission for the unbridged T-pad thus obtained is shown in Fig. 75 and the transmission is seen to increase 20 db per decade. The side band transmission for the bridged T pad is given in Fig. 32.

According to the Objectives the Director is to give satisfactory operation over a supply frequency range from 55 to 65 cps. Fig. 76 shows the frequency response of the unbridged T pad for various carrier frequencies. The transmission is independent of frequency to a corner frequency equal to the difference between the carrier and 60 cps, and rises 20 db per decade thereafter. This is because at low modulation frequencies the positive side band is decreasing while the negative is increasing 20 db per decade, (See Fig. 73), resulting in a flat frequency response to the side band frequency, which when added to the carrier frequency gives the null frequency of the network. For higher modulation frequencies both branches rise 20 db per decade, resulting in the normal side band transmission slope from a very sharp corner.

The side band frequency characteristic of the bridged pad, on the other hand, is almost independent of carrier frequency from 55 to 65 cps, as shown in Fig. 77. Fig. 33 shows that the slight variation of corner frequency of the bridged T pad between 55 and 65 cps will affect the frequency characteristic of the Control Device inappreciably. For this reason the bridged

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X1000

X100

X10

X1

X10⁻¹

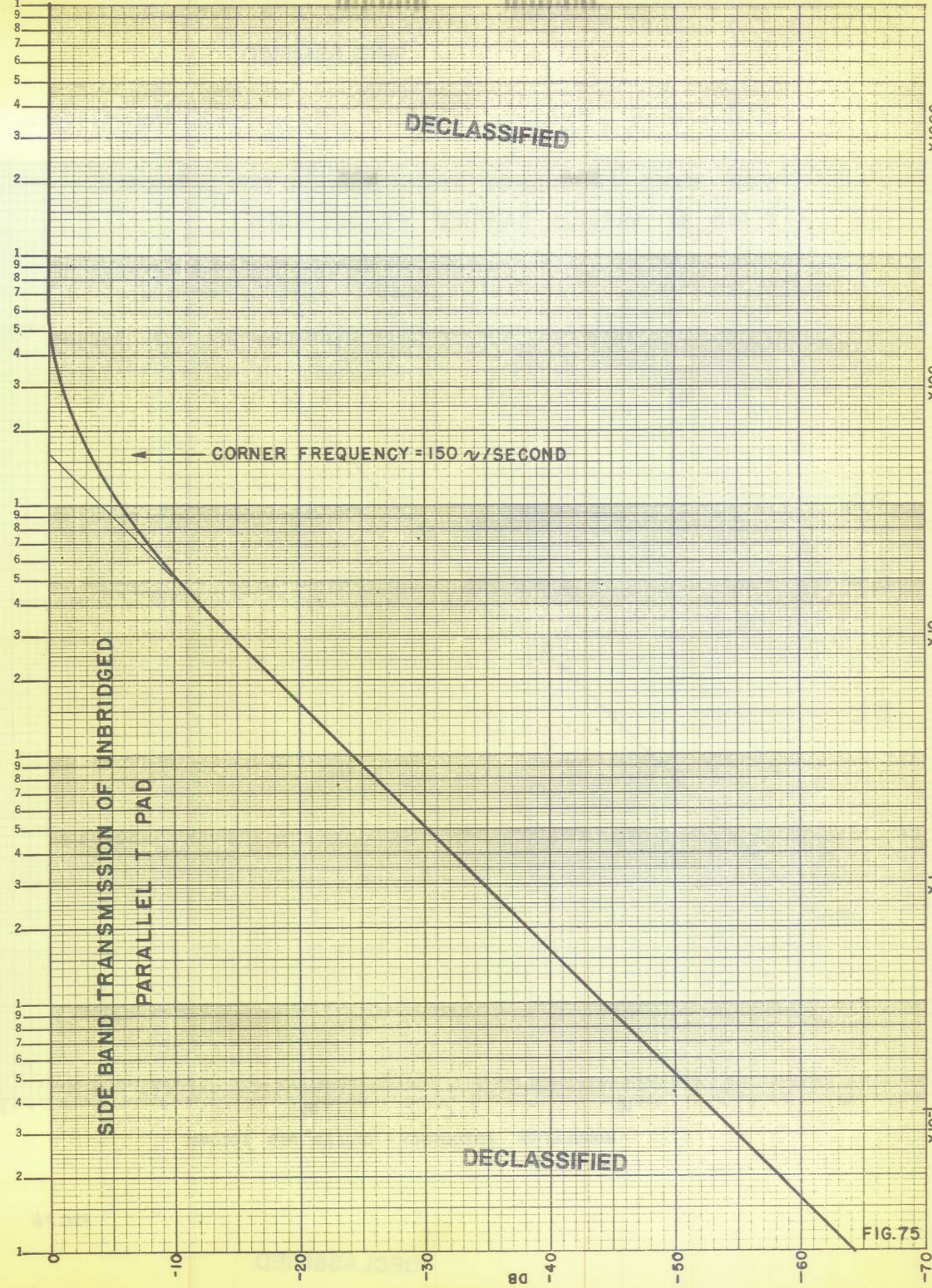
SIDE BAND FREQUENCY — ω / SECOND

SIDE BAND TRANSMISSION OF UNBRIDGED
PARALLEL T PAD

CORNER FREQUENCY = 150 ω / SECOND

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FIG. 75



dB

SIDE BAND FREQUENCY TRANSMISSION FOR UNBRIDGED T PAD AT VARIOUS CARRIER FREQUENCIES.

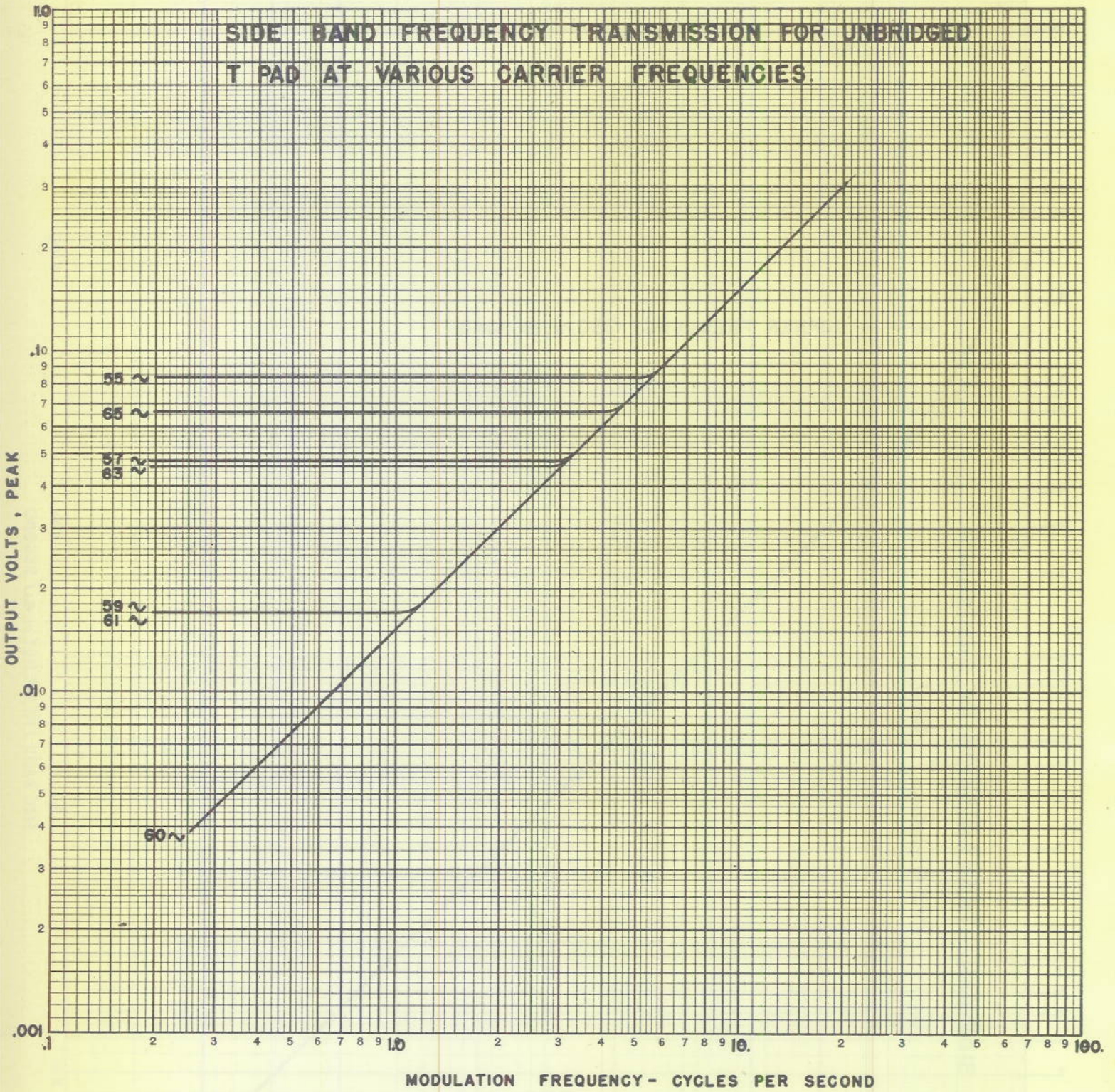


FIG.76

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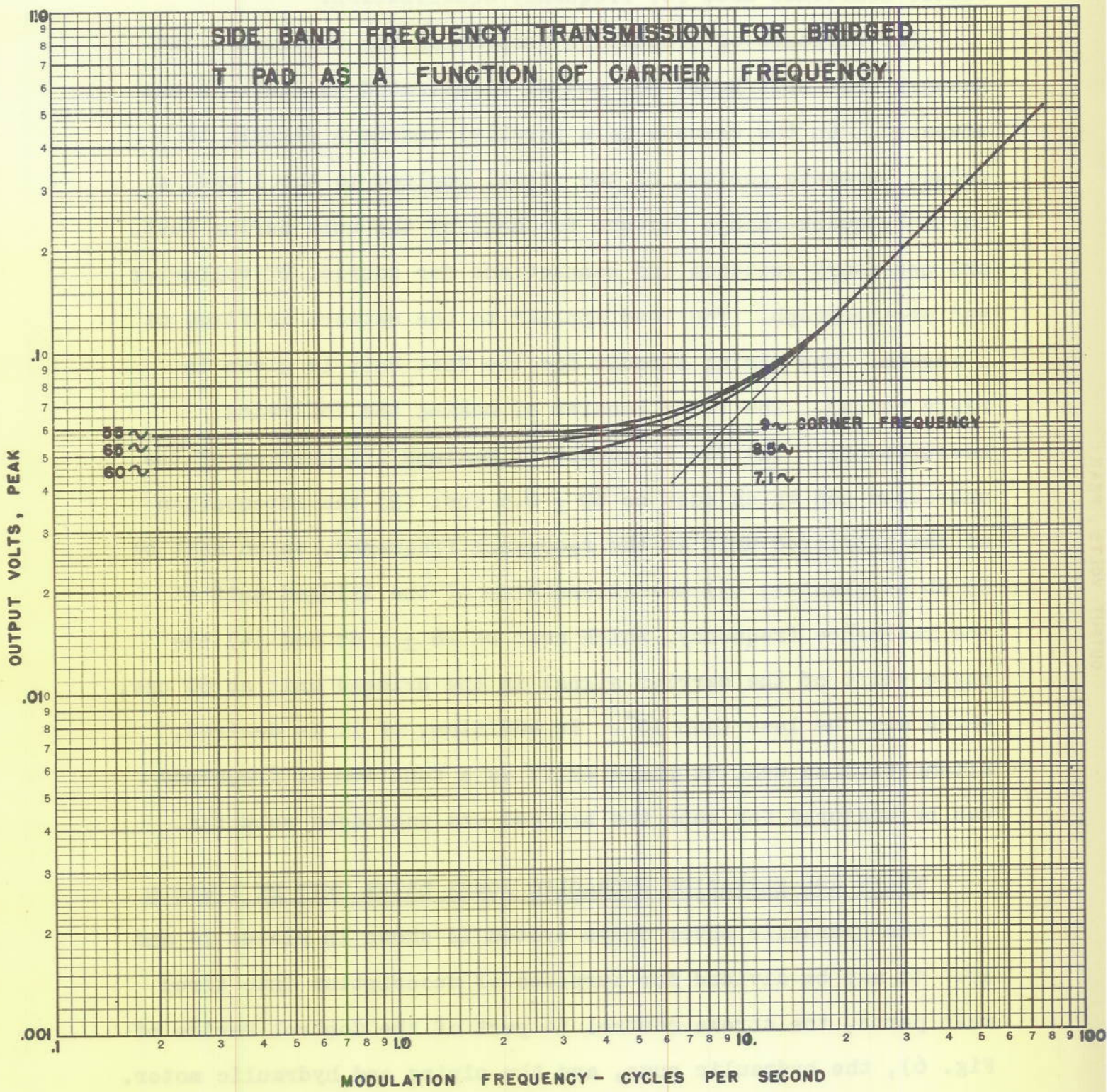


FIG. 77

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parallel T is much to be preferred to the high Q, LC resonant filter sometimes used for frequency equalization.

For purposes of production inspection the Parallel T Pad Network Test Unit BuOrd No. 909321 illustrated in Plate 56 was prepared. On the chassis is a parallel resonant circuit to reduce harmonic content of the signal applied to the T pad, a suitable quick-change fixture for holding the unit during test, and necessary switches and connections for source, VT voltmeter and oscillograph. The load applied to the network is fixed at 1 megohm. The wiring circuit for the Test Unit is given in Plate 56 (a). The tests consist of making the following measurements: (1) The frequency of maximum attenuation of the unbridged pad which must be 60 ± 0.5 cps; (2) the attenuation of the unbridged unit at the resonance frequency, which must be 55 db or greater; (3) the attenuation of the bridged unit at the resonance frequency, which must be 26 ± 1 db and (4) the phase shift of the carrier signal in the bridged unit at 60 cps, which must be less than 10° . In addition, if it is desired, attenuation as well as phase shift as a function of frequency can be measured for both the bridged and unbridged networks.

TRAIN AND ELEVATION HYDRAULIC POWER DRIVE UNIT MK 1 MOD 0

The hydraulic power drive system is shown in Plates 14 and 15. It may be divided for purposes of description into three main parts, the stroke control (a part of the Control Device of Fig. 6), the hydraulic pump, and the piping and hydraulic motor.

The hydraulic pump is a unit which not only produces oil pressure to cause oil to flow through the hydraulic motor, but also meters the flow of oil to control the speed at which the hydraulic motor rotates and hence the angular velocity of the Director.

The Hydraulic Pump

The hydraulic pump consists of two main parts, the pump proper and an amplifying or follow valve. The pump, of which a cross section is shown in Plate 43, is a series of pistons mounted on a plate which is made to rotate about an axis perpendicular to its plane by means of a 1.5 hp electric motor rotating at the constant speed of 3540 rpm. These pistons fit into a cylinder block which rotates at the same speed as the pistons. The cylinder block is mounted on a tilt plate in such a way that its axis can be made to assume any desired angle with that of the piston plate axis within limits provided. Thus, as the rotation of the assembly occurs, the pistons move in and out of the cylinders by an amount depending upon the angular tilt of the cylinder block. Valves are arranged in such a way that the motion of the pistons in their cylinders produces a flow of oil under pressure. The quantity of oil per revolution is directly proportional to the piston stroke and, therefore, to the angular tilt of the cylinder block. The tilt angle and the oil flow are adjusted by means of a lever system from the follow valve. The latter is shown in cross-section in Plate 44 and constitutes a hydraulic power

amplifier. The pilot valve is positioned by the relatively low-power stroke control to be described presently and the follow valve reproduces this motion powerfully to position the tilt block quickly and accurately. Fig. 78 shows the hydraulic motor speed and hence the oil current as a function of the position of the pilot valve and, therefore, of the angular tilt of the cylinder block from the normal position, since the hydraulic motor speed is proportional to the oil current.

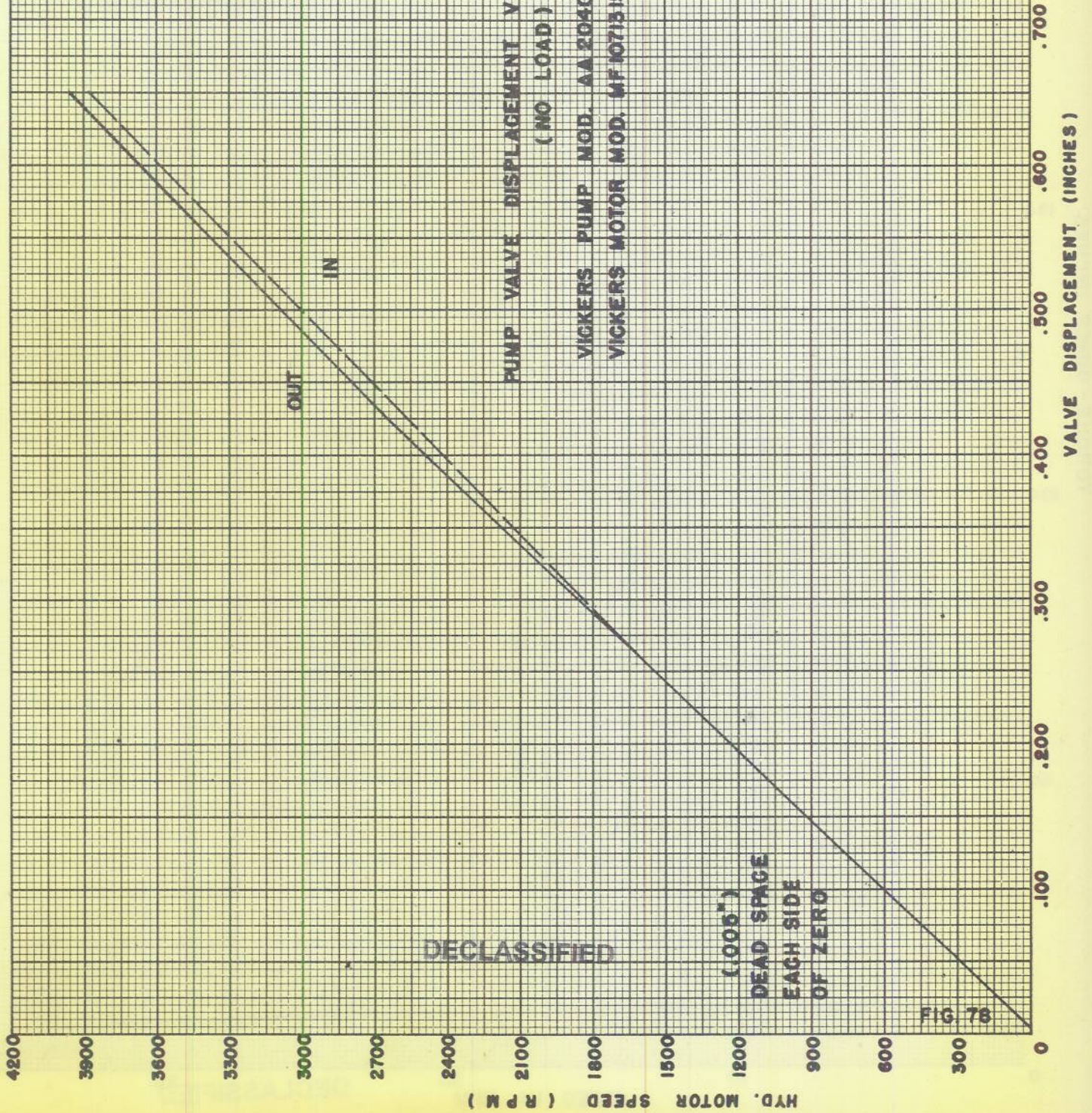
In using a system of this kind for driving a device such as a Director the performance is of particular interest at low angular rates and consequently at low pumping speeds. Because most of the friction in the Director is dry friction, the torque required to drive the Director at constant speed is practically independent of the angular velocity. This means that the pump must be capable of generating high pressures even though the pump speed is low. However, it is just in this region that internal leakage past valves and pistons in the pump will be most effective in reducing the pressure. For this reason it is essential that machine tolerances be held to the minimum possible by the use of the most modern machining and finishing methods.

Figs. 79 and 80 show the torque developed by the hydraulic motor as a function of speed for various constant angular tilts of the cylinder block. (Fig. 79 was taken with the Vickers 20400 pump, which is the same design as that in the Power Drive Unit Mk 1, while Fig. 80 shows data using the Vickers 16801, which differs only in the form of the pilot valve and the fact

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PUMP VALVE DISPLACEMENT VS HYD MOTOR SPEED
(NO LOAD)

VICKERS PUMP MOD. AA20400 SER. NO. X 131891
VICKERS MOTOR MOD. MF1071515A SER. NO. X 153281



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(.006")
DEAD SPACE
EACH SIDE
OF ZERO

FIG 78

TORQUE VS SPEED CURVES FOR VICKERS
HYDRAULIC MOTOR, MODEL MF 2713-15-BGE
OPERATED WITH VICKERS HYDRAULIC PUMP
MODEL AA 20400 AT VARIOUS CONSTANT
VALVE SETTINGS AS INDICATED.

COUNTERCLOCKWISE ROTATION

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TORQUE - OUNCE INCHES

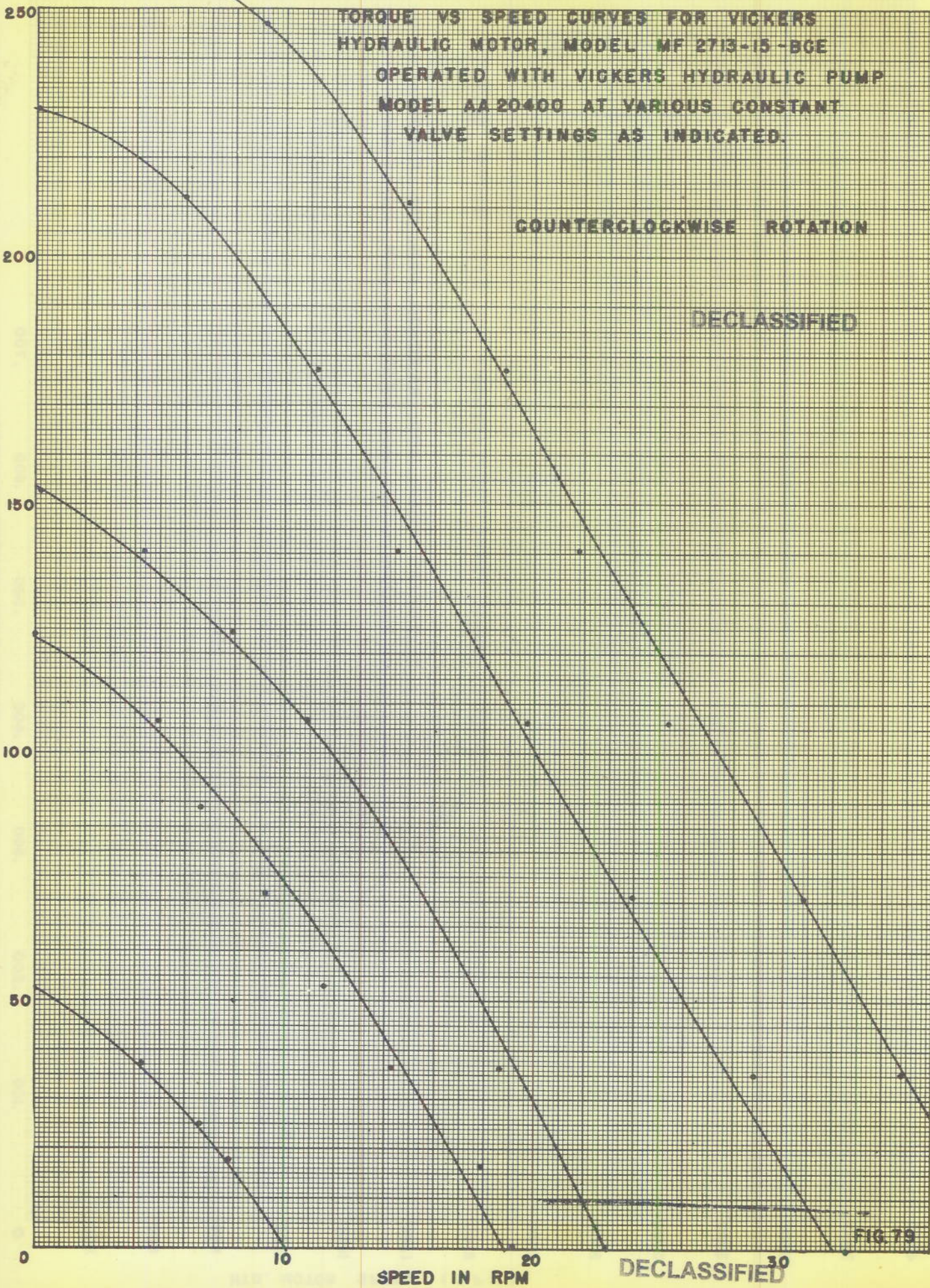


FIG 79

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VICKERS HYD. MOTOR MODEL AA-16801-A SER. NO. T 30054 B

(1200 RPM, 8.8 FT. LBS. TORQUE)

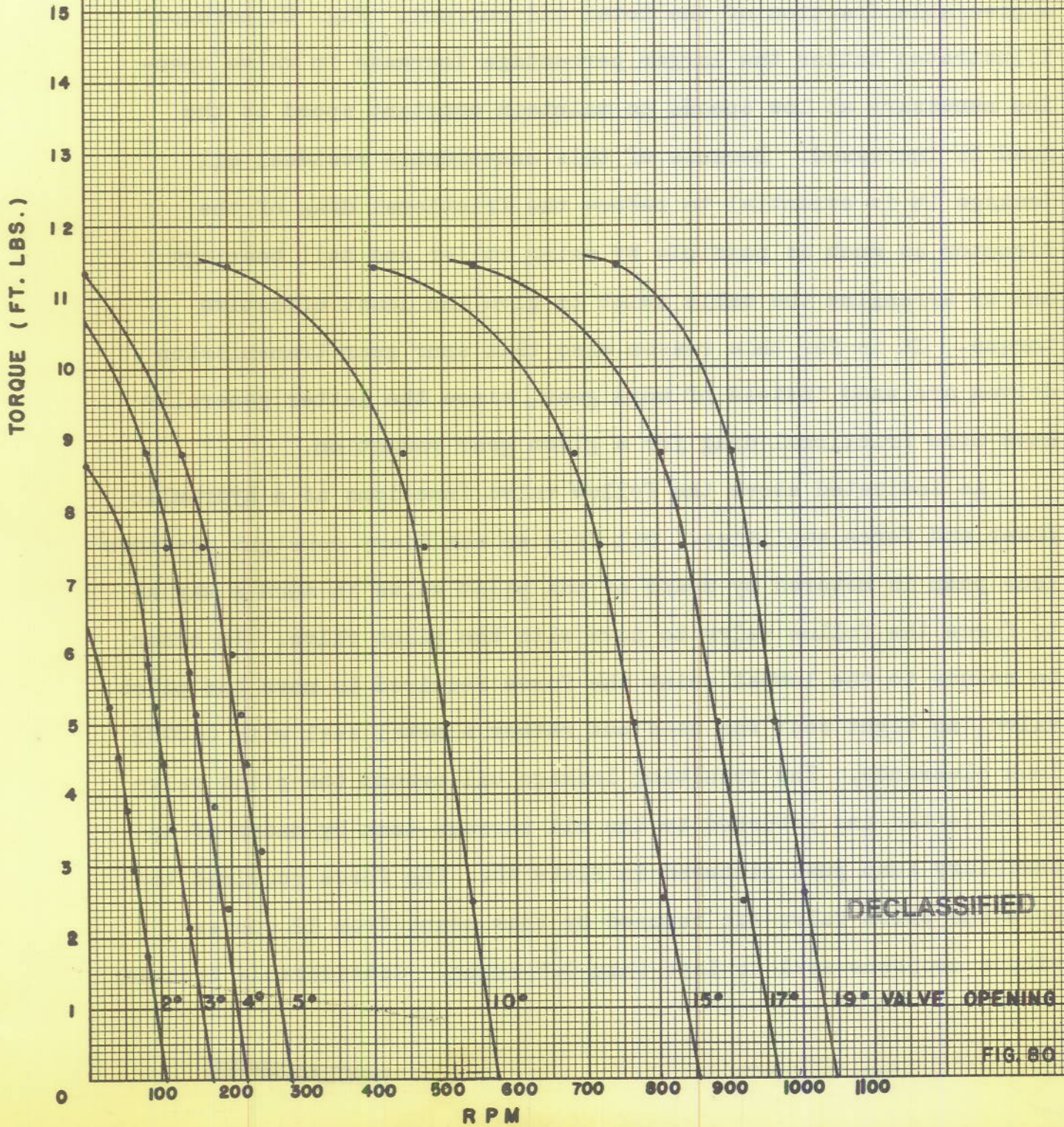
C.W. ROTATION

• PRONY BRAKE

• ROPE BRAKE

CONSTANT VALVE OPENING

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that maximum tilt block angle is limited to one-half that in the other units. Otherwise the pumps are identical.) It is seen that for small displacements of the pilot valve, that is, for low angular tilts, the torque decreases rapidly with tilt. This is true, of course, because the leakage oil current becomes an appreciable fraction of the total oil current. Fig. 81 perhaps illustrates better the larger percentage increase in valve opening necessary at low speeds to maintain constant speed as the load is increased. Because of this unavoidable residual oil leakage it is essential to reduce the frictional drag of the Director as much as possible by using roller and ball bearings and by arranging the cable twist to give the least effective torque. It is for this reason also that spur gear transmission drives are used instead of worm gear, since the latter generally have more frictional drag for a given gear reduction.

As indicated above the follow valve functions as a hydraulic power and force amplifier. Oil from an auxiliary constant pressure gear pump is metered by means of the pilot valve in such a way as to force the follow valve to move with the pilot valve. In order to reduce to the lowest point the force required to move the pilot valve, no tight seal was used but rather a metal seal with 0.0002 inch clearance. The resulting leakage oil around the pilot valve is collected and returned to the oil storage tank by means of an auxiliary sump pump pictured in Plate 46. The force required to move the pilot valve was reduced by this means from 12 ounces with a neoprene seal to less than 0.5 ounce. Considerable trouble

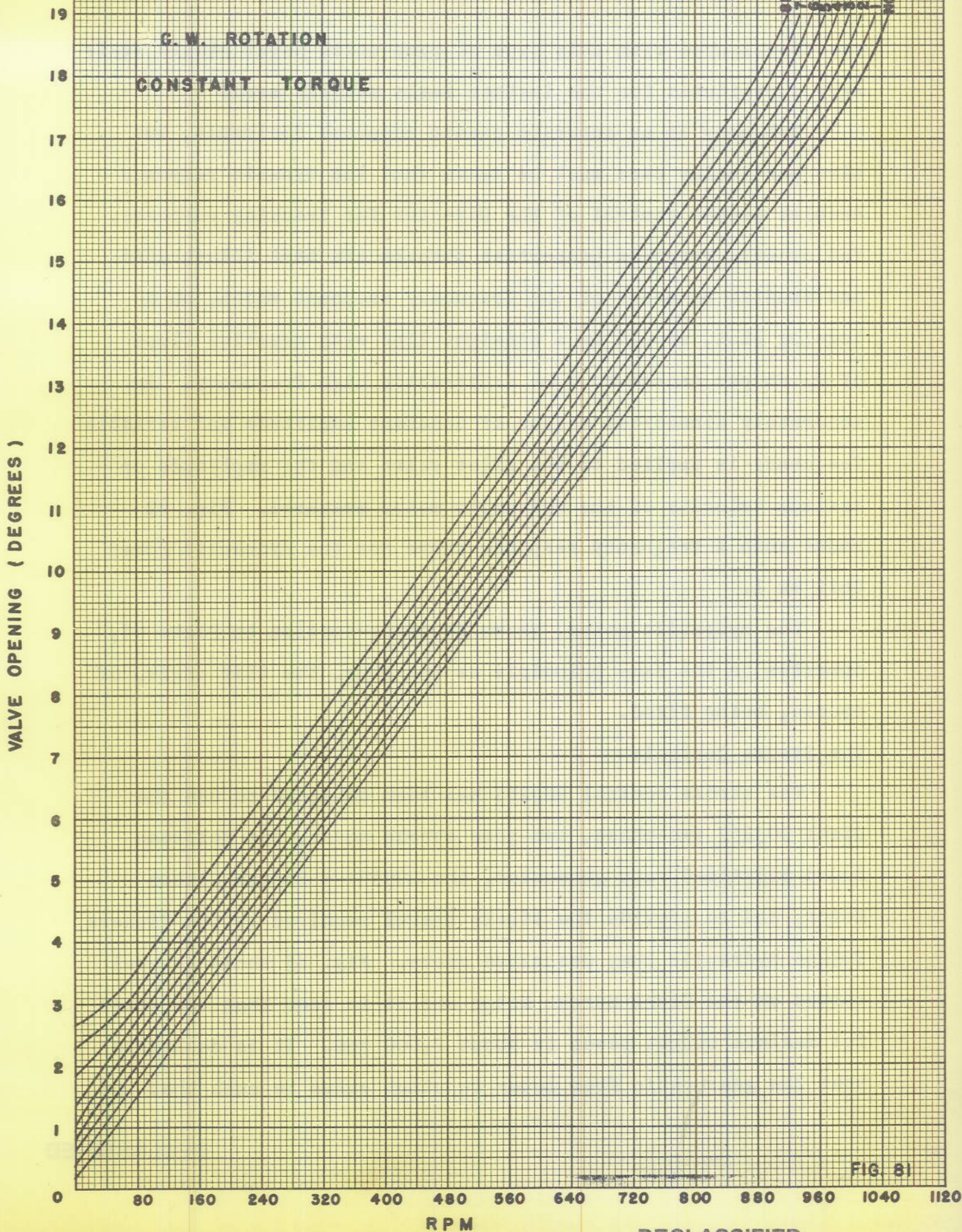


FIG. 81

was experienced with this type of pump until metal pintle seals were substituted for the leather seals usually used.

Not only is an accurate static response desirable, but also particular care must be taken that the dynamic response enables proper control of the Director for tracking purposes. The dynamic response properties perhaps are best illustrated and studied by means of the frequency response which, on a log-log plot, should be a straight line with negative slope of 20 db per decade to some arbitrarily high frequency. An accurately sinusoidal motion of constant amplitude and variable frequency is applied to the pilot valve and the amplitude or maximum velocity of the hydraulic motor measured. Fig. 82 shows such a frequency response curve for the Hydraulic Power Unit Mk 1.

The hydraulic motor, shown in cross-section in Plate 45, operates on the same principle as the pump, the tilt angle, of course, being fixed.

The Stroke Control:

The stroke control 903255 has been designed to use the Diehl 903257 two-phase, two-pole stroke motor, the Kollsman BuOrd #257468-5 rate generator, the 299574-4 Bodine Dither Motor, and to provide the stroke travel required by the Vickers 903254 hydraulic pump described above. Fig. 83 shows several curves on the Diehl Stroke Motor and it is seen that the speed for maximum output power is about 2,000 rpm. It is desirable that the gear ratio from motor to pilot valve be such that the

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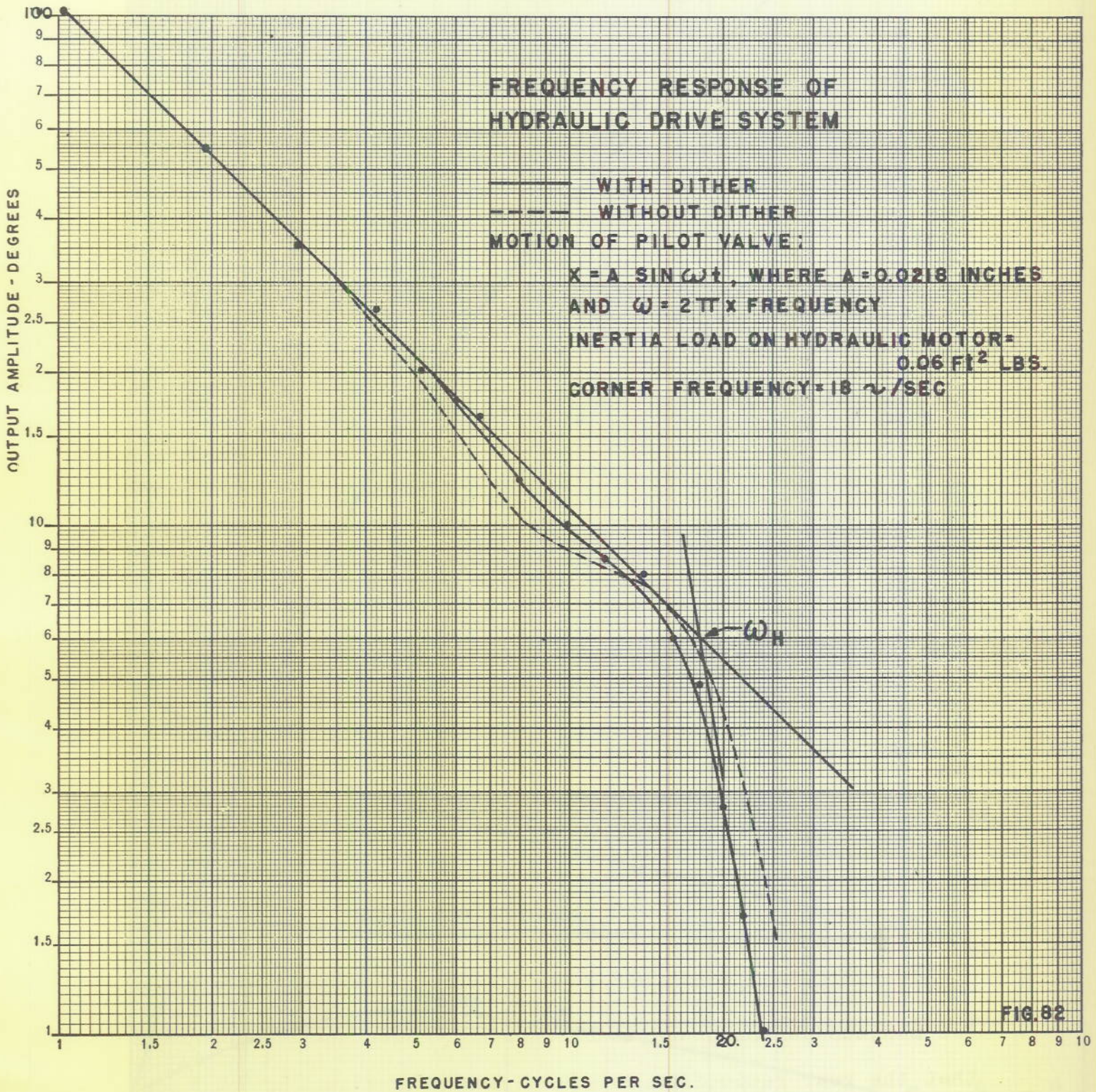
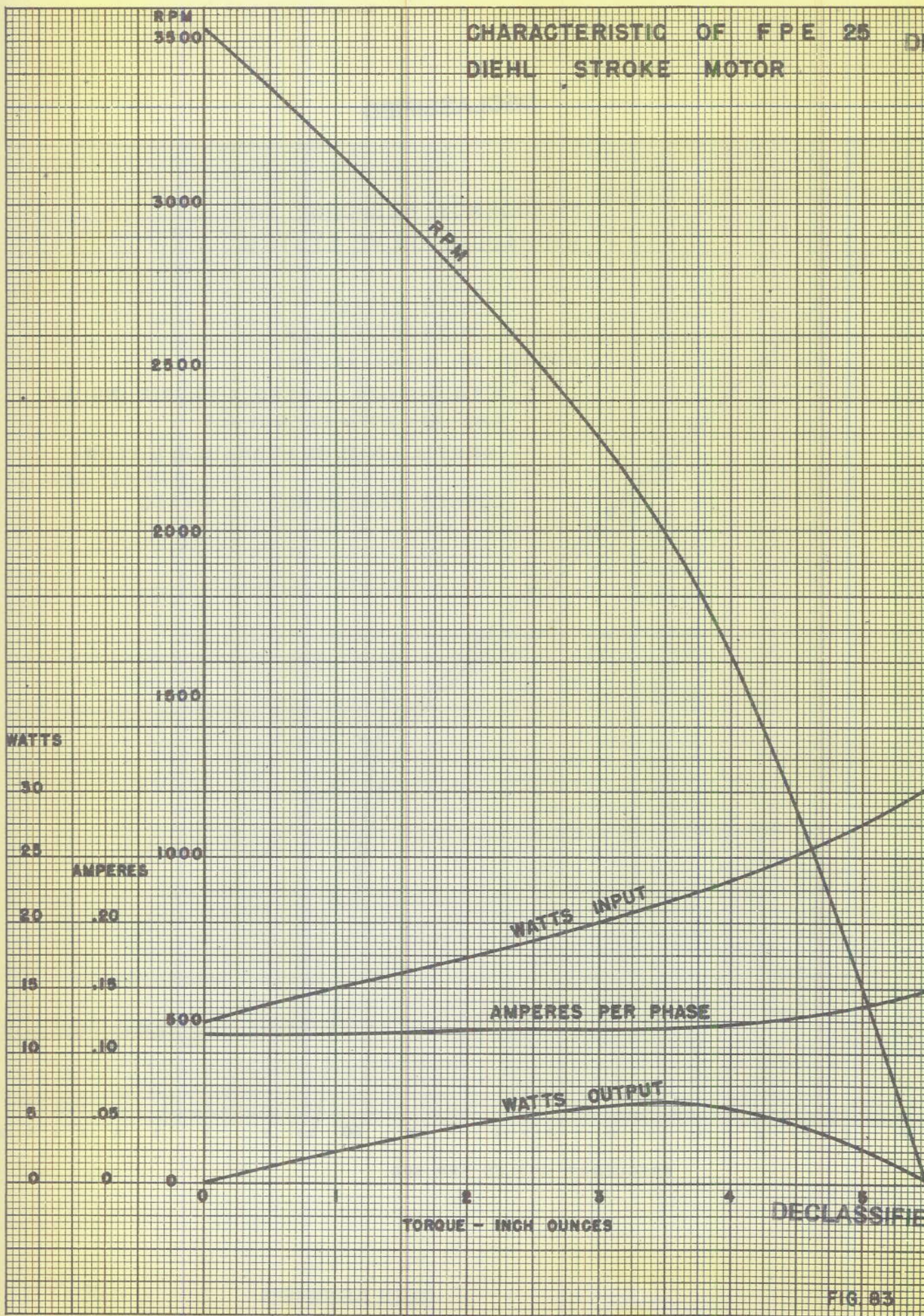


FIG. 82

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CHARACTERISTIC OF F P E 25
DIEHL STROKE MOTOR

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FIG 83

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motor will rotate at the speed for maximum output power when the valve is travelling at its maximum possible speed. Tests were made to determine this speed and the minimum time for reversal on several pumps was found to vary from 0.4 to 0.8 sec. If an average of 0.6 sec. is assumed, the optimum gear ratio turns out to be approximately 60 with the stroke control linkage as adopted by Vickers. For practical reasons a gear ratio of 68.3 was used since this ratio is not critical.

The stroke control gear diagram is shown in Plate 42. All gears are of the best precision, carefully mounted for free running with a minimum of backlash.

The ideal arrangement for incorporating the stroke generator would be to have it mounted on the same shaft as the stroke motor. Because of space limitations in the Director this was found to be not feasible. The generator is coupled to the stroke motor by a 1 to 1 gear ratio, and the motor mounting is so arranged that the motor may be adjusted for the minimum practicable backlash to the stroke generator.

The limit stop is operated by returning the pilot valve to the neutral position at the limit of Director motion by means of a flexible shaft which drives the worm gear and sector arrangement shown in Plate 42. This method has two desirable features: The deceleration when the limit is approached at full speed is smooth and not very large, and there is no difficulty in pulling the Director away from the limit stop.

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Should the Director for any reason rotate beyond the limit stop position, electric switches open the main power circuit, and as a final precaution rigid mechanical limit stops are provided. In order to reduce strain on the stroke control gears, spring fingers in the stroke control open during stopping process so that the stroke motor and generator are not forced to run backward by the action of the limit stop cam.

The Dither Motor rotates at approximately 1620 rpm and drives an adjustable eccentric by which the dither amplitude may be controlled. Ordinarily the latter is adjusted so that dither motion of the Director is just below the point of detectability. Dither adjustment also has an effect upon frequency response as shown in Fig. 82.

The best practice was followed in the installation of the high-pressure piping in the system, care being taken that all corners were well rounded and that adequate oil filtering was provided. Drain pipes from the hydraulic motors were first carried up an inch or so in order to assure that some residual oil would always remain in the front bearing of the hydraulic motor for lubrication purposes. The complete hydraulic flow diagram for the Director is shown in Plate 47.

Many troubles of various kinds were encountered from time to time with the hydraulic pumps. Foreign material in the oil especially is to be avoided because such materials score the pistons and cylinder walls, clog the oil filter, and may even increase internal leakage by separating the valve plate from the

cylinder block. Several times retaining pins have broken and made the pump useless until it was repaired. On some pumps received from the factory, the booster pressure for the follow valve was found to be set much too low. In order to perform an overall check it was decided to develop a test set on which all production units were to receive a final check. This test was to be performed in addition to all tests normally made during the manufacturing process at the factory.

TEST UNIT MARK 26 MOD 0

The test unit Mk 26 is pictured in Plates 48, 49, 50, and 51 and the electrical circuit is given in Plate 53. It consists of a table made from angle-iron upon the top of which is placed the hydraulic unit to be tested. The hydraulic unit is connected in a servo system which duplicates the Director drive in its essentials, except that the external loop is closed by means of a rate generator instead of a gyro. The hydraulic motor drives a disc whose moment of inertia is made to simulate that of the Director in train, and two rate generators, one of which acts as the feedback generator in the external servo loop; the other is used for measurement of instantaneous velocity by recording the output voltage on a Brush recorder. A control panel is provided on which are mounted the various controls, including means for driving the system in either direction at constant angular velocity and for driving the system in sinusoidal motion at constant amplitude and variable frequency. By this

means the frequency response of the entire servo system may be studied. Any deviation from the normal response usually is traceable to a fault in either the stroke control or the hydraulic pump. Standards are set up for acceptance of all hydraulic pumps on this test stand to be incorporated in the Mk 61 Director.

Plate 52 is a sample record of the instantaneous velocity of the hydraulic motor as a function of applied frequency for a normal unit. The response is practically flat with frequency to 5.5 cps, after which it falls off rapidly. A unit with excessive internal leakage in the hydraulic pump will give a frequency characteristic which falls suddenly at much lower frequency. If the replenishing pump pressure is low there will be a resonant rise at lower frequency than the normal corner frequency and then the usual decrease. If there is excessive friction in the stroke control the corner frequency will be lowered. While it is usually difficult to tell from abnormal results what the trouble may be, there is no doubt that a serious fault will manifest itself in an abnormal record. The cause of the faulty record must be determined from inspection or other tests. For this reason this test unit is recommended for auxiliary use as a final inspection test.

Procurement Specifications for the Test Unit Mk 26 Mod 0 are given in O.S. 3917.

THE HYDRAULIC SYSTEM ELECTRIC DRIVE MOTOR

This motor is made by the Howell Electric Company and has

a double-ended drive shaft for driving both train and elevation hydraulic pumps. It operates on 440 volts, 60 cycles, 3 phase, and is rated at 1.5 hp at about 3500 rpm. Tests have been made to determine whether the sudden load changes produced when the Director is accelerated appreciably affect the speed of the motor, and it was concluded that speed regulation of the motor are adequate for the conditions under which the motor is being used. Characteristic curves for the motor are shown in Fig. 84. These curves show that under the rated conditions of 1.5 hp the speed is approximately 3450 rpm, the current is about 2.1 amperes, the torque is some 2.3 ft-lbs, the efficiency 78 percent, and the power factor 92 percent. The power required by the Director is much lower than this except under high velocity and acceleration.

TELESCOPE MK 92 MOD 2

The Telescope is of the fixed-operator line-of-sight type; that is, the Pointer looks in a fixed direction parallel to the deck plane, and the Director line of sight is elevated by a prism rotated by the Director elevation drive. Arrangements are provided so that the train and elevation radar scope is likewise visible in the telescope so that the type of tracking can be selected and used without moving the head. The optical elements of the telescope are shown in Plate 59. The various optical components can be identified by reference to Plate 60, which is a general layout of the telescope. The telescope is equipped with such necessary items as light-filters for better

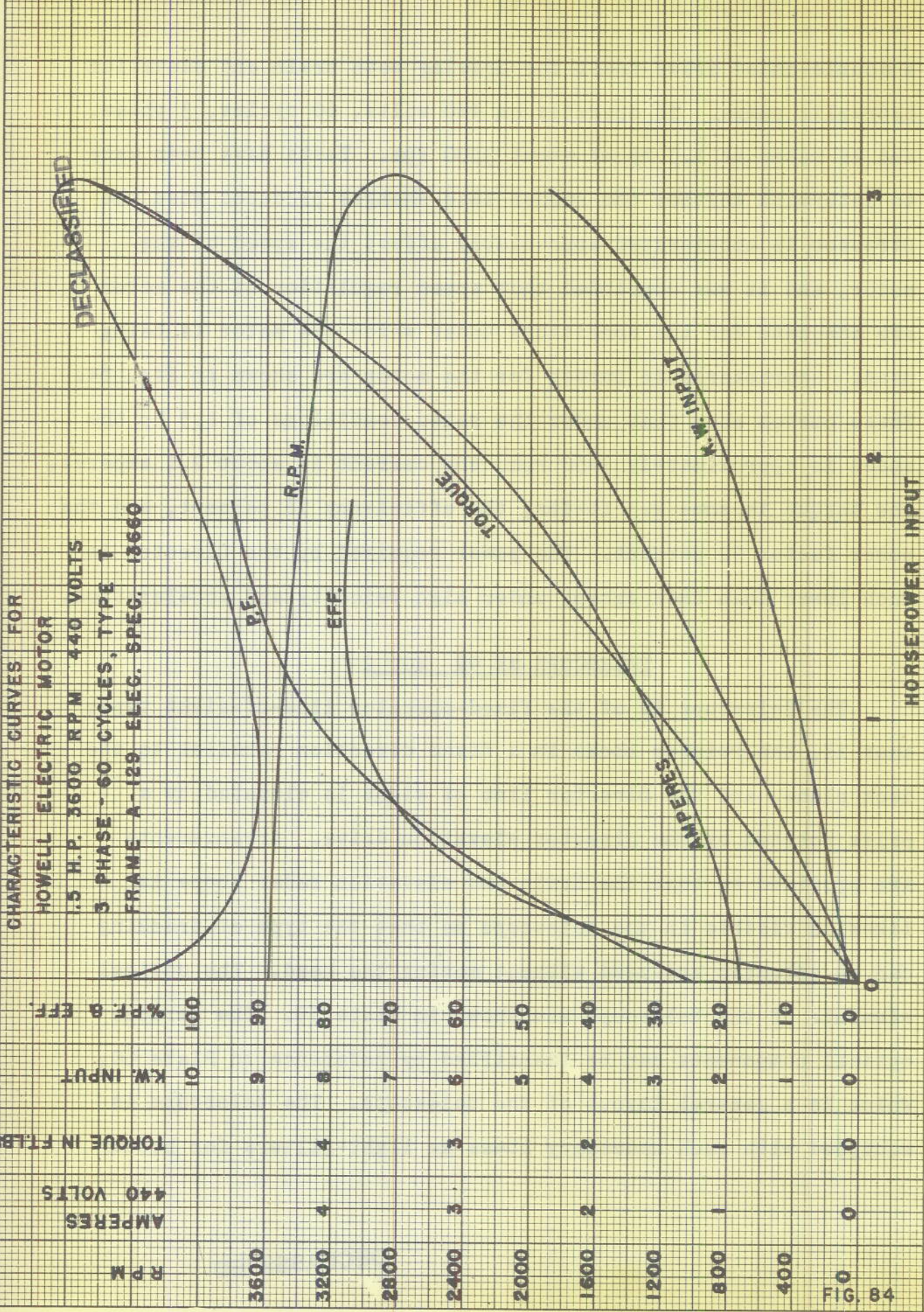


FIG. 84

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contrast between target and background, polarizing plates for adjustment of total light intensity, reticular lines which may receive side illumination of adjustable brightness for night work, and focusing means for the eyepiece. All optical surfaces except mirror surfaces are coated for low reflectivity and mirror surfaces are front coated. The telescope case is hermetically sealed and filled with dry nitrogen to avoid corrosion.

Torque required to turn the telescope drive as a function of temperature is shown in Fig. 88. The telescope drive is designed so that the total play in the drive and the windup due to all torques, including that necessary to drive the telescope, is less than one mil.

SLEWING SIGHT MK 6 MOD 0

The slewing sight is shown in Plates 57 and 58. Provisions are made so the sight may be used in either of two ways: As an "open sight" by locking the sight to follow the motions of the Director, or as a slew sight for the local acquiring of targets. Plunger locks are provided for the former purpose, while for the latter potentiometers are positioned by the relative motion between Director and Slew Sight line of sights to give a signal. When the Control Officer, who normally mans the slew sight, closes his finger switch, the signal causes the Director to move to reduce the angular error.

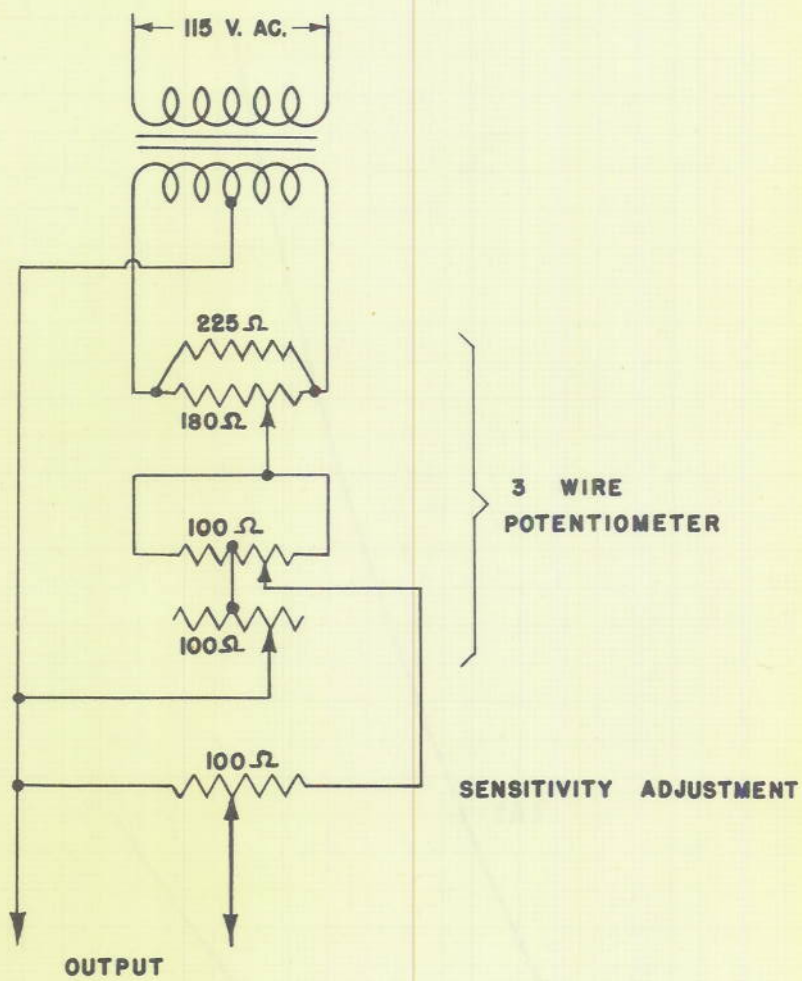
If the potentiometers are linear ones the sensitivity

about the alignment position is likely to be so large that sustained oscillation of the system will be produced when the servo loop is closed through the operator. To reduce this tendency and preserve the conditions which make for a low velocity error the potentiometers are shaped similarly to those of the Control Unit (Manual Rate) Mk 31 (Pointer's Control Unit) except that the motion to cause slewing is much less. This is accomplished with the circuit in Fig. 85. Fig. 86 shows the voltage output of the potentiometer. An angular displacement between Director and Slew Sight line of sights of 14° in train and 28° in elevation will cause the Director to slew. The constant velocity error as a function of velocity is shown in Fig. 87. The field of view of the Tracking Telescope Mk 92 Mod 2 is approximately 6° in diameter. This means that targets moving at velocities greater than 3.5 degrees per second in train or 1.7 degrees per second in elevation will be out of the field of the Pointer's Telescope when on the crosshairs of the slew sight. The Control Officer accordingly must "lead" high velocity targets if the Pointer is to be successful in acquiring them. Almost all targets will be acquired at velocities below 3.5 degrees per second, so this restriction is not considered very serious.

Angular limits for the slew sight are set by stops to be $\pm 60^\circ$ in train and $+90^\circ$ to -25° in elevation from the deck plane.

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SLEW SIGHT POTENTIOMETER CIRCUIT

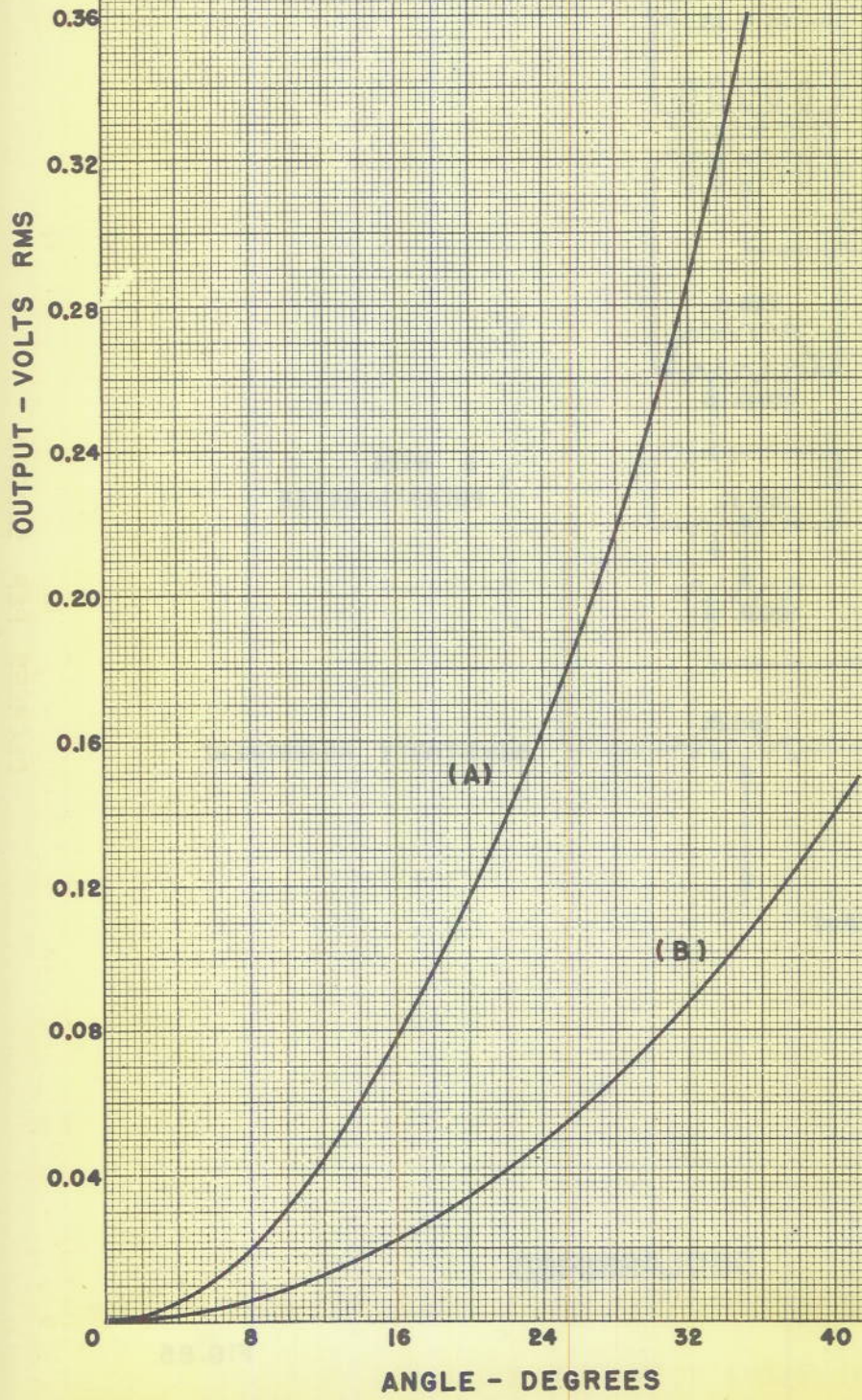


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FIG. 85

(A) SLEW SIGHT POTENTIOMETER OUTPUT CURVE
(B) TRACKING POTENTIOMETER OUTPUT CURVE
WITH NO AUXILIARY RESISTORS

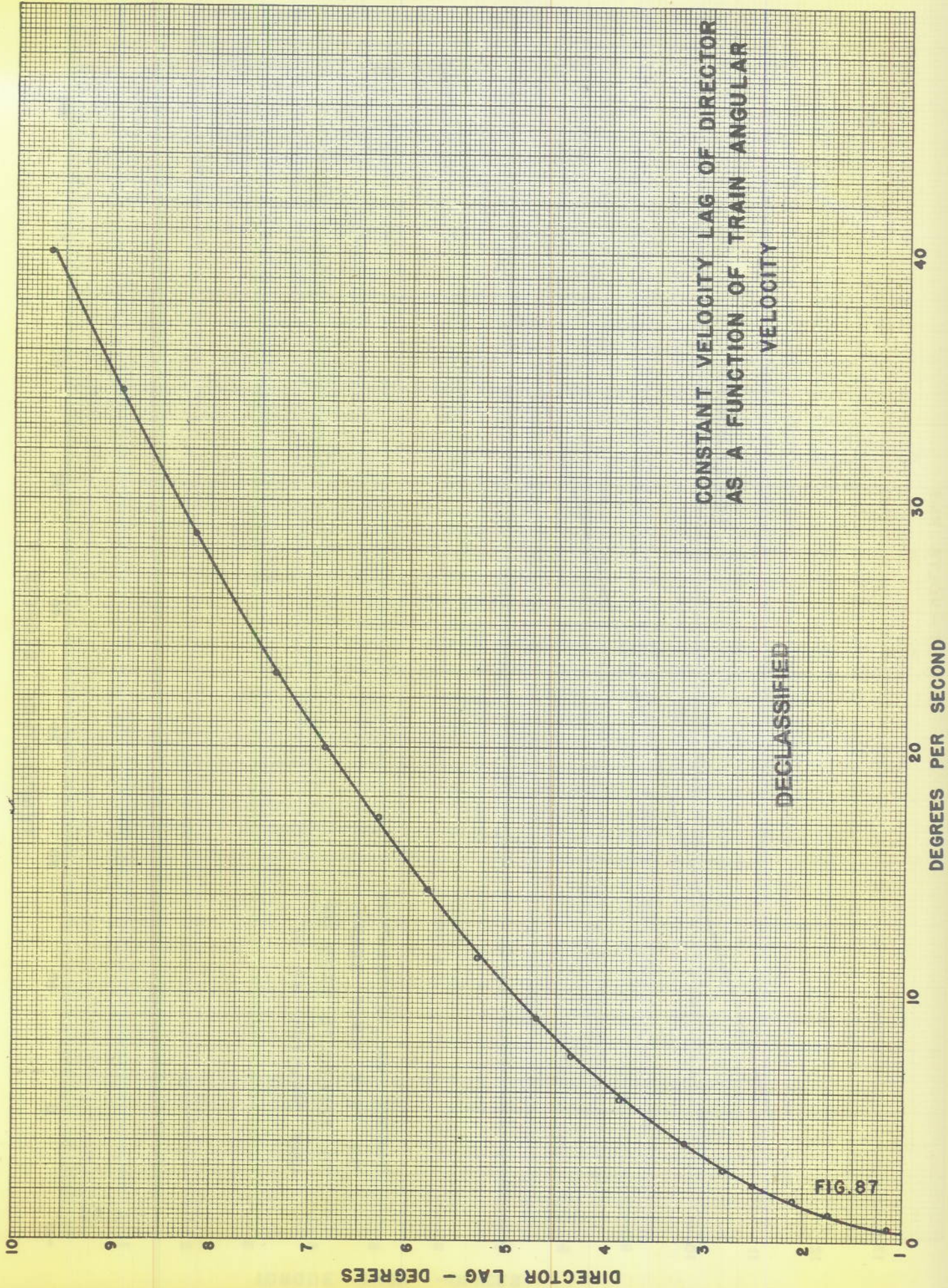
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FIG. 86

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CONSTANT VELOCITY LAG OF DIRECTOR
AS A FUNCTION OF TRAIN ANGULAR
VELOCITY

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FIG. 87

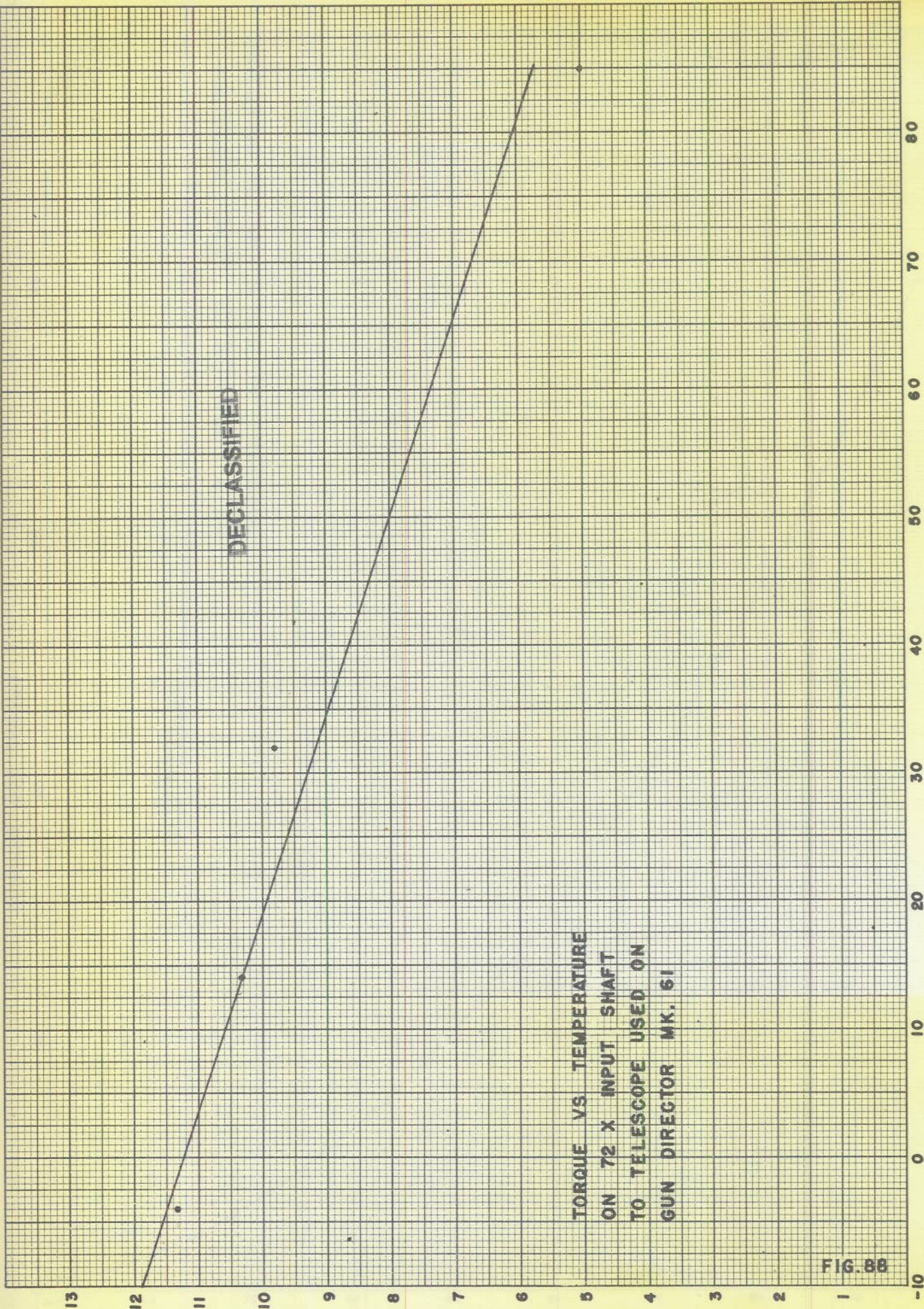
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TORQUE VS TEMPERATURE
ON 72 X INPUT SHAFT
TO TELESCOPE USED ON
GUN DIRECTOR MK. 61

FIG. 88

TORQUE INCH -OUNCES

TEMPERATURE DEGREES F



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AUTOMATIC TRACKING UNIT

The Automatic Tracking Unit (ATU) is a component of the Radar and Target Acquisition Unit Mk 47. It is contained in the Target Acquisition Unit chassis. The circuit is shown in Plate 69.

The principle of operation of the unit briefly is as follows. The 30 cps signal which normally feeds the spot scope circuits in the radar is brought to the grid of the first tube in the ATU. This is a cathode follower stage which feeds two ring modulators, one for each channel, train and elevation. The 30 cps signal from the lobing generator is used as reference. The resulting direct current in each channel is fed through the RC equalizer and then to a balanced modulator, which produces 60 cps which is applied to the tracking circuit of the Director. Phase relationships, of course, are such that the resulting Director motion is in the direction to eliminate the line-of-sight error with the target. Cross pointer meters in the direct current portion of the circuit indicate the tracking error to the operator.

In designing the circuit, performance specifications were first decided upon and the design then made to satisfy these specifications. Without going into detail, the method by which these specifications were fixed is one of obtaining the frequency spectrum of the worst tactical situation that the fire control system is to be expected to handle and then to set up a transmission band width for the automatic tracking system which will

transmit an acceptable portion of the band. The desirable band width turns out to be about 0.5 cps from zero frequency and if gain crossover for the entire circuit is placed at 0.5 cps the response of the closed loop will be flat to this frequency whether the system is a 20 or a 40 db per decade system. In the former case the system will be stable for all frequencies and in the latter instability will occur at gain crossover.

A 20 db per decade overall system would mean a flat frequency response for the ATU, since the Director is a 20 db per decade system. However, it is desirable that some provision be made for "coasting" to allow for short periods of fading of the radar signal. This can be accomplished by introducing an RC circuit in the direct current portion of the ATU. This, itself, is a 20 db per decade system and would make the open circuit response of the system fall 40 db per decade, which would produce an unstable system when the loop is closed. As shown previously (Fig. 15), such a system can be made stable if the characteristic is changed from -40 db to -20 db per decade in the neighborhood of gain crossover.

The equalizer selected, then, is one with a flat characteristic to the corner frequency required for coasting, a section of -20 db per decade to the second corner frequency (near the gain crossover frequency for the open loop) and the third section which is invariant with frequency (Fig. 43 (a)). The circuit is shown in Fig. 43 (b).

As shown previously (Eq. 52) the error ϵ for a system using such an equalizer would be

$$\epsilon = \frac{\dot{\theta}}{\omega_g} + \frac{\ddot{\theta}}{\omega_1 \omega_g}$$

and the values of ω_1 and ω_g consistent with the requirement of a band pass of 0.5 cps from zero frequency would be 0.1 and 100 rad per sec, respectively, so that

$$\epsilon = \frac{\dot{\theta}}{100} + \frac{\ddot{\theta}}{10} \quad (55)$$

where ϵ is in degrees if $\dot{\theta}$ is in deg per sec and $\ddot{\theta}$ is in deg per sec².

Also, since

$$\omega_2^2 = \omega_1 \omega_g \quad (56)$$

there results

$$\omega_2 = \sqrt{10} = 3.16$$

which corresponds to a frequency $f_2 = 0.5$ cps, in harmony with the performance specifications. The angular frequency ω_2 , then, not only is the upper corner frequency of the network but must be made the gain crossover frequency of the open loop radar-ATU-Director system.

The latter frequency is a function of the system gain and adjustment of the gain to satisfy the performance specifications (Eq. 55) is equivalent to setting the gain crossover frequency at ω_2 .

In practice means are provided for applying a signal in the ATU corresponding to an angular error of 0.1 degree. The gain in the ATU is then adjusted until the angular velocity of the Director is 10 deg per sec. There is no control for acceleration error sensitivity since this is fixed by the network when the above adjustment has been completed.

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PART IV

Recommended Changes in Design - Considerations for
Future Work.

In the course of the developmental work and tests - both laboratory and field - certain desirable modifications became apparent. They are listed here as a matter of record and perhaps a starting point for future efforts in improving the equipment.

GYROS

1. There seems to be no reason why computing and stabilization should not be done by the same gyros.
2. If heavy damping fluid is used in the computing gyros (as is done now), it should be the subject of an investigation to find one whose viscosity is independent of gyro frequency about the input axis. Curves similar to Fig. 22 taken on computing gyros should show a departure from linearity downward at very low frequencies, with a maximum far below the 20 db per decade characteristic, indicating that the effective damping became very low at high frequencies. This might be the source of some of the amplification of tracking error observed in the Fire Control System Mk 57.
3. Instead of using high viscous damping to smooth the

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gun orders electrical networks might be substituted, using gyros damped to 0.65 of critical. This calls for a reinvestigation of σ as related to a fire control system of this kind.

4. In addition, the following quantities might be introduced into the computer with networks: range, range rate, drift, superelevation, wind own ship's speed.
5. The gyros should be electrically driven.
6. The cross-roll gyro should be damped to 0.65 of critical.
7. The cantilever type of restraint should be discarded and one designed for the purpose which is clamped securely at both ends.
8. The pick-offs should be redesigned to eliminate the quadrature component in the signal and to reduce third harmonic further. Maximum signal to noise ratio should not be less than 1000 to 1. The maximum signal should be raised greatly - perhaps to 10 volts - so that signal levels in the control circuit will not be so low.
9. More care should be taken with the mechanical design.
 - a. Natural frequencies of all parts and combinations of parts should be above

30 cps.

- b. The gimbal suspension wires should be eliminated, because they allow lateral motion of the gimbal. Perhaps oil-under-pressure bearings can be developed for satisfactory use.
 - c. More attention must be given to reducing gyro vibration if the required S/N ratio of 1000 is to be reached. Rotors should be dynamically balanced, ball bearings should be of the highest precision and adequately lubricated for low vibration as well as longer life. Exhaustive tests should be made of the effects of shock and vibration and designs modified to pass adequate tests.
10. Pure 60 cps potential should be used for control circuits (or perhaps 80 cps to eliminate effects of pick-up from power circuits). Perhaps these should be generated and filtered for the purpose.

STROKE CONTROL

1. The stroke motor should be redesigned to have a lower impedance (see Fig. 27) and larger corner frequency. The maximum speed should be reduced, which would simplify the gearing in the stroke

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control even though this is contrary to original test data upon which present gearing was established.

2. The rate generator should be redesigned for smaller inter-winding capacity to decrease residual voltage. There is no attempt whatever to shield the windings now. More work should be done on the drag cups to improve uniformity so that residual will be independent of rotor position.
3. The dither speed should be increased to upwards of 3600 rpm.
4. There should be continued rigid inspection of the stroke controls as well as the complete hydraulic systems at the point of manufacture with a continual effort at improvement of machine tolerances consistent with operating requirements (temperature, vibration).
5. Work toward (a) a maximum acceleration of 200 deg per sec² and a slew velocity of 50 deg per sec.

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Mk 16 Below Deck Computer and

Mk 33 Fuze Time Computer*

1. The computing system should be redesigned to provide adequate and stable computing elements to operate with the gyros as modified by the recommendations.
2. The computers should be repackaged to eliminate waste space, large heavy drawers and to allow passing the standard Navy tests on shock and vibration.
3. The complexity of adjustment should be reduced.
4. Test facilities should be built into the computer circuits for quick overall tests in case of trouble.
5. Methods employed in the Mk 33 for computing time of flight and secondary ballistics should be reconsidered from the standpoint of increased stability and suitability for shipboard use. The Mk 33 might be packaged with the Mk 16 with fewer and smaller dials and controls on the front panel reduced to a minimum.
6. Cabinets should be redesigned for greater strength and better support of chassis.
7. Electrical components should be carefully laid out to reduce electrostatic and magnetic coupling to the minimum.

* See NRL Interim Report "Tests of Computers Mk 16 and Mk 33" by Wm. N. Shaddix: C-S67-7(1163/NVNS), November 18, 1946, for system performance tests.

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RADAR

1. Attention is called to the fact that the present operation of the Mk 39 Mod 3 and the Mk 47 Mod 0 is not the best and difficulty will undoubtedly be encountered when used with automatic tracking. Recent circuit modifications of these equipments have resulted in considerable improvement but to provide really adequate operation extensive modifications are required.
2. Provide a different receiver with AGC applied to plates and screens instead of grids.
3. The band pass of AGC circuits must be considered more carefully. Interaction effects between video and AGC circuits must be eliminated.
4. Careful attention should be paid to the video band pass to give fast recovery time and adequate AJ.
5. Pulse stretching should be used as a means of separating amplitude modulation of video from video, thus improving S/N and bettering AGC action.
6. Presentation: Adequate clamping should be provided of both fast and slow sweeps for position both in X and Y axes. Suitable blanking of the expanded notch keying pulse should be added so it doesn't appear on the main sweep.
7. Angle separation circuits: These circuits should be consolidated to reduce duplication and to reduce effects of noise and harmonics.

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8. Range Unit: The whole mechanical layout should be re-designed for better operation. Attention should be paid to providing adequate slew control, a balanced range crank, a suitable time constant of the rate aiding to allow its use with high speed targets. A time constant of 0.1 sec is desirable. Automatic range tracking is needed with position slew.
9. The cabinet should be redesigned so the operator can sit with knee room.
10. The radar might be arranged so that the A scope is beside the TAU for one man tracking, if necessary.
11. For search, the type of scan should be re-evaluated to determine preference between elliptical and spiral. The radar dish should be 48 inches in diameter to sharpen the beam and increase range; this change is being made but no test results are available as the 48" dish will not be ready for installation until August, 1947.

TARGET ACQUISITION UNIT

1. That the E scope - PPI presentation is the best has not been demonstrated. In preliminary work the E scope was found to be practically valueless except for fixing the Director elevation.
2. Facilities should be added for push button target acquisition from designation - in bearing, elevation and range.

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3. For search: The Director should be made capable of sector scanning a predetermined area automatically with the elevation held from drift by a vertical gyro, instead of the pendulous synchro now used.

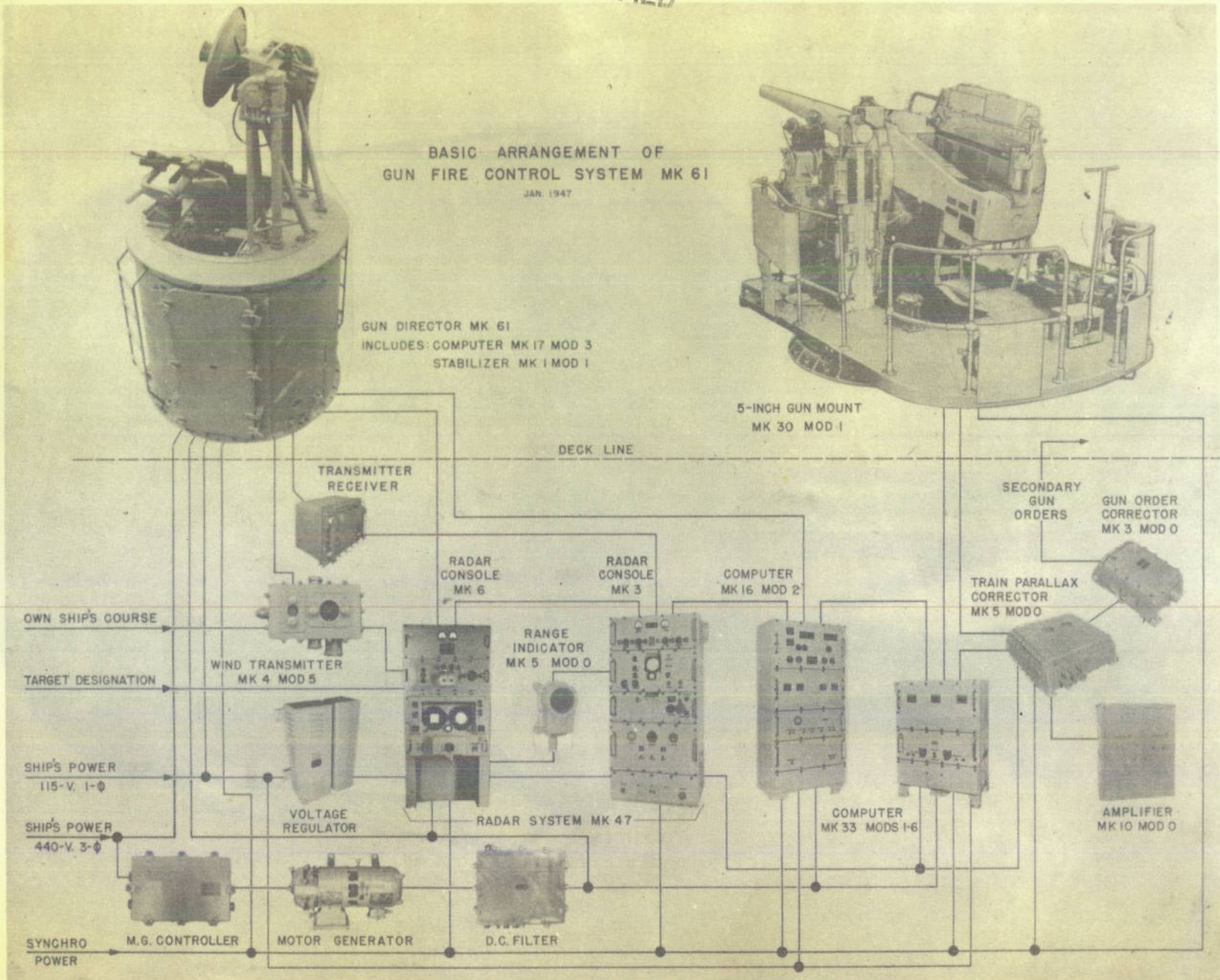
TARGET ACQUISITION UNIT

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BASIC ARRANGEMENT OF
GUN FIRE CONTROL SYSTEM MK 61

JAN. 1947



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PLATE 1

Gun Fire Control System Mk 61, Basic Arrangement

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PLATE 2 Mk 61 Director with Eastman 30" Antenna (Front View).

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PLATE 3

Mk 61 Director with Eastman 30" Antenna (Rear View)

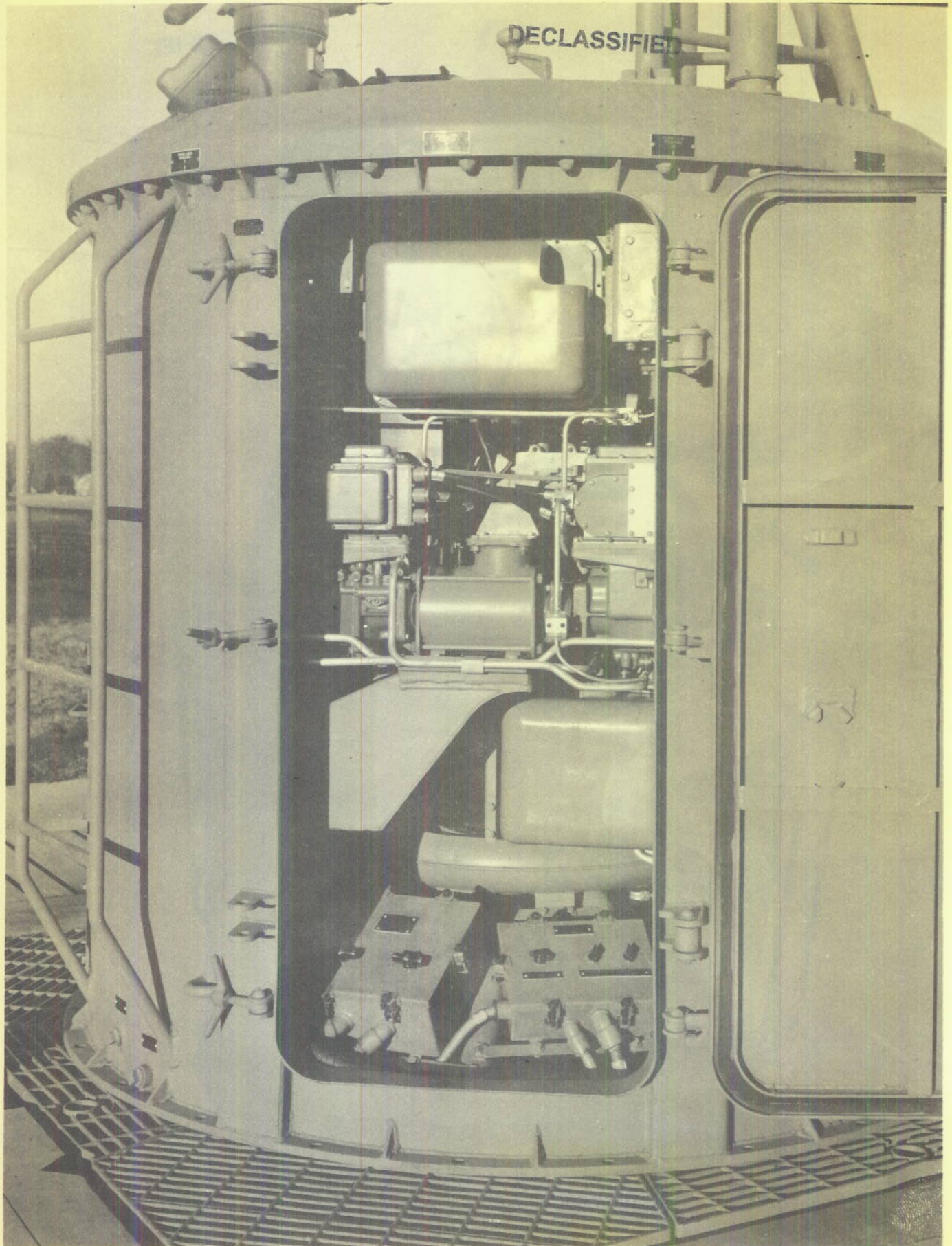


PLATE 4 Gun Director Mk 61 Mod 2 (View through Door showing Hydraulic Power Drive Mk 1 Mod 0) Locked Position No. 9).

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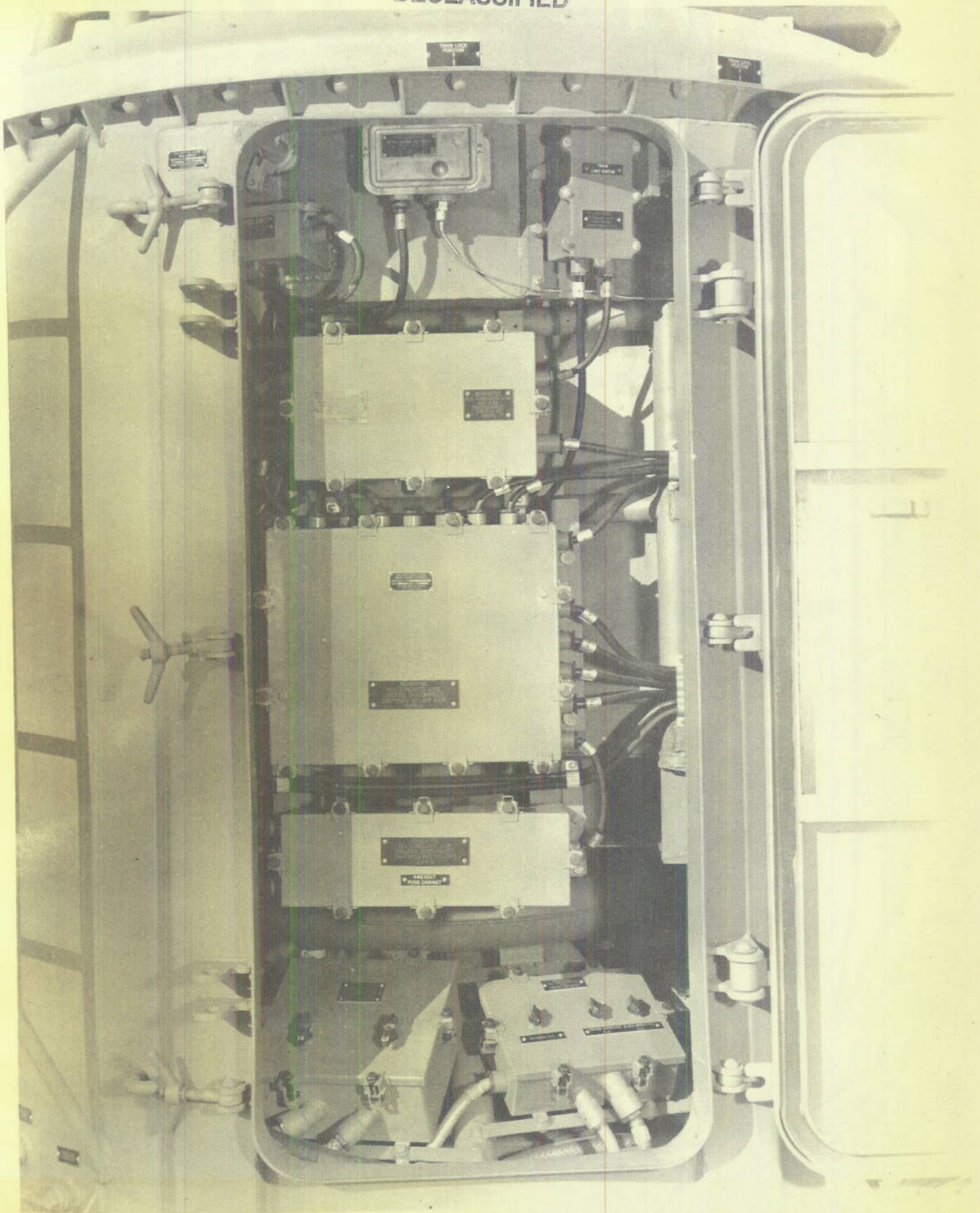


PLATE 5

Gun Director Mk 61 Mod 2 (View through Door showing Fuse Panels and Train Limit Switch) (Locked position No. 3).

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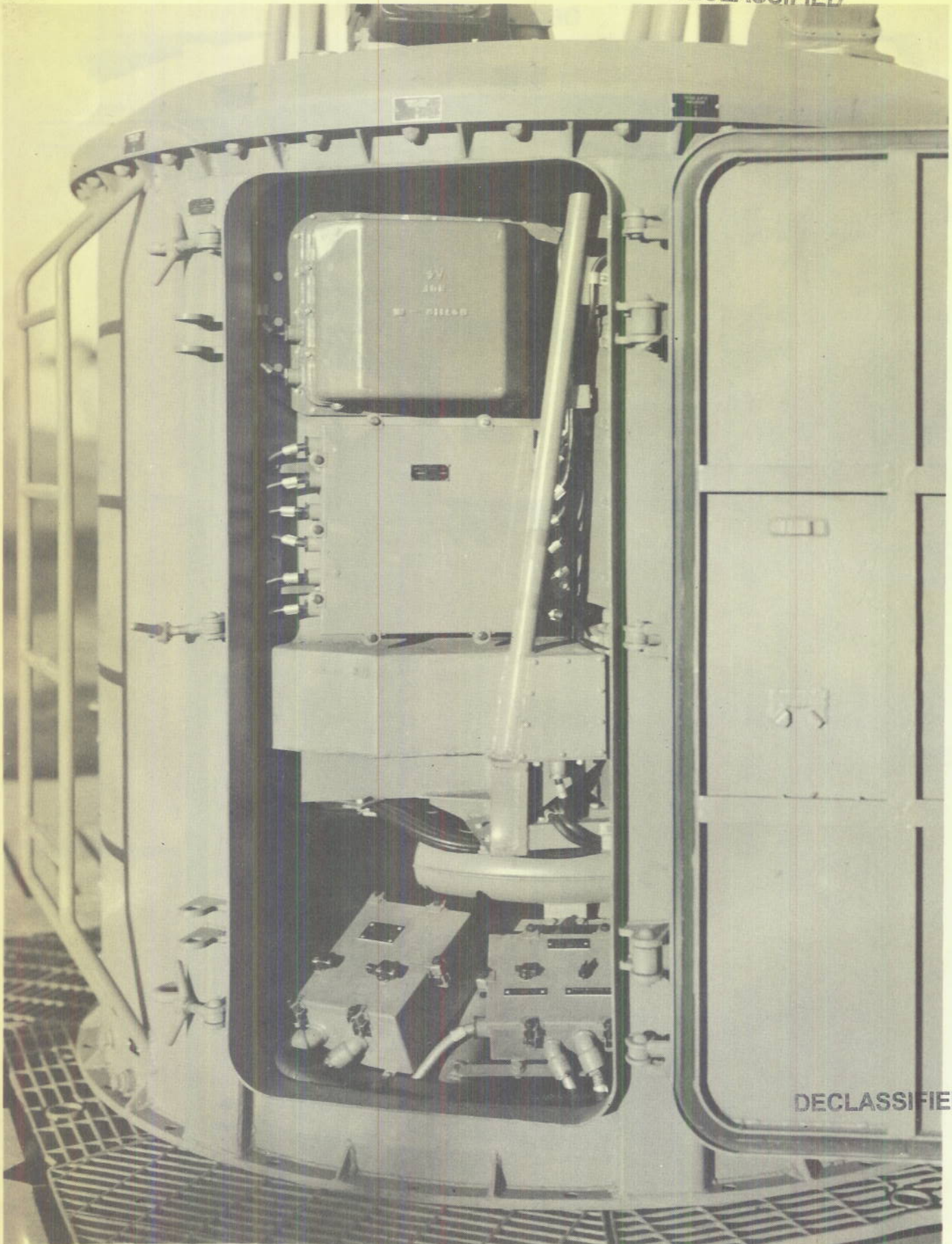


PLATE 6

Gun Director Mk 61 Mod 2 (View through Door showing Electrical Controls) (Locked position No. 5).

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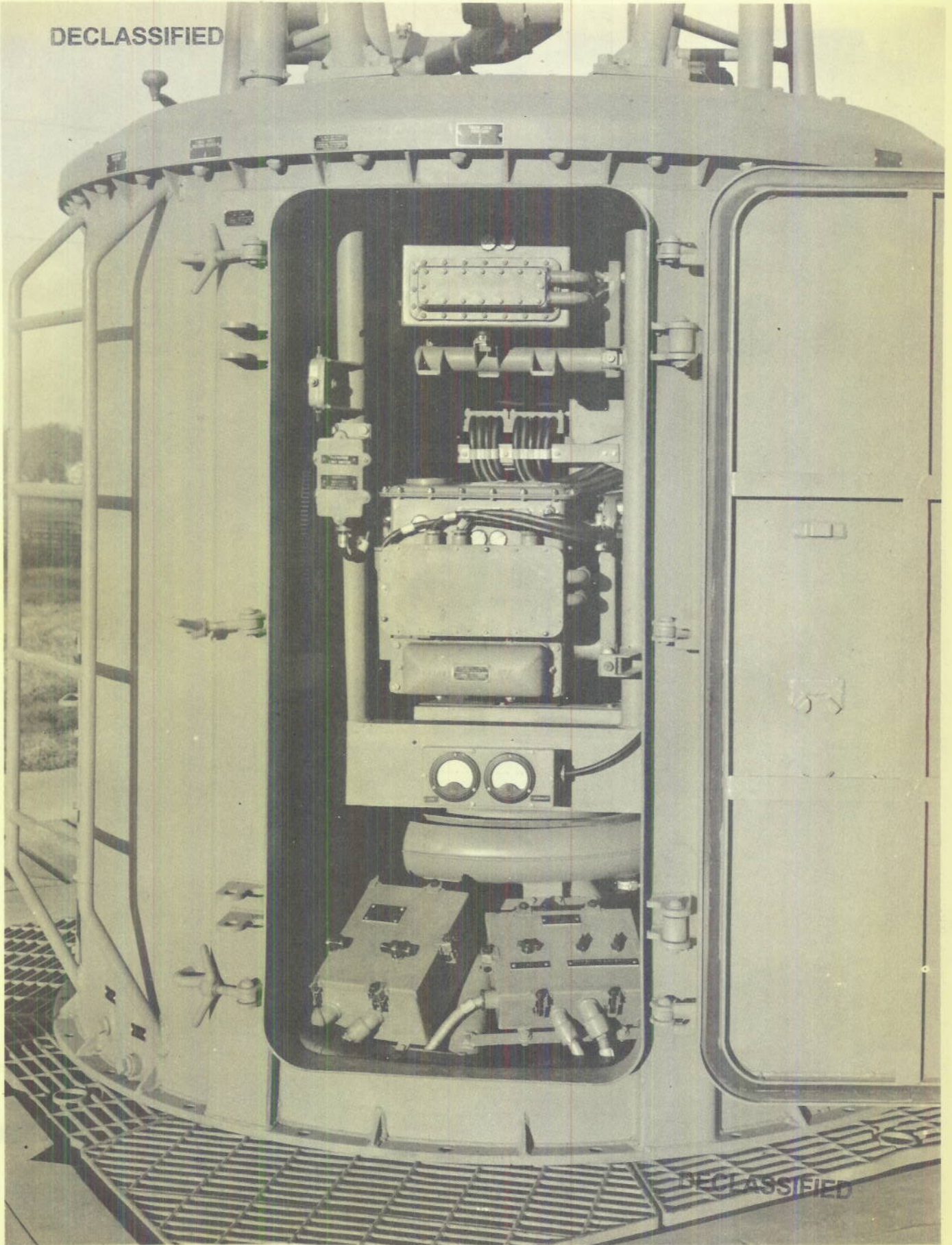
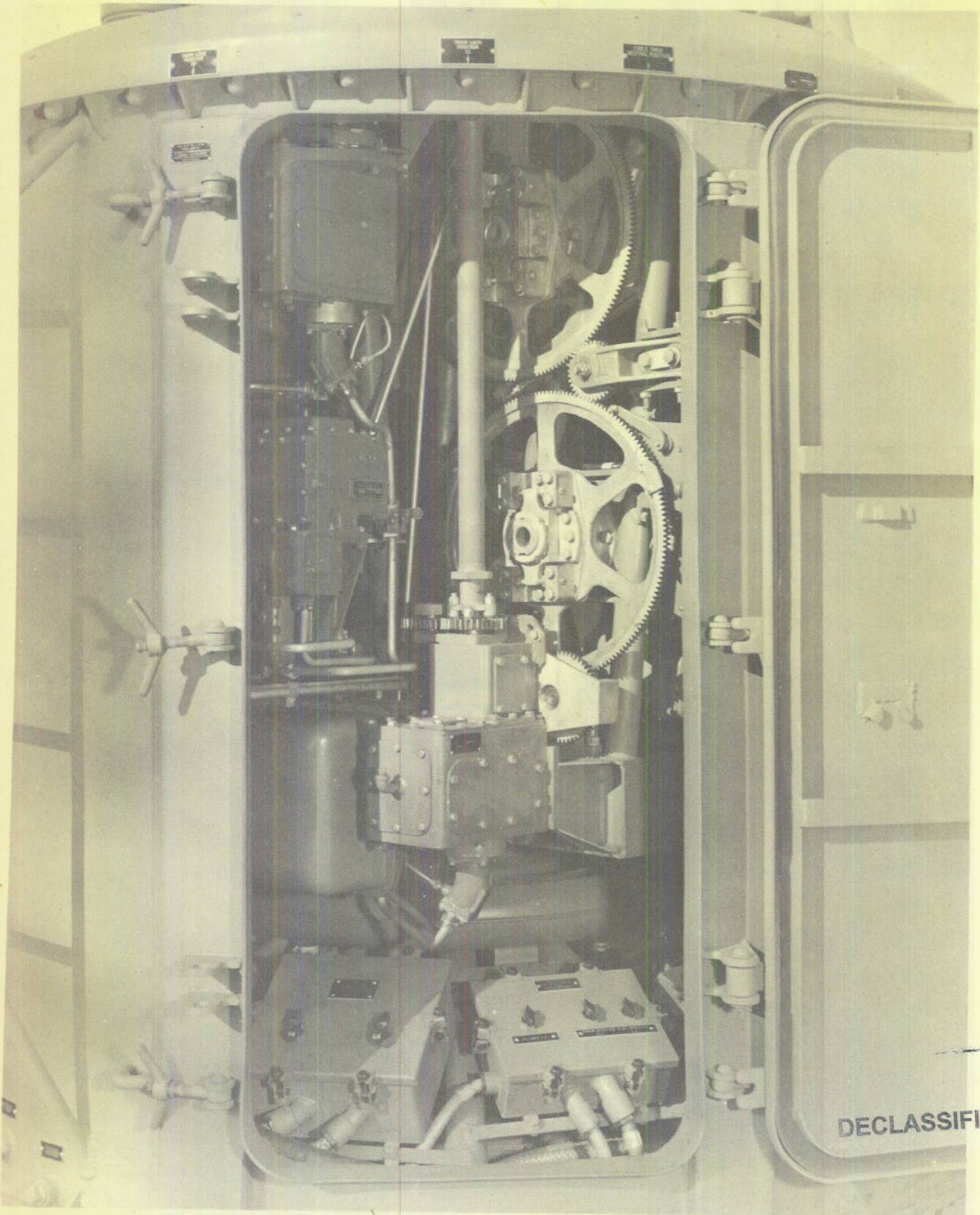


PLATE 6 (a) Gun Director Mk 61 Mod 2 (View through Door showing Computer Mk 17 Mod 3 and Stabilizer Mk 1 Mod 1) (Locked position No. 1)

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PLATE 6 (b) Gun Director Mk 61 Mod 2 (View through Door showing Elevation Gearing and Limit Switch) (Locked position No. 11).

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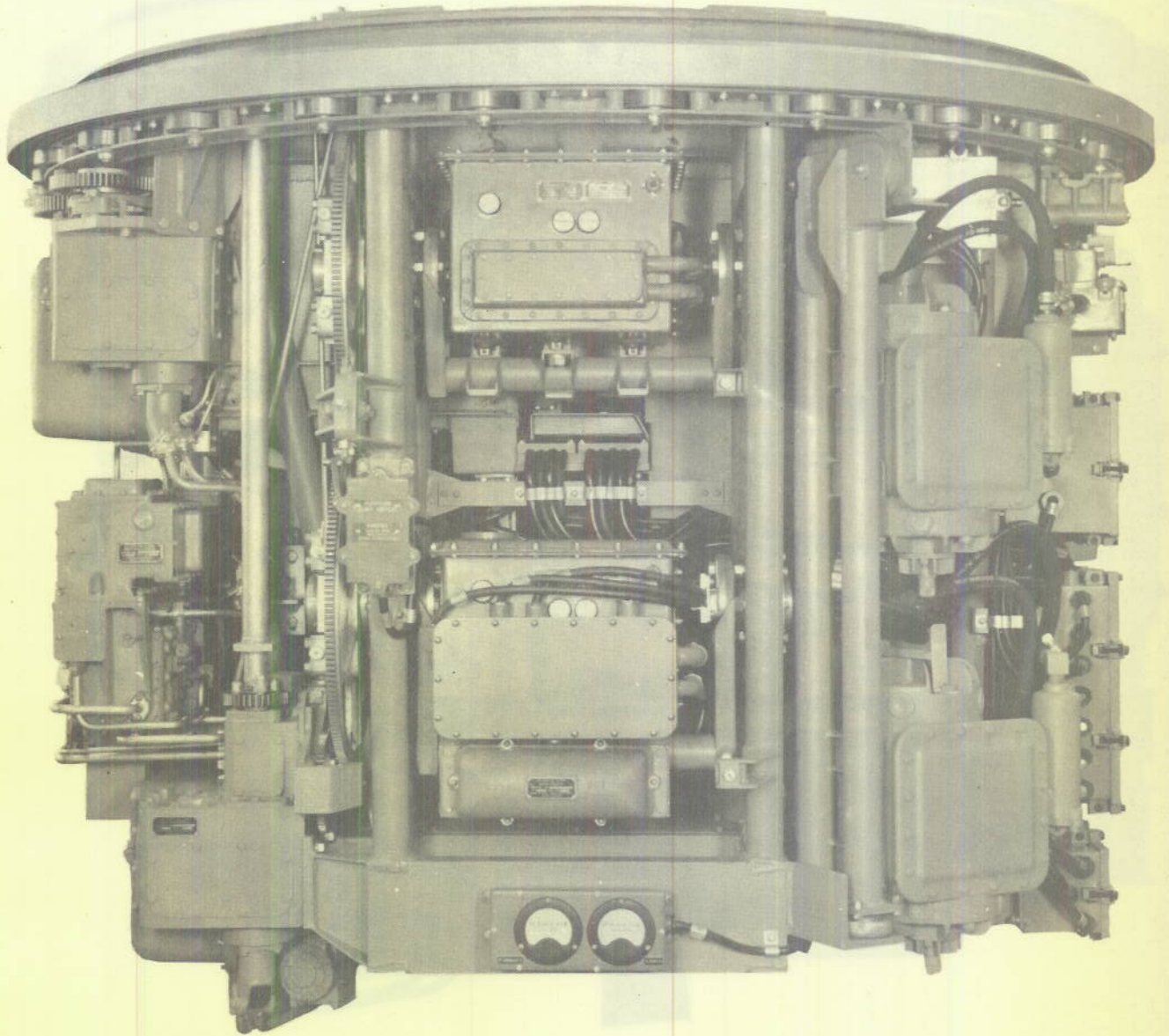
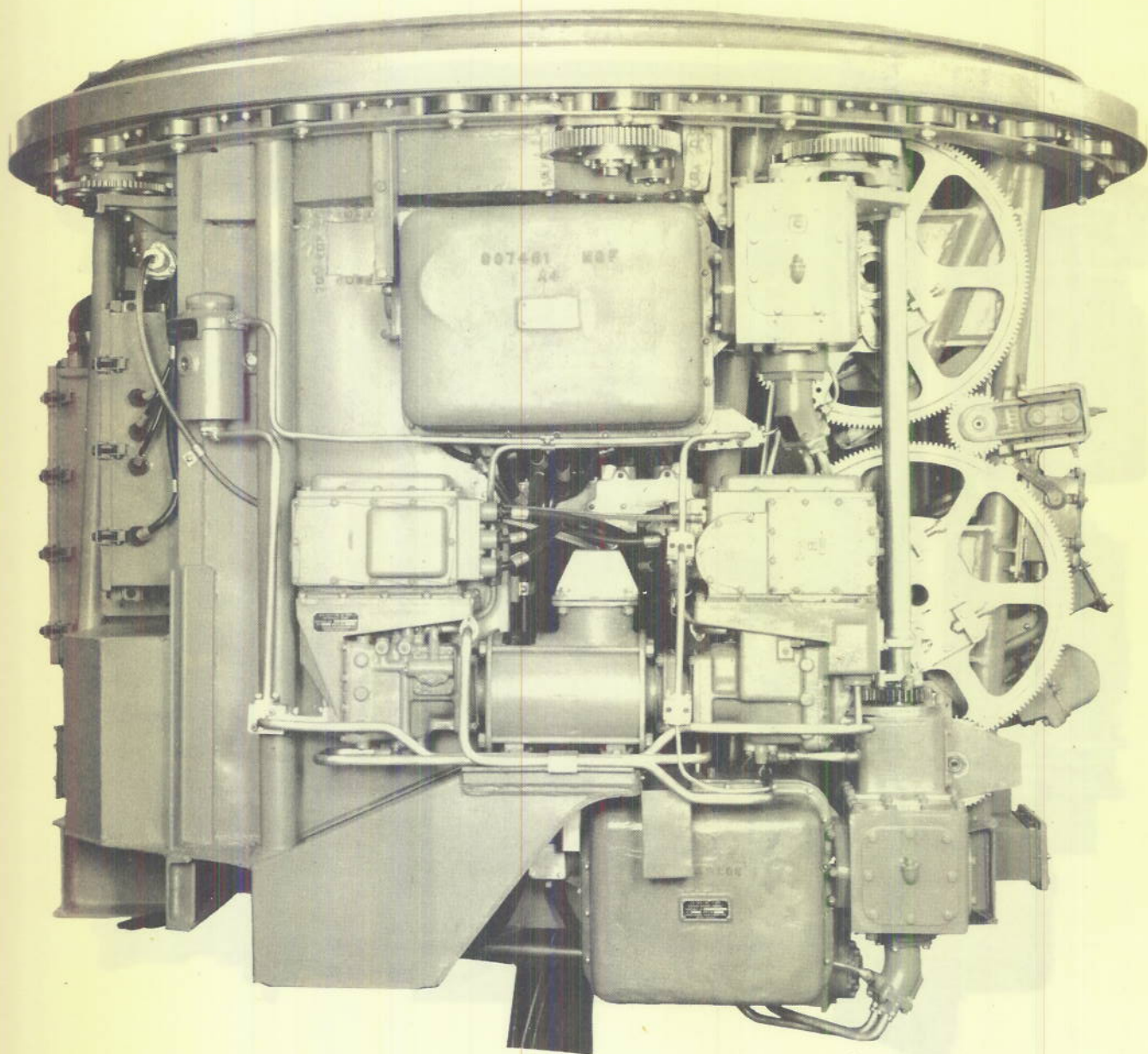


PLATE 7 Gun Director Mk 61 Mod 1 Basket (View of Computer Mk 17, Stabilizer Mk 1, Horizon Indicator Mk 4, and Air-Supply Units Mk 1).

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PLATE 8 Gun Director Mk 61 Mod 1 Basket (View of Hydraulic Power Drive and Synchros).

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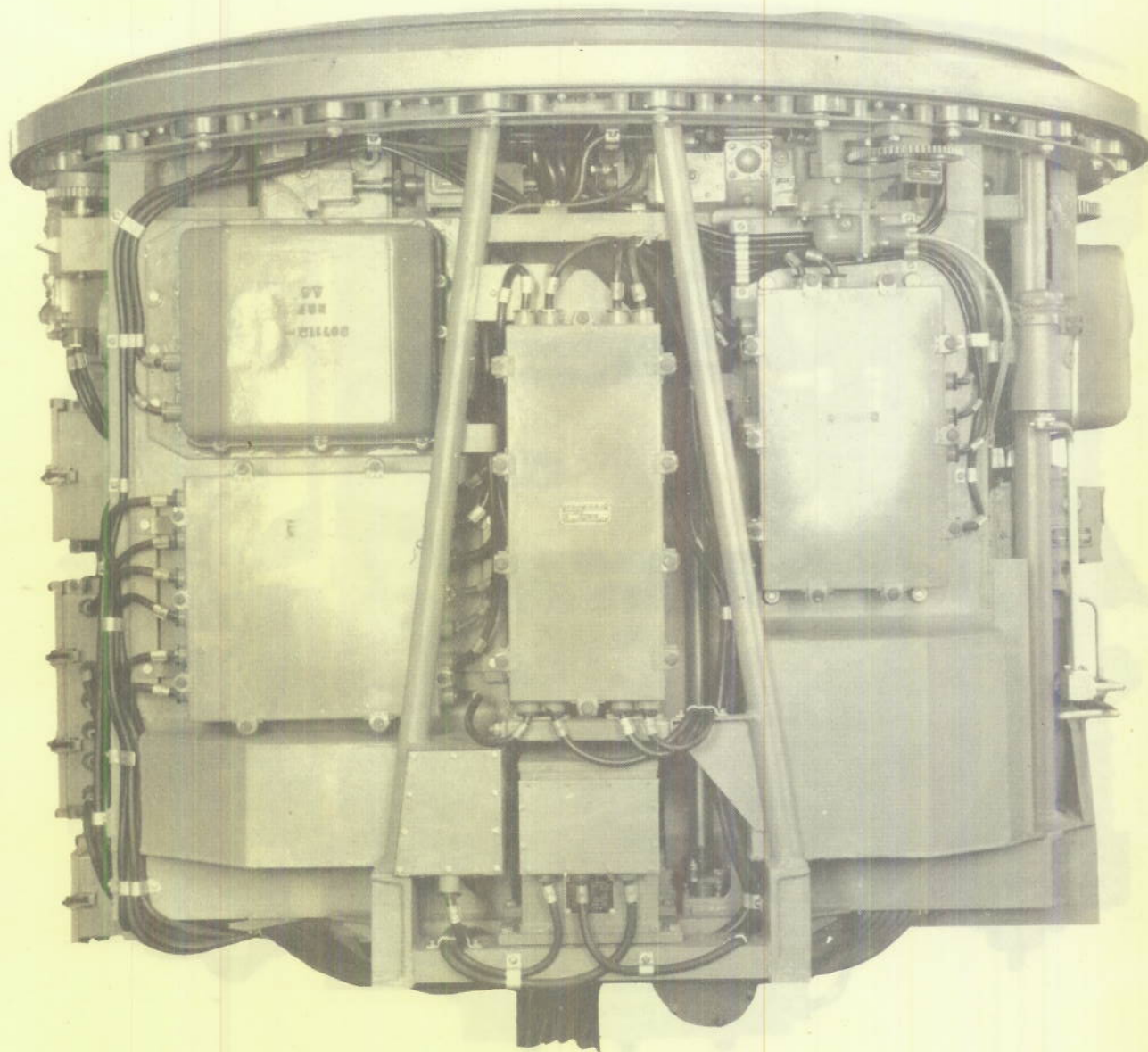


PLATE 9 Gun Director Mk 61 Mod 1 Basket (View of Electrical Control and Amplifier).

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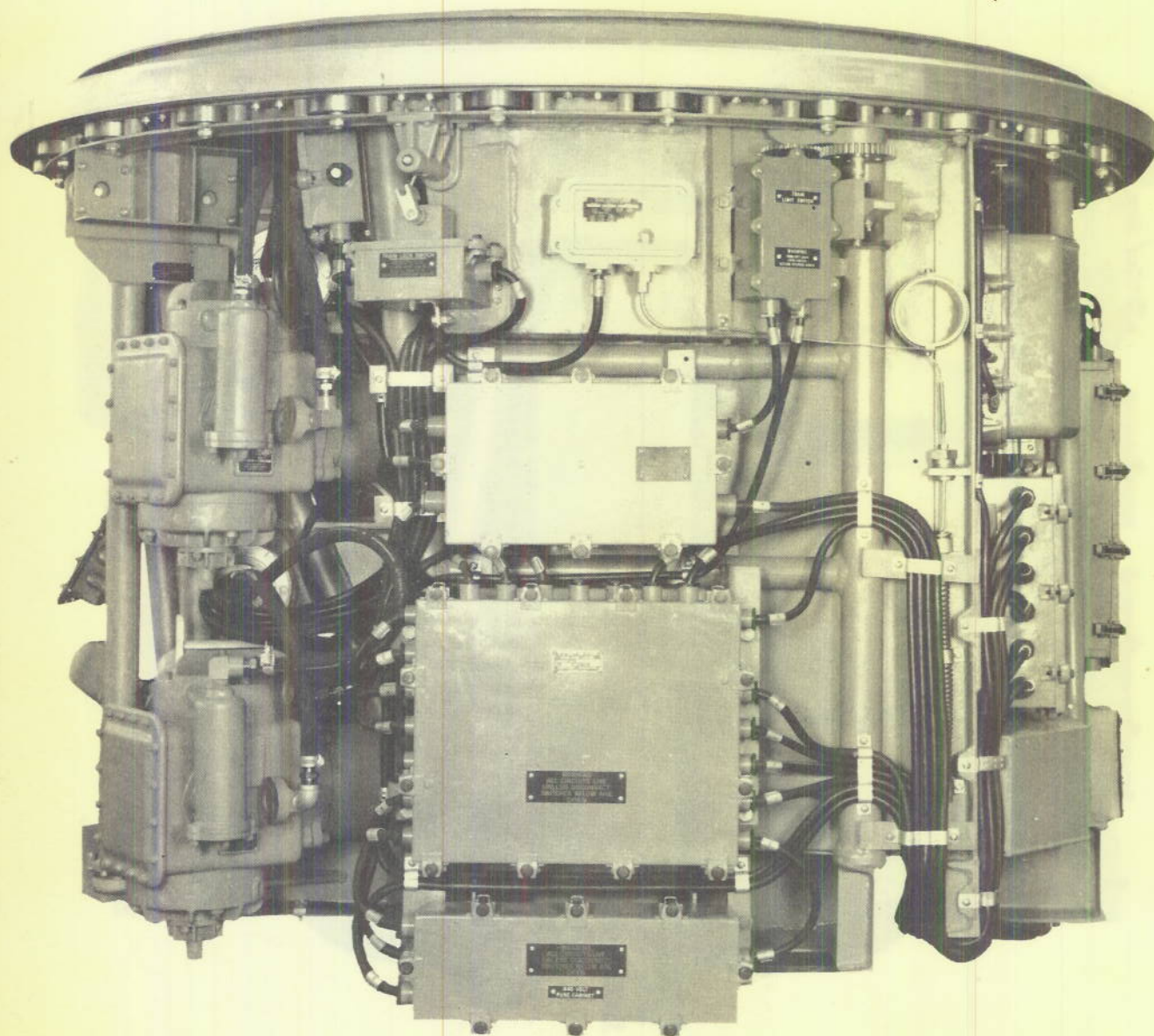


PLATE 10 Gun Director Mk 61 Mod 1 Basket (View of Fuse Panels with Covers removed).

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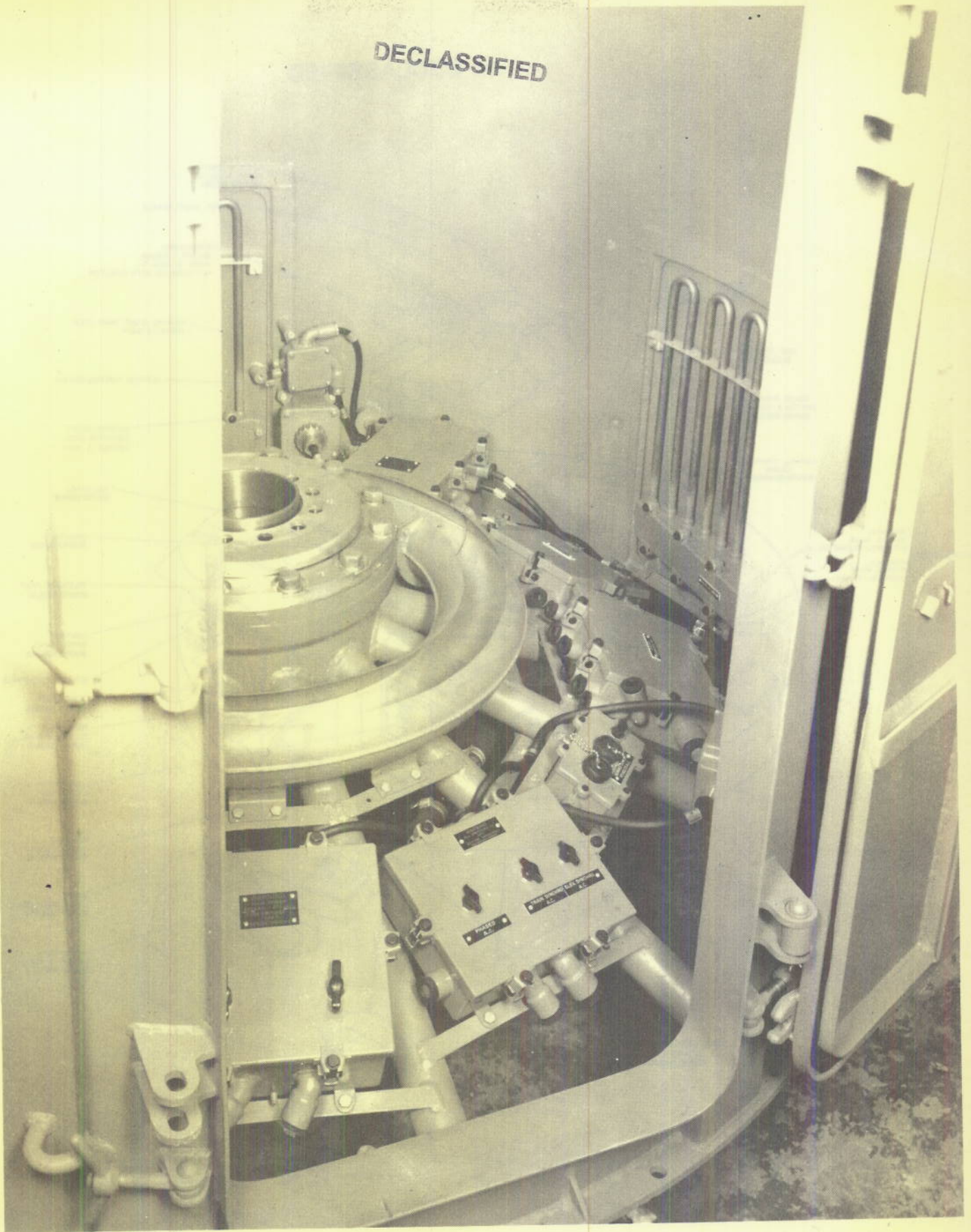
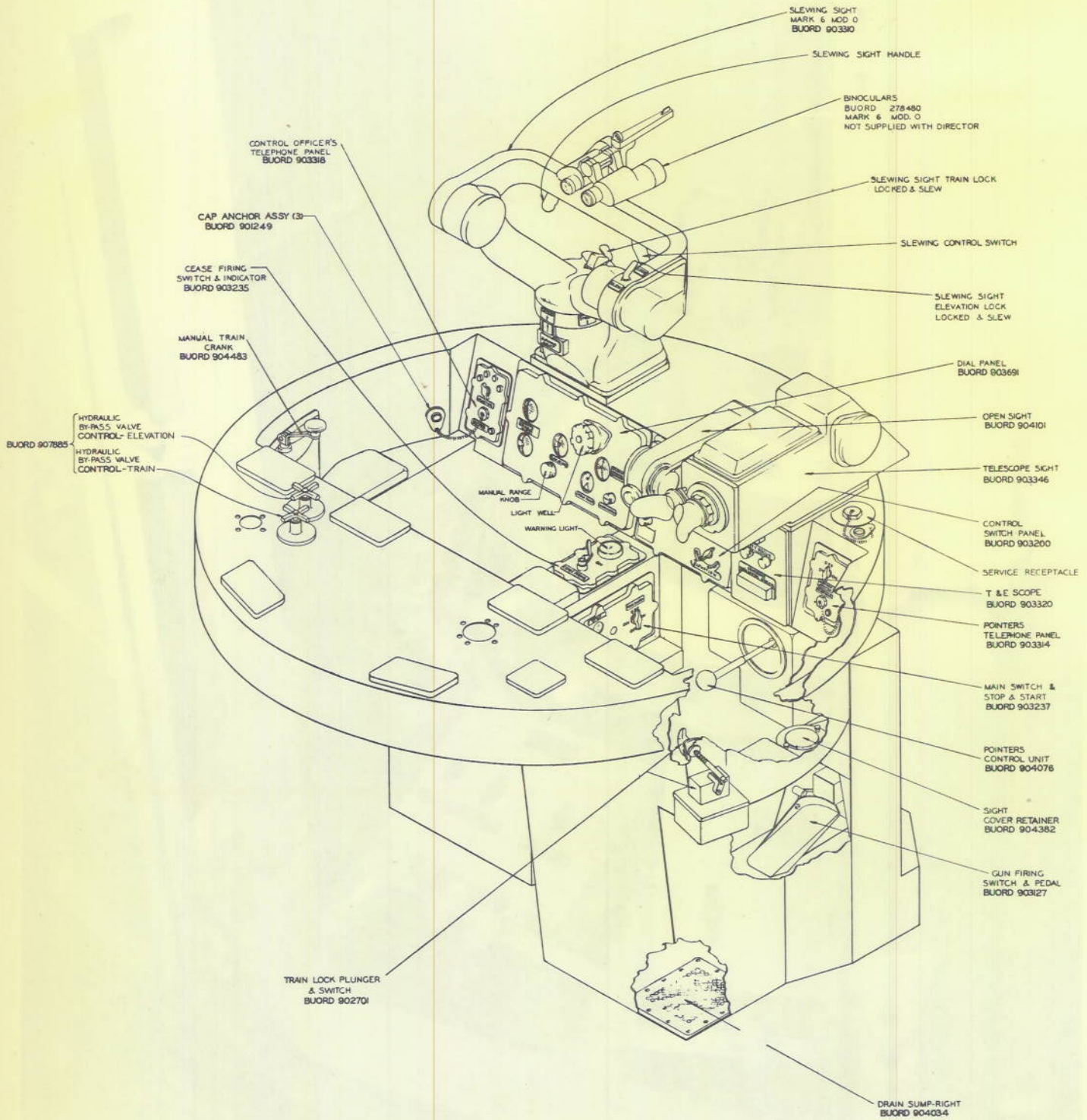


PLATE 11 Gun Director Mk 61 Mod 1 (View through door showing various switch and fuse boxes, water-pump and water-trough).

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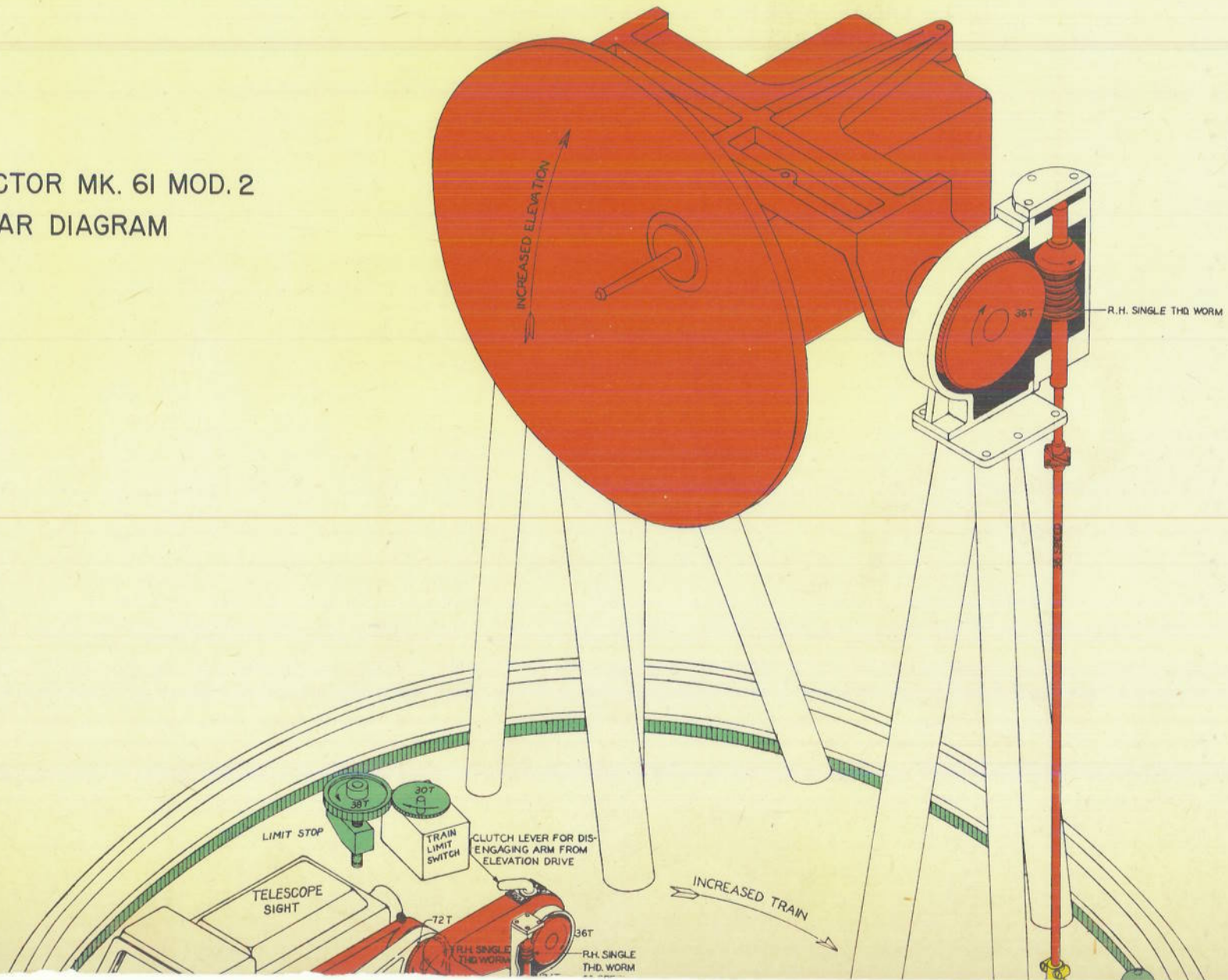
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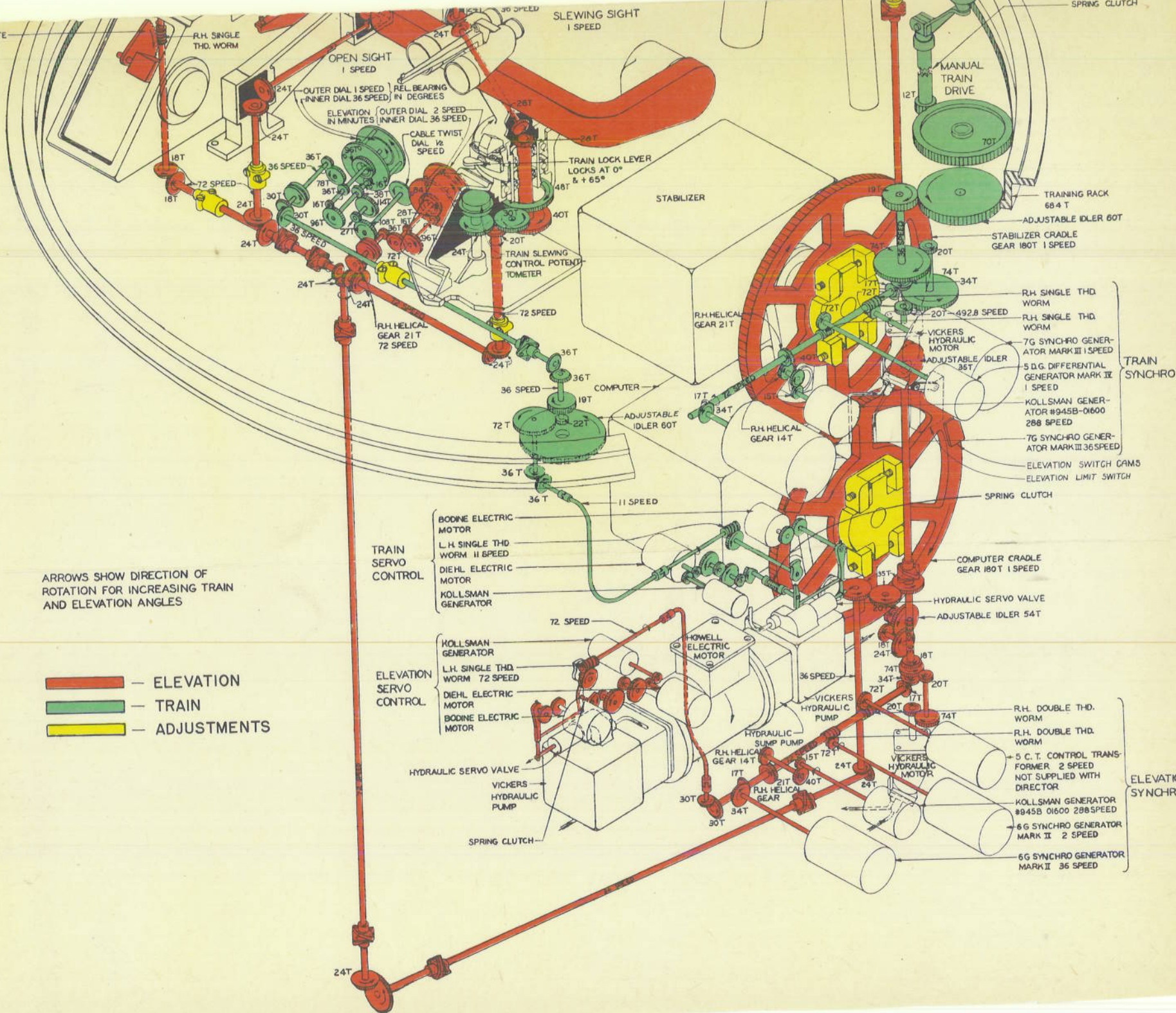
GUN DIRECTOR MK. 61 MOD. 2 GEAR DIAGRAM



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ARROWS SHOW DIRECTION OF ROTATION FOR INCREASING TRAIN AND ELEVATION ANGLES

- ELEVATION
- TRAIN
- ADJUSTMENTS



TRAIN SERVO CONTROL

- BODINE ELECTRIC MOTOR
- L.H. SINGLE THD WORM 11 SPEED
- DIEHL ELECTRIC MOTOR
- KOLLSMAN GENERATOR

ELEVATION SERVO CONTROL

- KOLLSMAN GENERATOR
- L.H. SINGLE THD WORM 72 SPEED
- DIEHL ELECTRIC MOTOR
- BODINE ELECTRIC MOTOR

TRAIN SYNCHRO

- R.H. SINGLE THD WORM
- R.H. SINGLE THD WORM
- 7G SYNCHRO GENERATOR MARK III 1 SPEED
- 5 D.G. DIFFERENTIAL GENERATOR MARK II 1 SPEED
- KOLLSMAN GENERATOR #945B-0600 288 SPEED
- 7G SYNCHRO GENERATOR MARK III 36 SPEED
- ELEVATION SWITCH CAMS
- ELEVATION LIMIT SWITCH

ELEVATION SYNCHRO

- R.H. DOUBLE THD. WORM
- R.H. DOUBLE THD. WORM
- 5 C.T. CONTROL TRANSFORMER 2 SPEED NOT SUPPLIED WITH DIRECTOR
- KOLLSMAN GENERATOR #945B 01600 288 SPEED
- 6G SYNCHRO GENERATOR MARK II 2 SPEED
- 6G SYNCHRO GENERATOR MARK II 36 SPEED

COMPLETE 1/2 SPEED

R.H. SINGLE THD. WORM

OPEN SIGHT 1 SPEED

SLEWING SIGHT 1 SPEED

MANUAL TRAIN DRIVE

TRAINING RACK 68.4 T

ADJUSTABLE IDLER 60T

STABILIZER CRADLE GEAR 180T 1 SPEED

STABILIZER

R.H. HELICAL GEAR 21 T

R.H. SINGLE THD. WORM

R.H. SINGLE THD. WORM

7G SYNCHRO GENERATOR MARK III 1 SPEED

5 D.G. DIFFERENTIAL GENERATOR MARK II 1 SPEED

KOLLSMAN GENERATOR #945B-0600 288 SPEED

7G SYNCHRO GENERATOR MARK III 36 SPEED

ELEVATION SWITCH CAMS

ELEVATION LIMIT SWITCH

SPRING CLUTCH

COMPUTER CRADLE GEAR 180T 1 SPEED

HYDRAULIC SERVO VALVE

ADJUSTABLE IDLER 54T

COMPUTER

ADJUSTABLE IDLER 60T

R.H. HELICAL GEAR 14 T

11 SPEED

72 SPEED

36 SPEED

74 T

34 T

72 T

17 T

20 T

74 T

20 T

74 T

20 T

74 T

20 T

74 T

20 T

74 T

20 T

HYDRAULIC SERVO VALVE

VICKERS HYDRAULIC PUMP

SPRING CLUTCH

HYDRAULIC SERVO VALVE

VICKERS HYDRAULIC PUMP

HYDRAULIC SUMP PUMP

R.H. HELICAL GEAR 14 T

17 T

21 T

40 T

24 T

30 T

30 T

34 T

30 T

30 T

R.H. DOUBLE THD. WORM

R.H. DOUBLE THD. WORM

5 C.T. CONTROL TRANSFORMER 2 SPEED NOT SUPPLIED WITH DIRECTOR

KOLLSMAN GENERATOR #945B 01600 288 SPEED

6G SYNCHRO GENERATOR MARK II 2 SPEED

6G SYNCHRO GENERATOR MARK II 36 SPEED

6G SYNCHRO GENERATOR MARK II 2 SPEED

6G SYNCHRO GENERATOR MARK II 36 SPEED

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6G SYNCHRO GENERATOR MARK II 36 SPEED

6G SYNCHRO GENERATOR MARK II 2 SPEED

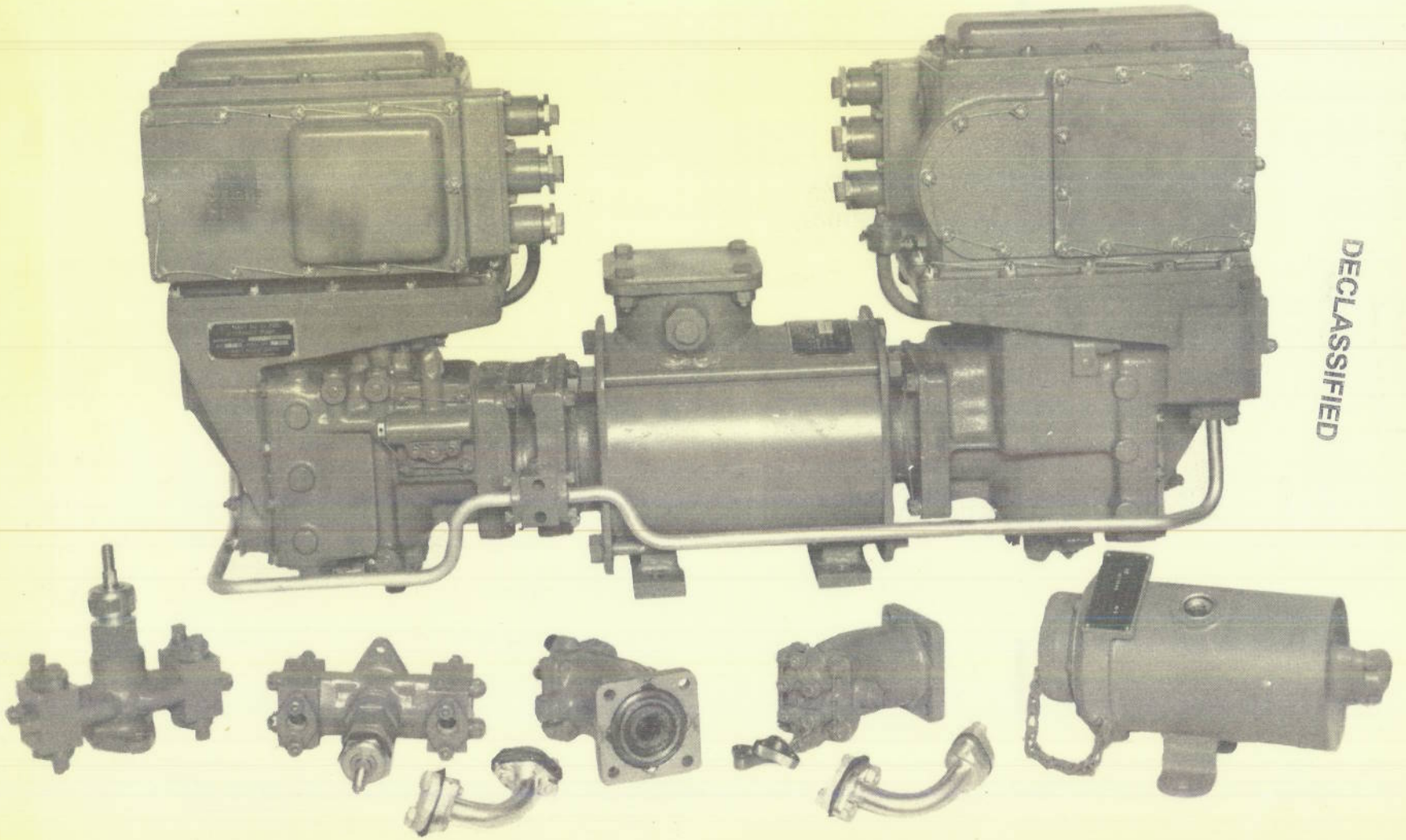
6G SYNCHRO GENERATOR MARK II 36 SPEED

6G SYNCHRO GENERATOR MARK II 2 SPEED

6G SYNCHRO GENERATOR MARK II 36 SPEED

24 T

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PLATE 14 Train and Elevation Hydraulic Power Drive Mk 1 Mod 0.

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FLOW DIAGRAM
TRAIN AND ELEVATION
HYDRAULIC POWER DRIVE MK. I MOD. O
FOR
GUN DIRECTOR MK. 61

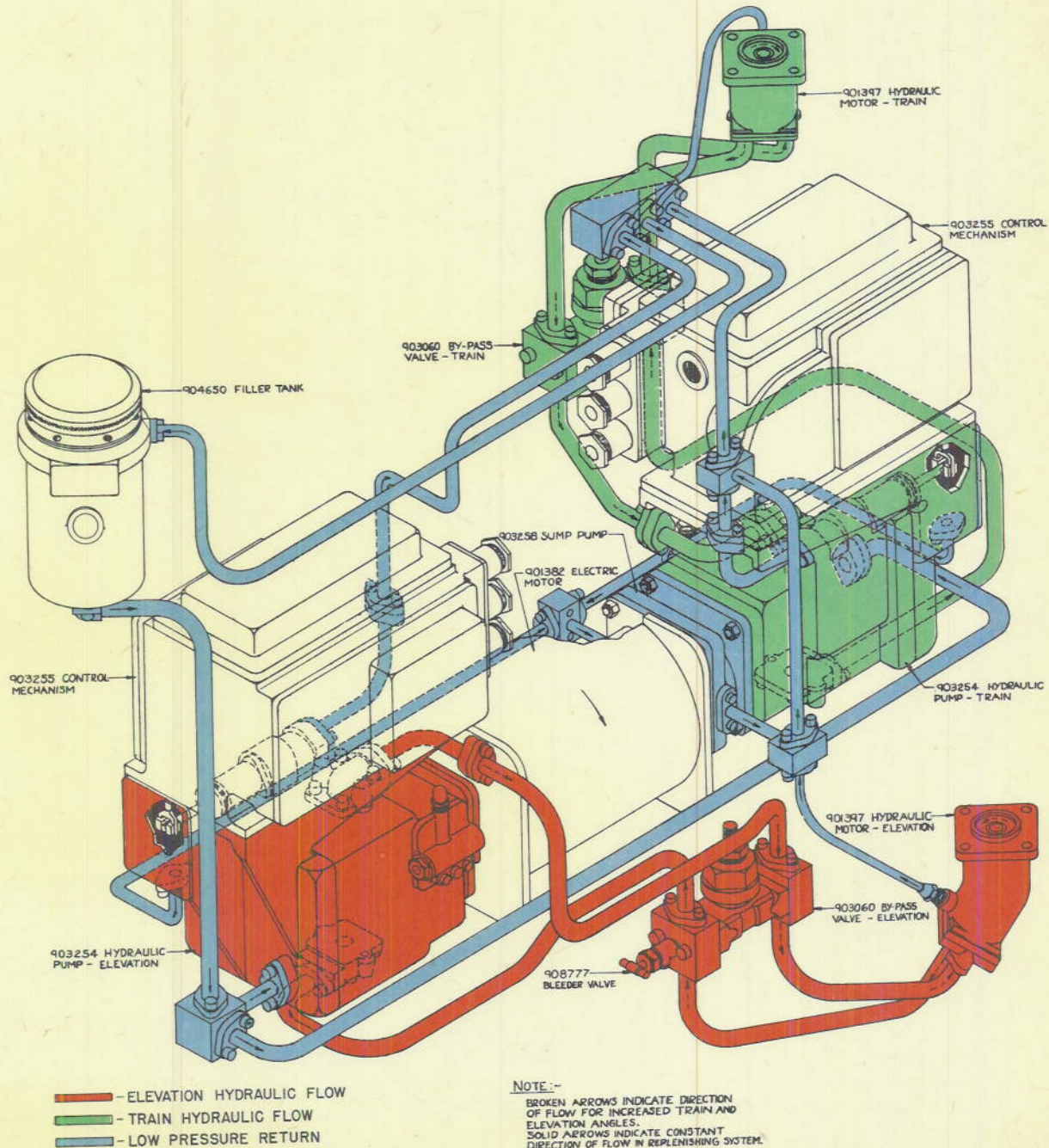
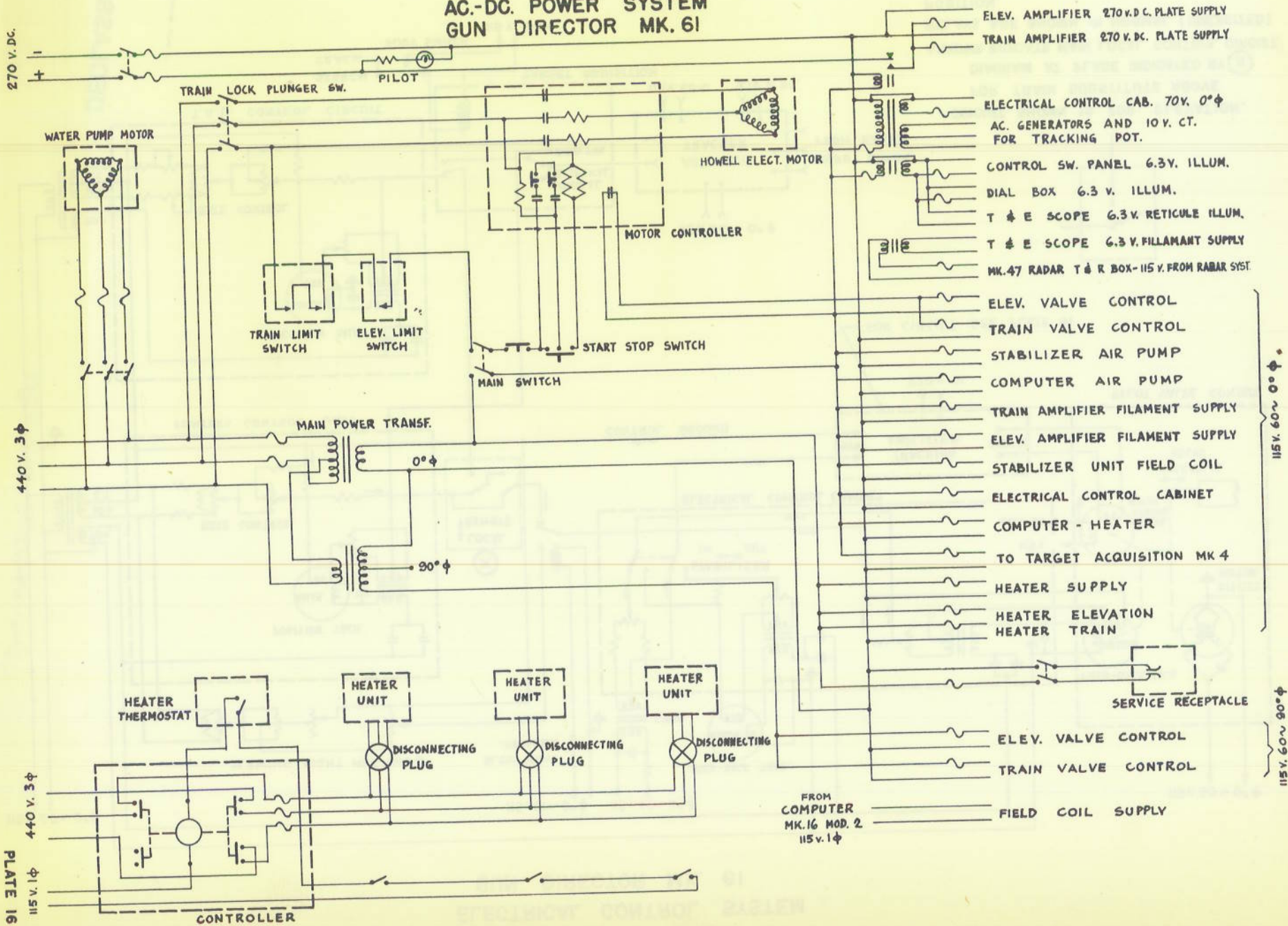


PLATE 15

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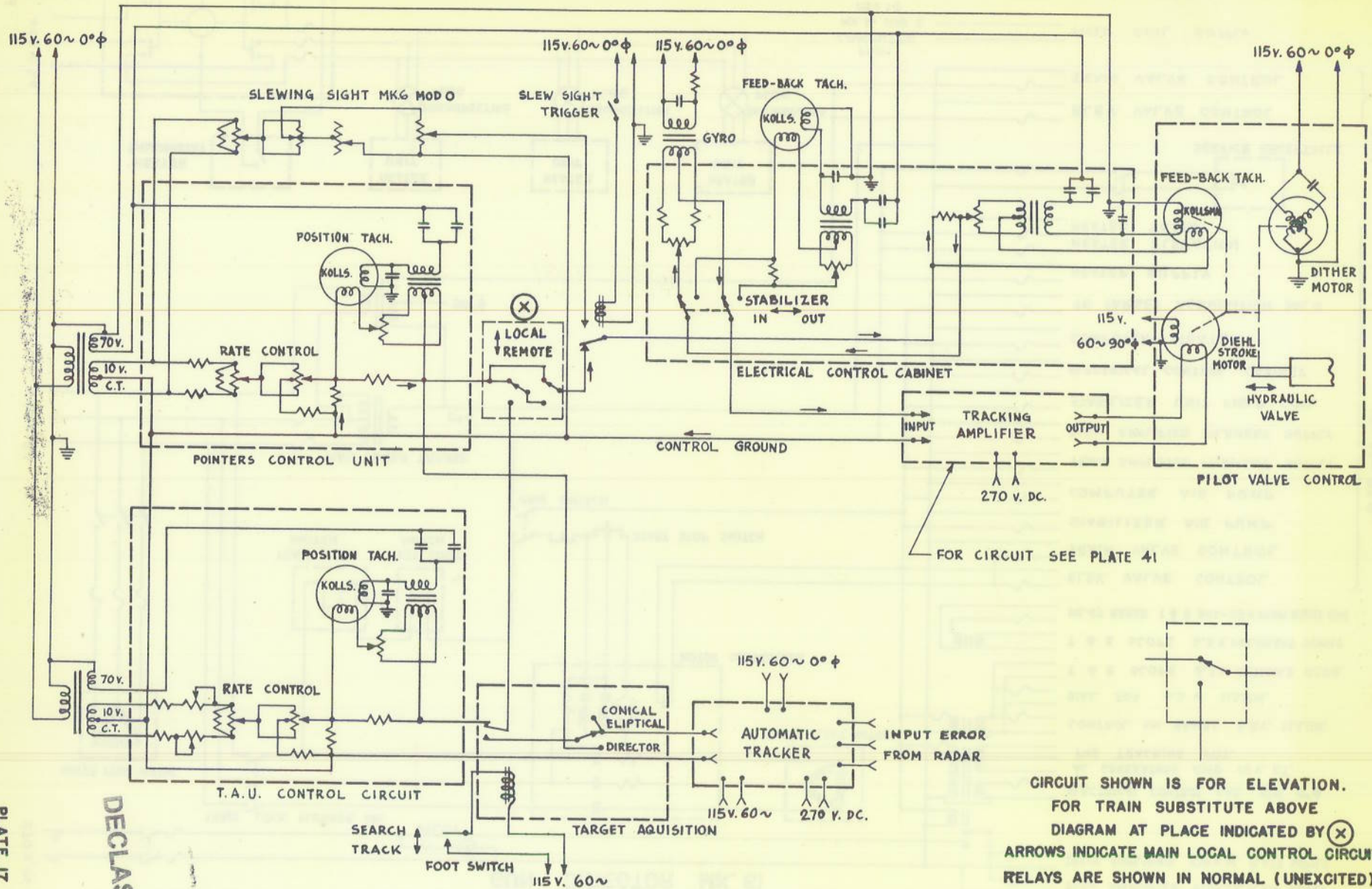
AC-DC. POWER SYSTEM GUN DIRECTOR MK. 61



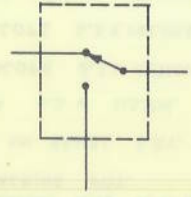
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ELECTRICAL CONTROL SYSTEM GUN DIRECTOR MK. 61

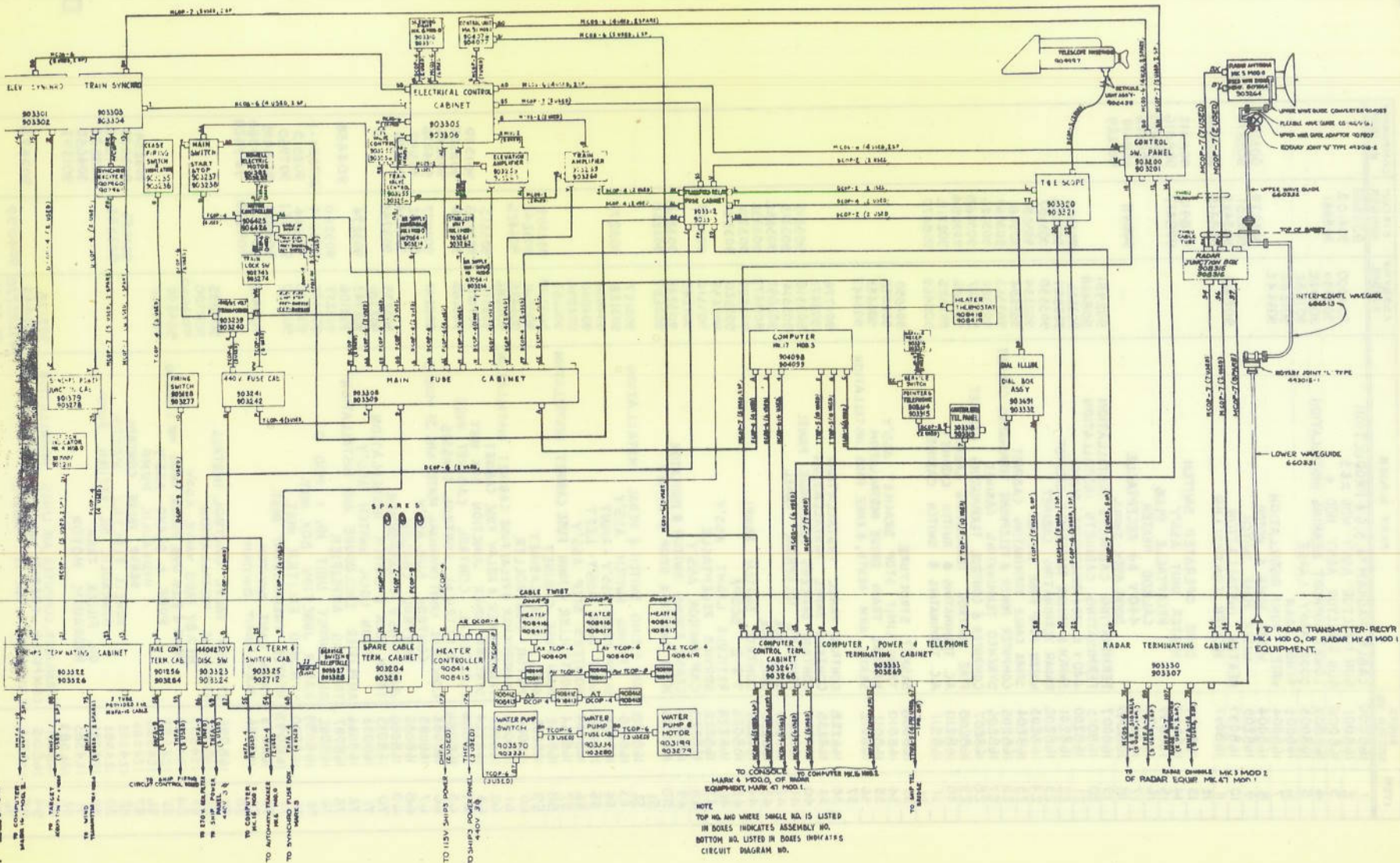


FOR CIRCUIT SEE PLATE 41



CIRCUIT SHOWN IS FOR ELEVATION.
FOR TRAIN SUBSTITUTE ABOVE
DIAGRAM AT PLACE INDICATED BY (X)
ARROWS INDICATE MAIN LOCAL CONTROL CIRCUIT.
RELAYS ARE SHOWN IN NORMAL (UNEXCITED)
POSITION.

CABLE DIAGRAM GUN DIRECTOR MK. 61



TO CONSOLE MARK 4 MOD. O. OF RADAR EQUIP. MK. 41 MOD. 1.

NOTE
TOP NO. AND WHERE SINGLE NO. IS LISTED IN BOXES INDICATES ASSEMBLY NO.
BOTTOM NO. LISTED IN BOXES INDICATES CIRCUIT DIAGRAM NO.

TO RADAR TRANSMITTER-RECVR MK. 4 MOD. O. OF RADAR MK. 41 MOD. 1 EQUIPMENT.

TO RANGE CHIMBLE MK. 3 MOD. 1 OF RADAR EQUIP. MK. 41 MOD. 1

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REF ID: A66500

GUN DIRECTOR MK. 61 BASIC COMPONENT ASSEMBLIES

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ITEM	BUORD. SKETCH NO.	PART NAME	ASSEMBLY NUMBER	CIRCUIT NUMBER	COMPONENT NUMBER
1	168000	CABLE DIAGRAM #4, 5, 6 & PRODUCTION		903349	
2	168001	GUN DIRECTOR ASS'Y MOD 2&3	904000	904102	
3	168006	GUN DIRECTOR ASS'Y MOD 4	908480	908481	
4	168002	LOWER SUPPORT BEARING INSTALLATION	904022		
5	168003	DOOR ASS'Y - LARGE	901232		
6	168003	RING GEAR	901244		
7	168004	WATER PUMP INSTALLATION	903442		
8	168004	WATER PUMP & MOTOR		903279	903199
9	168209	WATER PUMP SWITCH		903331	903570
10	168097	HEATER INSTALLATION	908613	908420	
11	168097	HEATER CONTROLLER		908415	908414
12					
13	168097	DOOR OPERATED SWITCH		908413	908412
14	168097	HEATER UNIT ASS'Y		908417	908416
15	168097	RECEPTACLE PLUG			908409
16	168097	CALROD HEATER			908326
17	168097	440 V 3φ RECEPTACLE		908411	908410
18	168097	DOOR ASS'Y - SMALL			901229
19	168007	TERMINATING CABINETS INSTALLATION	902951		
20	168013	TERMINATING CABINETS INSTALLATION	908468		
21	168200	440 V & 270V DISCONNECT SWITCH	903323	903324	
22	168201	SWITCH & DOUBLE RECEPTACLE CABINET	903327	903328	
23	168202	RADAR TERMINATING CABINET	903330	903307	
24	168203	WATER PUMP FUSE CABINET	903334	903280	
25	168204	SPARE CABLE TERMINATING CABINET	903204	903281	
26	168205	COMPUTER POWER & TELEPHONE TERMINATING CABINET	903333	903269	
27	168206	SYNCHRO TERMINATING CABINET	903322	903326	
28	168207	COMPUTER & CONTROL TERMINATING CABINET	903267	903268	
29	168208	FIRE CONTROL TERMINATING CABINET	901256	903284	
30	168210	A.C. TERMINATING & SWITCH CABINET	903325	902712	
31	168211	A.C. TERMINATING & SWITCH CABINET	908469	908470	
32					
33	168008	BASKET STRUCTURE	904050		
34	168010	TRAIN LIMIT STOP BRACKET ASS'Y	904078		
35	168011	MANUAL TRAIN DRIVE INSTALLATION	904483		
36	168012	SEATS, ARM RESTS, & KNEE PADS INSTALLATION	903447		
37					
38	168228	CONTROL PANEL INSTALLATION	901776		
39	168233	CONTROL PANEL INSTALLATION	908471		
40	168220	CONTROL OFFICER'S TELEPHONE PANEL	903318	903319	
41	168221	POINTER'S TELEPHONE PANEL	903314	903315	
42	168227	DIAL BOX	903691	903332	
43	168234	DIAL BOX	908472	903332	
44	168229	CONTROL SWITCH PANEL	903200	903201	
45	168083	T & E SCOPE	903320	903321	
46	168228	RETICULE LIGHT ASS'Y	902435		
47	168222	SERVICE RECEPTACLE	903316	903317	
48	168223	CAP ANCHOR ASS'Y	901249		
49	168225	CEASE FIRING SWITCH & INDICATOR	903235	903236	
50	168226	MAIN SWITCH & STOP & START	903237	903238	
51					
52	168018	GUN FIRING SWITCH & PEDAL INSTALLATION	903127		
53	168018	FIRING SWITCH ASS'Y	903128	903277	
54	168034	SUMP TANK ASS'Y - RIGHT	904034		
55	168034	SUMP TANK ASS'Y - LEFT	904046		
56	168034	POINTER'S STEP ASS'Y	904394		
57	168064	CONTROLLER & MAIN FUSE CABINET INSTALLATION	906687		
58	168062	MAIN FUSE CABINET	903308	903309	
59	168063	440 V FUSE CABINET	903241	903242	
60	168064	MOTOR CONTROLLER	906425	906426	
61	168065	TRANSFORMER & RELAY FUSE CABINET INSTALLATION	906686		
62	168065	TRANSFORMER & RELAY FUSE CABINET	903312	903313	
63	168224	SYNCHRO POWER JUNCTION BOX INST.	907873	903278	901379
64	168086	ELECTRICAL CONTROL CABINET INST.	908163	903306	903305
65	168086	ELECTRICAL CONTROL CHASSIS			903246
66	168085	CONTROL UNIT (MANUAL RATE) MK 31 MOD 0	908261	904077	904076
67	168085	CONTROL SUB-ASS'Y		903292	903197
68	168085	CONTROL CHASSIS		903294	903293
69	168066	440 CT/115 V TRANSFORMER	903239	903240	
70	168033	TRAIN LOCK & SWITCH INSTALLATION	902701		
71	168033	TRAIN LOCK SWITCH ASS'Y	902743	903274	
72	168066	AMPLIFIER ENCLOSURE AND INSTALLATION	904106		904458
73	168087	TRACKING AMPLIFIER	903259	903260	
74	168032	AIR SUPPLY UNIT MK 1 MOD 0	903472	903214	417054-1
75	168089	KADAR JUNCTION BOX INST.	908578	908315	908315
76	168230	SYNCHRO EXCITER INST.	908307	907961	907960
77	168093	HEATER THERMOSTAT INST.		908419	908418
78	168073	TRAIN LIMIT SWITCH	909407	909327	909326
79	168074	ELEV. LIMIT SWITCH		909329	909328
80					
81	168095	BY-PASS VALVE CONTROL INSTALL.	907885		
82	168096	HYDRAULIC INSTALLATION	908700		
83	124583	HYD. BY PASS VALVE ASS'Y	903060		
84	124583	TRAIN & ELEV. HYD. POWER DRIVE MK 1 MOD 0	904500		
85	124583	PUMP & SERVO ASS'Y	904600		
86	124583	HYDRAULIC PUMP			903254
87	124583	SERVO VALVE CONTROL		903256	903255
88	124583	HOWELL ELECTRIC MOTOR		903282	901382
89	124583	HYDRAULIC OIL RETURN PUMP			903258
90	124583	OIL FILLER TANK			904650
91	124583	HYDRAULIC MOTOR			901397
92	124583				
93	168031	STABILIZER, COMPUTER, AIR LINES INSTALLATION	902178		
94	168015	COMPUTER CRADLE INSTALLATION	903444		
95	172214	COMPUTER MK 17 MOD 3	493727, 28	904099	903423
96			29, 37, 41		
97		COMPUTER MK 17 MOD 4			

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**GUN DIRECTOR MK. 61
BASIC COMPONENT ASSEMBLIES
(CONTINUED)**

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ITEM	BUORD. SKETCH NO.	PART NAME	ASSEMBLY NUMBER	CIRCUIT NUMBER	COMPONENT NUMBER
98	168056	HORIZON INDICATOR MK 4 MOD 0	907001	903211	
99	168016	STABILIZER UNIT CRADLE INSTALLATION	903449		903424
100	136793	STABILIZER UNIT MK1 MOD 1	494218-494222	903262	
101		STABILIZER UNIT MK1 MOD 2			
102	168017	CRADLE GEAR INSTALLATION	903382		
103	168019	ELEVATION LIMIT STOP SUB-ASS'Y	904497		
104					
105	168020	ELEVATION DRIVE TAKE-OFF INSTALLATION	904072		
106					
107	168024	SIGHTS AND ELEVATION DIAL DRIVE INSTALLATION	906800		
108	168035	TRAIN SYNCHRO & TRANS. INSTALLATION	904150		
109	168035	TRAIN TRANSMISSION ASS'Y	904062		
110	168039	TRAIN SYNCHRO ASS'Y	903303	903304	
111	168036	TRAIN SYNCHRO & TRANSMISSION INSTALLATION	908249		
112	168036	TRAIN TRANSMISSION ASS'Y	908473		
113	168037	TRAIN SYNCHRO ASS'Y	907339	903304	
114	168038	TRAIN SYNCHRO TAKE OFF INSTALLATION	908474		
115					
116	168044	ELEV. SYNCHRO & TRANSMISSION INSTALLATION	904149		
117	168044	ELEV. TRANSMISSION & TAKE OFF ASS'Y	904063		
118	168049	ELEV. SYNCHRO ASS'Y	903301	903302	
119	168045	ELEVATION SYNCHRO & TRANSMISSION INSTALLATION	908262		
120	168045	ELEVATION TRANSMISSION & TAKE OFF ASS'Y	908475		
121	168046	ELEVATION SYNCHRO ASS'Y	908303	903302	
122	168047	ELEVATION SYNCHRO TAKE OFF INSTALLATION	908476		
123	168030	TRAIN DIAL DRIVE INSTALLATION	907896		
124					
125					
126	168054	WAVE GUIDE & CABLE TWIST INSTALLATION	904091		
127	168054	WAVE GUIDE (LOWER)			660331
128	168054	INTERMEDIATE WAVEGUIDE			686513
129	168054	ROTARY JOINT "L" TYPE			493015-1
130	168054	WAVE GUIDE SUPPORT			908317
131	168067	WAVE GUIDE ASS'Y 30" RADAR DISH	686512		
132	168067	UPPER WAVEGUIDE			660332
133	168067	ROTARY JOINT "U" TYPE ASS'Y			493015-2
134	168067	UPPER CONVERTER WAVEGUIDE			660333
135	168067	FLEXIBLE WAVEGUIDE			CG-179A/U(6)
136	168067	UPPER ADAPTOR			678636
137	168067	ANTENNA BOX MK5 MOD 0 USED WITH RADAR SYSTEM MK47	607044	903264	
138					
139	168072	WAVEGUIDE ASS'Y 48" RADAR DISH			
140	168072	UPPER WAVEGUIDE			493015-2
141	168072	ROTARY JOINT "U" TYPE ASS'Y			
142	168072	UPPER CONVERTER WAVEGUIDE			
143	168072	FLEXIBLE WAVEGUIDE			
144	168072	UPPER ADAPTOR			
145	168072	ANTENNA BOX MK5 MOD 0 USED WITH RADAR SYSTEM MK47			
146					
147	168067	30" RADAR DISH SUPPORTS & EQUIPMENT INSTALLATION	907470		
148	168072	48" RADAR DISH SUPPORTS & EQUIPMENT INSTALLATION	908591		
149	168068	RADAR BEARING HOUSING (CABLE)	904069		
150	168060	RADAR WORM TRANSMISSION INSTALL.	907840		903630
151	168058	30" RADAR DRIVE SHAFT ASS'Y - UPPER HALF	906364		
152	168059	48" RADAR DRIVE SHAFT ASS'Y - UPPER HALF	908341		
153	168057	RADAR DRIVE SHAFT ASS'Y - LOWER HALF	904470		
154	168009	RING GEAR BEARING & SEAL INSTALLATION	904054		
155					
156	168070	OPEN & PRISM TELESCOPE SIGHT INSTALLATION	904466		
157	167919	MAIN ASS'Y - PRISM TELESCOPE MK 92 MOD 2	909997		
158	122702	AUXILIARY EYEGUARD ASS'Y	904300		
159	168082	STOWAGE BOX ASS'Y	904309		
160	168071	OPEN SIGHT ASS'Y	904101		
161	168090	SLEWING SIGHT MK 6 MOD 0	903310	903311	
162	168090	SLEW CONTROL CHASSIS		903249	903248
163	168100	SAFETY BELT 30" RADAR DISH	907495		
164	168100	CANOPY COVERING 30" RADAR DISH			
165	168	SAFETY BELT 48" RADAR DISH			
166	168	CANOPY COVERING 48" RADAR DISH			
167					
168	168094	DIRECTOR CABLING			
169	124575	SPARES HYDRAULIC			
170					
171	MAILED 21789	SPARES - GUN DIRECTOR MK 61 MOD 2			
172					
173					
174					
175	168090	BINOCULARS MK 39 MOD 1	493978		
176	168231	POWER FILTER CABINET	904068	904030	
177					
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BASIC COMPONENTS FOR GUN FIRE CONTROL SYSTEM MK. 61

		<u>Mark</u>	<u>Mod.</u>	<u>Mfr.</u>
Gun Director		61	2	Norge
T&E Hydraulic Power System		1	0	Vickers
Control Unit (Manual Rate)		31	0	USNGF
Horizon Indicator		4	0	Norge
Stabilizer Unit		1	1	Eastman
Computer		17	3	Eastman
Telescope		92	2	USNGF
Slewing Sight		6	0	USNGF
Binoculars		39	1	GFM
Air Supply Unit (2 required)		1	0	GFM
Computer		16	2	Sub. Sig.
Computer		33	1 to 6	Sub. Sig.
Train Parallax Corrector		5	0	Reeves
Amplifier		10	0	Reeves
Radar Equipment	<u>Bu of Ships No.</u>	47	1	Sub. Sig.
Radar Console	CEM 55 AJU	3	2	"
Radar Modulator	CEM 50 AGH-1	1	1	"
Radar Range Unit	CEM 23 AJU	6	2	"
Radar Indicator (Console)	CEM 55 AJR	7	2	"
Radar Power Supply	CEM 20 AFU	11	2	"
Radar Console	CEM 55 AJT	6	0	"
Radar Amplifier (Servo)	CEM 50 AKF	35	0	"
Radar Tracker (Automatic)	CEM 50 AKE	5	0	"
Target Acquisition Unit	CEM 55 AJS	5	1	"
Radar Antenna (30" Dish)	CAJS 66 ANA	5	1	"
Radar Transmitter Receiver	CEM 43 ADG	4	0	"
Waveguide Fittings				"
Regulating Transformer	NT-301496			GFM
Range Indicator		5	1	GFM
Wind Transmitter		4	5	Sperry
	<u>Bu. Ord.No.</u>			
Motor Controller	500302			Sub. Sig.
Motor Generator Set (270V DC)	292366			"
Filter & Fuse Cabinet (270V DC)	904068			USNGF
Push Button Station	500300			Sub. Sig.
Fuse Box		3	1	GFM
Fuse Box		4	0	GFM
	<u>Bu of Ships No.</u>			
Connection Box (20 wire) 4 req'd.)	9-S-4302-L			GFM
Disconnect Switches Fused 3 pole 440V. (3 req'd.)				GFM

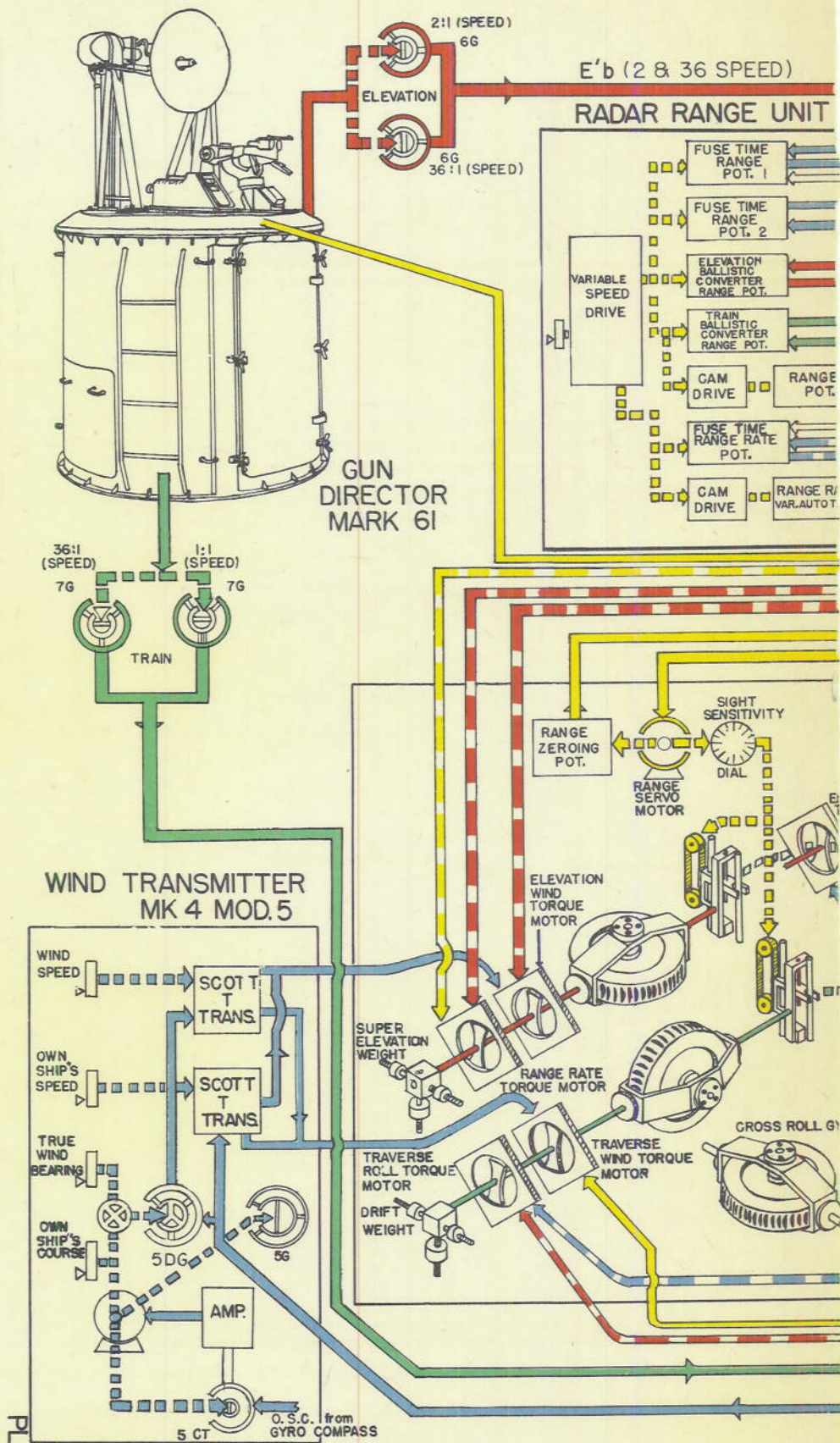
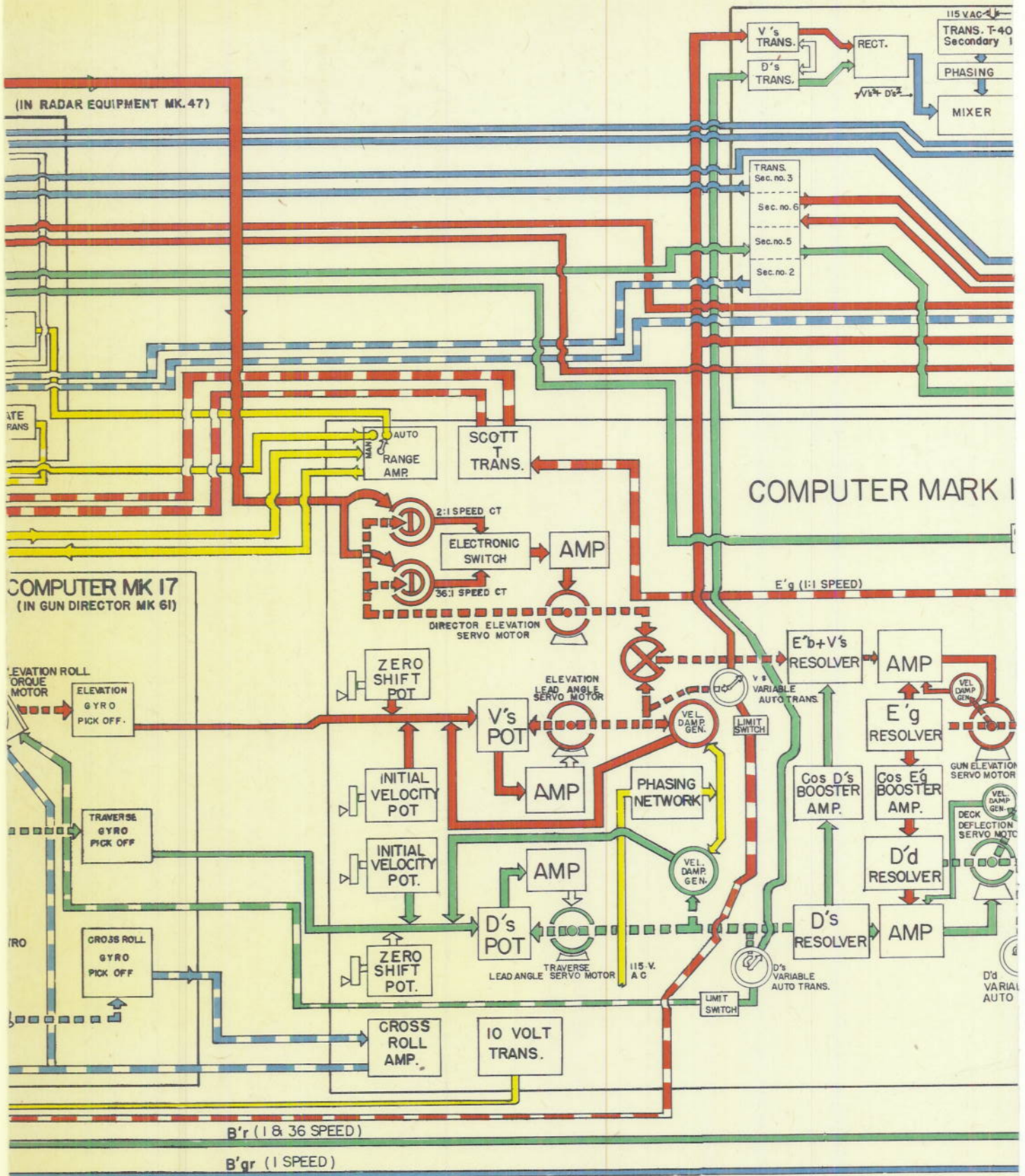
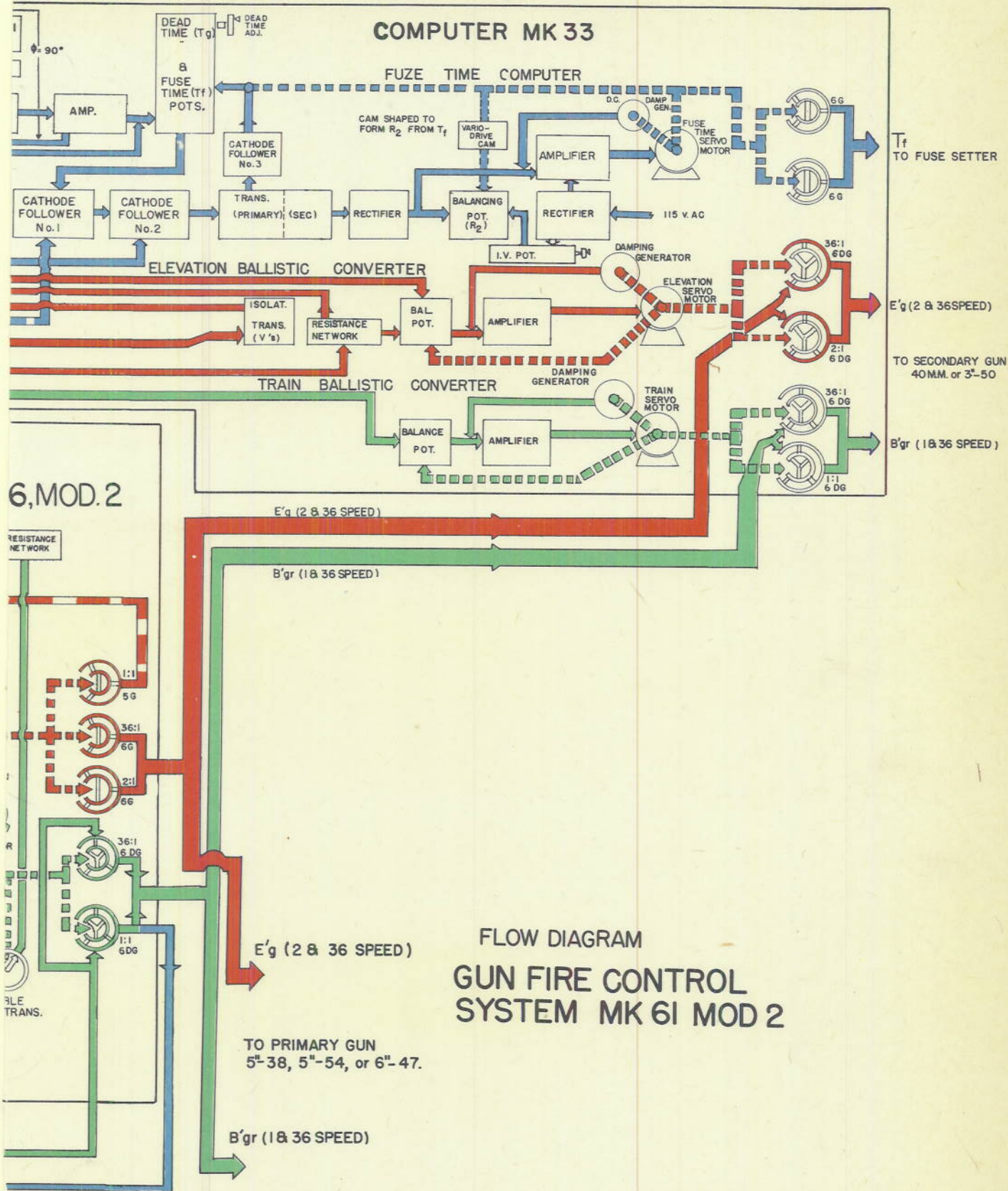


PLATE 23



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COMPUTER MK 33



FLOW DIAGRAM
GUN FIRE CONTROL
SYSTEM MK 61 MOD 2

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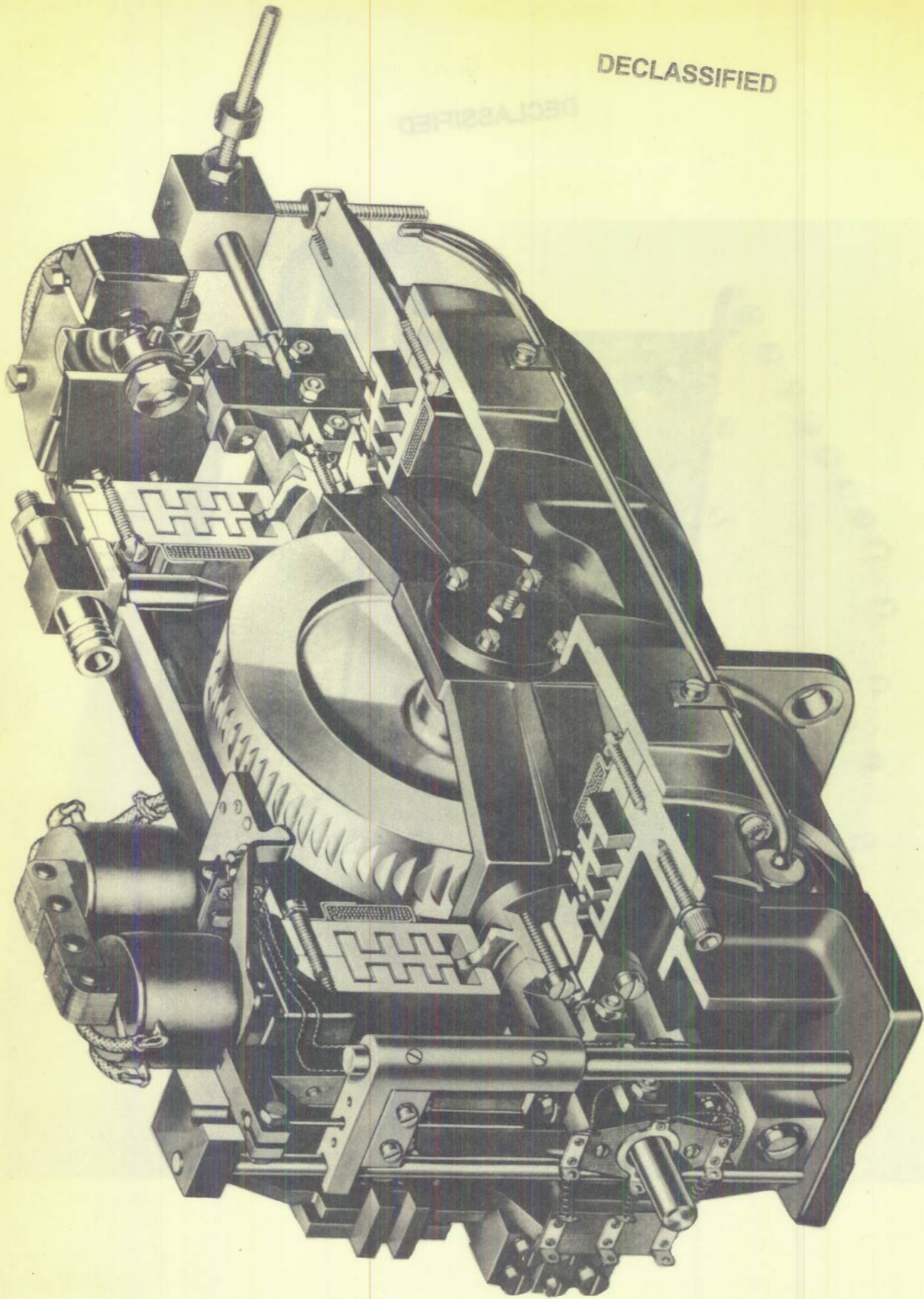


PLATE 25 Elevation Gyro of Stabilizer Mk 1.

DECLASSIFIED

REF ID: A66582
DECLASSIFIED

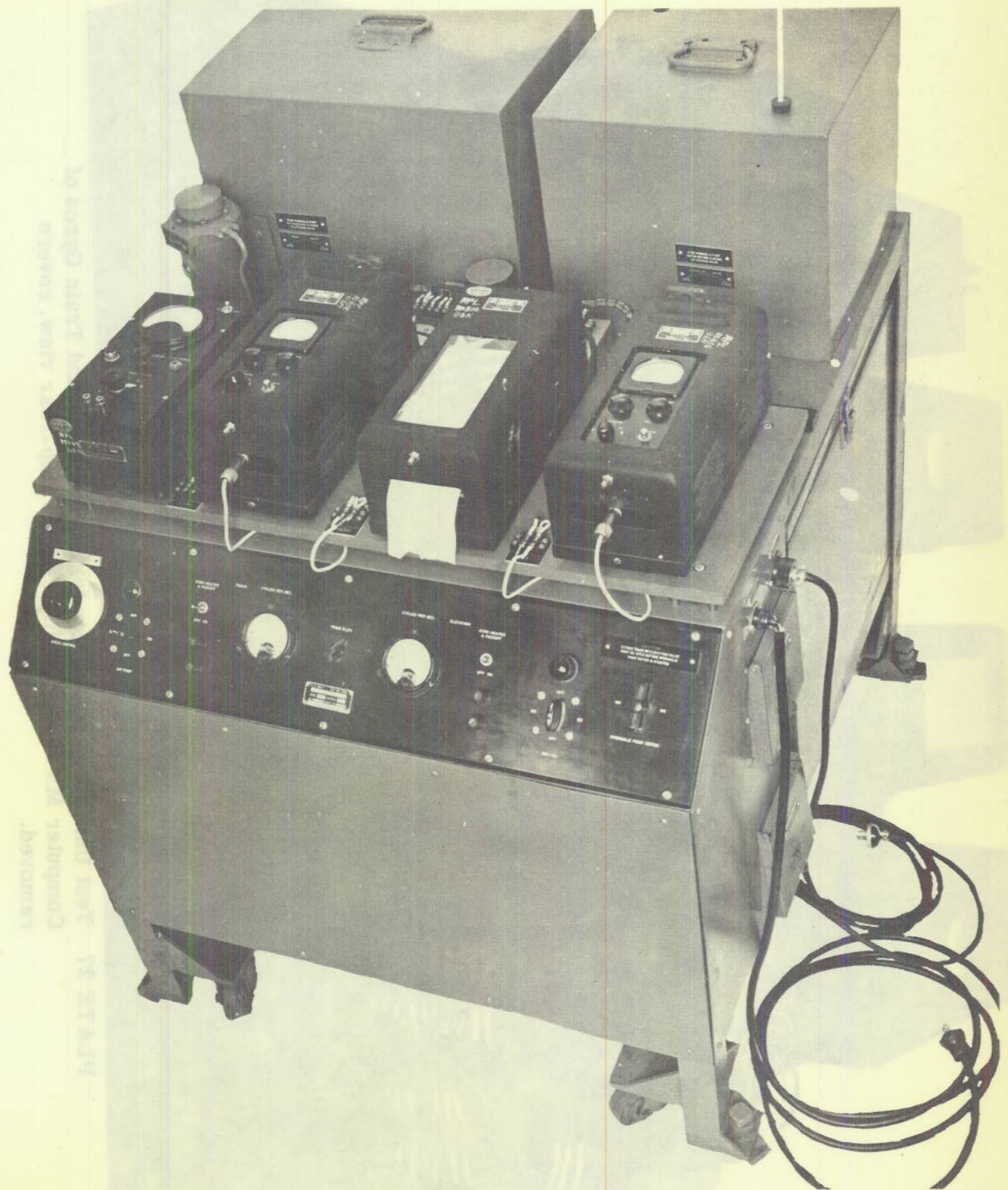
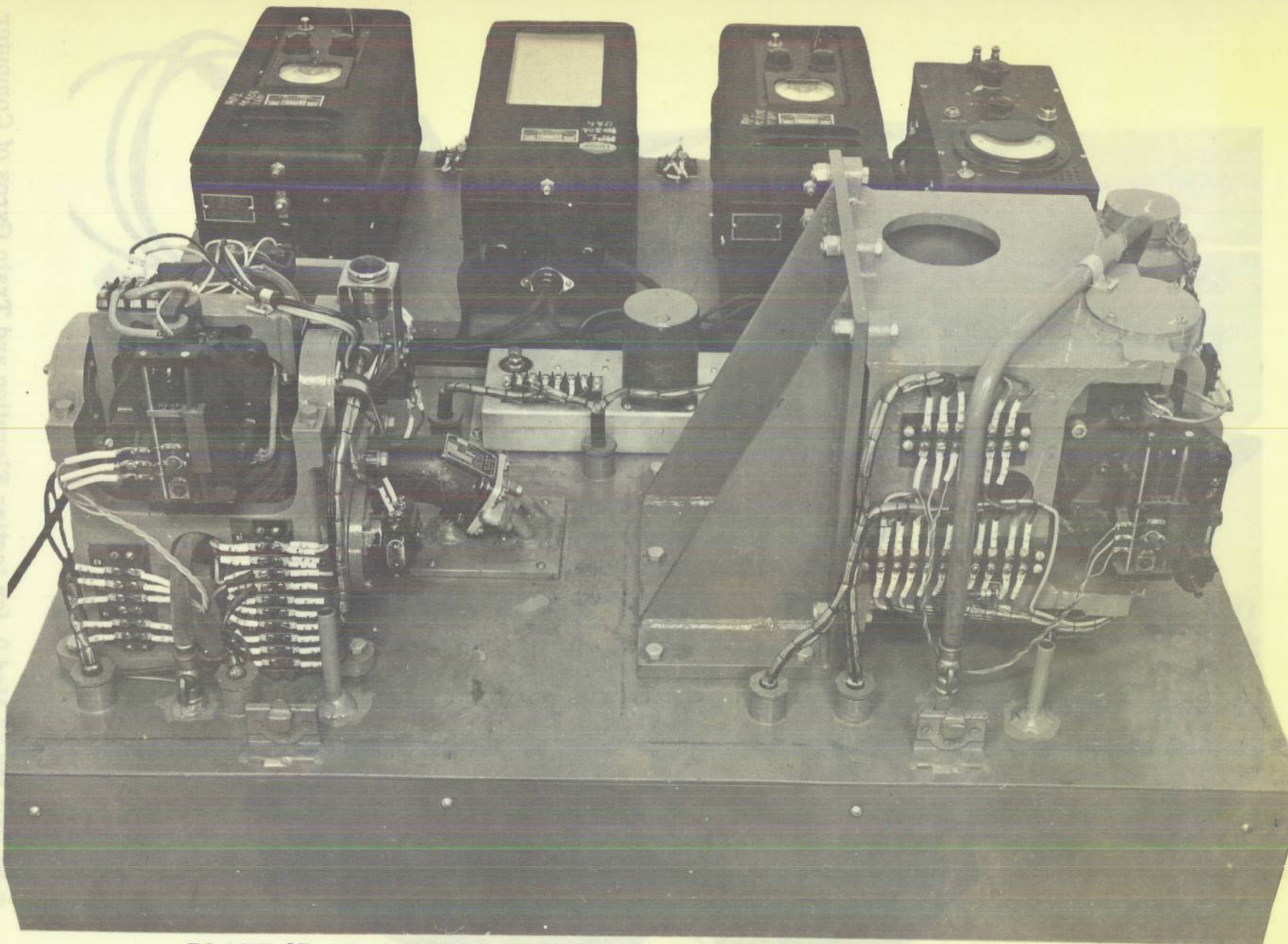


PLATE 26 Test Unit Mk 27 Mod 0, for testing Elevation and Train Gyros of Computer Mk 17 and Stabilizer Mk 1.

DECLASSIFIED

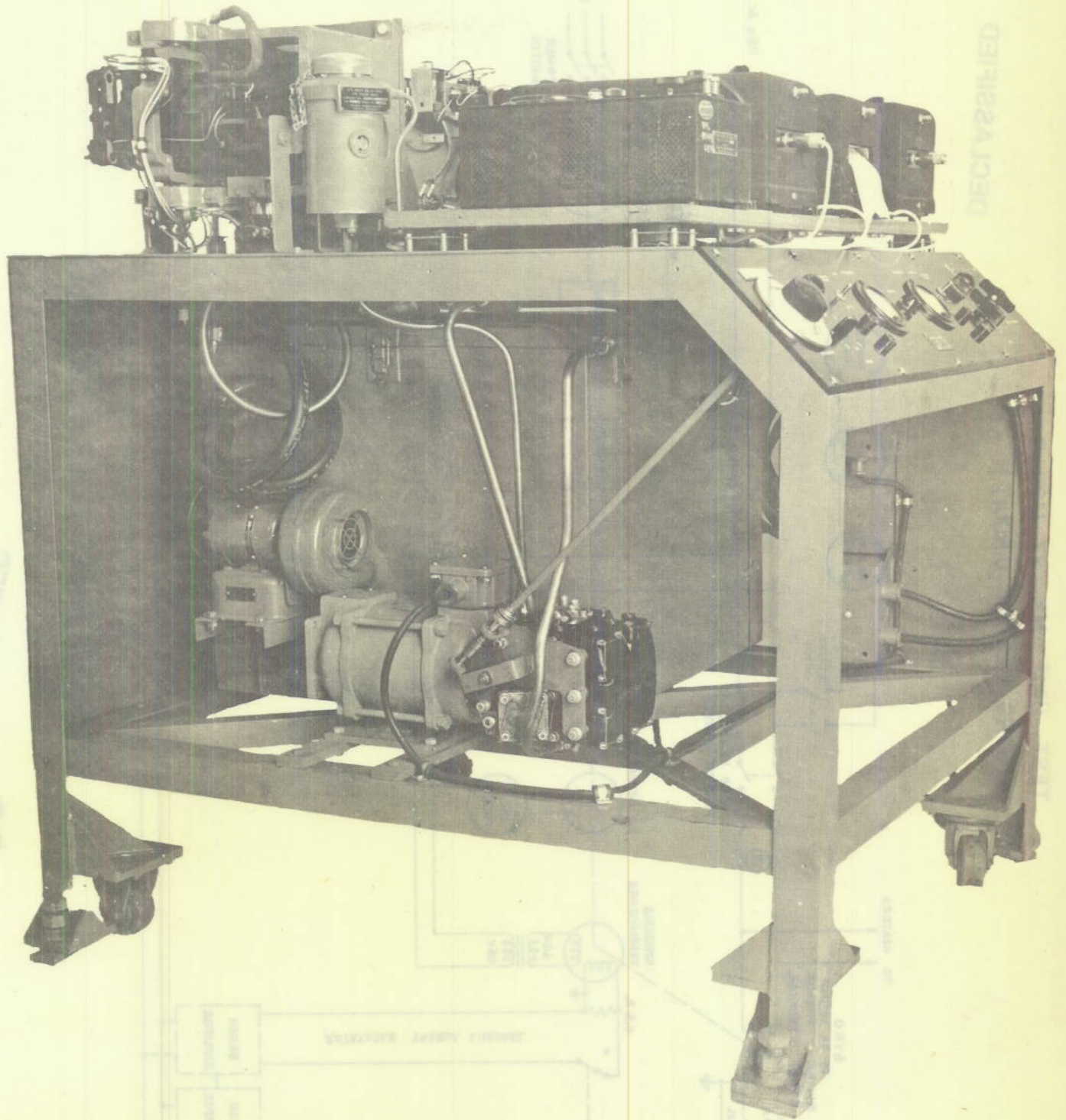
DECLASSIFIED



DECLASSIFIED

PLATE 27 Test Unit Mk 27 Mod 0, for testing Elevation and Train Gyros of Computer Mk 17 and Stabilizer Mk 1; top-rear view, covers removed.

DECLASSIFIED

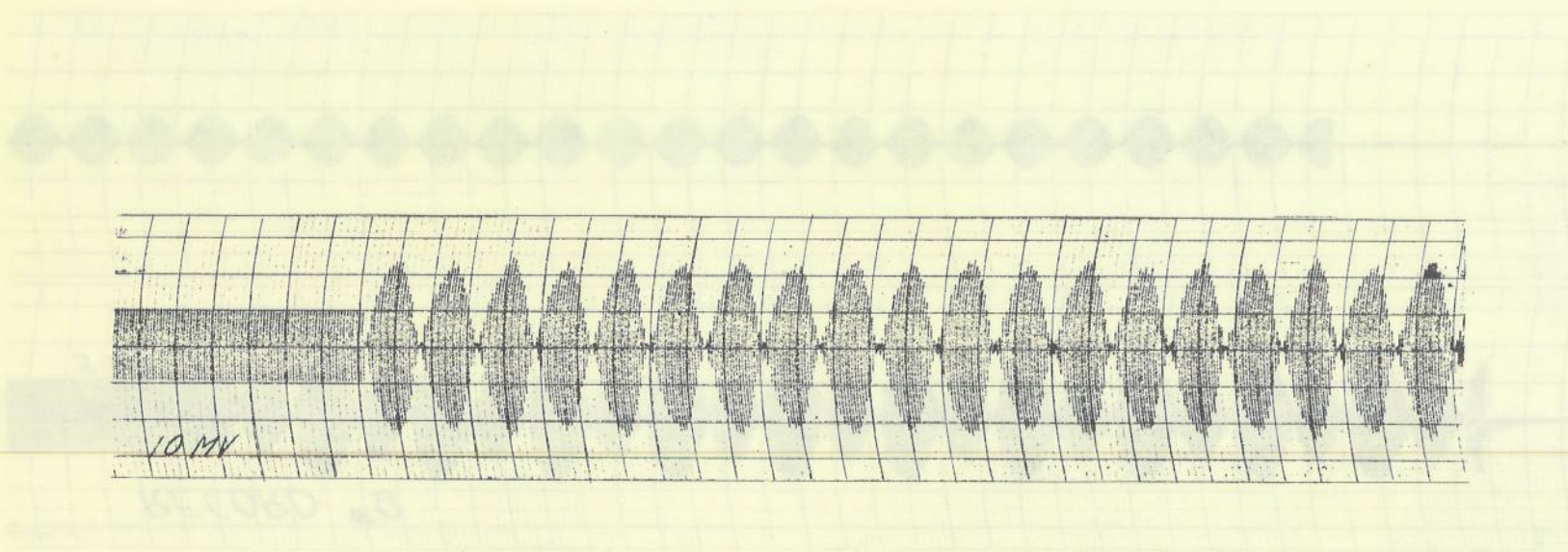


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PLATE 28 Test Unit Mk 27 Mod 0, for testing Elevation and Train Gyros of Computer Mk 17 and Stabilizer Mk 1; side view, covers removed.

DECLASSIFIED

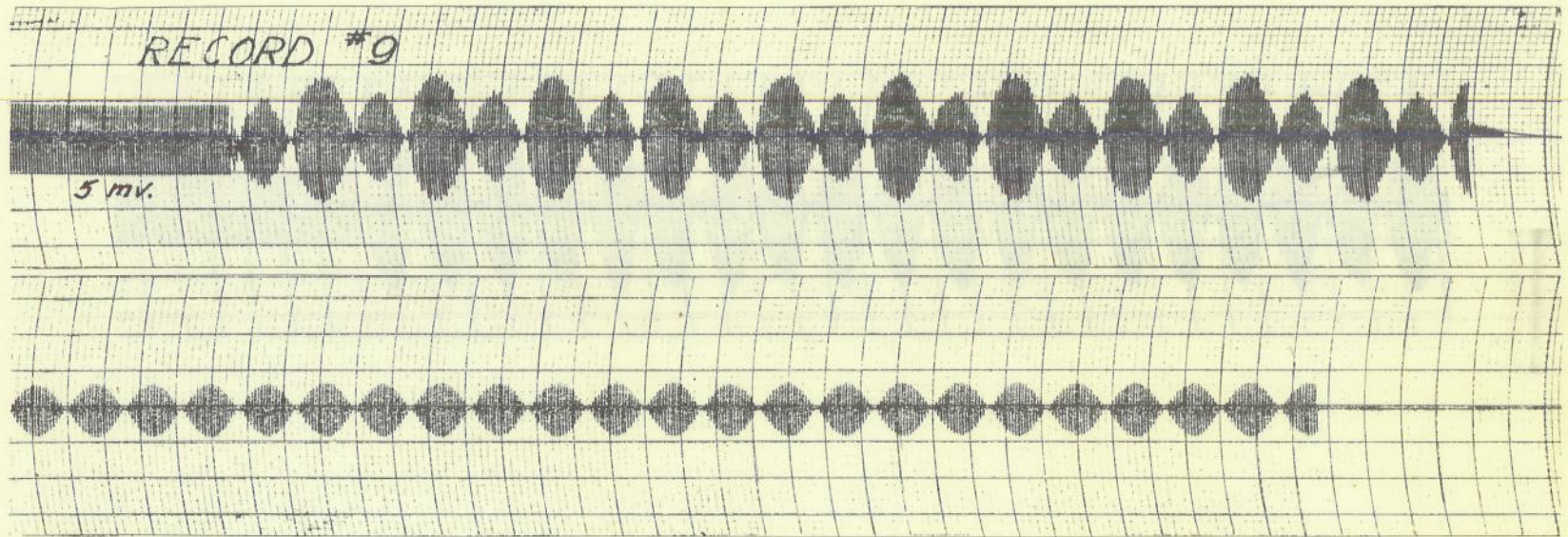
SAMPLE RECORD OF TEST - 1.5 CYCLES PER SECOND



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SAMPLE RECORD WITH RANGE WIRE UNCLAMPED

DECLASSIFIED



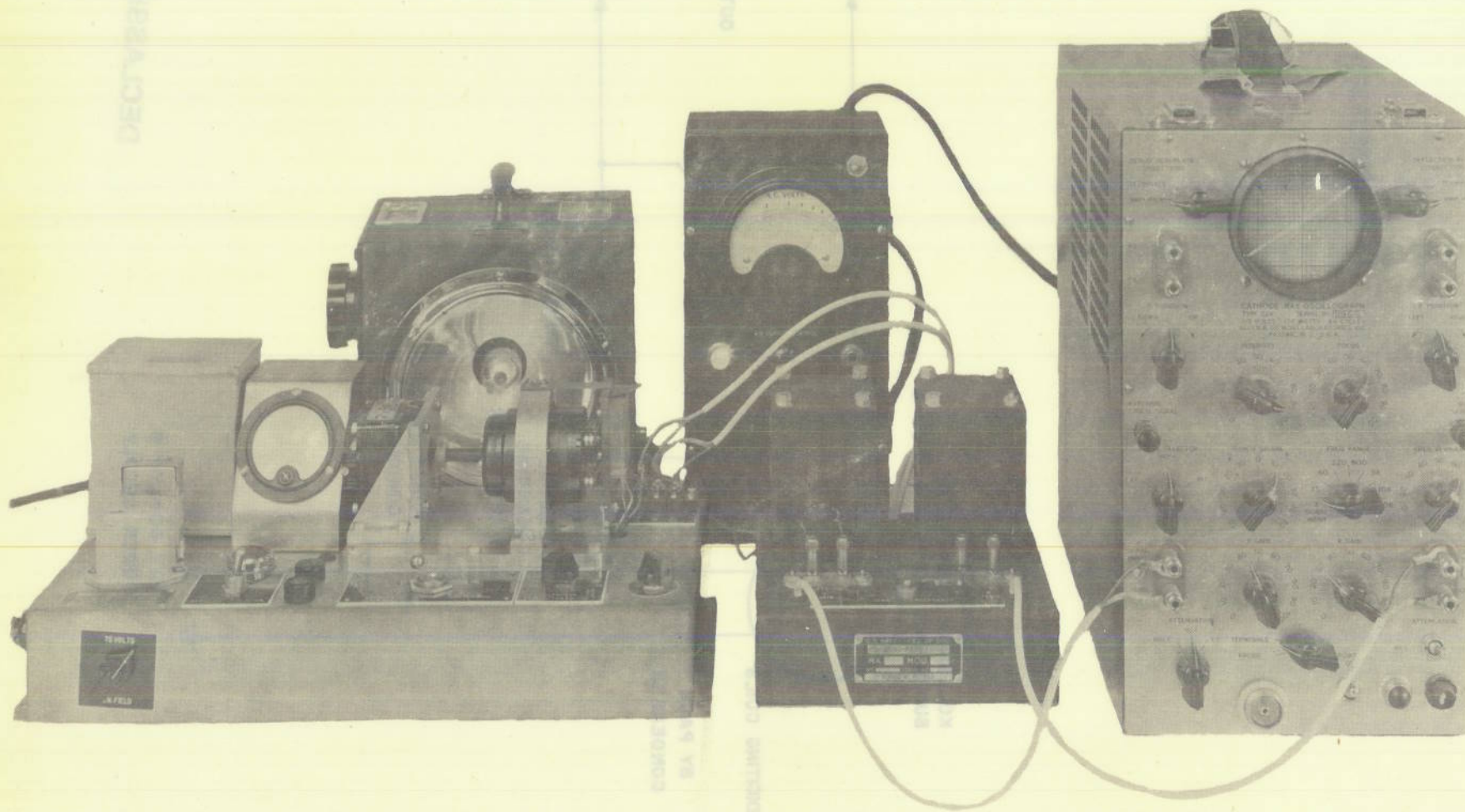
DECLASS.

SAMPLE RECORD OF TEST - 12 CYCLES PER SECOND

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DECLASSIFIED

DECLASSIFIED



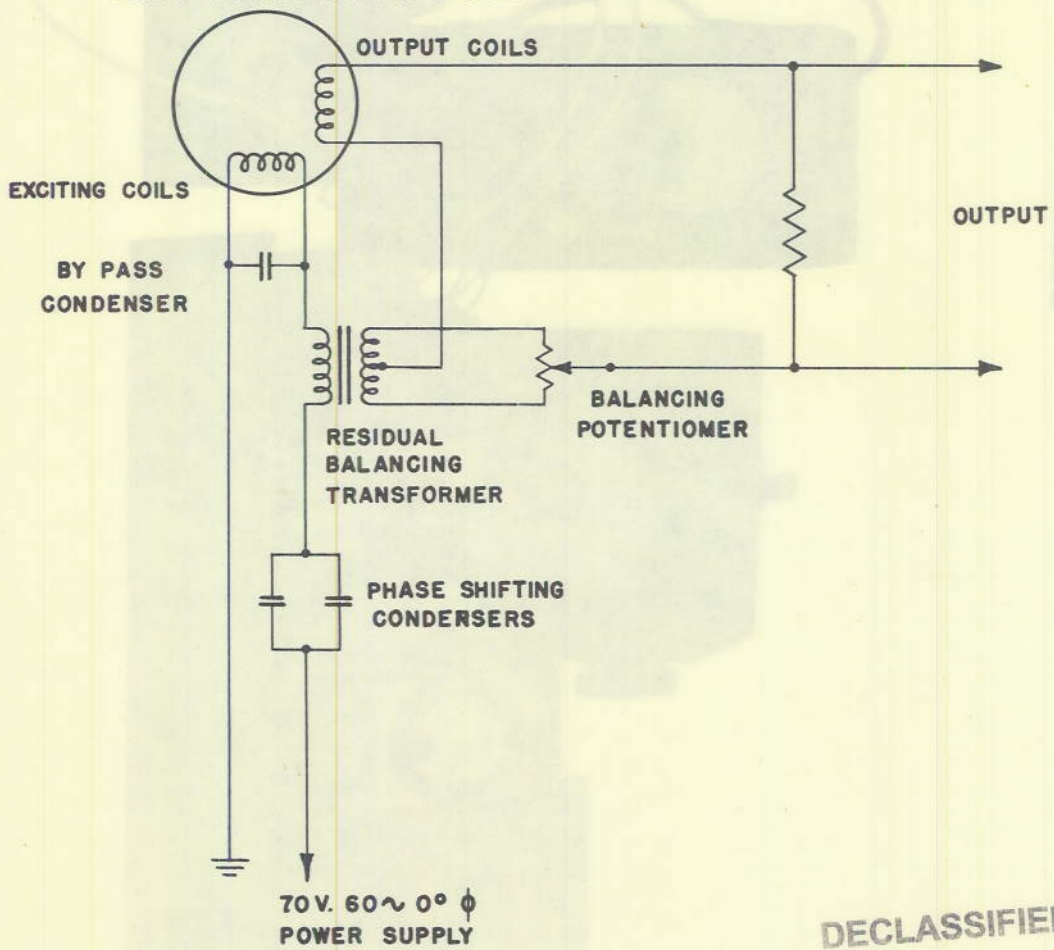
DECLASSIFIED

PLATE 32 Test Unit Mk 29 Mod 0 and 60-cycle Band-Pass Filter, for testing Kollsman Generators.

TACHOMETER (KOLLSMAN) INDUCTION GENERATOR BASIC CIRCUIT

DECLASSIFIED

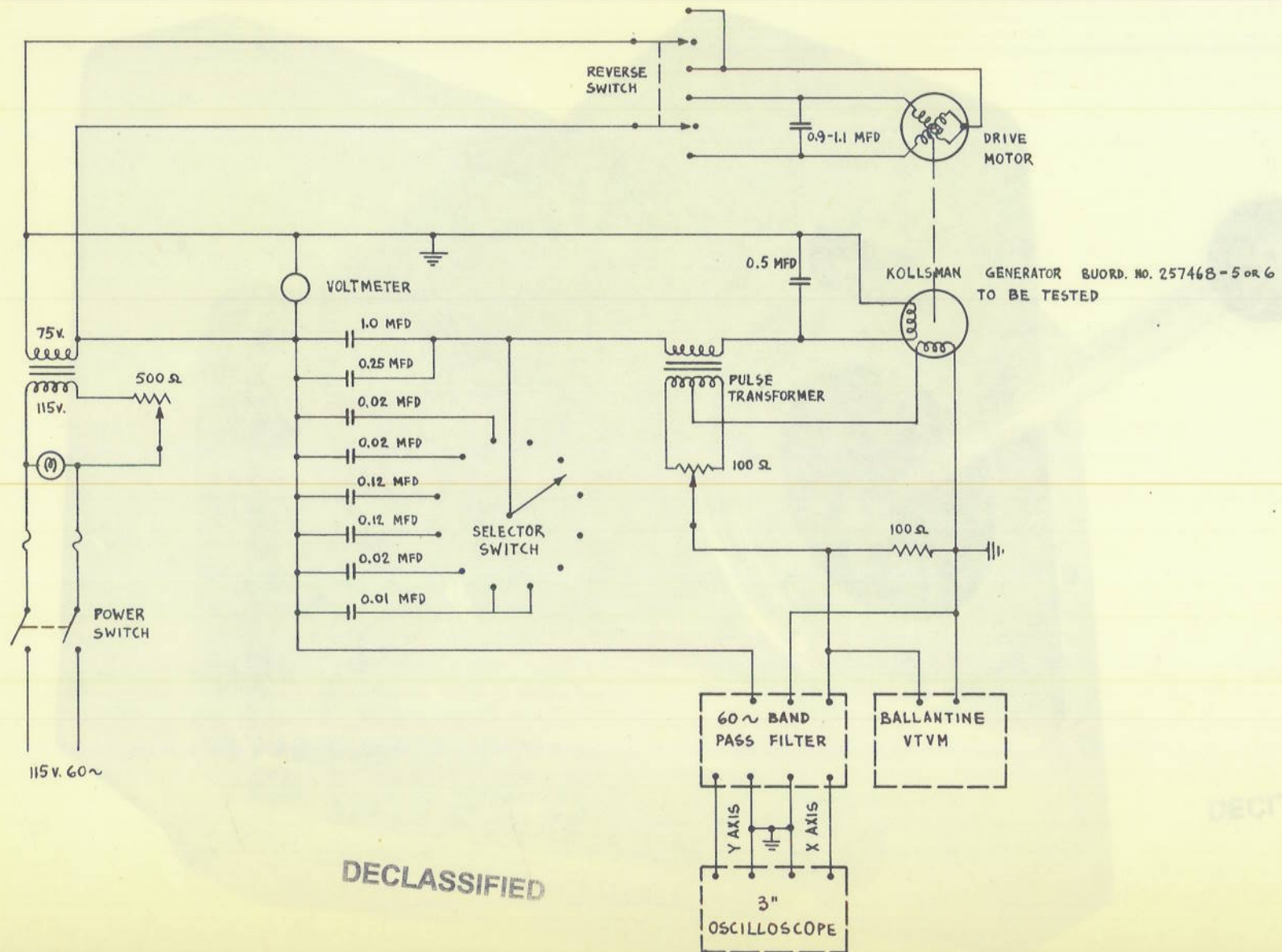
TACHOMETER
KOLLSMAN GENERATOR
BUORD. DWG. NO. 257468-5 OR-6



DECLASSIFIED

TEST UNIT MK. 29 MOD. 0
KOLLSMAN GENERATOR TESTER CIRCUIT

DECLASSIFIED



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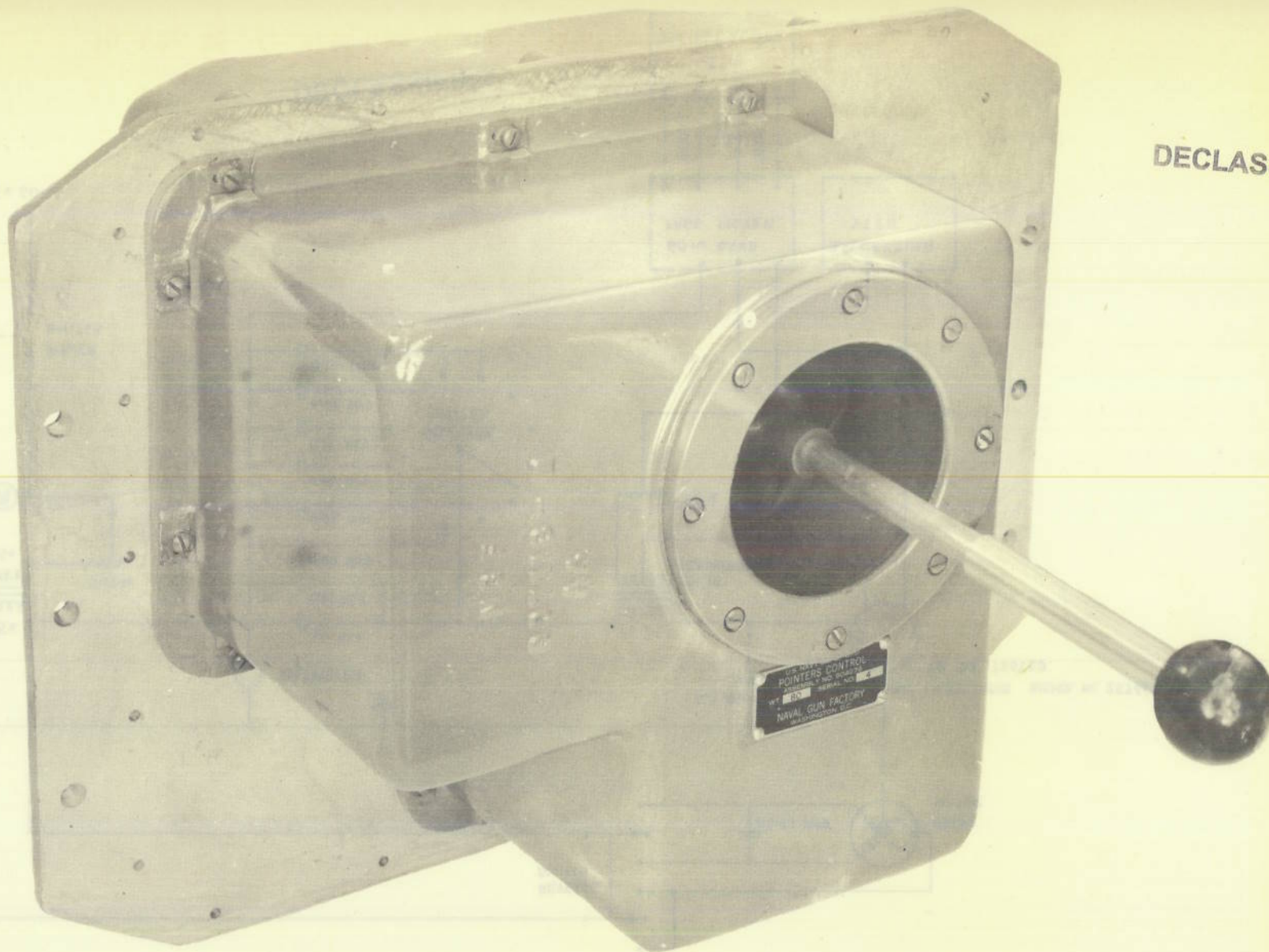


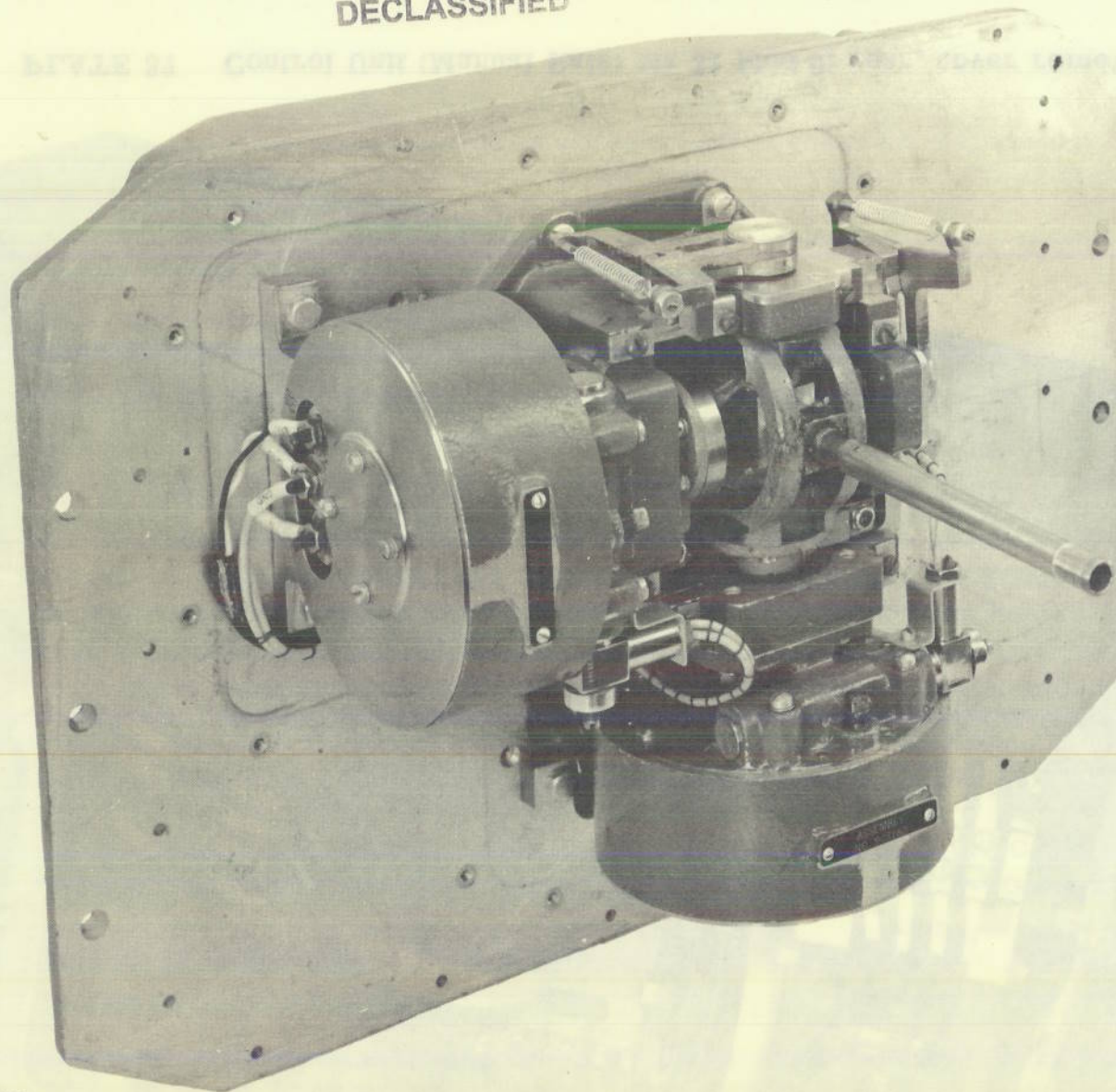
PLATE 35 Control Unit (Manual Rate) Mk 31 Mod 0; front view.

DECLASSIFIED

1001 0111 MK 31 MOD 0

DECLASSIFIED

DECLASSIFIED



DECLASSIFIED

PLATE 36 Control Unit (manual Rate) Mk 31 Mod 0; front cover removed.

DECLASSIFIED

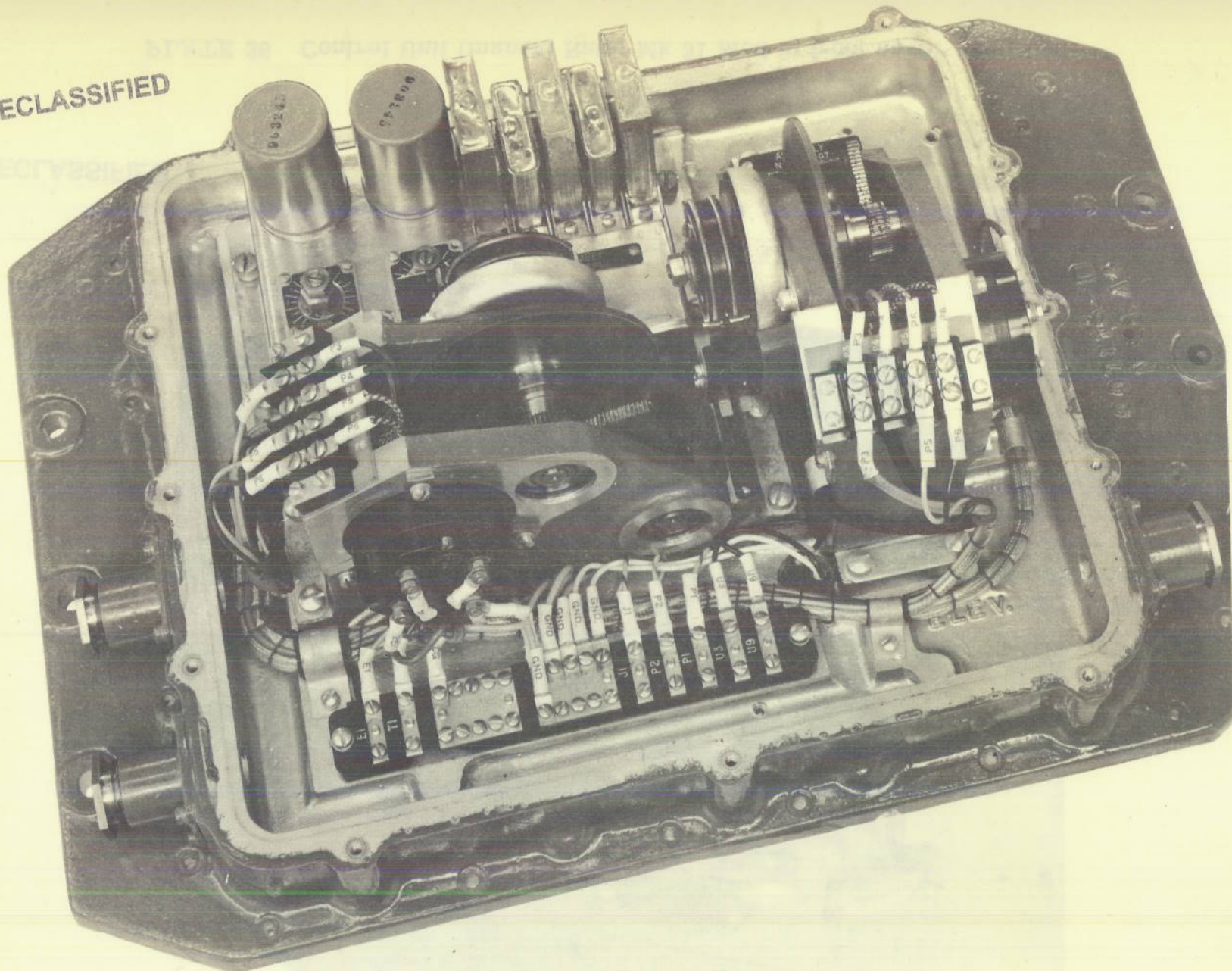
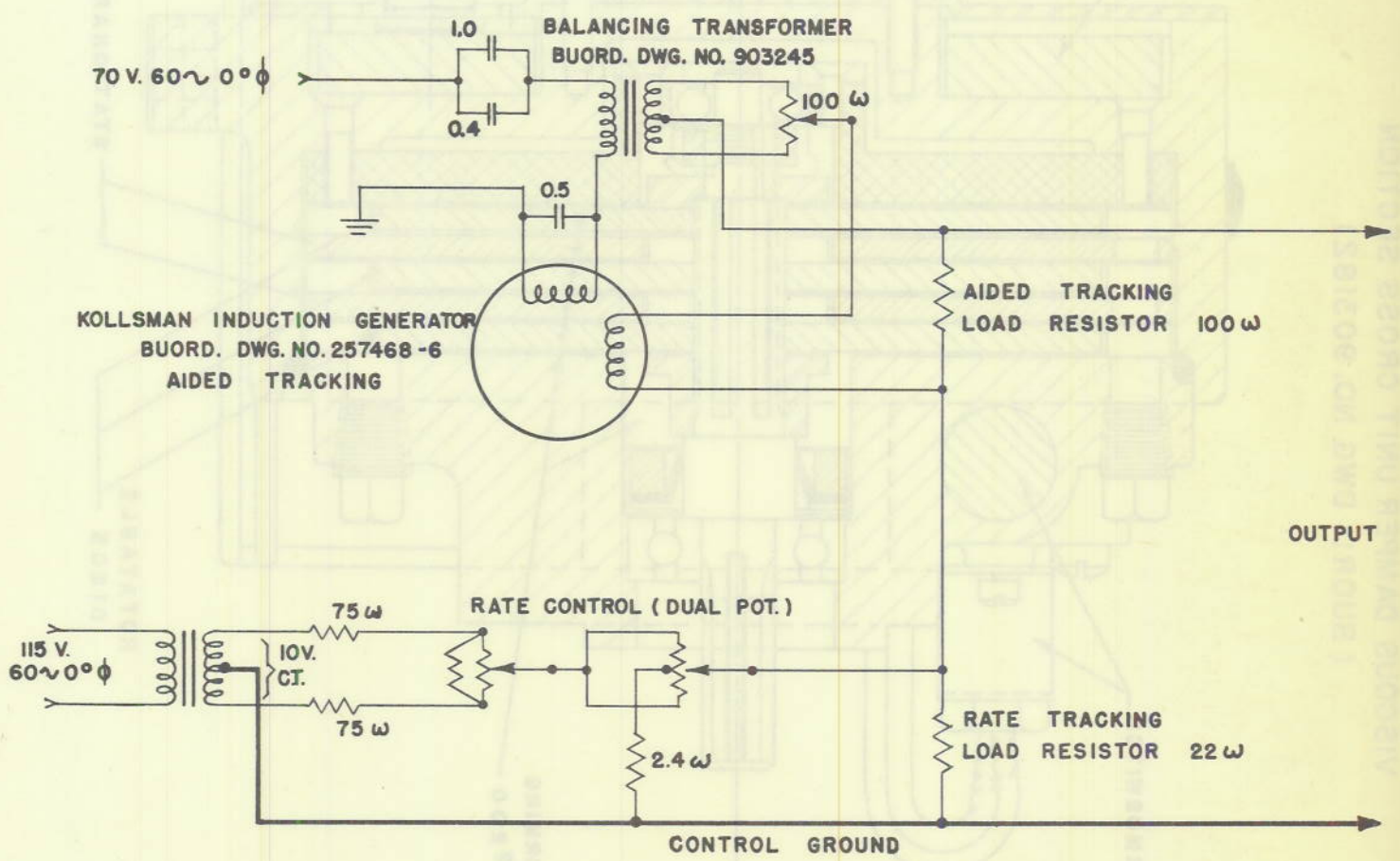


PLATE 37 Control Unit (Manual Rate) Mk 31 Mod 0; rear, cover removed.

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CONTROL UNIT (MANUAL RATE) MK. 31 MOD. 0
TRAIN CIRCUIT
(ELEVATION CIRCUIT SIMILAR)

DECLASSIFIED



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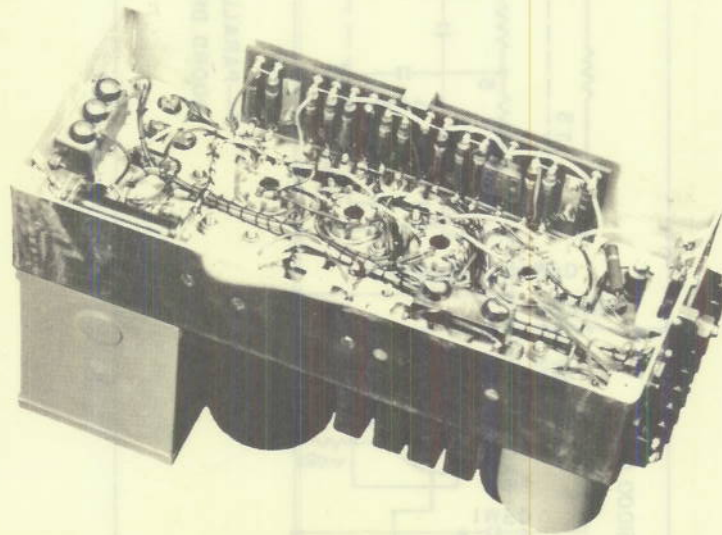
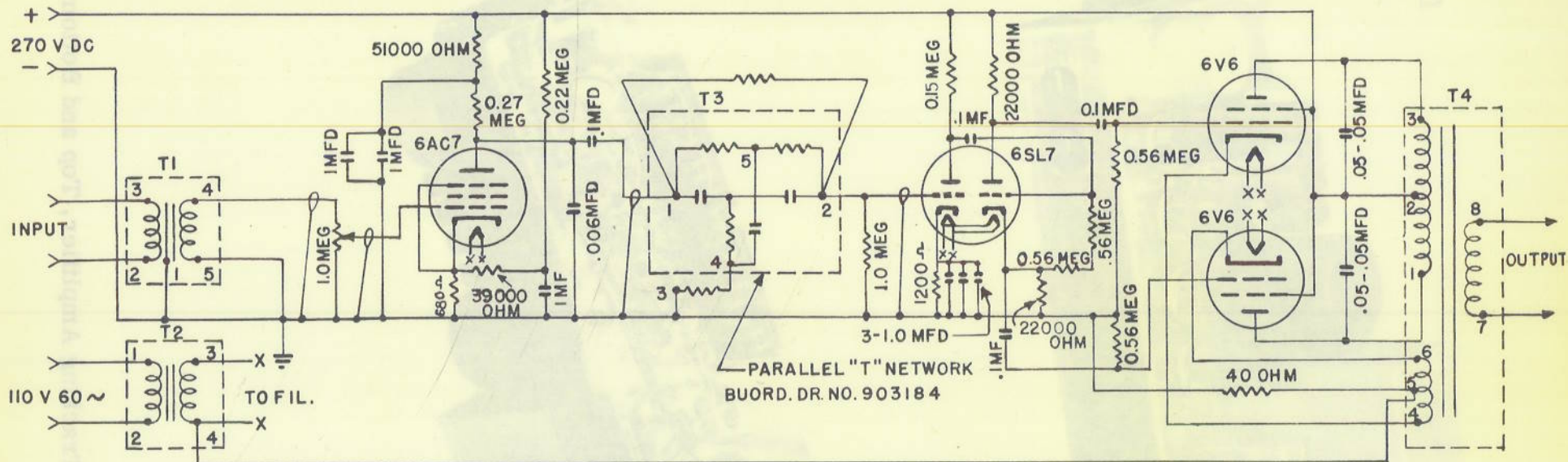


PLATE 40 Tracking Amplifier, Top and Bottom views.

DECLASSIFIED

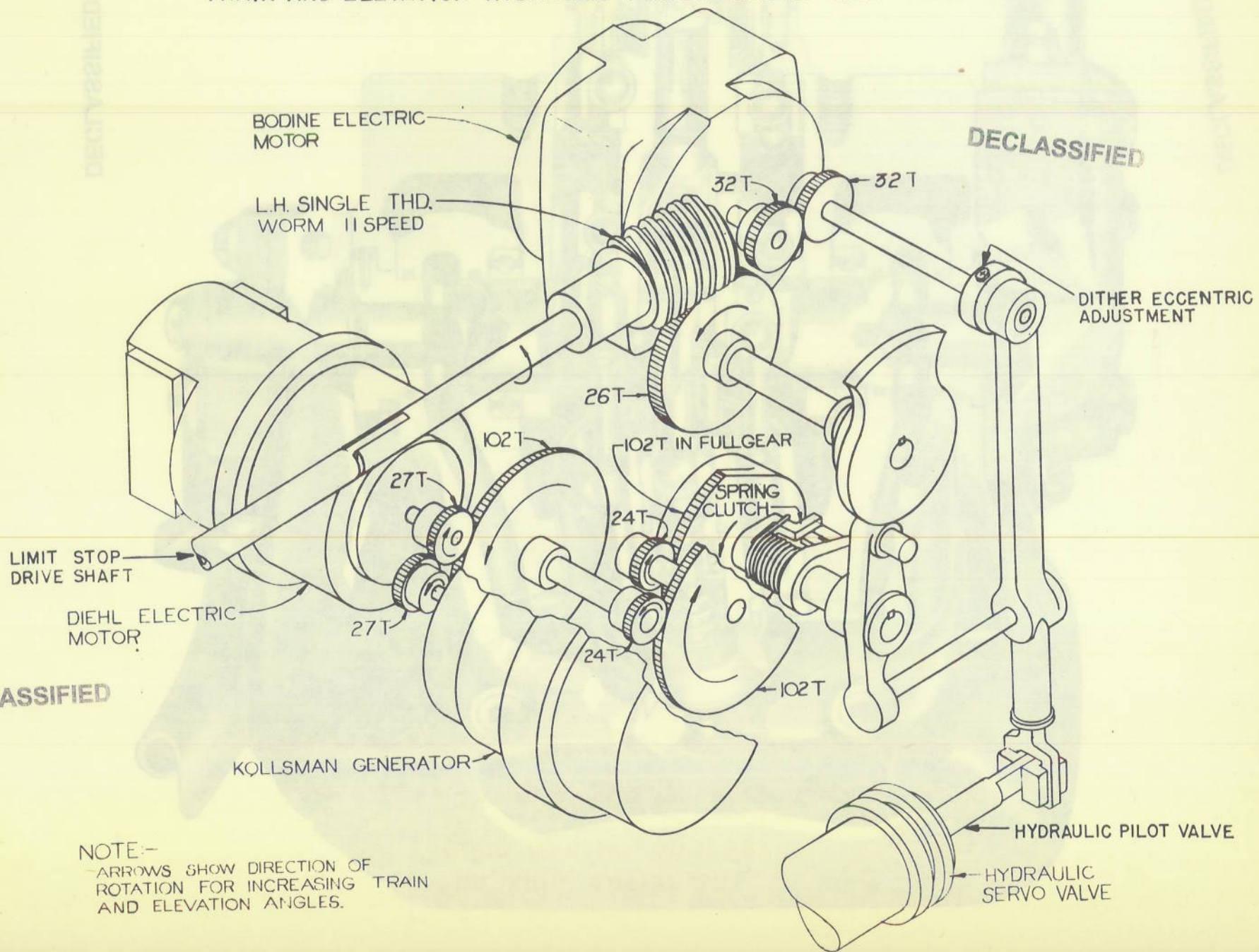
TRACKING AMPLIFIER
(BUORD. DWG. NO. 903259)
 FOR
GUN DIRECTOR MK. 61

DECLASSIFIED

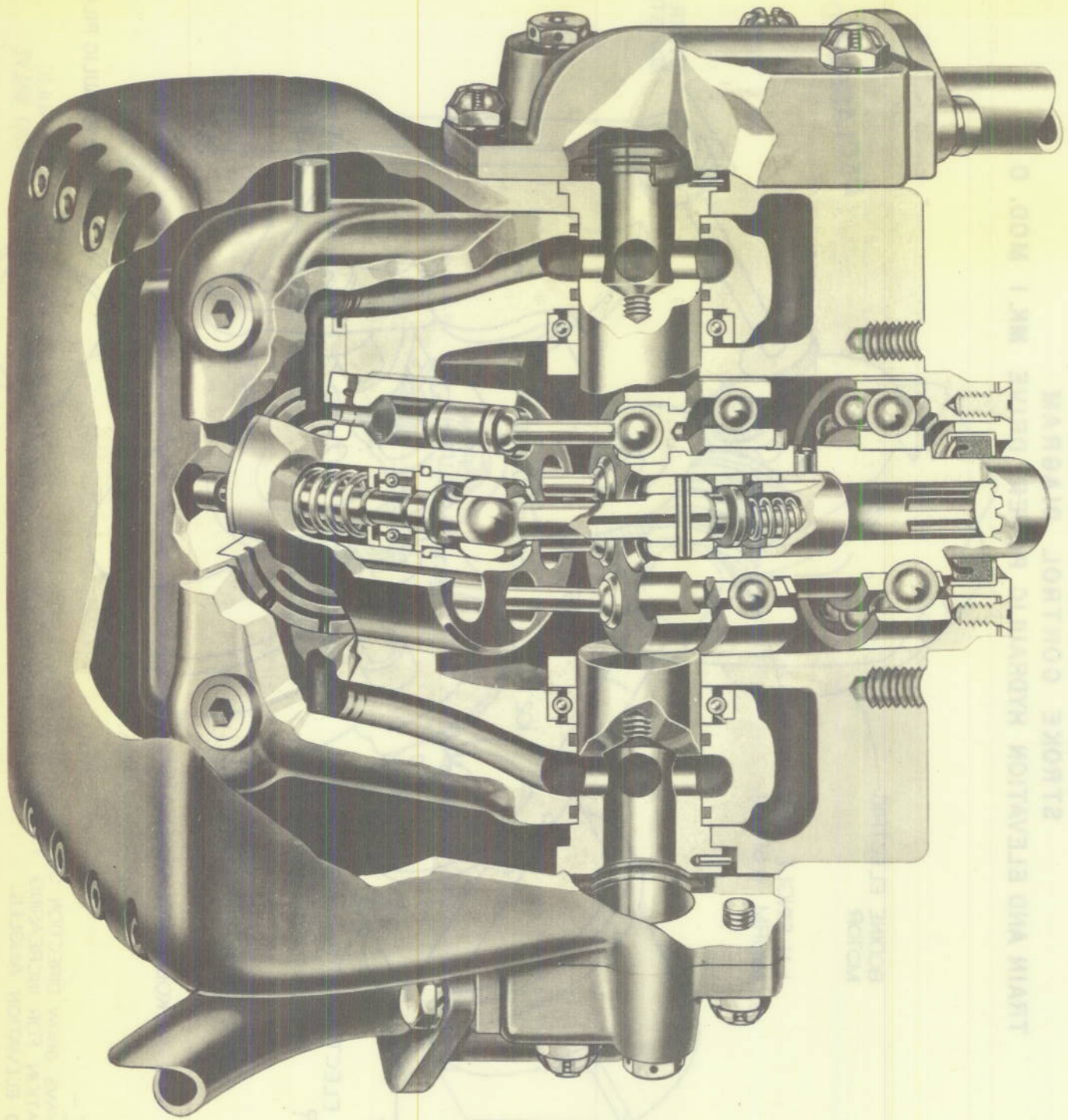


DECLASSIFIED

**GUN DIRECTOR MK. 61
STROKE CONTROL DIAGRAM
TRAIN AND ELEVATION HYDRAULIC POWER DRIVE MK. I MOD. 0**



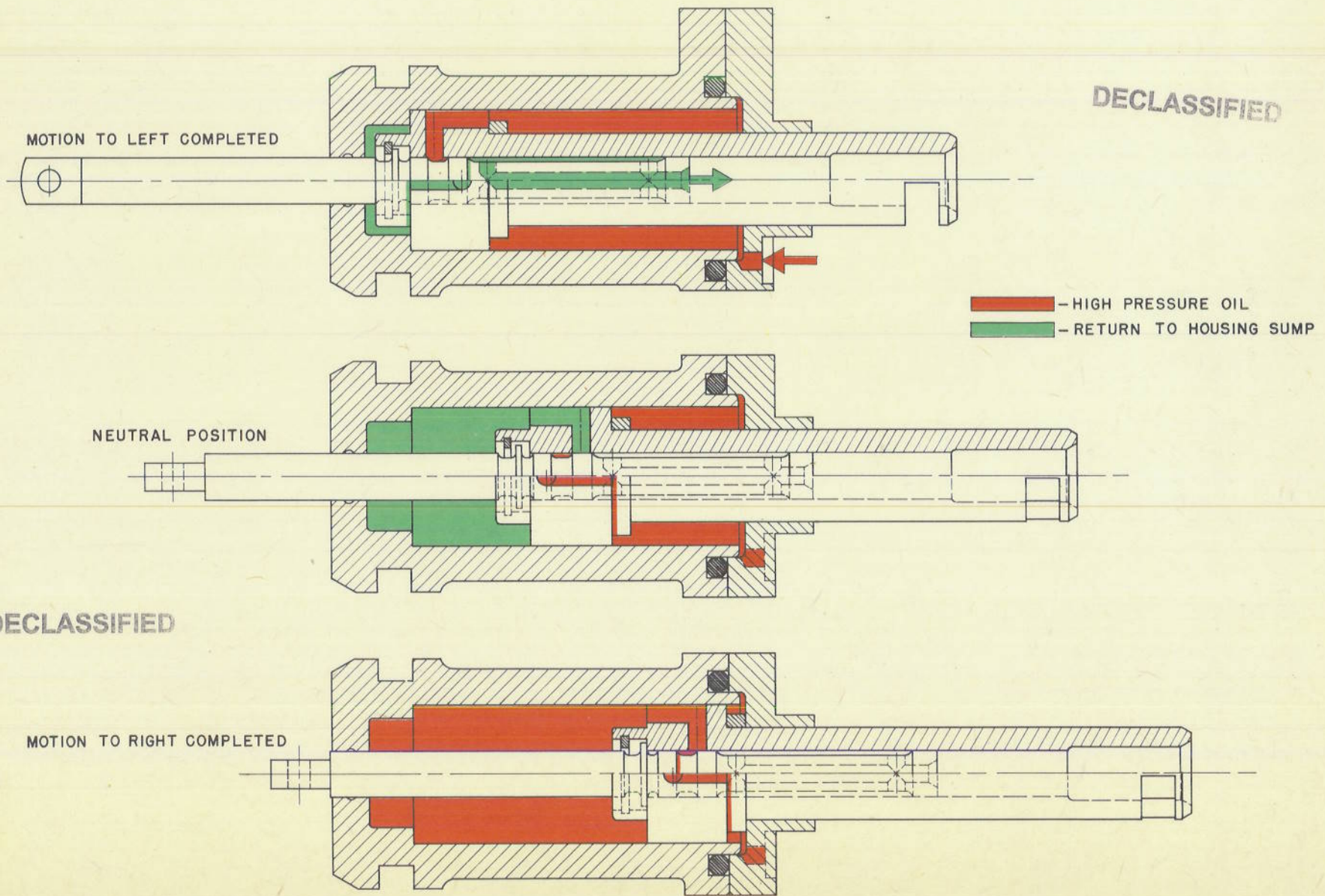
DECLASSIFIED



DECLASSIFIED

PLATE 43 Train and Elevation Hydraulic Power Drive Mk 1 Mod 0 (A-End Cross-Section).

CONTROL CYLINDER
OF
TRAIN AND ELEVATION HYDRAULIC POWER DRIVE MK I MOD O



DECLASSIFIED

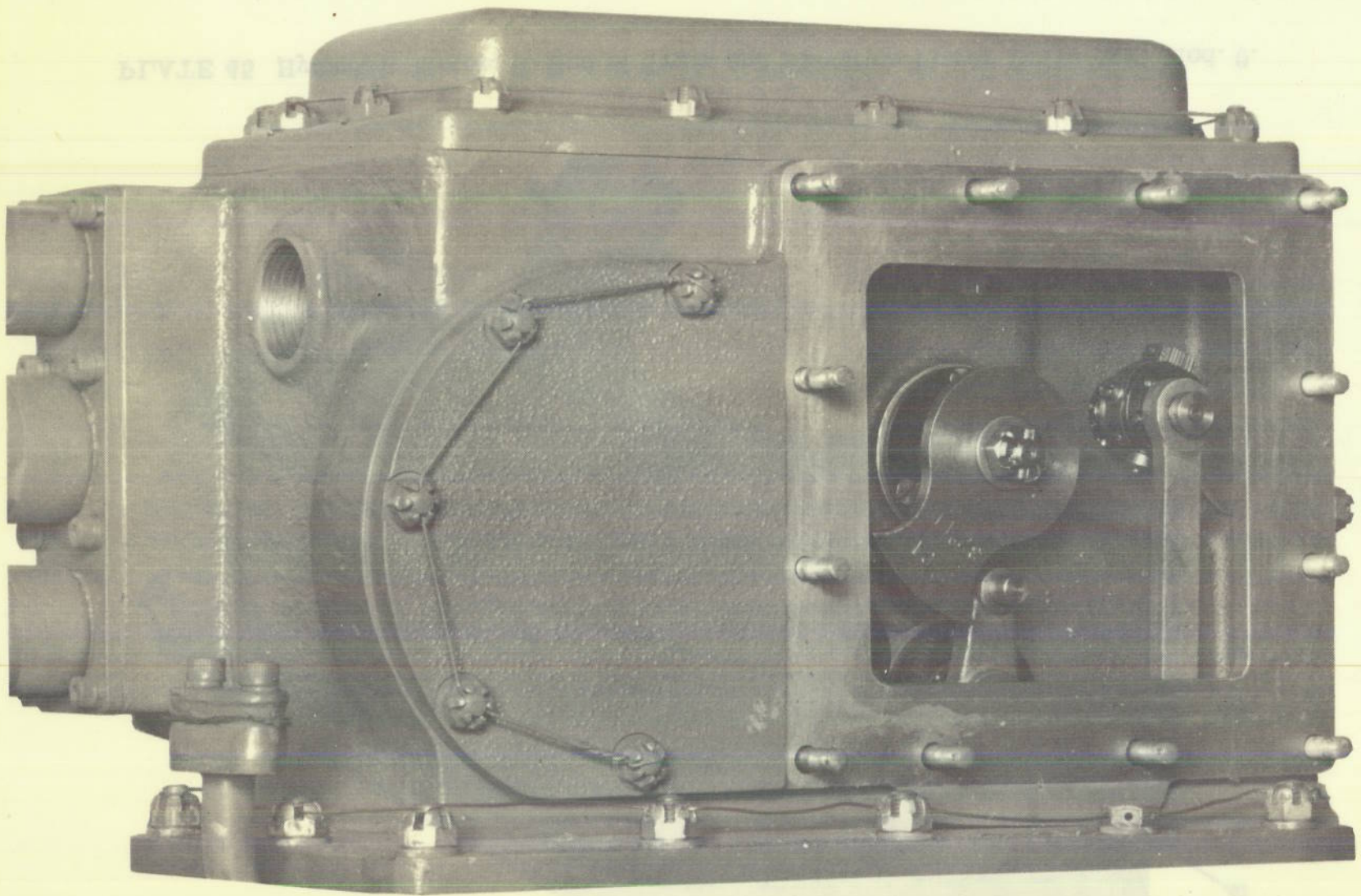


PLATE 44 (a) Dither Adjustment.

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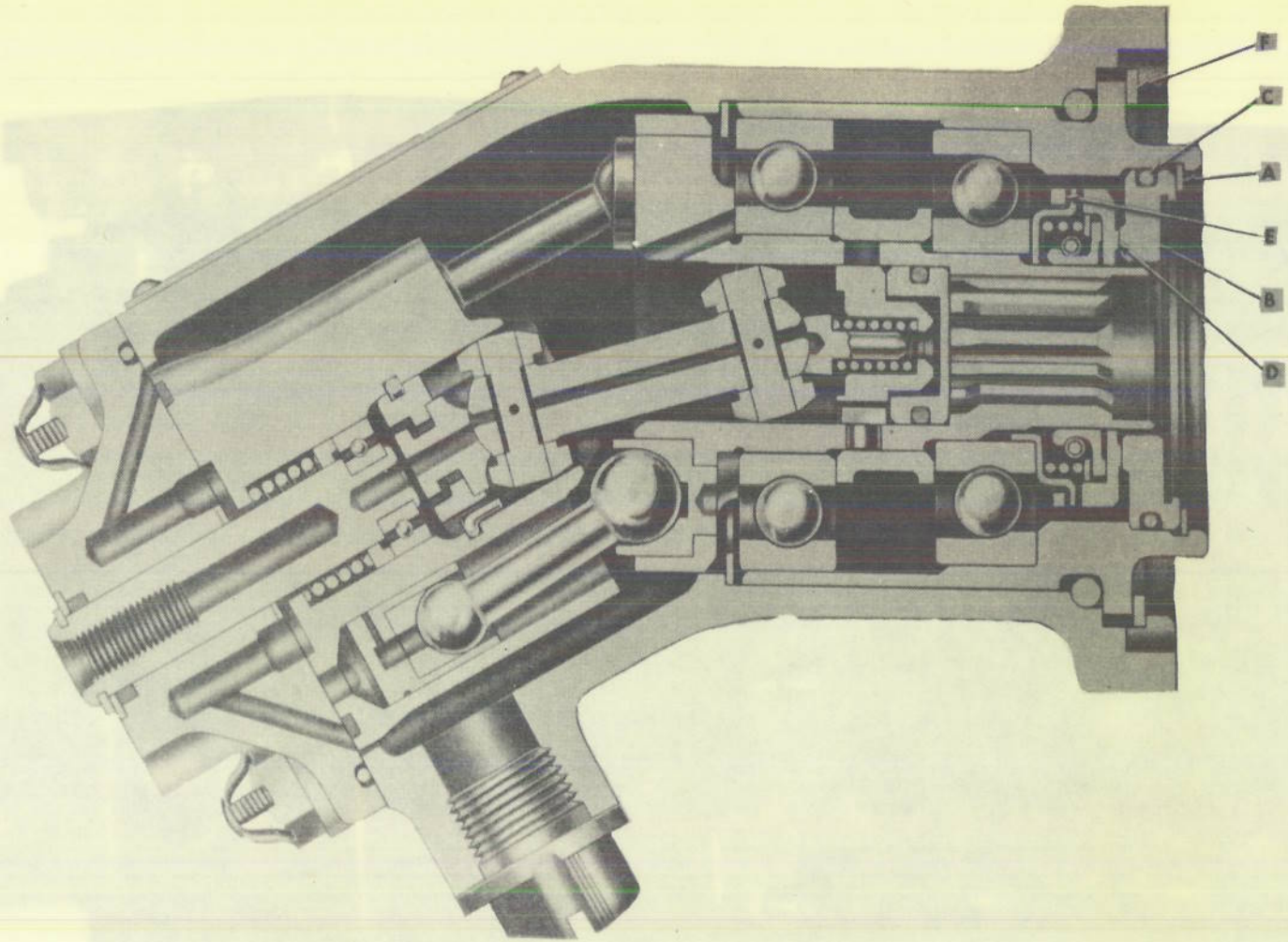
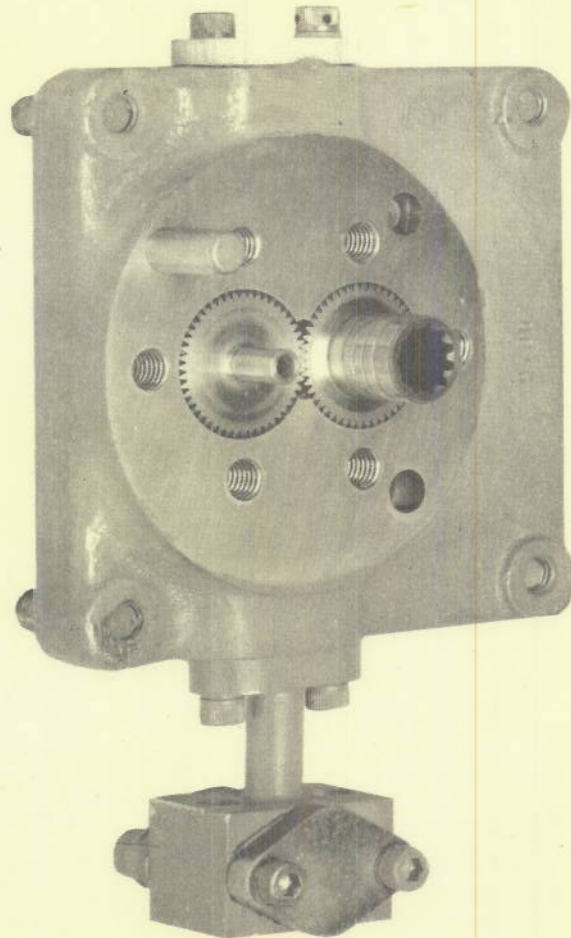
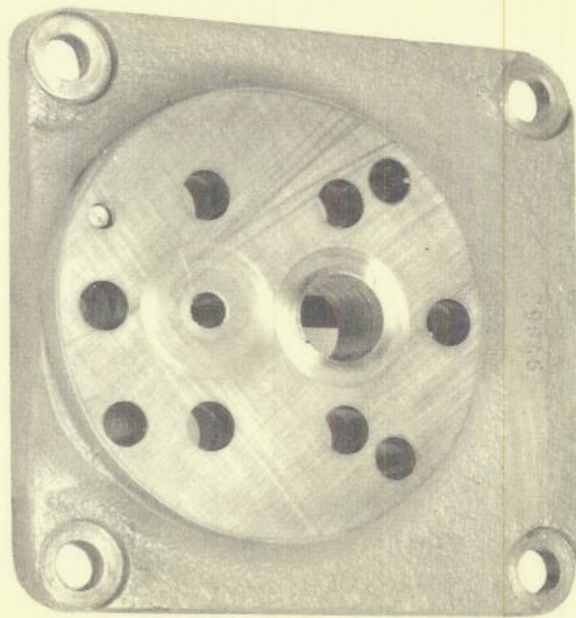


PLATE 45 Hydraulic Motor; B-End of Train and Elevation Power Drive Mk1 Mod. 0.

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DECLASSIFIED



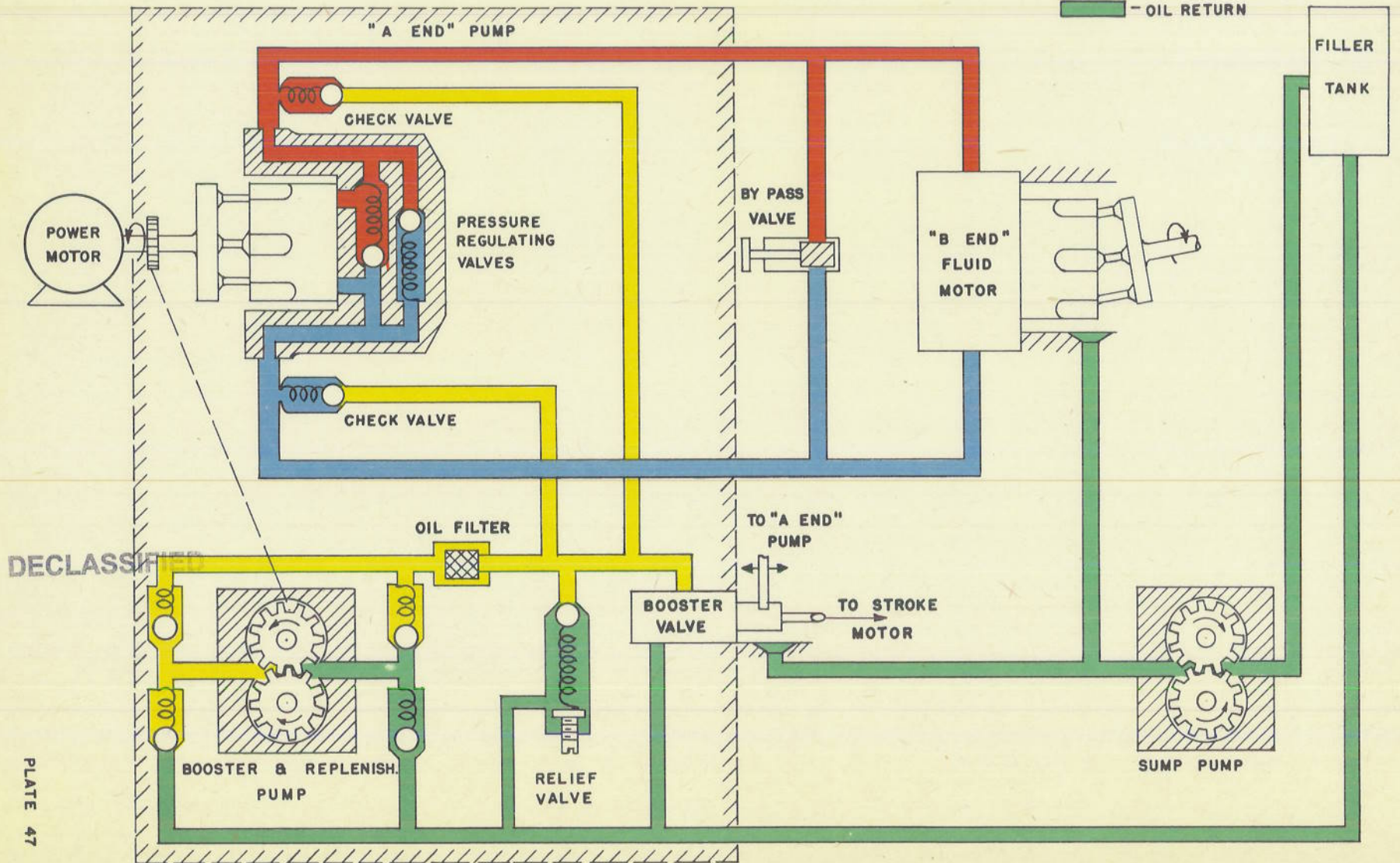
DECLASSIFIED

PLATE 46 Sump Pump.

DECLASSIFIED

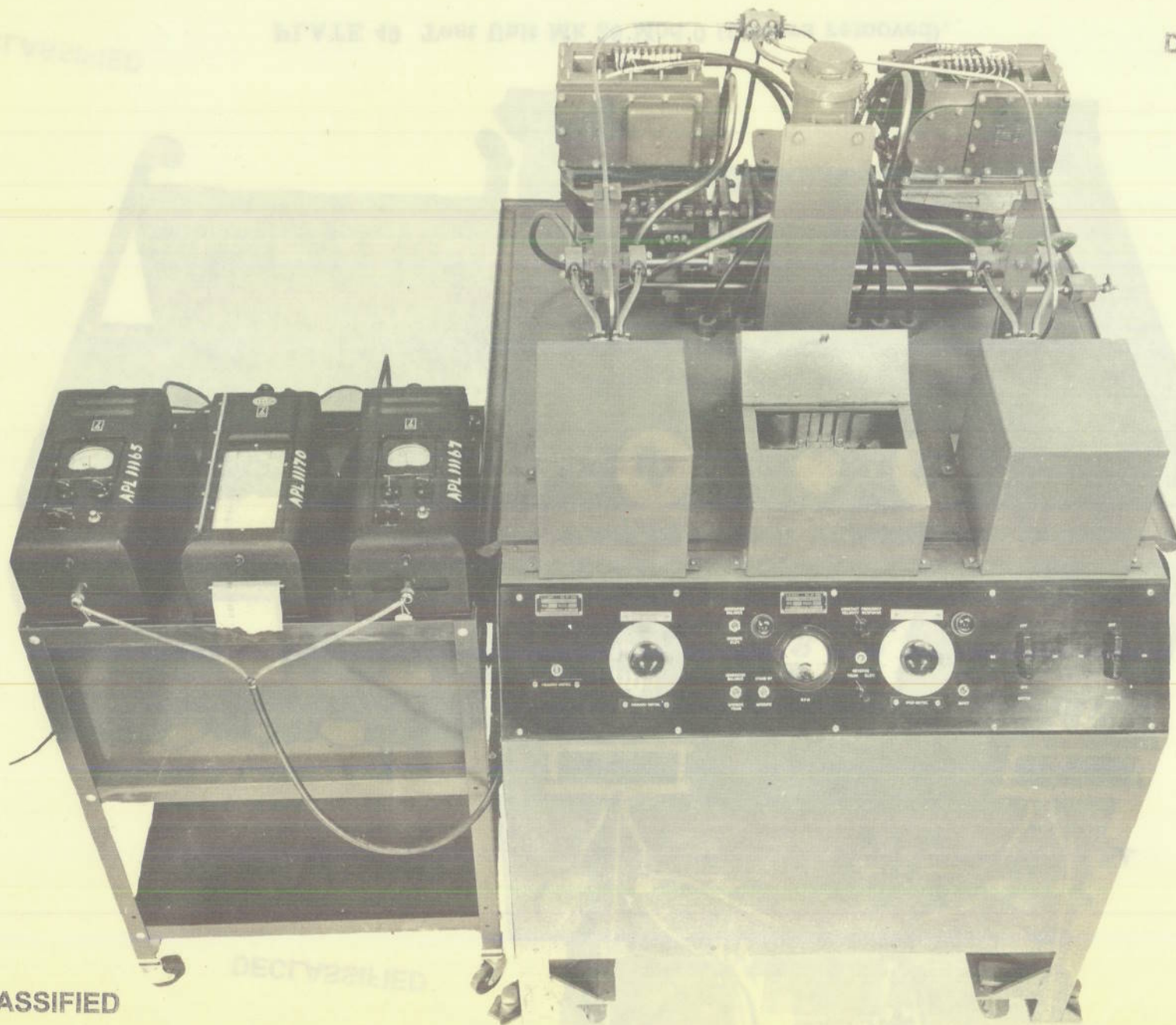
T & E HYDRAULIC POWER DRIVE MK. I MOD. O
HYDRAULIC FLOW DIAGRAM

- HIGH PRESSURE
- LOW PRESSURE
- BOOSTER PRESSURE
- OIL RETURN



DECLASSIFIED

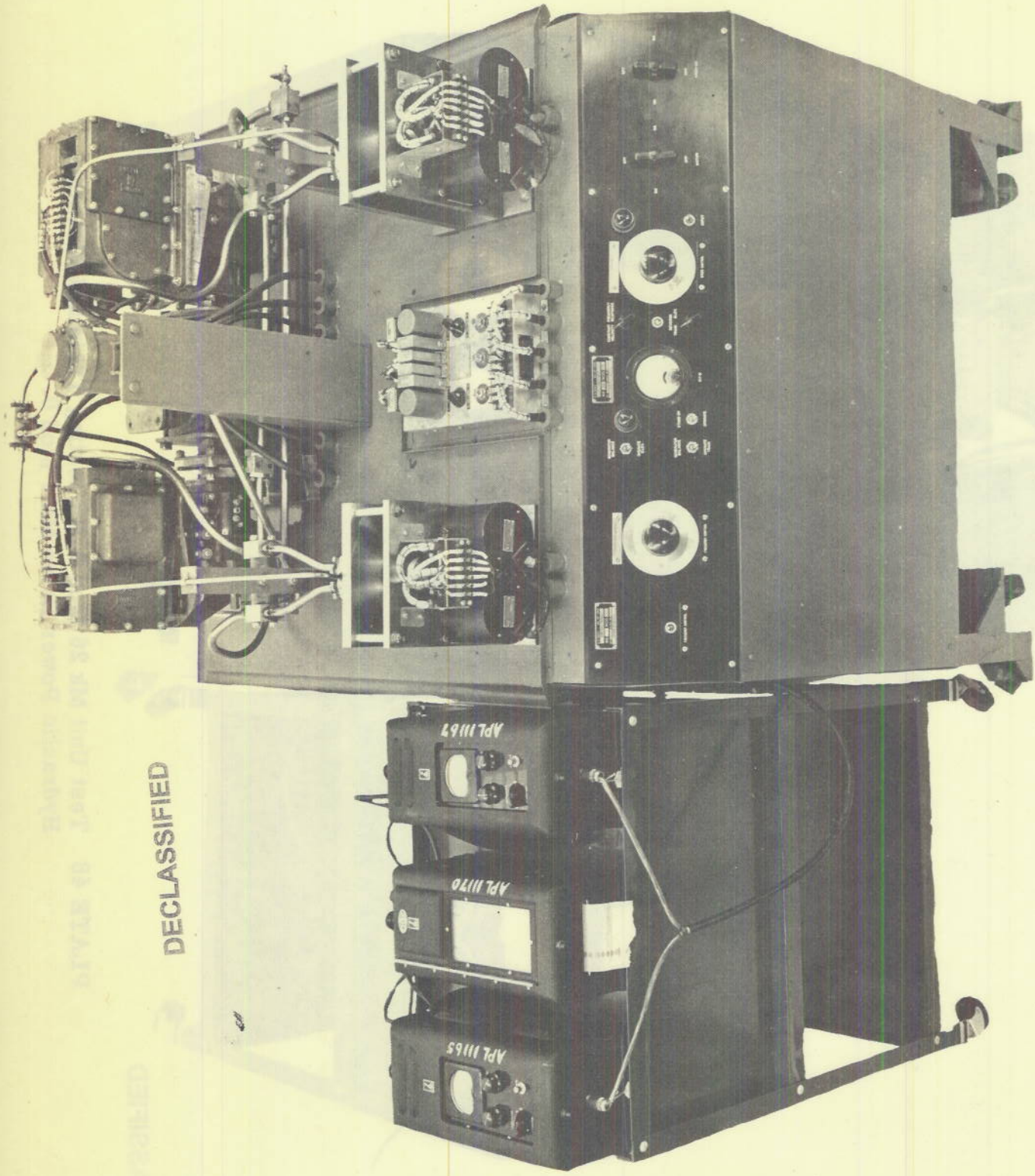
DECLASSIFIED



DECLASSIFIED

PLATE 48 Test Unit Mk 26 Mod 0, for testing Train and Elevation Hydraulic Power Drive Mk 1 Mod 0.

DECLASSIFIED

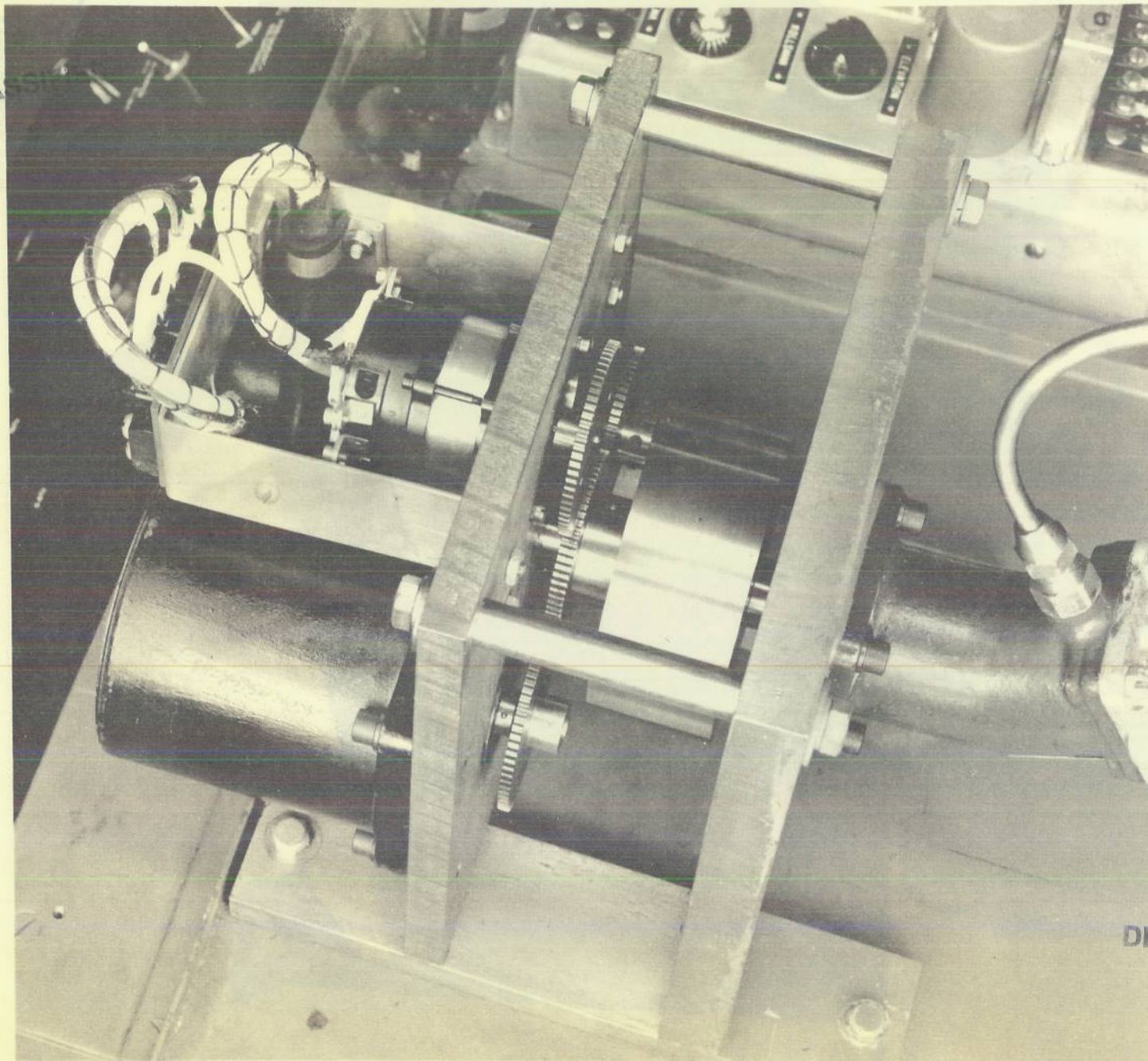


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PLATE 49 Test Unit Mk 26 Mod 0 (Covers removed).

DECLASSIFIED

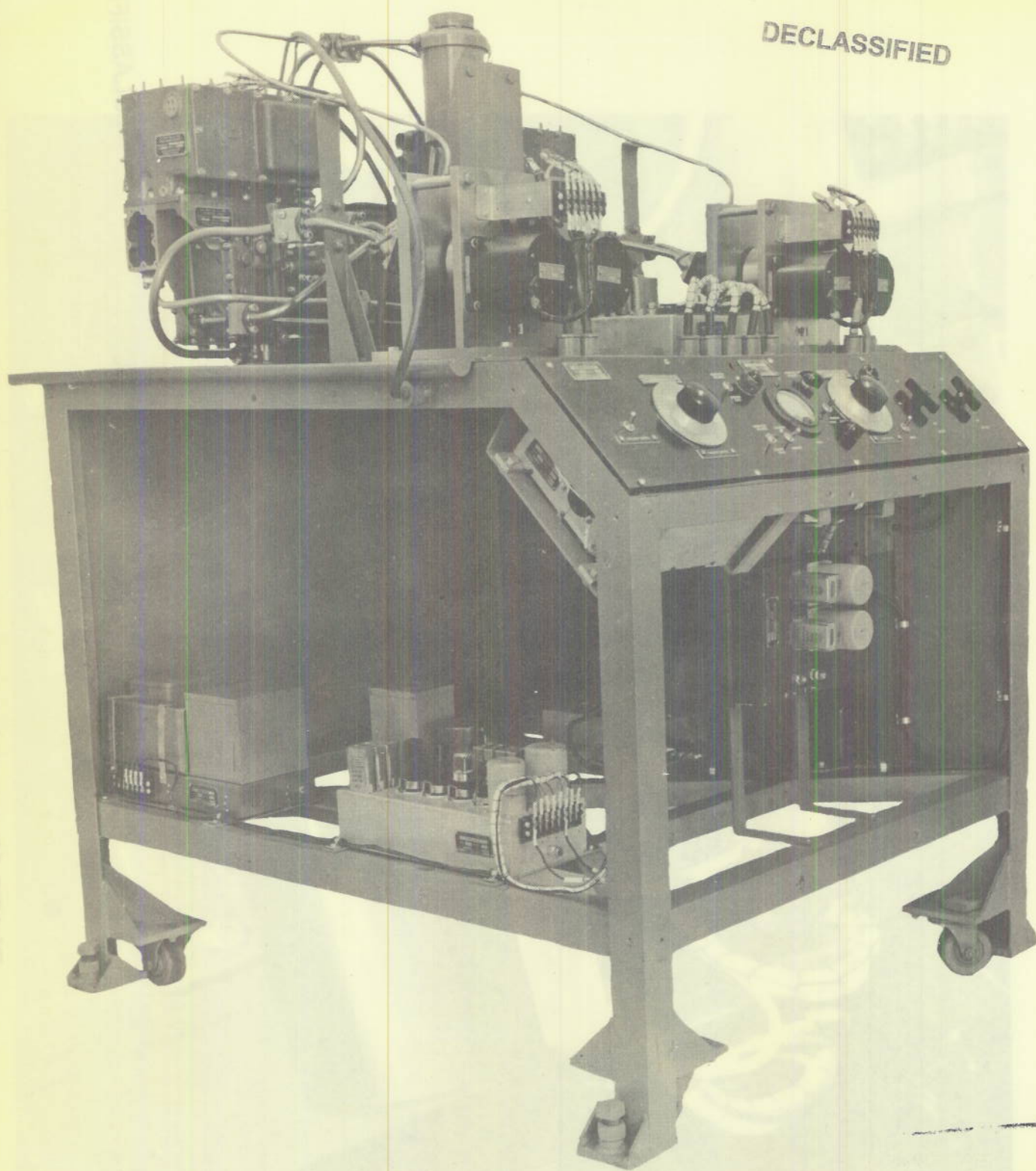
DECLASSIFIED



DECLASSIFIED

PLATE 50 Inertia Wheel of Test Unit Mk 26 Mod 0.

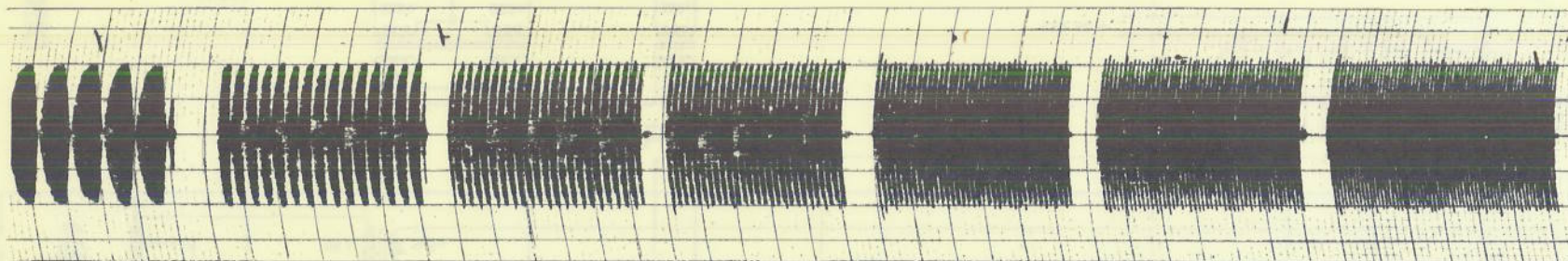
DECLASSIFIED



DECLASSIFIED

PLATE 51 Test Unit Mk 26 Mod 0 (Cover removed).

SAMPLE TEST RECORD FOR HYDRAULIC SYSTEM



FREQUENCIES - \sim /SEC - 0.55

1.3

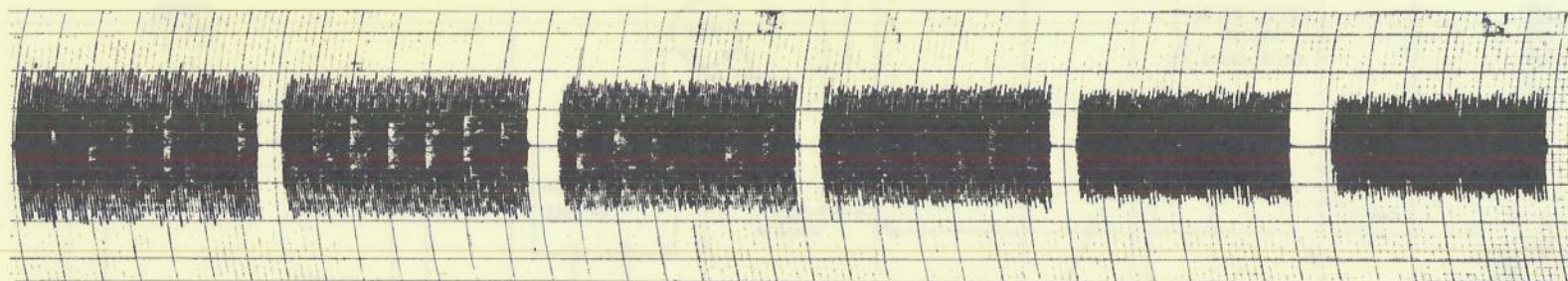
2

2.7

3.4

4.2

5



5.6

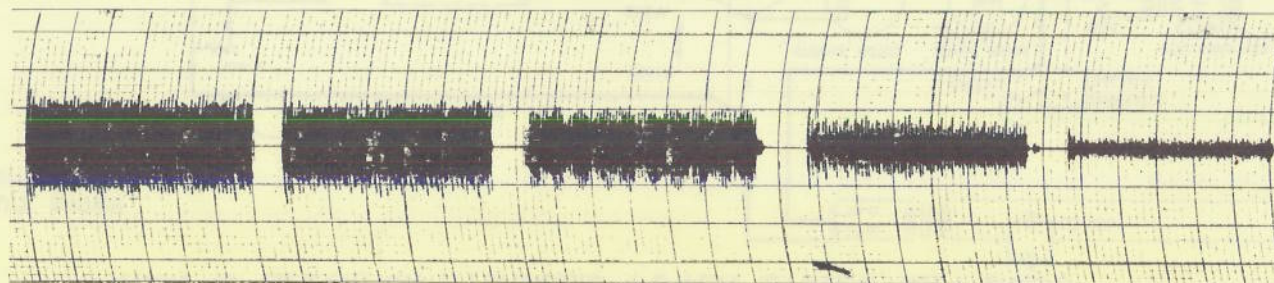
6.2

7

7.7

8.5

9.2



9.9

10.6

11.8

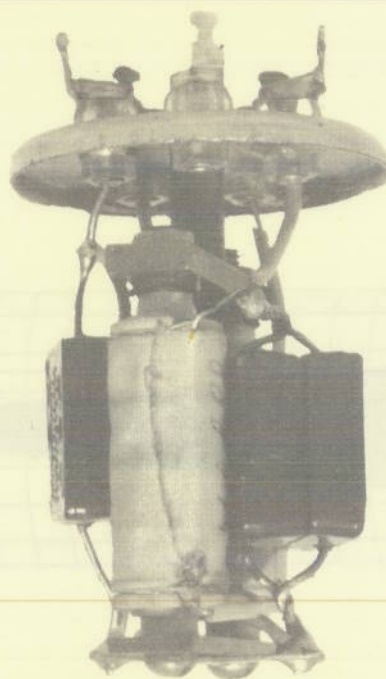
14.2

16.2

DECLASSIFIED

DECLASSIFIED

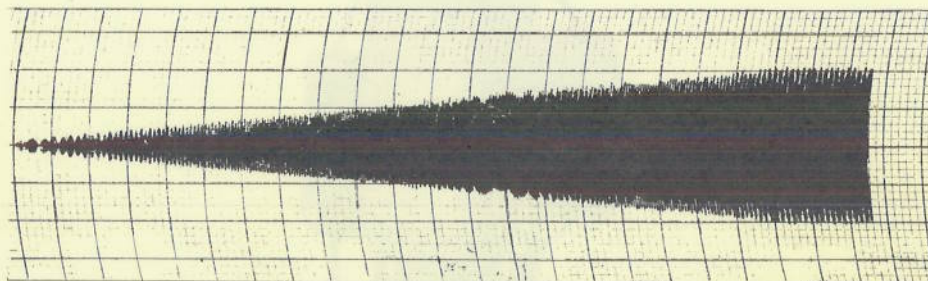
DECLASSIFIED



DECLASSIFIED

PLATE 54 Parallel-T Network (BuOrd 903184).

RECORD OF SIDE BAND TRANSMISSION
OF
UNBRIDGED T PAD WITH INCREASING FREQUENCY



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DECLASSIFIED

DECLASSIFIED

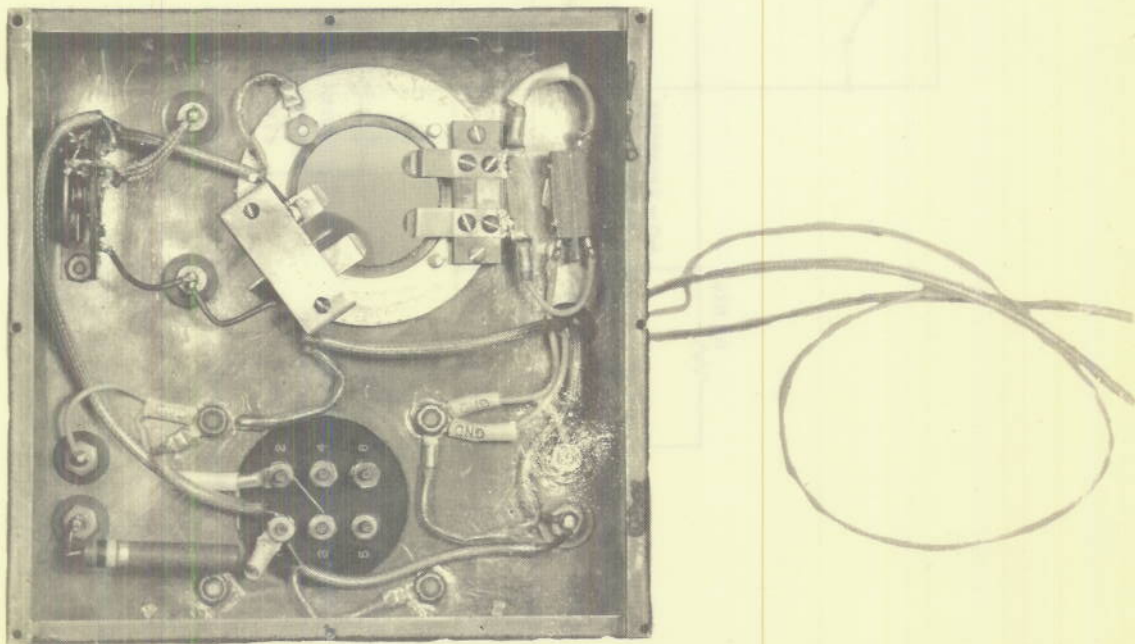
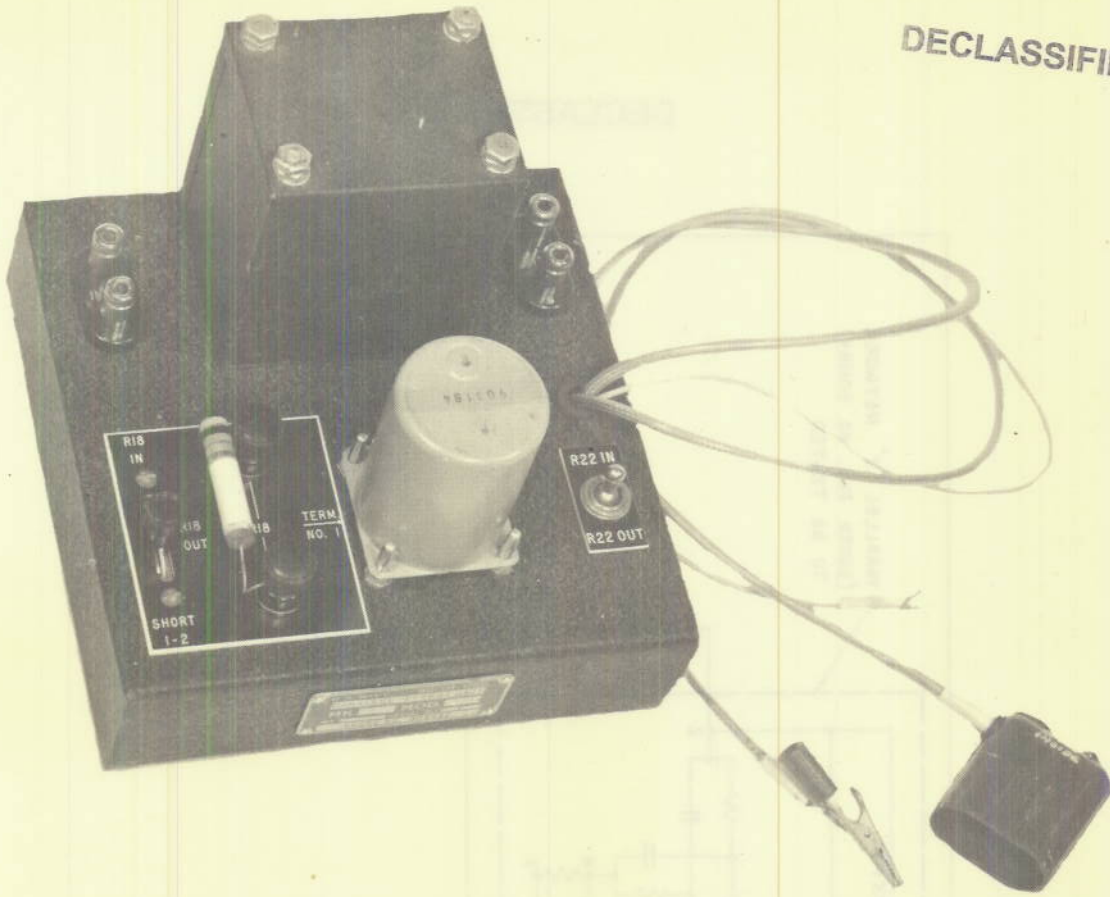
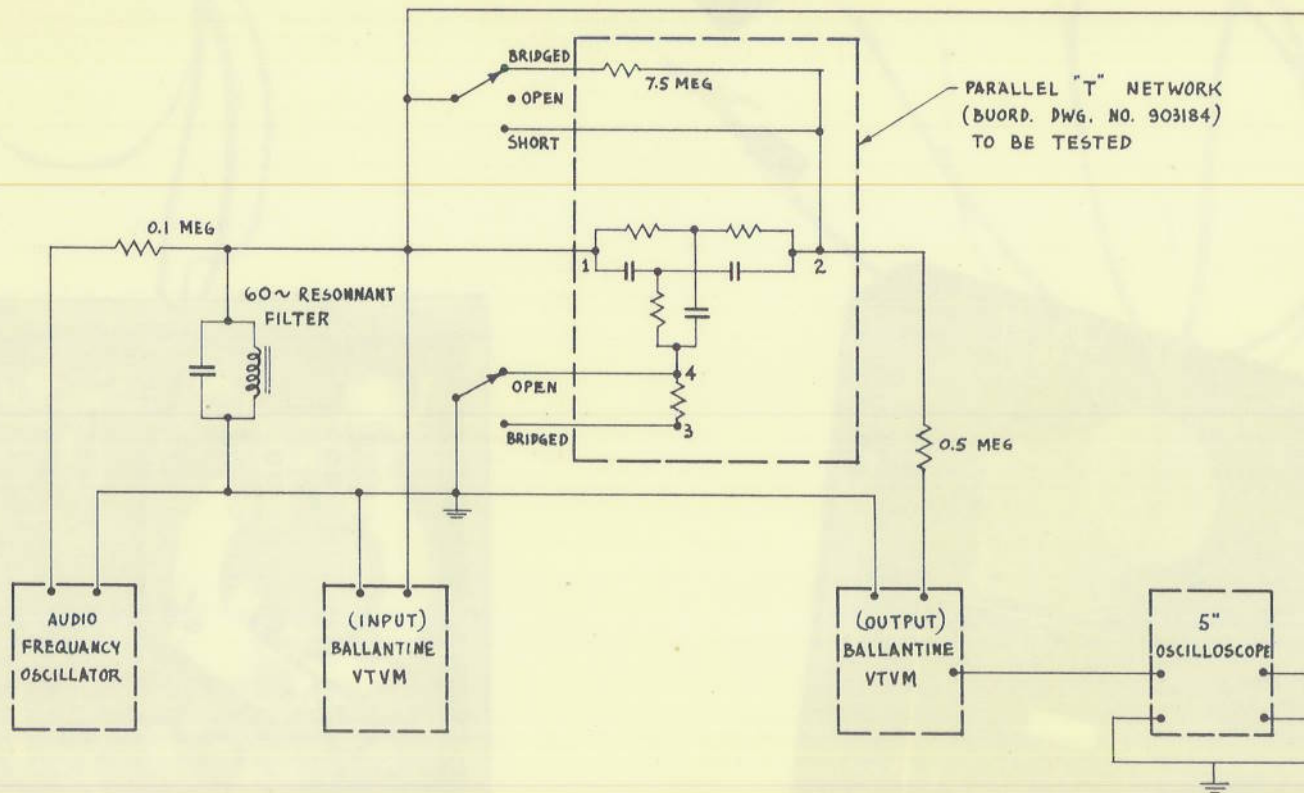


PLATE 56 Parallel-T Network Test Unit (BuOrd 908452).

DECLASSIFIED

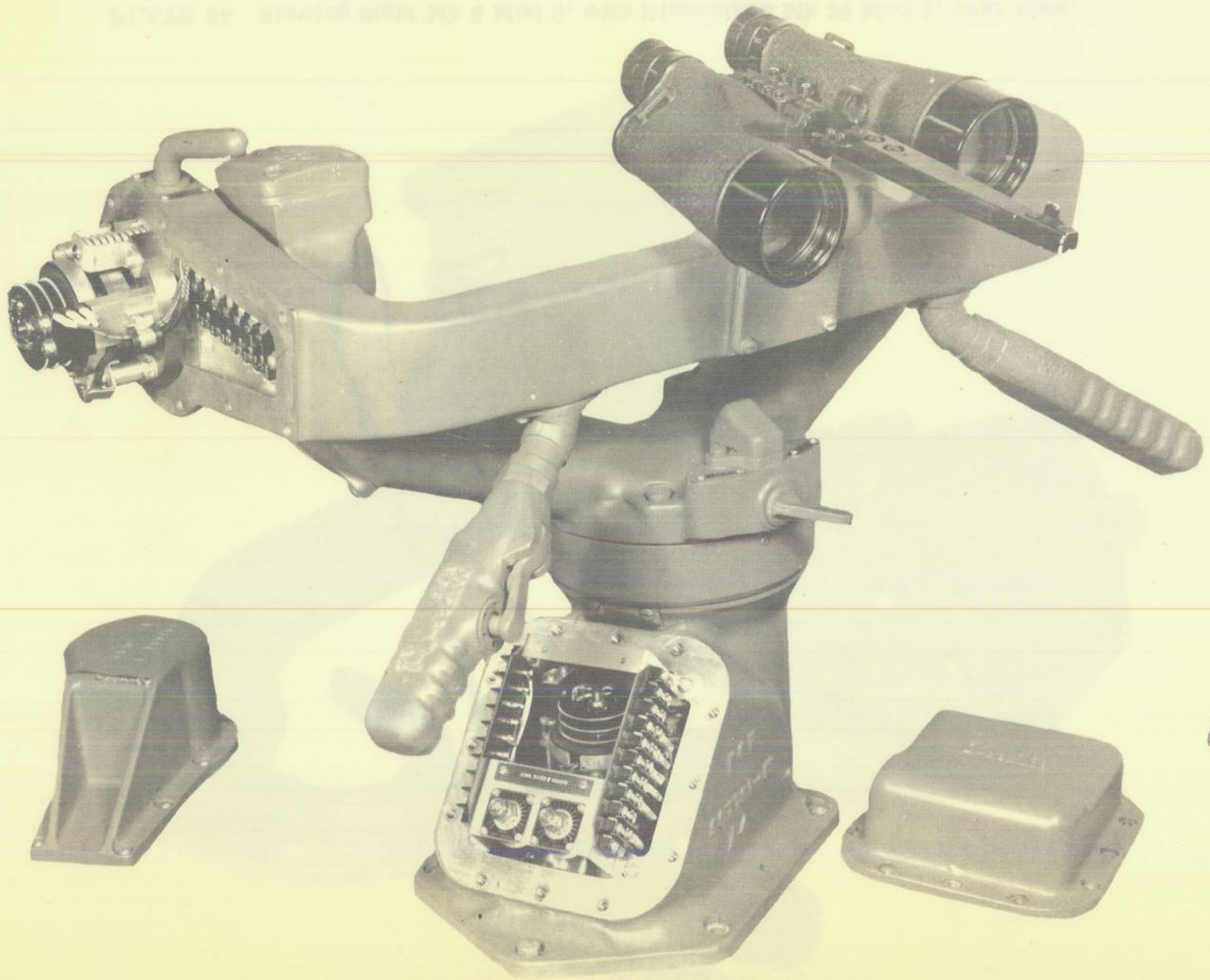
PARALLEL T NETWORK TESTER CIRCUIT
(BUORD. DWG. NO. 909321)



DECLASSIFIED

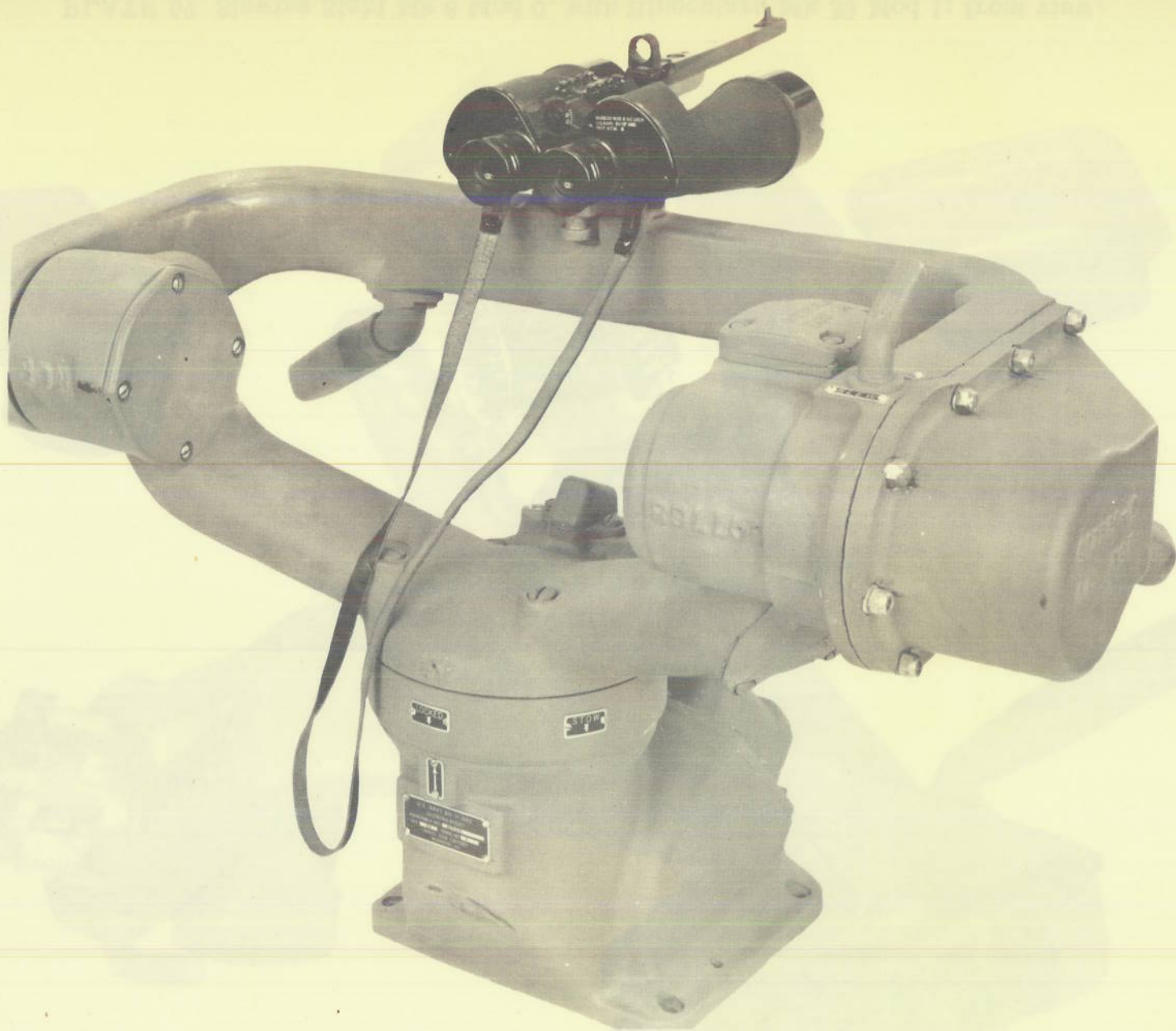
DECLASSIFIED

DECLASSIFIED



DECLASSIFIED

PLATE 57 Slew Sight Mk 6 Mod 0, with Binoculars Mk 39 Mod 1; front view.

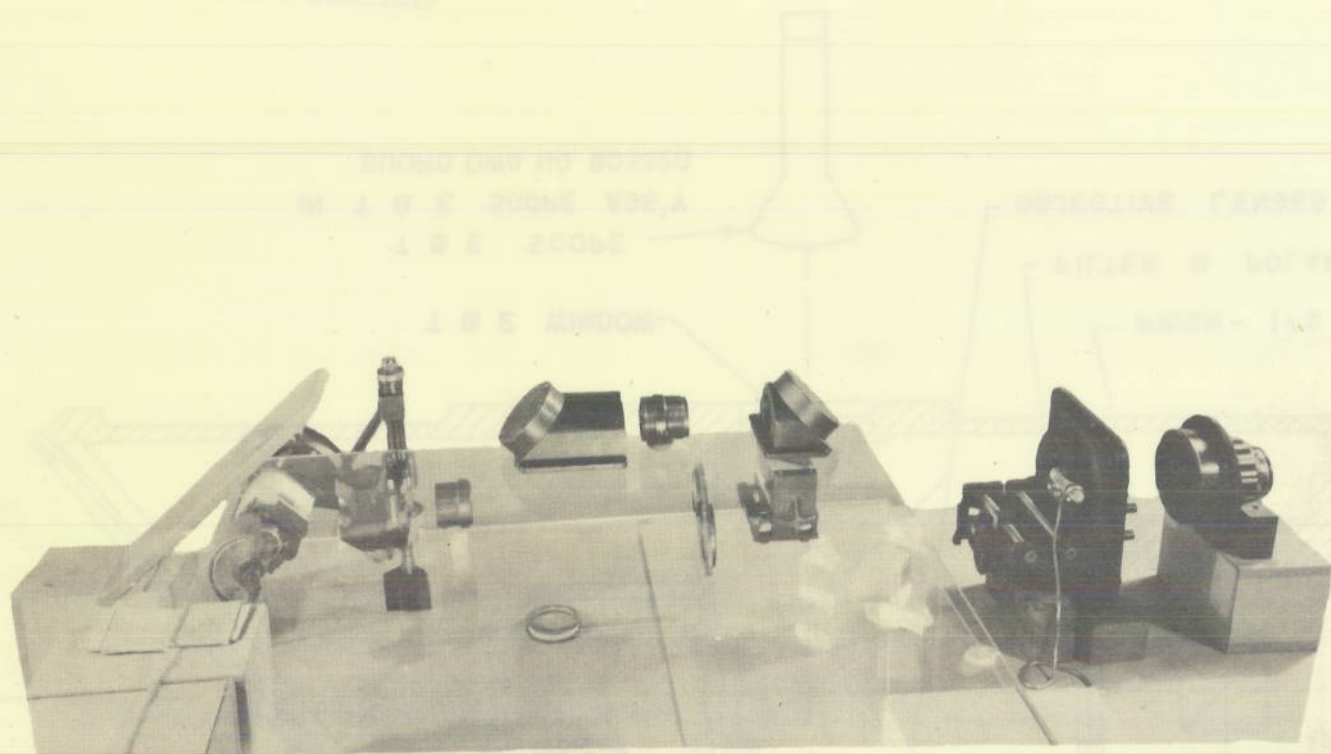


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PLATE 58 Slewing Sight Mk 6 Mod 0, with Binoculars Mk 39 Mod 1; rear view.

DECLASSIFIED

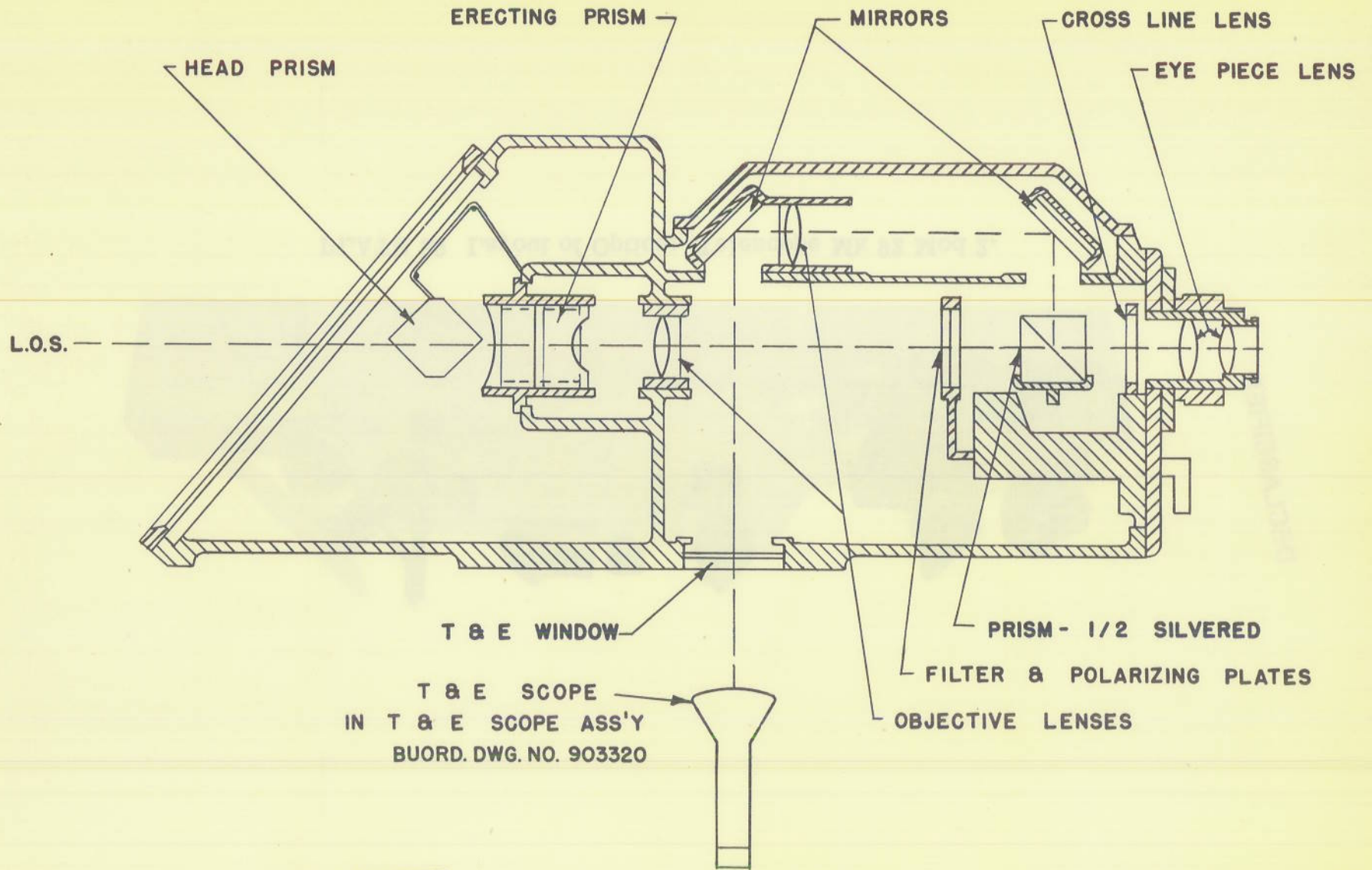


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PLATE 59 Layout of Optics: Telescope Mk 92 Mod 2.

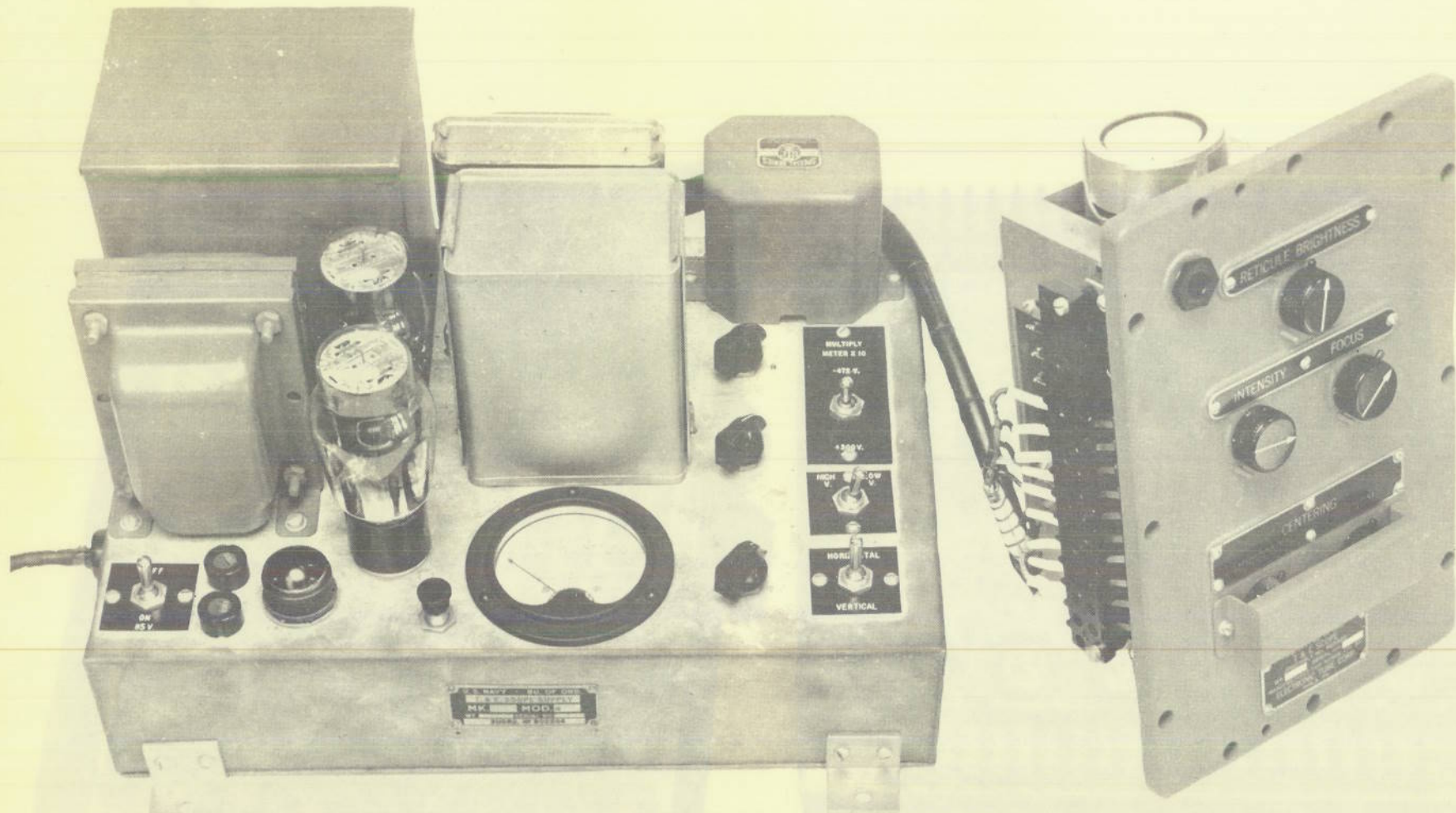
TELESCOPE MK. 92 MOD. 2
CROSS SECTION - SHOWING LOCATION OF ELEMENTS

DECLASSIFIED



DECLASSIFIED

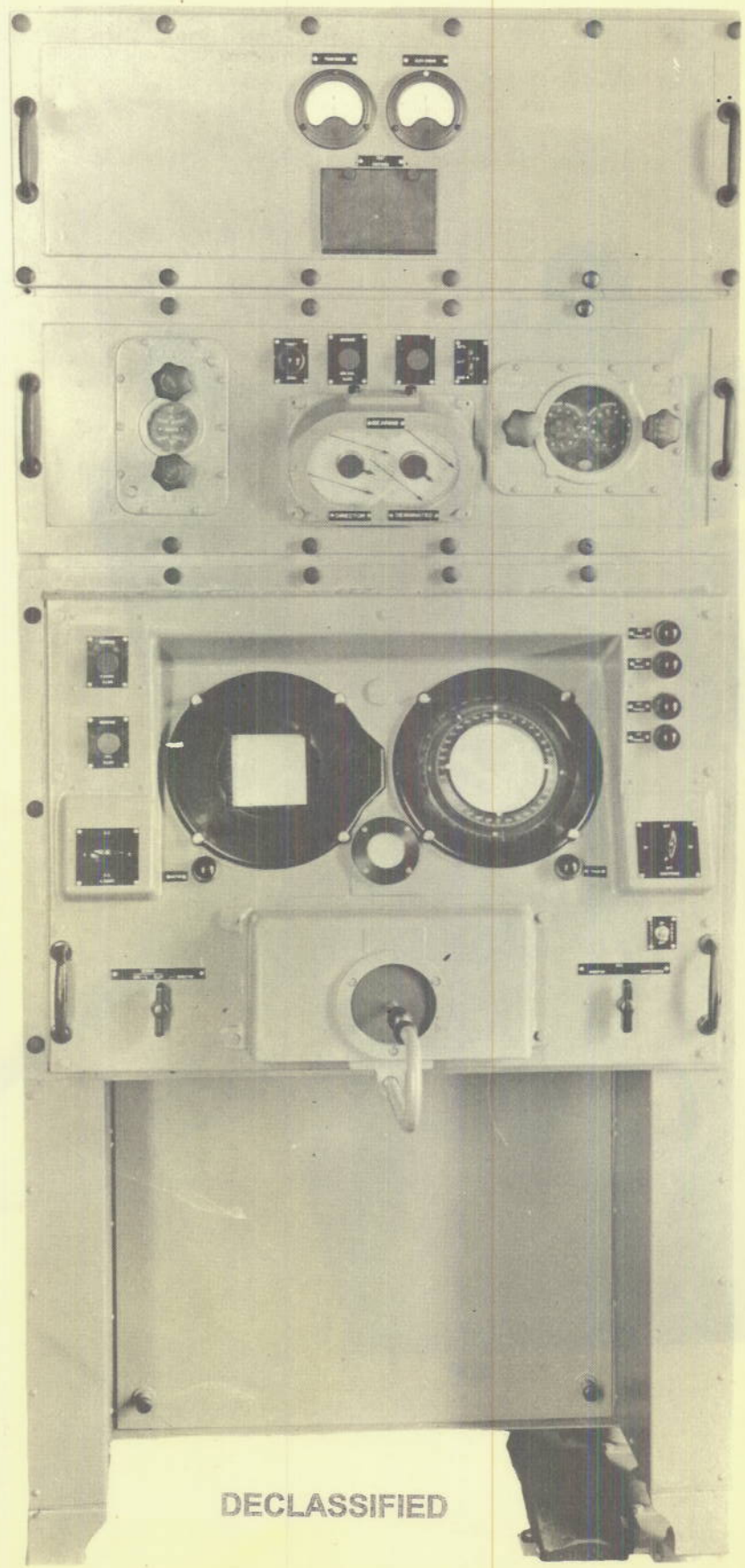
DECLASSIFIED



DECLASSIFIED

PLATE 61 Power Supply for Testing Train and Elevation Scope.

DECLASSIFIED



DECLASSIFIED

PLATE 63 Target Acquisition Unit Console for Radar System Mk 47 APL Design Incorporating Wind Transmitter Mk 4 Mod 5.

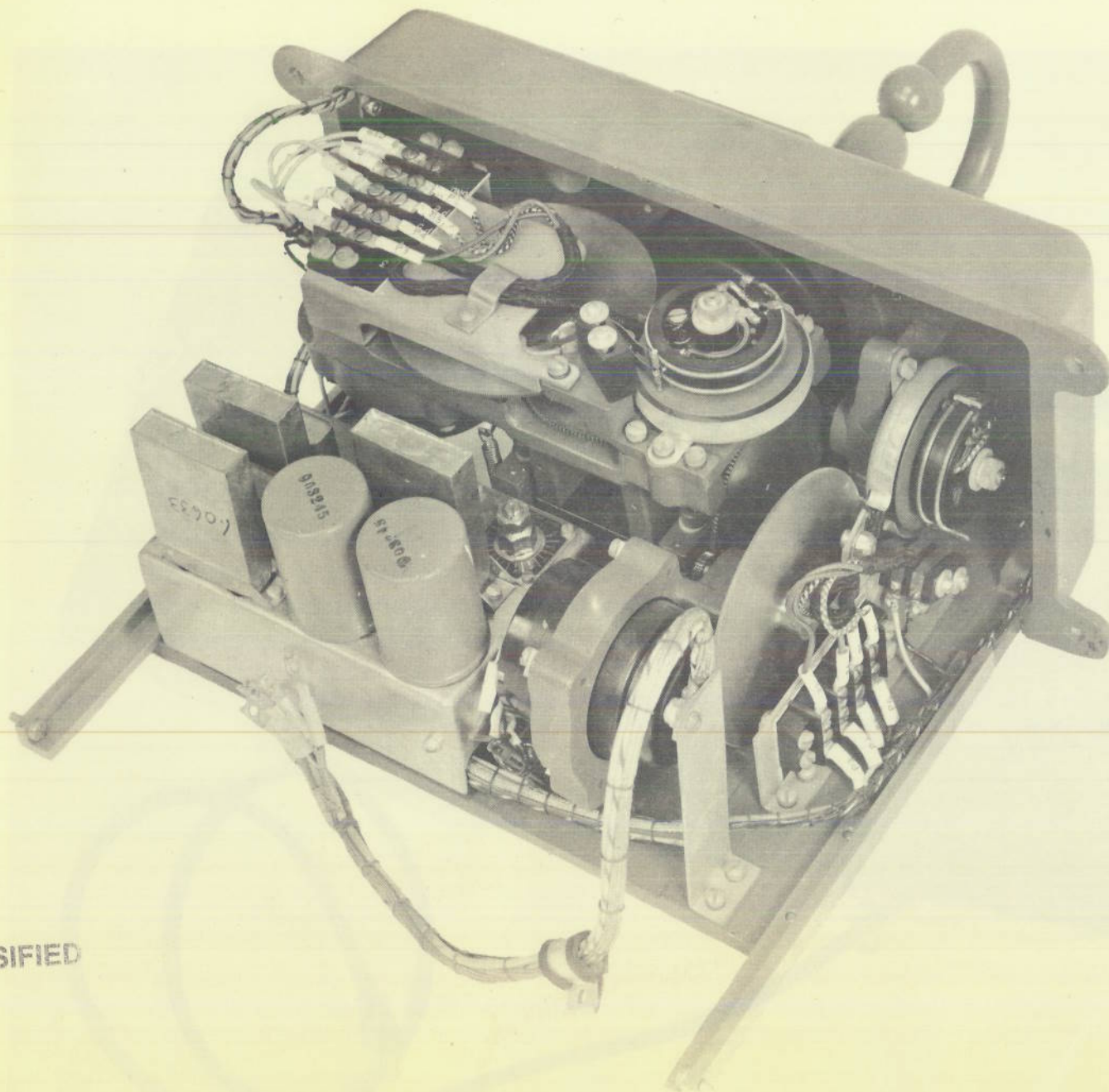
DECLASSIFIED



DECLASSIFIED

PLATE 64 Target Acquisition Control Unit (Joystick); front view, APL model

DECLASSIFIED



DECLASSIFIED

PLATE 65 Target Acquisition Control Unit; rear view, APL model.

DECLASSIFIED

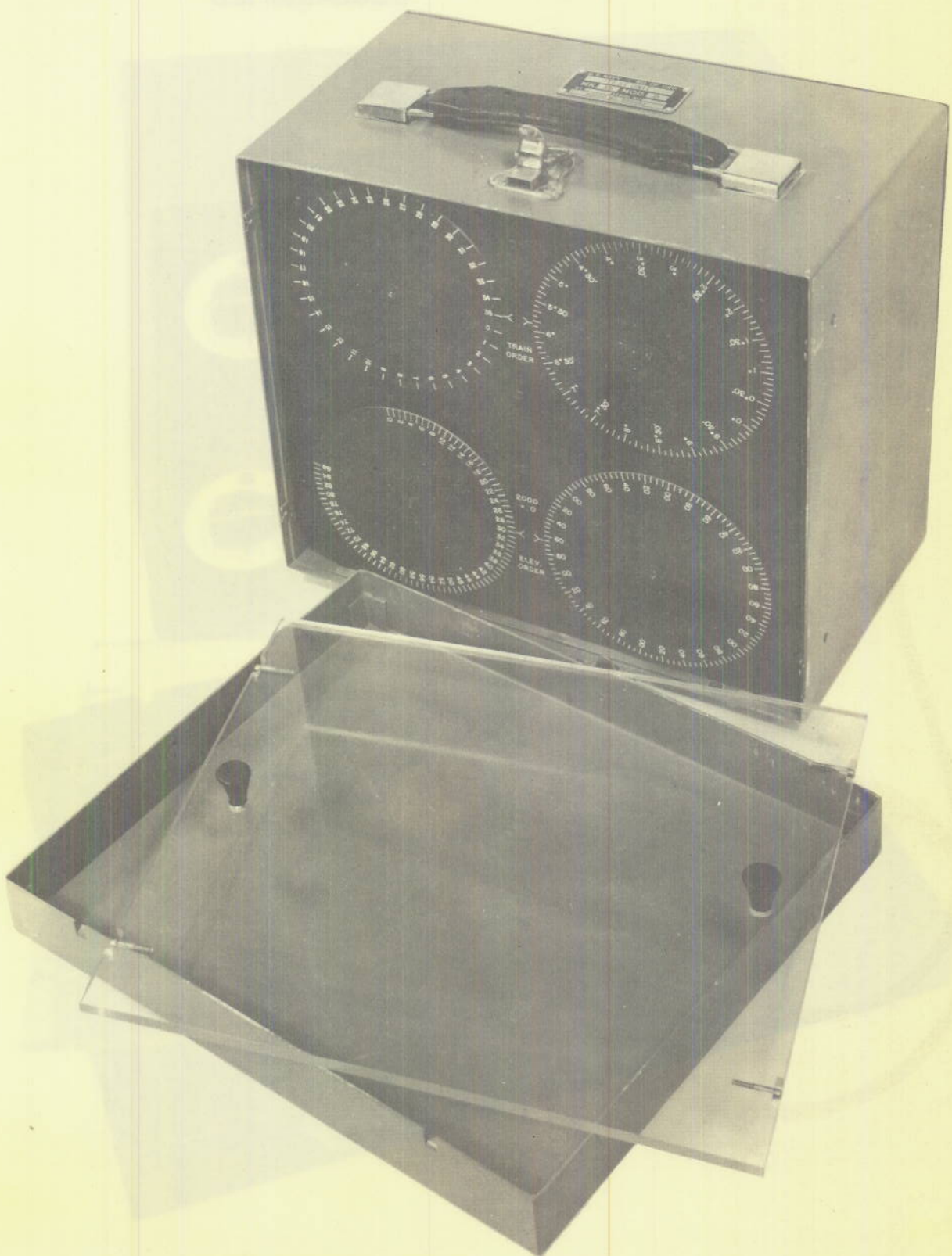


PLATE 67 . Test Unit Mk 35 Mod 0 (Synchro Dial Box).

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DECLASSIFIED

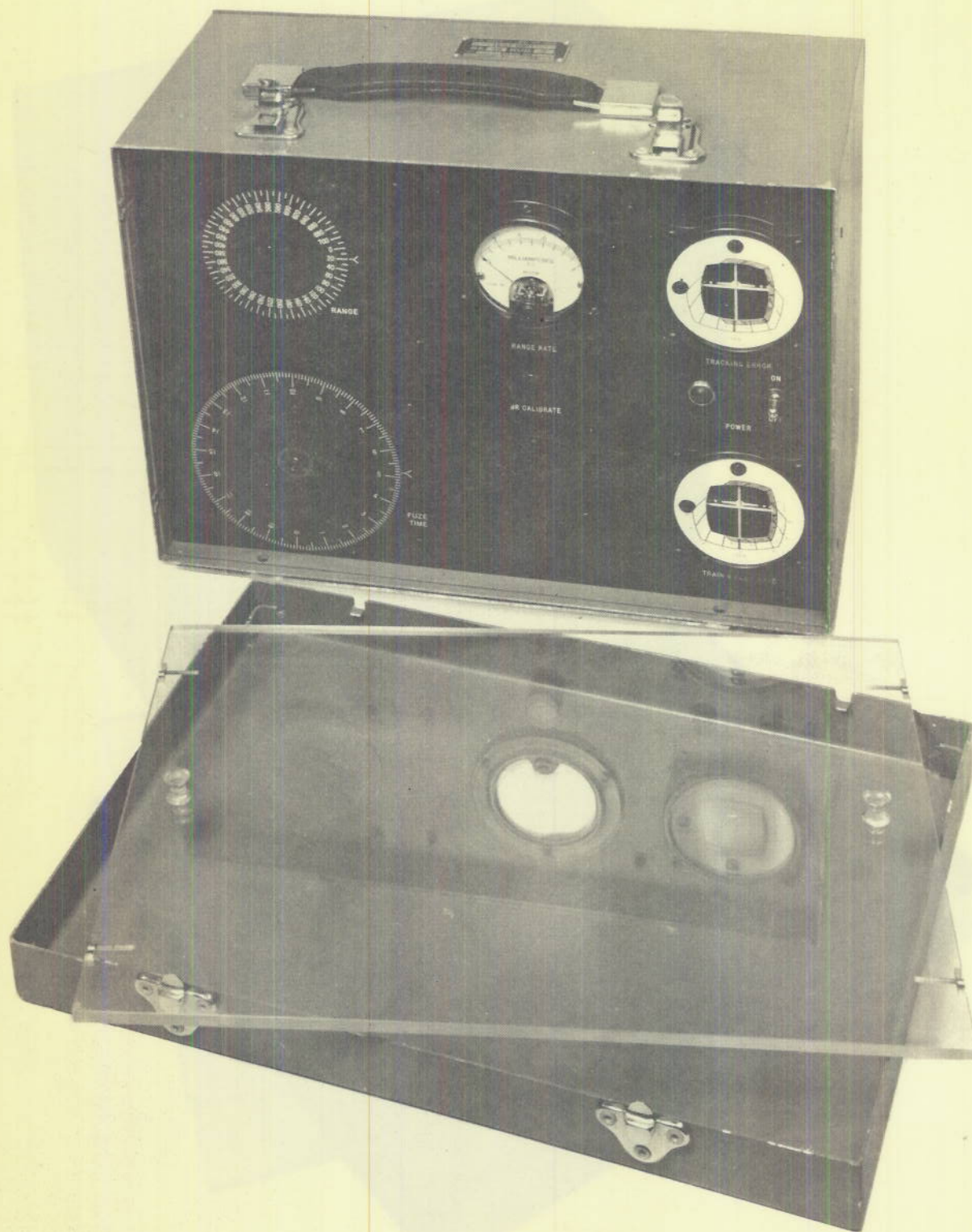
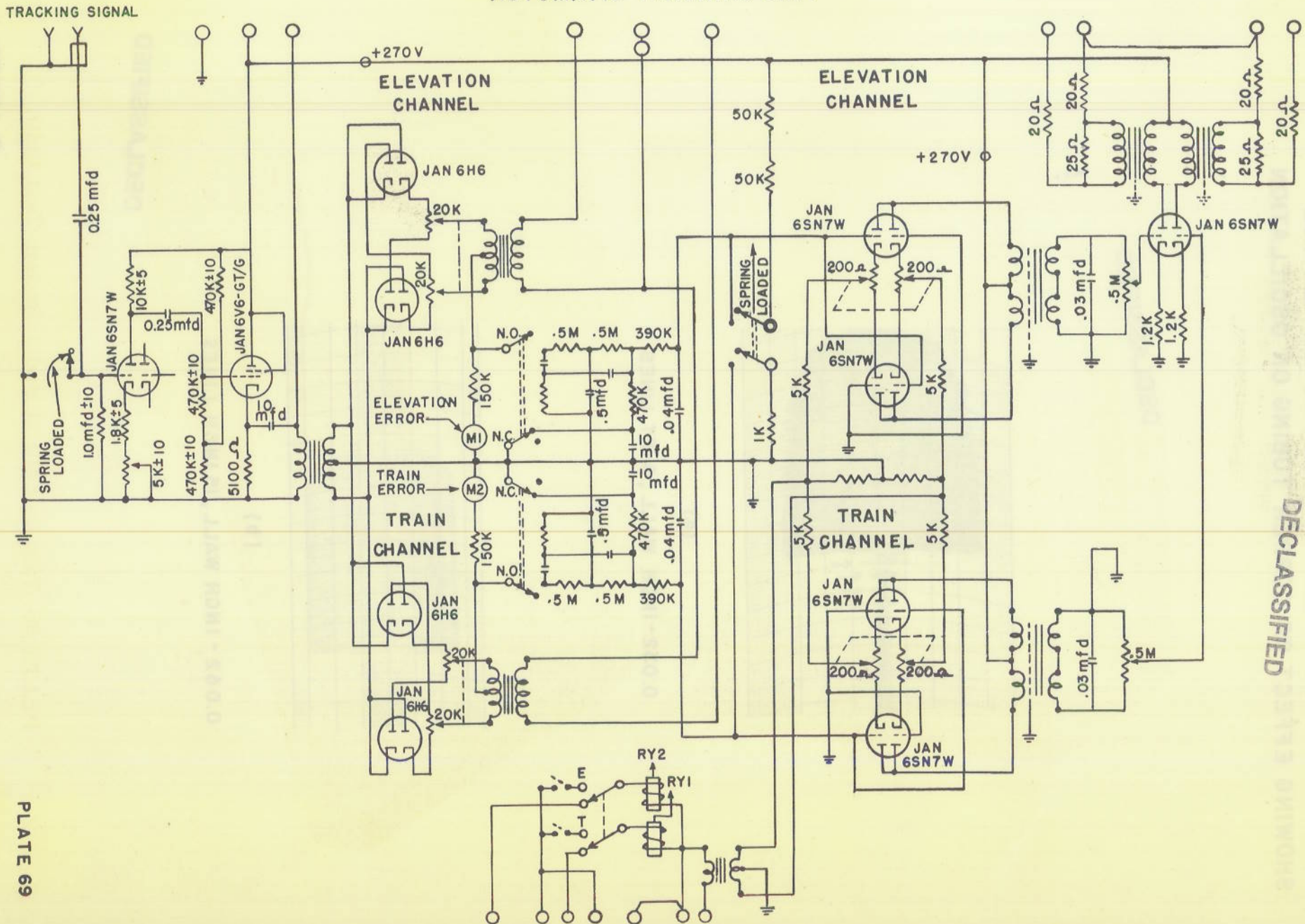


PLATE 68 Test Unit Mk 36 Mod 0 (System Test Unit).

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AUTOMATIC TRACKING UNIT

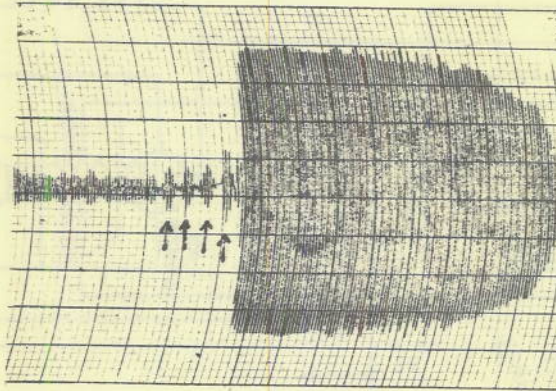


DECLASSIFIED

DECLASSIFIED

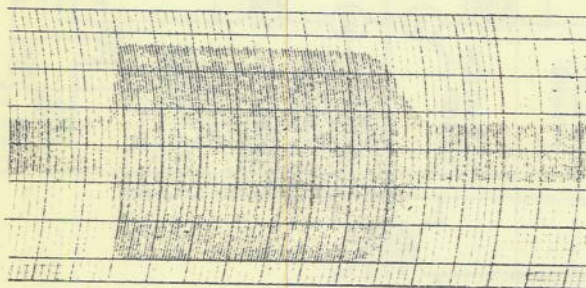
ANGULAR VELOCITY OF HYDRAULIC MOTOR VS. TIME
SHOWING EFFECT OF COPPER TUBING ON OSCILLATION

DECLASSIFIED



(a)

0.032-INCH WALL, 5-FT. LINES



(b)

0.062-INCH WALL, 15 INCH LINES

DECLASSIFIED