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DEPARTMENT OF THE NAVY

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DESIGN DETAILS AND OPERATING PROCEDURE FOR THE TMB NETWORK ANALYZER

by

John H. Kenney and Ralph C. Leibowitz

INSTRUMENTATION DIVISION

RESEARCH AND DEVELOPMENT REPORT

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ABSTRACT

This report describes the physical characteristics, components, and instrumentation of the TMB Network Analyzer, and gives the layout arrangement and some construction details. The procedure for setup and operation of the network analyzer is explained sufficiently to permit the reader to utilize the facility. A brief description of the methods and techniques employed in calibrating the components used with the analyzer is included.

INTRODUCTION

The TMB Network Analyzer is an array of passive electrical elements of resistance, inductance, capacitance, and transformers that can be connected to form various electrical networks. These networks in turn, represent mechanical systems under study. The analyzer is arranged to permit insertion of 144 electrical components. The inserted inductance, capacitance, and resistance elements represent the electrical equivalents of springs, masses, and damping, respectively, in the mobility or mass-capacitance analog.* Thus a complex system such as a ship's hull or shafting and machinery can be represented. External oscillatory forces in the mechanical system are simulated by feeding alternating current signals into the electrical network. The points of resonance, or natural frequencies, and various modes of vibration are easily determined by varying the frequency of the a-c signal and observing the resonance peaks at appropriate points in the network with an a-c meter and oscilloscope. The effects of changing mass, stiffness, or spring constant in the mechanical system can be observed by simply varying a capacitance or inductance in the electrical system. In this way a complete study and analysis of a complex mechanical system can be made, using the network analyzer.

The original TMB analyzer was designed and assembled in the early 1940's to simulate with an electrical "machine," the torsional and logitudinal vibrations of the mechanical system comprising a ship's propeller, shaft, and associated machinery. The choice of arrangement of the electrical network and methods of inserting the electrical parameters was influenced by the requirements of this problem. From an analysis of the mechanical system and its electrical counterpart, the type and relative number of parameters were determined which would give a lumped parameter analog that represents each subdivision of the shaft. This information set the criteria for the early design. Subsequent changes in design were dictated by needs for extending the application of the network analyzer.

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*A comprehensive study of the analog solution of beam vibration was made in TMB Report 1317, "Theory of Freely Vibrating Nonuniform Beams, Methods of Solution and Application to Ships," by Ralph C. Leibowitz and E.H. Kennard.

About three years ago, because of numerous temporary additions, and unreliable operation caused by mechanical and electrical defects which had developed in the original assembly, it was decided to completely rebuild the analyzer. No essential change was made in the original circuit design or principle of operation. The analyzer was, however, completely rearranged physically, new cabling systems were run, and newly designed contacts for the plug-in chassis and components were installed. This report describes the present arrangement of the analyzer and gives operating procedures for setting up the parameters to obtain solutions of mechanical problems.

GENERAL DESCRIPTION

The TMB Network Analyzer is best described by referring to Figures 1, 2, and 3 showing, respectively, the general layout, a typical analyzer panel, and the floor plan of the analyzer structure. In Figure 2 a typical analyzer panel is defined by the nomenclature which will be used throughout this report.

The present network analyzer is made up of twelve panels, arranged as shown in Figure 3. The total panel space of the analyzer includes 144 compartments, or slots, into which are inserted the plug-in chassis containing the R, L, and C parameters. Each panel contains the necessary compartments, wiring, and connectors for inserting and interconnecting 12 separate components. The resistors, inductors, and capacitors used with the analyzer are mounted in plug-in chassis, as shown in Figure 4. All the chassis are physically alike and can be inserted into any compartment in the analyzer. If only three or less parameters are required to represent a mechanical section in the electrical analog, as is the case in the beam problem, then a total of 48 analog sections is possible. When the number of parameters required to represent a mechanical section increases, the maximum number of sections that can be represented on the analyzer decreases. Since the number of compartments in the analyzer is fixed, the maximum number of sections that can be represented for any given problem will be determined by the number of parameters required to represent a typical mechanical section.

The words *section* and *station* are the standard terminology associated with the process of structural analysis of a shaft or beam by the use of equivalent electrical networks. In the analogy the beam is divided into a given number of parts called *sections,* and the points where the beam is divided are called *stations*. The mechanical section, or that part of the beam between two successive stations, is represented on the analyzer by certain capacitances, inductances, resistances, and transformers. The analog stations have the same relation to the analog section as the mechanical stations have to the mechanical sections.

At the base of each panel, inside the cabinet, are located four Hycor transformers. The normal hookup of the transformers is to connect all the primary windings of each transformer in series and all the secondary windings in series. This gives the maximum inductance at a one-to-one ratio. The ratio can be readily changed by changing the number of coils in either the primary of secondary or both. Figure 5 shows the transformer in schematic form. The coil terminals are numbered to coincide with the terminal numbers on the transformer case. Using

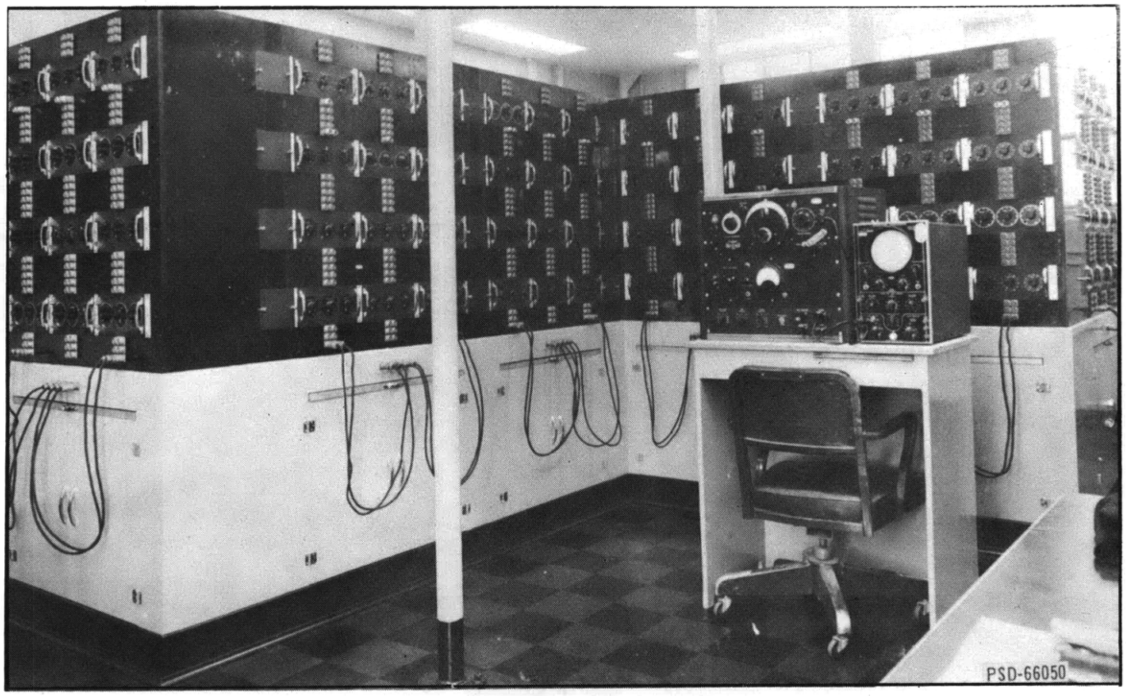


Figure 1 – General View of TMB Network Analyzer

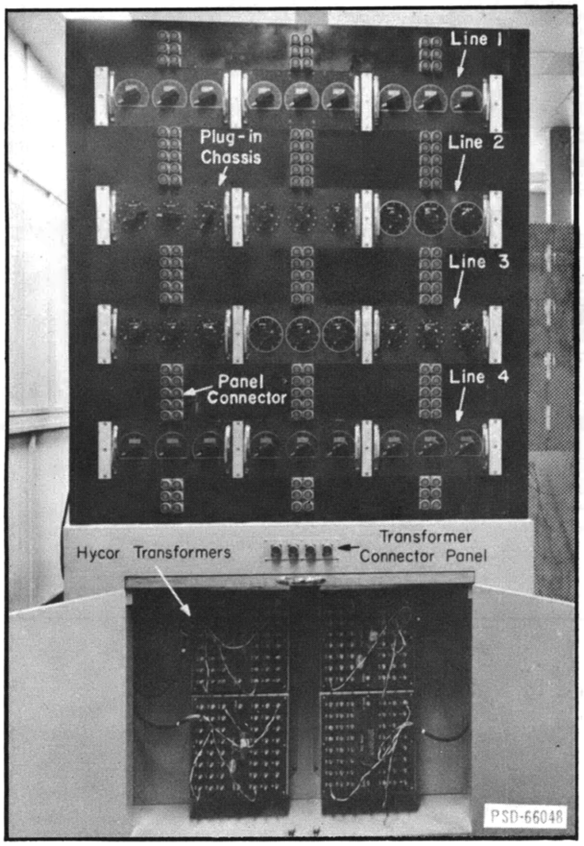


Figure 2 – Typical Analyzer Panel and Transformers

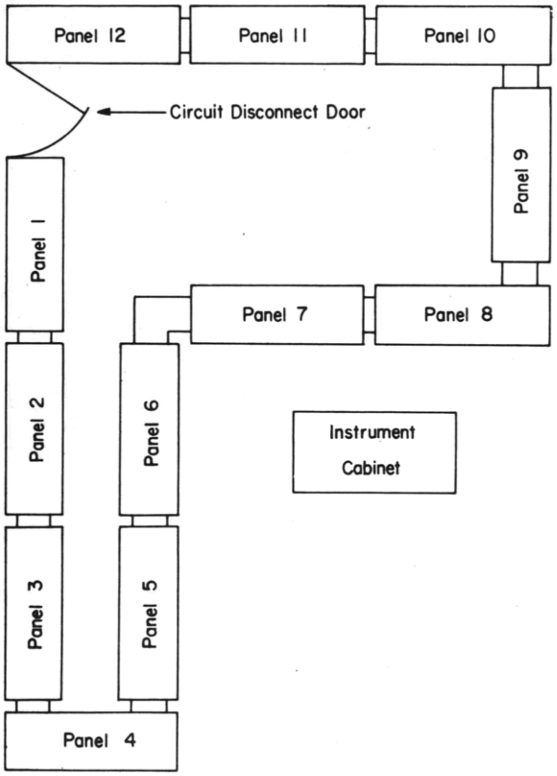


Figure 3 – Floor Plan of TMB Network Analyzer

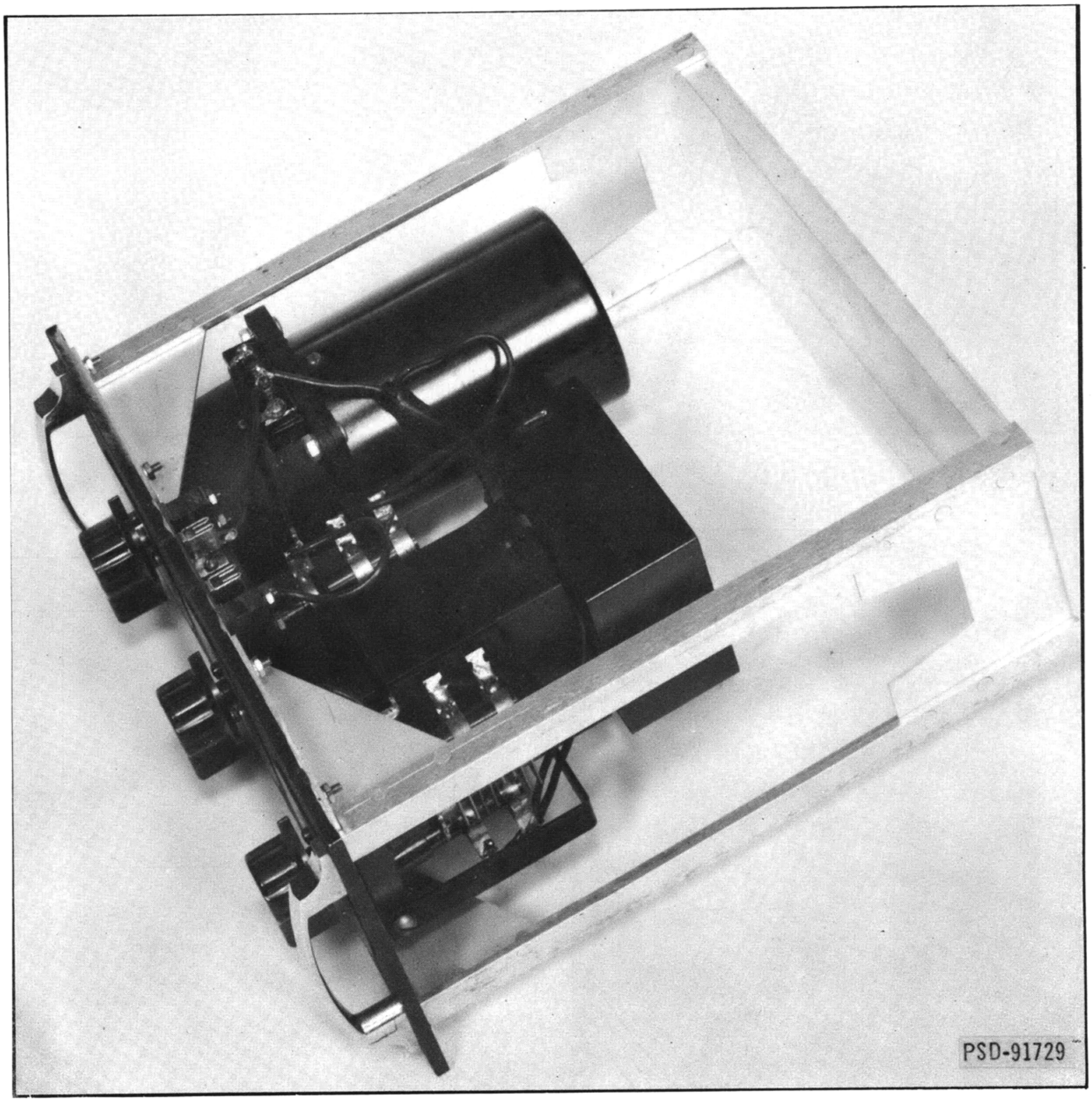
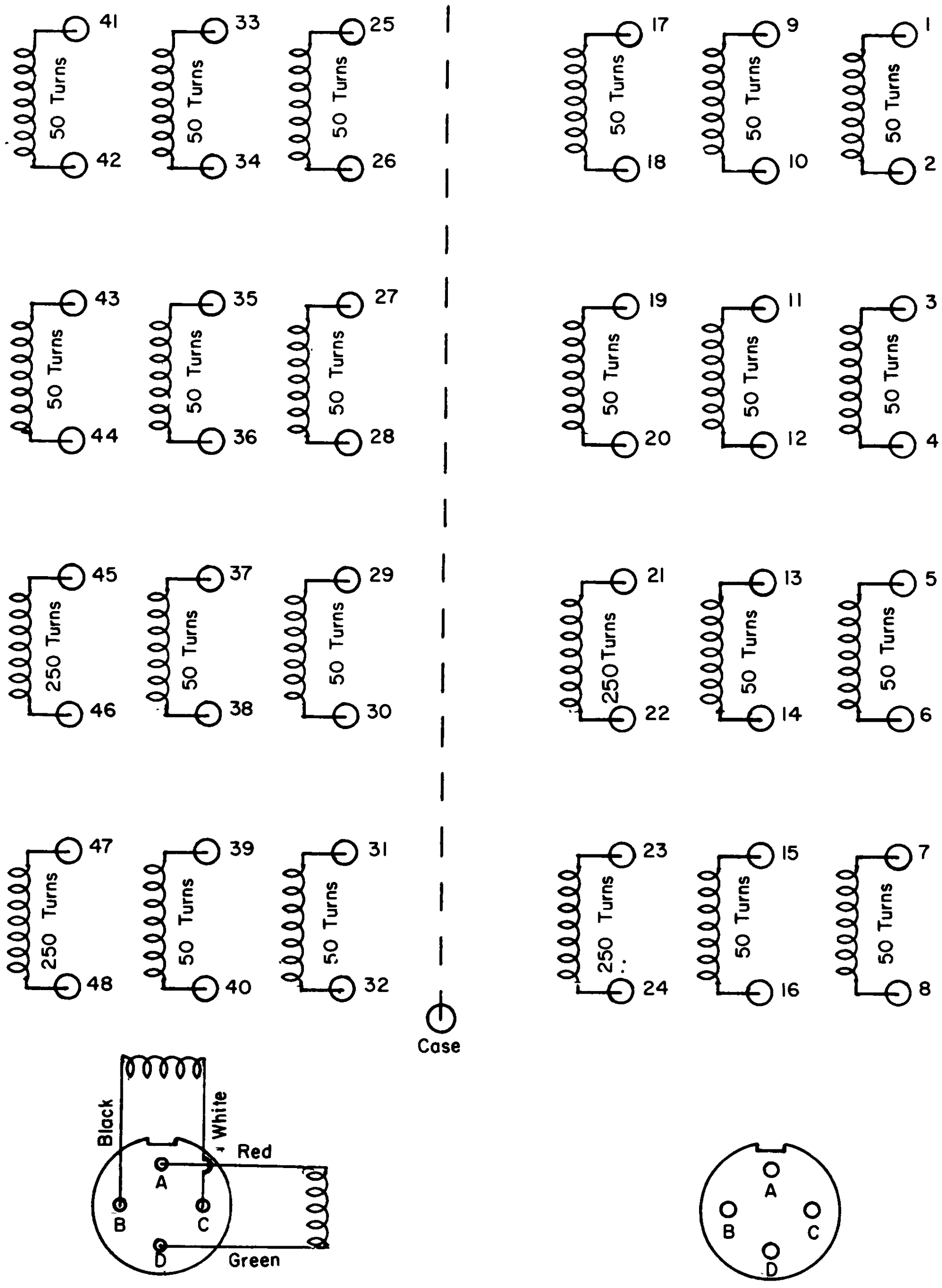


Figure 4 – Plug-In Chassis used in Network Analyzer



Transformer Panel Connector

Analyzer Panel Connector

Figure 5 – Coil Terminal Connections on Hycor Transformer

this schematic as a reference, the operator can adjust the turns ratio of the transformer to suit his particular problem.

The primary and secondary terminals of each of the four transformers are brought out to a connector panel above the cabinet doors, and special cables are provided for connecting the transformers into the electrical network. Figure 5 identifies the leads at the transformer, both as to color code and connector pin numbers.

The input and output cables are connected at the rear of the analyzer panels inside the enclosed area. There are 48 separate output cables and 6 individual input or drive cables. Access to the cables is through a circuit disconnect door provided for this purpose. Figure 6 is a view through this door, showing a portion of the interior of the analyzer. An output cable is located at each of the possible 48 station positions in the analyzer; see Figure 7. These cables are normally connected to the circuit conductor designated as the V-line. There are no mechanical restrictions on the cables, however, and they can be used to monitor any circuit in the network. The letters V and M designate the shear force and bending moments, respectively, in applications of the analyzer to the problem of vibrating beams. The letter G designates the grounded circuit conductor in the analog circuit. These designations will become clearer when the circuit for a typical beam section is discussed.

The output cables have been numbered according to their line and station position in the analyzer. The cable located at Line 1, Station 1, is labeled 1-1. The cable located at Line 2, Station 13, is labeled 2-1, etc. The opposite ends of the cables are connected at the control panel and are identified by the dial numbers of two switches, the line selector switch and the station selector switch. Figure 7 shows, in block diagram form, the output cables in relation to line and station position, the numbering system, and the control switches.

The six drive cables are located at different points in the analyzer. The distribution is such that every station position can be reached by at least one of the drive cables. The cables, lettered A through F, are shown in block diagram form in Figure 8. The cable selected for driving the electrical network is connected to the sine-wave generator by setting the pointer on the drive cable selector switch, at the control panel, to the corresponding letter on the cable. With very minor adjustments at the terminal board, in the instrument cabinet, two or more stations can be driven at the same frequency simultaneously. By using an additional oscillator and by making the proper connection at the terminal board, two stations can be driven at different frequencies simultaneously.

Located at each station position is a lead connected to the metal framework of the analyzer. The frame is the common ground for the analog circuit, and the lead connected to the frame is used to ground the circuit conductor designated as the G-line.

The analyzer circuit conductors terminate at the banana-jack terminals located in the circuit disconnect door. Figure 9 shows the circuit disconnect door in the closed position with all circuit lines broken at the circuit conductor terminals. It is at these terminals that the jumpers shown in Figure 7 are inserted. The V-, M-, and G-lines, identified in Figure 9, are the analyzer circuit conductors represented in Figures 7 and 8.

Figure 6 – Interior of Network Analyzer

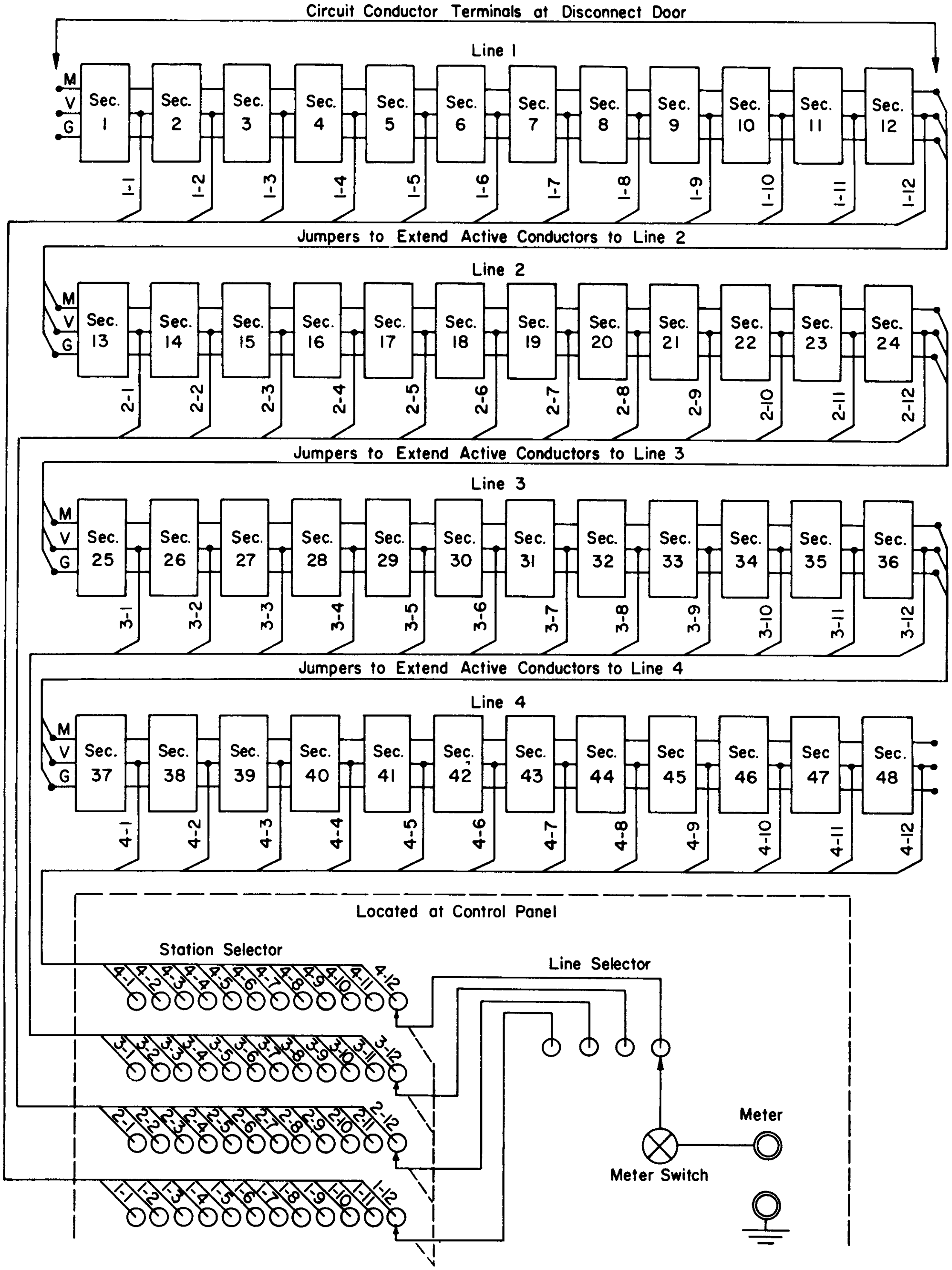


Figure 7 – Output Cable Location and Associated Circuitry

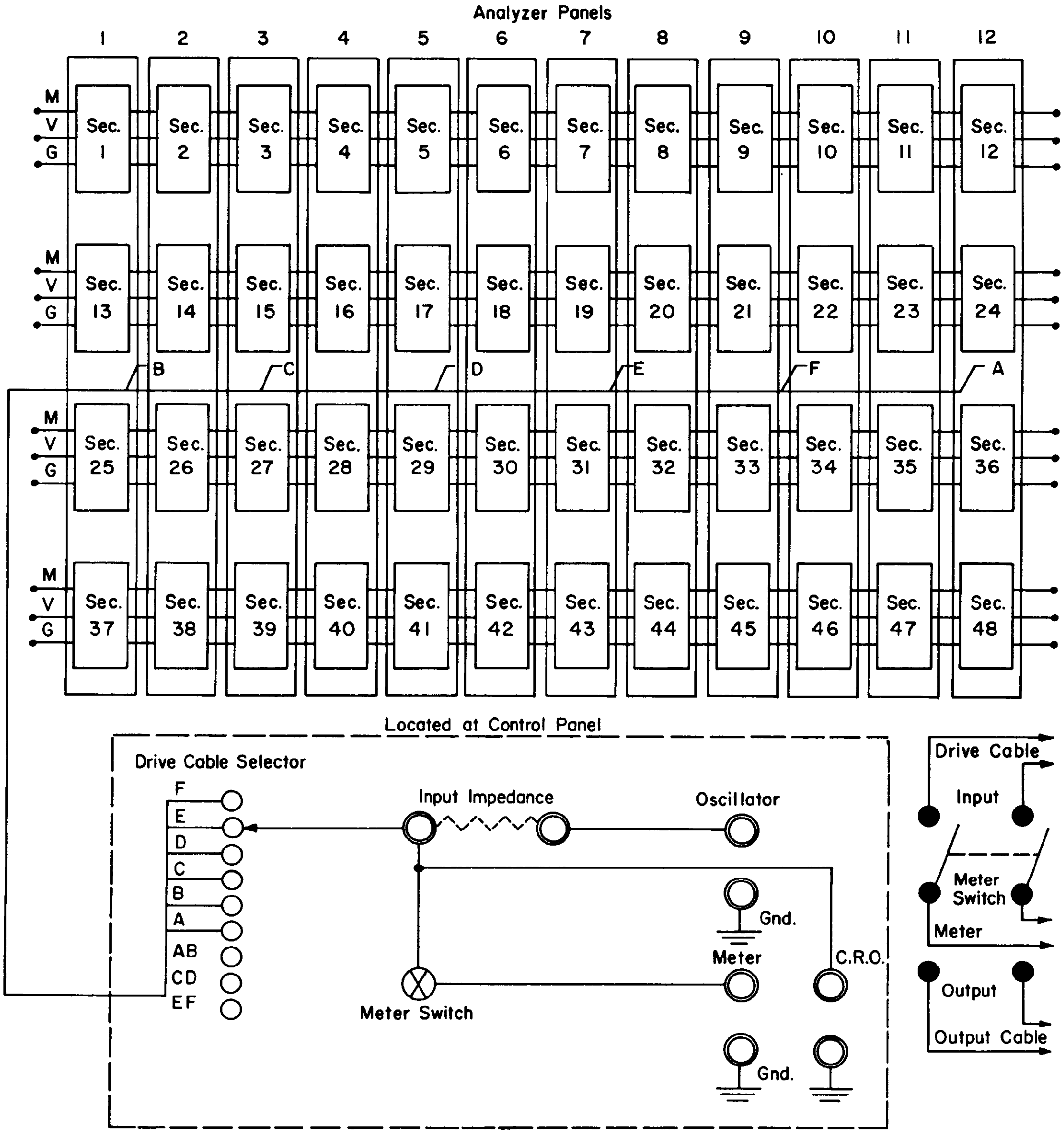


Figure 8 – Drive Cable Location and Associated Circuitry

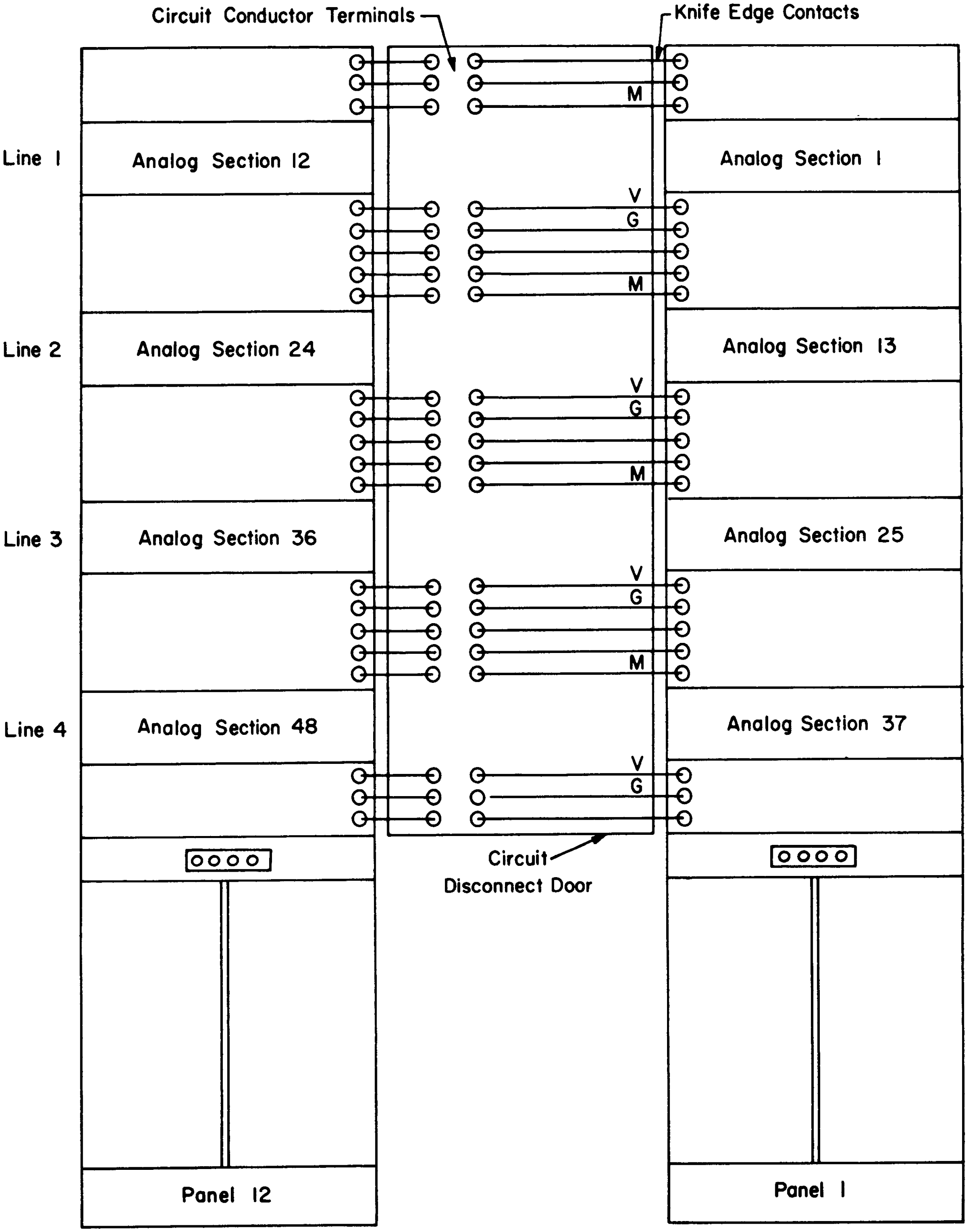


Figure 9 – Circuit Disconnect Door and Adjacent Panels

ANALOG SECTION AND STATION SETUP

The position of the sections and stations on the network analyzer can be explained by referring to Figure 2. For purposes of explanation, the panels can be considered as being connected in a straight line. The configuration of the analyzer structure is important only in considering space requirements and ease of operation. The TMB Network Analyzer, as can be seen in Figure 2, consists of four separate lines. Each line contains the necessary circuit conductors to represent the V-, M-, and G-circuits in the analog, and three compartments for inserting the plug-in chassis containing the R, L, and C parameters. The compartments in a given line of one panel are separated from the corresponding group of compartments in the next panel by the connector blocks between adjacent analyzer panels. The output cables are connected at these connector blocks, which are the analog station positions equivalent to the mechanical station positions on the beam. The group of parameters between two successive analog stations comprises the analog section. The lumped parameters of the analog section are equivalent to the lumped parameters at certain station and midstation positions on the beam. For setting the analog sections in tandem on the analyzer, the standard procedure is as follows:

Station 0, or the driving station, is designated as the station immediately to the right of the circuit-disconnect door on Line 1, as shown in Figure 9. The drive cable is connected to the V-line-circuit conductor at the terminal in the disconnect door. The components in Line 1 become the parameters assigned to the first analog section. The components in Line 1, Panel 2, are the parameters for the second analog section, and the components between Analog Station 2 and Analog Station 3 in Line 1 comprise the third analog section. The sections are continued around on Line 1 until Analog Section 12 has been set into the analyzer.

If the number of analog sections required for the problem exceeds 12, the operator must utilize Line 2 of the analyzer. All that is required is that the active circuit conductors of Line 1 be connected to the corresponding circuit conductors in Line 2. These connections are made at the line-circuit terminals in the disconnect door, using the jumper leads provided for this purpose. The analog sections are added in Line 2, exactly as was done in Line 1. If only 3 panel parameters were used at each analog section, the procedure could be continued through 48 analog sections. A study of Figure 8 will clarify the section distribution system used with the analyzer.

In practice, when working with a 24 section analog or less, the operator can begin the analog sections at Line 2. This brings the components to about eye level on the analyzer, and affords more convenience in manipulating the dials on the R, L, and C components. However, the operator may utilize a section layout which best suits his particular problem.

CONNECTING THE PHYSICAL PARAMETERS ACCORDING TO THE ELECTRICAL SCHEMATIC

As an aid to the operator in setting up the electrical network on the analyzer, a worksheet has been prepared which is an exact half-scale replica of a typical analyzer panel. The worksheet shows all the circuit conductors, connectors, and compartments which are a part of the panel. To explain the normal transition from the circuit schematic of the electrical circuit to the analog section on the analyzer, a typical beam section analog will be considered. Figure 10 shows the electrical circuit for the typical beam section.

Since each section is identical in form, the operator need only work out the network connections for one section on the analyzer worksheet. The parameters $(\Delta X/KAG)'$, $(\Delta X/EI)'$, and $(\mu\Delta X)'$ representing the values for $\Delta X/KAG$ (shear flexibility), $\Delta X/EI$ (bending flexibility), and $\mu\Delta X$ (mass), respectively, always take the same relative positions on the network analyzer. The operator begins by drawing in, on the worksheet, at the proper position, the schematic representation for each of the parameters, as shown in the electrical schematic provided for his use. The next step is to draw in on the connector symbols the lines which will connect the parameters, as shown on the electrical schematic. The transformers can be represented as shown in Figure 11, a scaled-down drawing of a typical analyzer worksheet . Figure 11 also shows the position of the components and the type of connectors required to represent two analog sections having the configuration of the electrical circuit shown in Figure 10. It should be noted that the two sections shown are not successive sections. The section in Line 2 is Section N, and the section in Line 3 is N + 12. Within practical limits, any connection drawn on the worksheet can be duplicated on the panel by one of the pre-wired cannon connectors used with the analyzer. The connectors are clearly marked, and with very little practice the operator can insert them rapidly. Figure 12 shows an analyzer panel complete with connectors and parameters which duplicate the two sections, as shown on the worksheet in Figure 11,

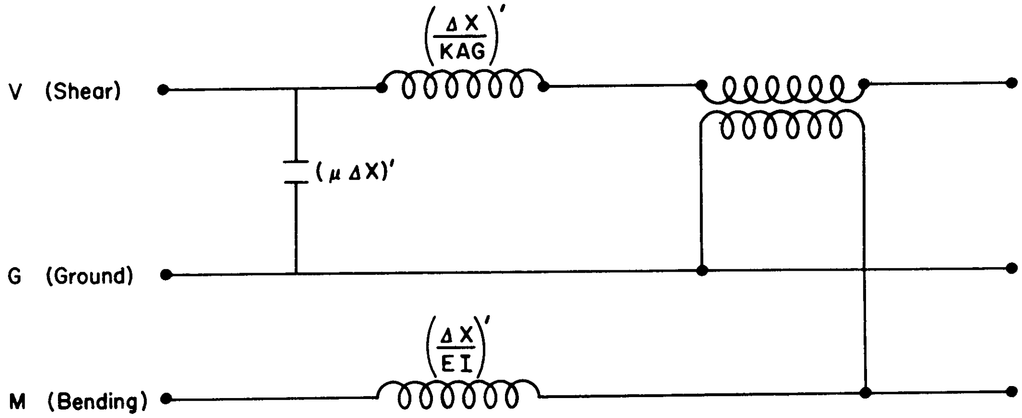


Figure 10 – Electrical Circuit for Typical Beam Analog

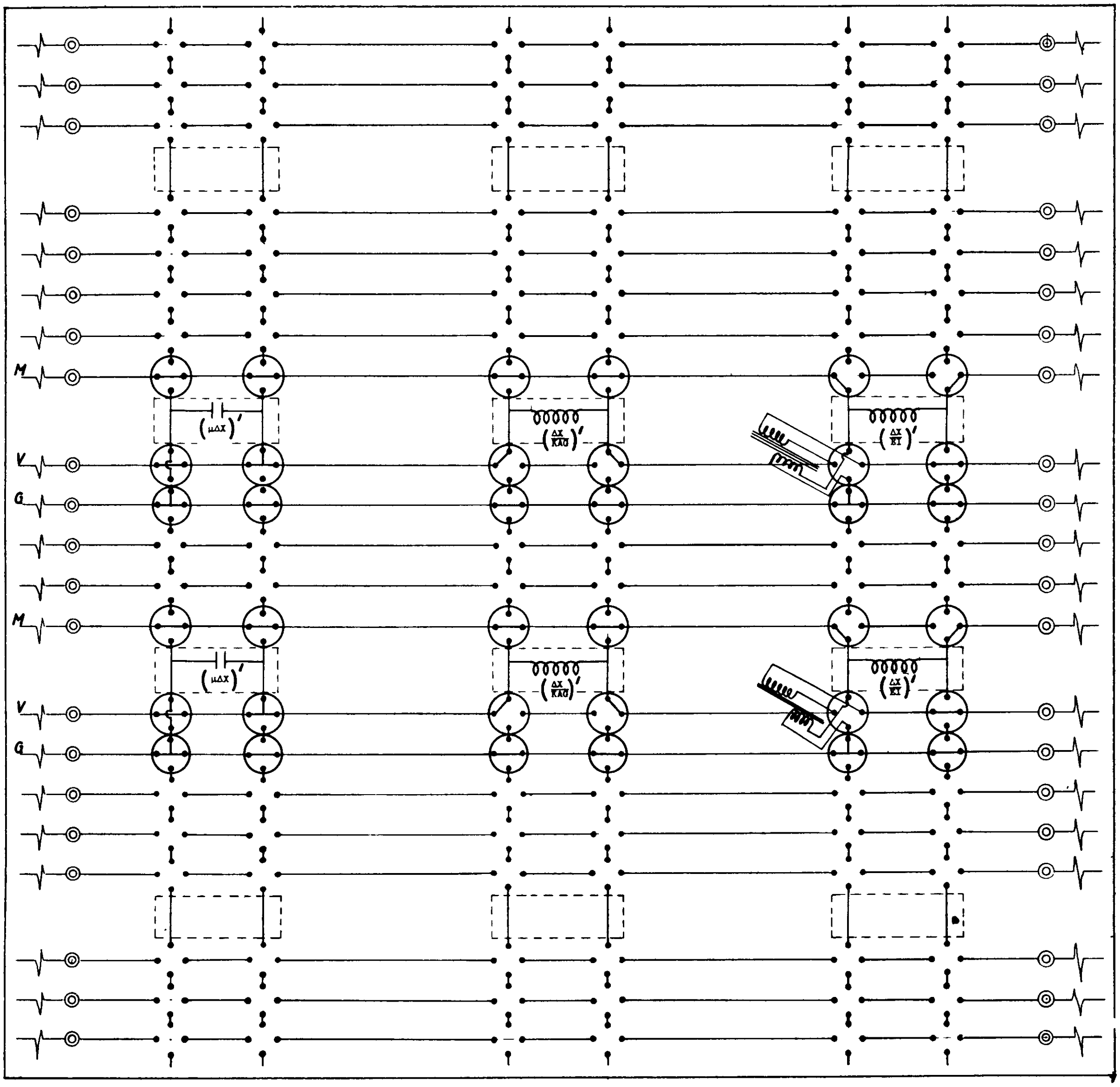


Figure 11 – Analyzer Worksheet Showing Parameters and Connectors for Two Sections of Typical Beam Analog

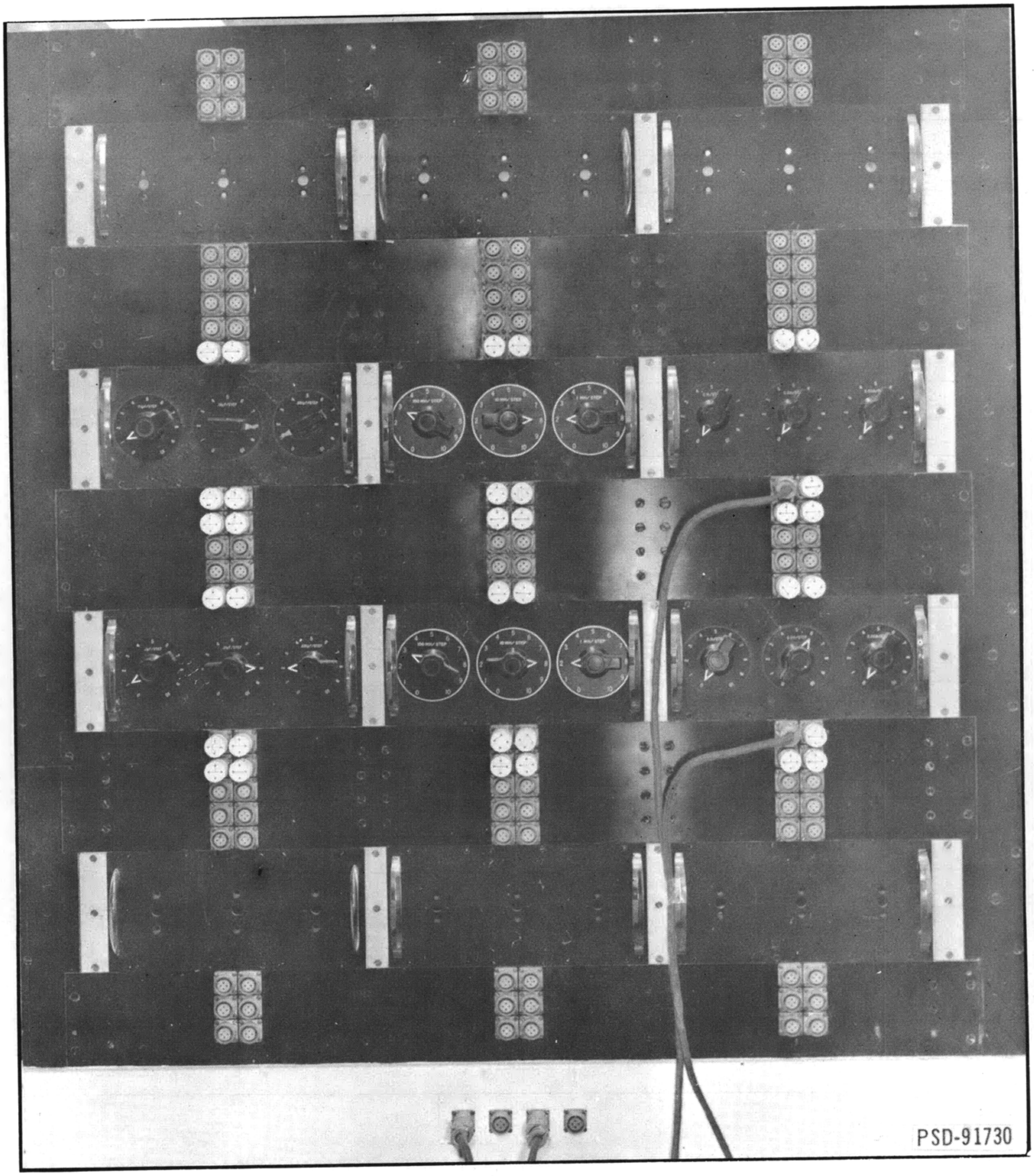


Figure 12 – Analyzer Panel Showing Two Analog Sections For Typical Beam Problem

and represent two analog sections, each having the form of Figure 10. When the required number of sections are connected on the analyzer, the operator can proceed to dial in the correct values for $(\Delta X/KAG)'$, $(\Delta X/EI)'$, and $(\mu\Delta X)'$ at each individual section. The calibrated value for every inductance and capacitance decade used with the analyzer is available to the operator in a folder secured to an analyzer panel. Included in the folder is a detailed description of the methods and instrumentation used in making the calibration. A less detailed description of the methods of calibration is given in Appendixes A and B.

INSTRUMENTATION

INSTRUMENTS USED

The instruments used with the network analyzer (Figure 13) are few and relatively simple to operate. A General Radio oscillator, Type 1304B, is used to produce the driving function for the electrical analog. A Hewlett Packard electronic counter, Model 522B, measures the critical resonance frequencies of the analog circuit. A Ballantine a-c voltmeter, Model 300, is used to measure the peak amplitudes at resonance. A Dumont cathode-ray oscilloscope, (C.R.O.) Type 208, indicates the phase relationship between the signal at the driving station and the signal at the output stations. The C.R.O. is not used to measure the actual angular displacement of the signals. However, if such precise measurements are required, a phase meter can replace the oscilloscope for the measurement. Completing the instrumentation is a control panel that contains the terminals and switching circuits for connecting the drive and output cables to the measuring and indicating devices. Figures 7 and 8 contain schematic drawings of the control panel.

On the front of the control panel are four 2-terminal General Radio connectors labeled OSCILLATOR, INPUT IMPEDANCE, METER, and C.R.O. Three cable-selector switches and a meter switch complete the panel array.

The DRIVE CABLE SELECTOR is a 9-position switch in which only six positions are active. The positions marked AB, CD, and EF are not wired at the cable connector panel inside the instrument cabinet. However, with minor circuit changes these positions can be used to facilitate driving two or more stations simultaneously. In any of the six active positions the switch connects the drive cable, indicated on the plate, to one terminal of the INPUT IMPEDANCE connector. When a resistor is inserted across the INPUT IMPEDANCE terminals, the resistor is connected in series with the cable and connected to the oscillator. The circuit is shown in Figure 8.

The STATION SELECTOR is a 4-pole, 12-position switch. Each of the four switch sections connects to the cables located at the stations in the four lines in the analyzer. The arms of the switch sections connect to the LINE SELECTOR switch. The circuit is shown in Figure 7.

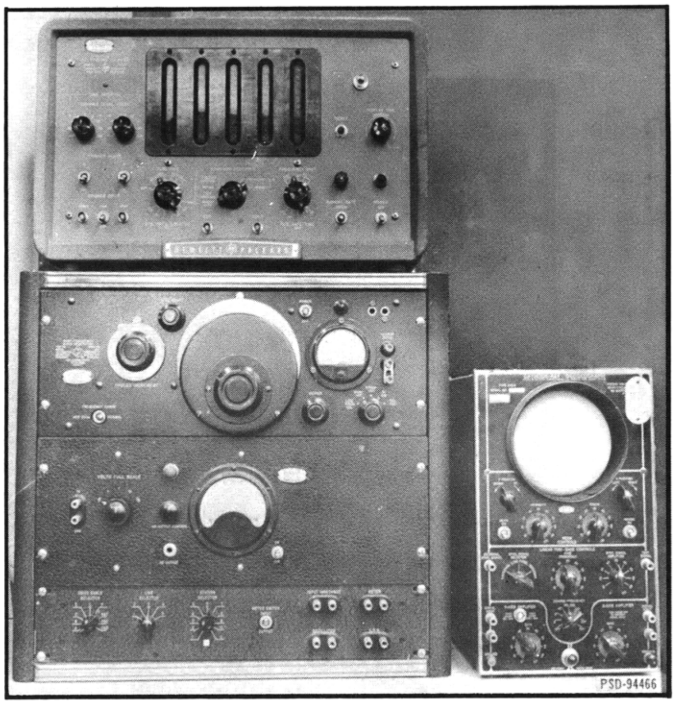


Figure 13 – Instruments Used with Network Analyzer

The LINE SELECTOR is a single-pole, 4-position switch that connects the stations in a particular line on the analyzer to the a-c meter and C.R.O. through the meter switch. This circuit is shown in Figure 8.

The METER switch is a double-pole, double-throw, toggle switch that is connected to the meter terminals. In the INPUT position the meter switch connects the a-c meter to the drive cable indicated on the DRIVE CABLE SELECTOR dial, and in the OUTPUT position the meter switch connects the a-c meter to the output cable indicated by the LINE and STATION selector switches.

All cables, including the main ground cable, enter the instrument cabinet through the vertical tube at the left of the cabinet. They have been properly connected at the main terminal board and to the control panel. It is not intended that the operator make any rearrangement at the terminal board.

INSTRUMENT SETUP

Using the cables provided, carry out the following procedure: Connect the oscillator and the electronic counter to the terminals labeled OSCILLATOR.

Connect the vertical input terminals of the C.R.O. (located at the lower left of C.R.O. front panel) to the terminals on the control panel marked METER. The a-c meter is connected to these same terminals internally.

Connect the horizontal input terminals of the C.R.O. (located at lower right of C.R.O. front panel) to the terminals on the panel marked C.R.O. Turn the COARSE frequency knob on the C.R.O. to the OFF position.

Insert a resistor of not less than 100,000 ohms into the terminals marked INPUT IMPEDANCE. The resistor is mounted in a connector which mates with the terminals on the panel. This resistor is for the purpose of providing an effectively constant impedance for the function generator.

Set the meter switch to the input position.

Turn on power to the oscillator, a-c meter, electronic counter, and C.R.O. Allow a warmup period of about fifteen minutes, then make the following adjustments:

If the electronic counter is *not* used, the oscillator must be adjusted for zero frequency. To do this, set the main dial on the oscillator to the zero frequency position. Set the venier dial to zero. Vary the ZERO ADJUST dial until a zero beat is indicated on the output meter on the oscillator. A more accurate adjustment can be obtained if the Ballantine a-c voltmeter, with the .01 voltage scale setting, is used in place of the oscillator meter. When the electronic counter is used with the analyzer, this adjustment is not necessary.

Select a suitable display time on the electronic counter. This is a very simple adjustment and the dial is clearly marked.

Adjust the intensity, focus, and position of the trace on the C.R.O. These adjustments are labeled on the front panel of the oscilloscope.

DETECTING THE CRITICAL FREQUENCIES OF VIBRATION

With the electrical analog of the mechanical system set up on the network analyzer, the operator may proceed to vary the oscillator and observe the a-c meter for peak readings indicating a resonance at the first critical frequency. This is done by slowly raising the frequency of the oscillator, starting at about 30 cps, until a peak reading is observed. When the reading is recorded, the frequency can be further increased until the next peak is observed on the meter. The procedure is continued until the highest resonance frequency of interest is recorded.

To obtain mode shapes at any or all of the resonance frequencies, the following procedure is observed:

Set the oscillator to the first critical frequency, and set the meter switch to the INPUT position. Adjust the output level of the oscillator to some reference level on the a-c meter. (One to three volts is recommended.) The amplitude thus set is the amplitude of the mode-shape curve at Station zero. Then set the meter switch to the OUTPUT position and read and record the amplitude and phase of the station outputs, as determined by the position of the selector switches. The resultant output is a curve plotted in relative amplitude versus station position. Follow the same procedure for each resonance frequency of the analog circuit. Always return the meter switch to the INPUT position when changing to a new critical frequency.

ACKNOWLEDGMENTS

The authors wish to express appreciation to Dr. N.H.Jasper and Mr. W.S. Campbell for their critical and constructive review of this report. Mr. A.W. McIver contributed substantially by assisting with the calibration measurements and numerical calculations.

APPENDIX A

NETWORK ANALYZER DECADE CAPACITORS

CAPACITANCE MEASUREMENTS

Calibration of the network analyzer decade capacitors was accomplished, using the comparison technique for measurement. That is, instead of making direct capacitance measurements of each decade, instrumentation was selected which would compare the value of the analyzer capacitance with a known standard capacitance. This method of measurement is relatively rapid, accurate, operationally simple, and gives information in the desired form.

A Bruel and Kjoer deviation test bridge, Type 1502, nominally accurate to within 0.25 percent, was used for making the comparison. The bridge compares the value of the capacitance to be measured, with a standard capacitance. The bridge output is the difference in percent between the measured and standard capacitance including the sign, either positive or negative, and is displayed on a front panel meter.

The range of capacitance used in the analyzer is from 0.001 μf to 1.0 μf. This range was conveniently covered by using two General Radio capacitors as standards. For measuring the analyzer capacitances having a nominal value of 0.001 μf, a General Radio precision capacitor, Type 722-D, was used as the standard. For measuring the analyzer capacitances in the range from 0.002 μf to 1.0 μf, a General Radio decade capacitor, Type 219-K, was used. The two standard capacitors selected have a nominal accuracy of 1 percent.

The bridge and standard capacitors selected for making the capacitance measurements were further checked against other devices having nominal accuracies in the order of 0.1 percent. As a result of these checks it was feasible to use the General Radio capacitors as standards for the Bruel bridge and to expect accuracies of 1 percent or better.

Arranging the instruments as shown in Figure 14, every position of each analyzer decade capacitor was compared with a corresponding position of one or the other of the standard capacitors. A calibration sheet for each analyzer decade capacitor was compiled, showing the corrected value for each decade position. These sheets are available at the analyzer and are identified by the station position of the capacitor. Table 1 represents a typical calibration sheet for a decade capacitor. In this table, Column A denotes the nominal value of both the standard capacitance C_s and the analyzer or unknown capacitance C_u . Column F gives the actual or corrected value for the analyzer capacitance.

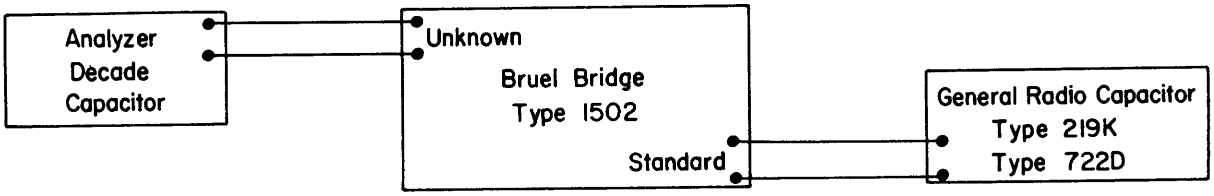


Figure 14 – Instrument Arrangement for Measuring Capacitance

TABLE 1

Calibration Table for Typical Capacitance Decade

A	B	C	D	E	F
C_s, C_u Nominal μf	C_s Actual μf	$\frac{C_u - C_s}{C_s}$ times 100 percent	$\frac{C_c}{C_s}$ times 100 percent	Col C minus Col D percent	Col B plus (Col B × Col E) μf
0.001	0.001	3.9		3.9	0.001039
0.002	0.002005	6.0	5.70	0.30	0.002011
0.003	0.003005	3.9	3.80	0.10	0.003008
0.004	0.004000	2.70	2.85	−0.15	0.003992
0.01	0.010050	1.4	1.14	0.26	0.010076
0.02	0.020000	0.4	0.57	−0.17	0.019966
0.03	0.030000	1.1	0.38	0.72	0.030216
0.04	0.039700	−0.1	0.29	−0.39	0.039545
0.7	0.700	1.9	0.02	1.88	0.713160
0.8	0.800	1.8	0.01	1.79	0.814320
0.9	0.900	1.9	0.01	1.89	0.917010
1.0	1.000	1.8	0.01	1.79	1.017900

A – Nominal value of standard and unknown
B – Actual value of standard
C – Reading on Bruel Bridge
D – Percent of error due to cable capacitance (114 $\mu\mu f$)
E – Actual percent of error in C_u
F – Actual value of C_u in μf

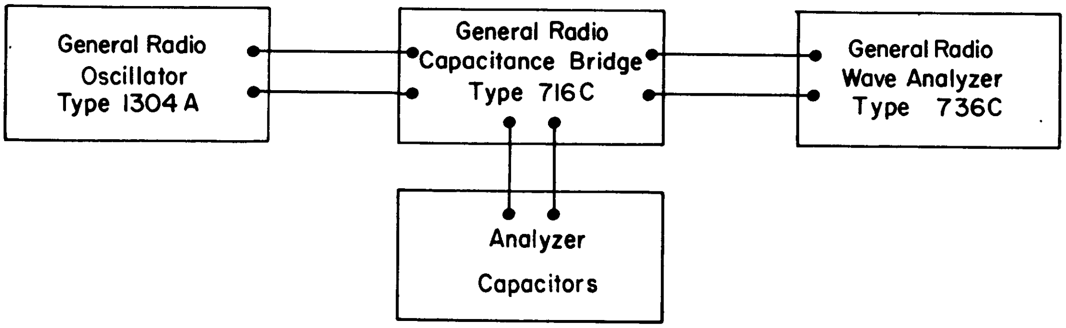


Figure 15 – Instrument Arrangement for Measuring Dissipation

DISSIPATION MEASUREMENTS

The instrumentation used to make the dissipation measurements is shown in Figure 15. A General Radio capacitance bridge, Type 716-C, was used to measure the dissipation directly. In this mode of operation, the Type 716-C can measure the dissipation factor to within ±0.0005 for values of dissipation below 0.1. The General Radio oscillator, Type 1304-A, was used to drive the bridge at 1000 cps; the General Radio wave analyzer, Type 736-A, was used simply as a null detector. With the setup described above, the dissipation for each decade capacitor in the analyzer was measured.

The resistance of the capacitors was computed from the expression

$$R = \frac{D}{\omega C}$$

where D is the capacitor dissipation in farads,

R is the d-c resistance of the capacitor in ohms, and

ω is $2\pi f$ radians/sec.

Tables showing the dissipation and resistance for each decade capacitor in the analyzer are available to the operator at the analyzer. Table 2 is typical. Column C denotes the capacitor dissipation, and Column D the nominal d-c resistance of the capacitor.

The comparison technique was used to measure the capacitance to ground of the V- and M-conductors on the analyzer. Twenty sections were connected, as shown in Figure 16, and the total capacitance of the V-conductor C_{V_t} was measured, using the Bruel bridge and the Types 722-D and 219-K capacitors as standards. The standard capacitor was varied until the comparator read 0 percent. The value of the standard at that position was read as C_{V_t}. Similar measurements were made on the M-conductor. The total capacitance of the V-conductor measured 10,236 $\mu\mu$f or 487 $\mu\mu$f for each station. This measurement shows that for accurate capacitance representation it is necessary to subtract 0.001 μf at alternate stations. The total M-line capacitance C_{M_t} measured only 2981 $\mu\mu$f, or 142 $\mu\mu$f for each station, which is negligible.

The output and drive cables were not connected when the measurements were taken. However, their effect on the value of C_{V_t} and C_{M_t} and also on the critical frequencies, when connected, was negligible. Experimentation also showed that the 500,000-ohm input impedance of the a-c voltmeter in use had negligible effect on the critical frequencies. Measurements taken using a meter with an imput impedance of 10 megohms yielded the same critical frequencies.

TABLE 2

Dissipation – Resistance Table for Typical Network Capacitors

A	B	C	D
Nominal Cap μf	Actual Cap μf	Dissipation Factor at 1 *kc*	Nominal $R = D/\omega c$ Ω
0.001	0.001044	0.0138	2197.452
0.002	0.002019	0.0092	732.484
0.003	0.003020	0.0054	286.624
0.004	0.004018	0.0038	151.273
0.005	0.005021	0.0036	114.649
0.006	0.006018	0.0028	74.309
0.007	0.007017	0.0028	63.694
0.008	0.008019	0.0025	49.761
0.009	0.009012	0.0022	38.924
0.01	0.010016	0.0019	30.254
0.01	0.010036	0.0012	19.108
0.02	0.019886	0.0009	7.165
0.03	0.030456	0.0004	2.123
0.04	0.039744	0.0010	3.980
0.05	0.050350	0.0005	1.592
0.06	0.059886	0.0005	1.326
0.07	0.070168	0.0003	0.682
0.08	0.080208	0.0007	1.393
↓	↓	↓	↓
0.8	0.811120	0.0009	0.179
0.9	0.913410	0.0005	0.088
1.0	1.01590	0.0006	0.095

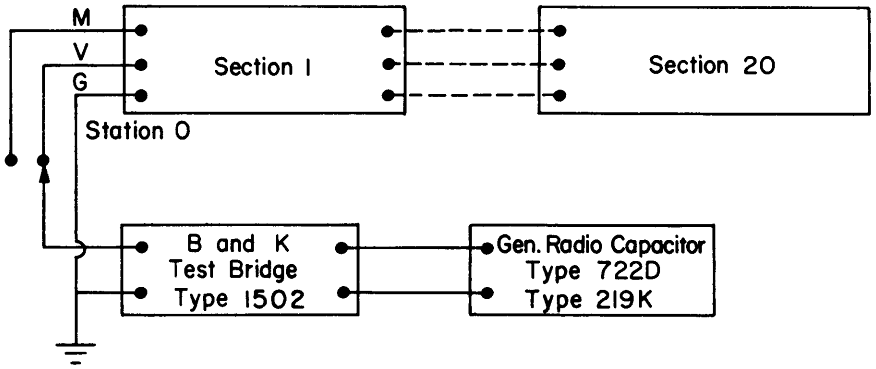


Figure 16 – Instrument Arrangement for Making Capacitance-to-Ground Measurements on V, M, and G Circuit Conductors

APPENDIX B

NETWORK ANALYZER DECADE INDUCTORS AND TRANSFORMERS

INDUCTANCE MEASUREMENTS

Measurements of the network analyzer inductances were obtained in a manner analogous to that of the capacitance measurements. A General Radio decade inductor, Type 1490B, was used as a standard for the Bruel bridge in measuring the analyzer inductors. The General Radio inductor was calibrated at the National Bureau of Standards against secondary standards accurate to within 0.2 percent of their nominal value. The calibrated or corrected inductance values L_c of the decade inductor, Type 1490B, are accurate to within 0.5 percent.

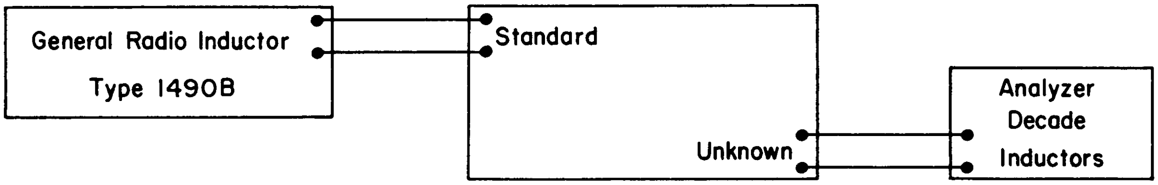


Figure 17 – Instrument Arrangement for Measuring Inductance

Arranging the Bruel bridge and the decade inductor as shown in Figure 17, the inductance L_u of every position of each analyzer decade inductor was compared with a corresponding inductance value L_c on the standard. A calibration table for each analyzer decade was compiled, showing the corrected value for each decade position. In this table L_c and L_u are nominal values of the standard and analyzer inductances, respectively. L_c (actual) is the calibrated value of the standard. Table 3 is a typical calibration. Column D denotes the corrected value of the analyzer inductance L_u . The actual tables are available at the analyzer and are identified with the inductor by station position.

INDUCTOR RESISTANCE MEASUREMENTS

A Rubicon Wheatstone bridge, Type 1052, nominally accurate to within 0.1 percent, was used to measure the resistance of every position of each analyzer decade inductor. A typical Freed inductor decade unit, of the type used with the analyzer, has a resistance range from 0.06 ohms at the 1-millihenry step to 24 ohms at the 1-henry step.

CALCULATION OF INDUCTOR Q

The Q's of the inductors were calculated for a frequency f of 100 cps from the equation

$$Q = \frac{2\pi fL}{R}$$

TABLE 3

Calibration Table for Typical Inductance Decade

A	B	C	D
L_c, L_u Nominal *mh*	L_c Actual *mh*	$\frac{L_u - L_c}{L_c}$ × 100% Actual	Col B + (Col B × Col C) *mh*
1	0.986	-1.10	0.972
2	1.981	0.50	1.982
3	2.968	-0.70	2.947
4	3.986	-0.25	3.976
5	4.985	-0.40	4.965
6	5.975	0.10	5.981
7	6.979	-0.50	6.944
8	7.965	-0.35	7.937
9	8.989	-0.35	8.957
10	9.970	-0.25	9.945
10	9.970	-0.25	9.945
20	20.019	0.65	20.149
30	29.879	0.10	29.909
40	39.910	0.25	40.009
50	49.869	0.15	49.944
60	59.849	0.40	60.008
70	69.788	0.20	69.928
↓	↓	↓	↓
700	699.983	0	699.982
800	799.673	-0.10	798.873
900	900.972	-0.15	899.621
1000	1001.965	-0.20	999.961

where R is the value of resistance measured in ohms for the particular inductance L in henrys. A typical analyzer inductor decade unit has a range of Q values (at 100 cps) from about 10 at the 1-millihenry step to about 25 at the 1-henry step. Tables denoting corresponding resistance and Q values for each analyzer decade unit are available at the analyzer. Table 4 is representative.

NETWORK ANALYZER TRANSFORMERS

Detailed measurements on the Hycor transformers used with the network analyzer have been made, but the data are not presented in this report. The complete transformer data obtained from these measurements are available in the files of the Structural Mechanics Division

TABLE 4

Typical Dissipation – Resistance Table for Analyzer Inductors

A	B	C	D
L Nominal mh	Resistance Read Ω	Col 3 − R_L Actual Ω	$Q = \frac{2\pi f L}{R}$
1	0.495	0.065	9.661
2	0.520	0.090	13.955
3	0.545	0.115	16.382
4	0.577	0.147	17.088
5	0.604	0.174	18.045
6	0.630	0.200	18.840
7	0.649	0.219	20.073
8	0.675	0.245	20.506
9	0.697	0.267	21.168
10	0.722	0.292	21.506
10	0.729	0.299	21.003
20	1.026	0.596	21.073
30	1.197	0.767	24.563
40	1.468	1.038	24.200
50	1.739	1.309	23.987
60	2.017	1.587	23.743
70	2.174	1.744	25.206
80	2.444	2.014	24.345
90	2.706	2.276	24.833
100	2.966	2.536	24.763
100	2.944	2.514	24.980
↓	↓	↓	↓
700	17.24	16.81	26.151
800	19.71	19.28	26.058
900	21.55	21.12	26.761
1000	24.02	23.59	26.621

Resistance of Lead R_L is 0.43 ohms.
Frequency------ 100 cps

at the Model Basin. Further information is available in TMB Report 1317. Pertinent data on the transformers, inductors, capacitors, and resistors that are a standard part of the TMB Network Analyzer are given in Table 5.

Since there are four transformers at each network analyzer panel and two section positions at each panel, there are twelve possible combinations for employing these transformers. To determine whether any one of these combinations causes extreme variations in the resonance frequencies, a test problem of a beam in bending without shear was placed on the network analyzer. The fundamental frequency was measured, employing each possible transformer combination. These readings were then compared with the theoretical fundamental frequency and with each other. The results of these tests showed that the interchanging of transformers on the network analyzer has negligible effect on the fundamental resonance frequency.

TABLE 5

Components of the TMB A-C Network Analyzer

	Components							
	Inductors		Capacitors		Resistors			Transformers[4]
Range or Ratio[1]	0.001–1.11	0.01–11.1	0.001–1.11	0.01–11.1	10–11,100	100–111,000	1000–1,110,000	1:1 to 1:18
Accuracy	1%	1%	1%	1%	0.05%	0.05%	0.05%	Total Series Inductance per Side, 280 henrys
Frequency Range	10 cps–5 kc	10 cps–2 kc	10 cps–15 kc	10 cps–10kc	--	--	--	10 cps–10 kc
Dissipation Factor[2]	0.01	0.007	0.002	0.001	--	--	--	Total Series Resistance per Side, 5 ohms
Number of Units on Hand[3]	85	10	100	10	20	20	10	64

[1] The resistance, inductance, and capacitance values of the decade components are in ohms, henrys, and microfarads, respectively.

[2] This is the ratio of energy dissipated to energy stored per cycle at 1000 cps.

[3] For the resistors, inductors, and capacitors the quantities indicated are the available number of three-dial decades in the ranges shown.

[4] These transformer specifications refer to 49 of the 64 transformers and were manufactured by Hycor Corp. The specifications for the remaining 15 transformers manufactured by Computer Engineering Associates, Inc. are electrically superior to the Hycor transformers, and may be found in TMB Report 1317.

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